Lessons Learned from the Great East Japan Earthquake Disaster

Report of the JSME Research Committee on the Great East Japan Earthquake Disaster

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Title		i
Preface		1
Chapter 1 **Lessons Learned from the Disaster —An Overview—**	Masaki SHIRATORI	3
Chapter 2 **Features of the 2011 Tohoku Earthquake and Tsunami**	Kojiro IRIKURA	9
Chapter 3 **Damage to Machines and Equipment, and Good Practices for Seismic Countermeasures**	Satoshi FUJITA, Izumi NAKAMURA, Osamu FURUYA, Keisuke MINAGAWA, Tetsuya WATANABE and Takayoshi KAMADA	14
Chapter 4 **Understanding the Mechanism of Tsunami-induced Damage to Machines and Structures Based on a Discipline of Mechanics**	Shinobu YOSHIMURA, Hitoshi NAKAMURA, Hiroshi KANAYAMA, Takayuki AOKI, Takehiro HIMENO, Yuzuru SAKAI, Seiichi KOSHIZUKA, Daigoro ISOBE and Hideki FUJII	24
Chapter 5 **Application of Robot Technologies to the Disaster Sites**	Hisashi OSUMI	58

Chapter	Authors	Page
Chapter 6 **Analysis of Traffic and Physical Distribution within the Disaster Areas**	Takayoshi KAMADA	74
Chapter 7 **Damages to Energy Infrastructures**	Yasuo KOIZUMI, Tomio OKAWA, Hitoshi ASANO, Takao NAKAGAKI, Jun INUMARU, Fumio INADA and Mamoru OZAWA	79
Chapter 8 **Nuclear Codes and Standards Issues and Future Perspectives**	Masaki MORISHITA	90
Chapter 9 **Crisis Management for Earthquakes, Nuclear Power Plant Accidents and Other Events**	Keiji KONDO, Masayuki NAKAO, Tsutomu ARAKI and Atsushi AKISAWA	100

Preface

The Tohoku Region Pacific Coast Earthquake and following tsunami, which occurred on March 11th 2011, caused unprecedented devastation in Japan, especially to the Tohoku and North Kanto regions. This event has become known as the Great East Japan Earthquake disaster.

Furthermore, the earthquake and tsunami seriously damaged the Fukushima Daiichi Nuclear Power Plant (NPP), resulting in the meltdown of the fuel in the reactor core, the destruction of the nuclear reactor buildings due to hydrogen explosions and large-scale release of radioactive materials into the environment, which has destroyed the lives of people living in that area. A catastrophe of this extremity has never before been experienced by Japan.

This disaster was unique in the following ways:

- The magnitude of the earthquake was enormous at M9.0.
- The scale of the tsunami caused by the earthquake was huge.
- An extensive area was affected and a great number of people suffered as a result.
- Previously unencountered challenges were met in tackling the NPP incident and controlling the release of the radioactive materials.

The Japan Society of Mechanical Engineers formed the following two committees soon after the earthquake under the direct leadership of the executive committee:

- Committee on emergent damage analyses, surveys and proposals
- Committee on long-term proposals

The members of both committees have been working from the viewpoints of:

- What the engineers and researchers who engage in mechanical engineering can learn from the disaster;
- How they can put this into practice in the future.

There were many areas to be assessed and many subjects to be addressed. In order to do this job effectively, the JSME established eight working groups (WGs) in the first committee and four in the second. In this report the authors focus their attention on the activities of the first committee, hereafter referred to as the "JSME Research Committee on the Great East Japan Earthquake Disaster".

The committee consists of the following eight WGs:

WG0: Characteristics of the Earthquake and Tsunami
WG1: Damage to Machines and Equipment and Good Practices for Seismic Countermeasures
WG2: Understanding the Mechanism of Tsunami-induced Damage to Machines and Structures Based on Mechanical Analysis
WG3: Application of Robot Technologies to the Disaster Sites
WG4: Analysis of Traffic and Physical Distribution Systems within the Disaster Areas
WG5: Damages to Energy Infrastructures
WG6: Codes and Standards Issues and Future Perspective
WG7: Crisis Management for Earthquakes, Nuclear Power Plant Accidents and Other Events

The investigation policy is such that:

- Investigations should be conducted ethically and the findings should be made accessible to all.
- Damage caused by the earthquakes and/or tsunami are investigated.
- Questionnaires and interviews are used alongside information published by the government, TEPCO, and other companies and organizations.
- Good practices to implement in the future are determined.
- Messages to the public and the JSME members should be prepared as quickly as possible.

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The committee began its activities at the end of March, 2011. Each WG worked with great motivation and gathered many data about the damages sustained. They also determined the lessons that have to be learned from the disaster and how to incorporate them into our practices in the future. The final report (in Japanese) was published at the end of July 2013 under the following title:

“Report on the Great East Japan Earthquake Disaster -Mechanical Engineering Volume-”, by the Joint Editorial Committee for the Report on the Great East Japan Earthquake Disaster, Japan Society of Mechanical Engineers, 2013.

The present report, written in English, is a summary of the above Japanese report. It has been written so that people overseas can understand what we have learned from the disaster. In the first chapter, these lessons, which are the products of the work of WG0 to WG7, are summarized in the form of four proposals. In the following chapters, the contributions of each WG are discussed in more detail.

We, the authors, appreciate the efforts of the committee and WG members whose names are listed in the Japanese report. We would also like to express our thanks to all who cooperated with us during our research, the members of the executive committee, and the office staff of JSME for their support throughout.

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Report of the JSME Research Committee on the Great East Japan Earthquake Disaster

Chapter 1

Lessons Learned from the Disaster —An Overview—

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Abstract
In this chapter four lessons learned through research are presented in the form of proposals. These were arrived at through extensive discussions between the committee members about what we, as mechanical engineers, can learn from the disaster and what we can contribute to society as a result. The four proposals are summarized as follows.

I To develop the approach to system integration of large scale systems.
II To review how the design basis is determined and how we can prepare for events beyond the scope of the design basis.
III To better inform the public about risks associated with new products.
IV To incorporate the lessons learned into our codes and standards, and foster engineers with the skills to tackle disaster related tasks, with the aim of passing these lessons on to future generations.

Keywords: Tohoku Region Pacific Coast Earthquake, Great East Japan Earthquake Disaster, Tsunami, System Integration, Design Basis, Beyond Design Basis, Risk Communication, Codes and Standards

1. Introduction

Through the activities of the working groups (WGs) we have compiled many data about damages caused by the Great East Japan Earthquake Disaster and have learnt many lessons as a result. The members of the WGs worked with great motivation, and the results of their research are summarized in the groups' reports and proposals, the details of which are given in the following chapters. When we read these reports and proposals, we find that the contents cover various areas of mechanical engineering and provide many well justified suggestions for the field's progression, particularly for preparing against earthquakes that may strike in the future. The worth of the present report stems directly from the value of the reports and proposals of each WG.

The scale of the Tohoku Region Pacific Coast Earthquake, tsunami and resulting disaster was so huge that it is impossible for the committee to consider all the areas within mechanical engineering. Therefore, the reports and proposals of the WGs describe only some aspects of mechanical engineering. The problem yet to be solved is what we, as engineers and researchers working in the field of mechanical engineering, can learn from this disaster and what messages we should send to the public. To this end, as the research of the WGs was concluding, we, the committee members, started considering these issues and through extensive discussions arrived at four proposals which are summarized below and presented in detail in the following sections.

I To develop the approach to system integration of large scale systems.
II To review how the design basis is determined and how we can prepare for events beyond the scope of the design basis.
III To better inform the public about risks associated with new products.

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IV To incorporate the lessons learned into our codes and standards, and foster engineers with the skills to tackle disaster related tasks, with the aim of passing these lessons on to the next generation.

2. Proposal I To develop the approach to system integration of large scale systems.

In large scale systems such as nuclear power plants, knowledge is integrated from various fields of science and technology. It has been proven that this integration can cause vulnerability to disasters such as earthquakes and tsunamis. In order to overcome these weaknesses, it is necessary to develop the approach to system integration of large scale systems through the training of specialists who overview the entire system, identify the weak points, and introduce the safety measures required. With this in mind, engineers and researchers who are engaged in mechanical engineering, especially the members of the JSME, should work towards efficient systematization in the field of "design science".

In most of the proposals presented by the WGs, it is highlighted that the weak points are a result of differing specialist knowledge between the experts involved. For example, mechanical engineers have not paid much attention to the threat of tsunamis in the past because they consider it to be an issue addressed in the field of civil engineering. However, the accident at the Fukushima nuclear power plant revealed many instances, such as securing a back-up power supply and ensuring that rooms can be made water tight, in which mechanical engineers could have prepared against the tsunami. It is areas such as these that are particularly affected by catastrophes. Such problems cannot be solved by specialists of any one field; we need to collect and systematize knowledge from many areas.

Generally, researchers at universities are interested in highly specialized and advanced fields. They are not so eager to incorporate perspectives from other fields. However, knowledge of system integration, in terms of design, manufacturing and operation, can be accumulated through experience in industry. For example, in the car and electronics industries of Japan, the understanding of such concepts is very high, allowing Japanese companies to compete as world leaders in their markets.

On the other hand, for industries such as nuclear power or aerospace/aeronautics, in which very large scale systems are developed, we cannot say that the understanding of system integration in Japan is sufficient. For mass-produced products like cars and electronic devices, we can accumulate knowledge through experience and repetitions of experiments. This is of course difficult for large scale systems, especially if the experiments are conducted on the same scale as the system. Recently, engineering simulations have shown the potential to overcome the difficulties inherent to such experiments. In order for engineering simulations to be really useful, an approach through which they can validly describe the behaviors of real world systems has to be established.

When the development of a large scale system begins, a team composed of specialists from many different fields is assembled. The project then progresses through the concurrent works of these specialists. In this case it could be useful to adopt the approach of program/project management to overview and manage the progress of the project. It is also essential to employ an external risk management team who oversee the project as well.

The approach to system integration can be structured in terms of the following levels:

- Individual level: research and systematization of system integration
- Team level: progression of the project
- Organizational level: policy making and being accountable for the public
- National level: implementing codes and standards and granting permissions for project go-ahead
- Global level: global standardization and business

The proposals made in the reports of the WGs concern aspects of all of these levels.

In the JSME, activities are often lead by academic researchers whose main interests lie in well recognized branches of science. As a result, there have been few motivated individuals that have challenged the approach to design science. The achievements of the majority of researchers can be put into practical use by incorporating them into codes and standards; however, most academic researchers are predominantly interested in writing and publishing papers in established journals, and lack interest in contributing in this way. Academic researchers should take more interest in the ways in which their research can directly benefit society.

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On the other hand, engineers working in industry gain experience of system integration in their daily work. Such experience may be useful for improving the approach to the system integration. Considering this, the JSME will encourage activities through which industry based engineers can combine and share their varying experiences with academic researchers and discuss how to improve, and ultimately systemize, the approach to system integration.

The committee would like to propose that the JSME promote such activities more actively. This proposal can also be adopted by companies, national laboratories and other engineering societies that are involved in the development of large scale systems.

3. Proposal II To review how the design basis is determined and how we can prepare for events beyond the scope of the design basis.

In the design of industrial products, the first step is to determine certain specifications. In terms of safety, the specifications are usually arrived at by estimating the maximum value of external loads that the product will be subjected to. It is difficult to estimate such forces for natural hazards such as earthquakes and tsunamis; thus, it is possible that the estimated maximum loads can be exceeded in extreme cases. Therefore, the following two steps need to be taken:

(1) Better estimating maximum loads and determining the design basis.

(2) Preparing for catastrophes beyond the scope of the design basis.

The lessons learned from the 3.11 disaster are that we, as mechanical engineers, should inform the public how the design basis (specifically the safety requirements) is determined and how we can prepare for accidents beyond the scope of the design basis, so that the above procedures are accepted by society.

These lessons should be applied to all large scale systems, not only nuclear power plants, but also chemical plants, railroad systems and so forth.

As for (1), the estimated values, which outline the design basis or safety requirements, are determined through assessment by a group of specialists. Assessments of this sort are made by considering the balance between the function, safety and cost of the product. The details are usually quite in depth and are therefore not accessible to the public. It is merely stated that the product is safe because the design basis was determined by specialists.

The specialists know that there is some chance, albeit very low, that the applied load exceeds the estimated value. Therefore, society should be made aware how the design basis was determined and what can be done to prepare for events not accounted for in the design basis. It is important that the design basis be accepted by society; to this end, the design basis should be determined through communication between the specialists and society, and set at a level recognized as an “acceptable risk”.

Engineers and researchers who are involved in the manufacture of industrial products should be clear that the products can never be absolutely safe. They should understand that acceptance of the product ultimately lies with society, based on the balance between risk and benefit.

As for (2), such approaches have been called “design in depth” in the field of nuclear engineering. In nuclear power plants, the design in depth with the following five levels has been recommended by the IAEA:

① Preventing the occurrence of accidents

② Preventing the expansion of accidents

③ Mitigating the effects of accidents

④ Countermeasures against severe accidents

⑤ Disaster prevention measures

In these five levels, ①～③ are known as design basis accidents (DBA) of which very careful regulation is carried out in Japan by the government. It was believed that events related to levels ④ and/or ⑤, which are known as beyond design basis accidents (BDBA), could never occur because the levels ①～③ were implemented extensively. In Japan this belief has been termed the “myth of absolute safety”. In the case of the Fukushima Daiichi nuclear power plant (1F), the measures of ①～③ failed to cope with the tsunami, and

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severe accidents followed by core melt-down occurred, resulting in the release of a large amount of radioactive materials into the environment, forcing the people living near the site to evacuate. The effects of the disaster were magnified because level ④ and ⑤ measures were not in place adequately.

The lesson learned from the accidents that occurred at 1F is that the extent to which measures against disasters are taken should be decided by society. We have to develop engineering strategies to prevent such damage. From this point on, the important considerations are to (a) determine the safety requirements for a given estimated risk, (b) present it to society, (c) concur with society on a critical damage level that cannot be exceeded, and (d) prepare for catastrophes that will exceed that level by implementing both hardware and software countermeasures.

4. Proposal III To better inform the public about risks associated with new products.

Engineers engaged in manufacturing products should predict the risk associated with and the benefit offered by a new product in the planning stage. They should make this information available to the public so that the product can be deemed acceptable. In short, they should learn the following two skills:

(1) Risk management: accurately predicting risk and preparing for it.

(2) Risk communication: informing society of risks in a way that is understandable, with the aim of gaining society's acceptance.

These skills are necessary not only for individual engineer/researcher but also for organizations such as universities, companies and governments.

The committee would like to propose that the JSME tackle this problem earnestly, provide society with the necessary information in a timely manner, and ultimately seek acceptance from society.

In modern society, people enjoy the benefits of highly advanced science and technology in the form of products used in their daily lives, but do not always understand the fundamental scientific and technological concepts behind them. As such concepts span a broader range and become more in-depth, it becomes increasingly difficult to understand them. As a result, people accept the fundamentals of science and technology without an understanding of them, which is left to the specialists, and place their interest only in the value and benefits of using the product.

As described in the previous section, when planning a new product, it is necessary to determine specifications related to the safety requirements. For example, we have to estimate the maximum external load that the product will be subjected to over its life. Specialists who design products know that situations are possible in which these critical values are exceed, although the probability is low. However, people use the products with total peace of mind* because they have confidence in the specialists claims of safety and security and are unaware that such a possibility exists. Therefore, if an accident does happen, it is difficult for the specialists to explain why or how the accident happened, and may lose credibility as a result.

The reason why nuclear power plant accidents are particularly problematic compared with incidents occurring in other more general machines and structures is the release of radioactive material into the environment. We have to recognize that the amount of radioactive material released in the 1F disaster was far over the amount allowed by society. On the other hand, it is very difficult for people to understand the explanations given by specialists concerning the health risks for humans caused by exposure to very low levels of radiation. Misunderstandings cause other social problems such as the spread of inaccurate information. It is hence the duty of the specialists to accurately and plainly inform the public so that people are aware what is true and what is not true. This will be of particular importance when decisions are made regarding the future operation of nuclear power plants and the best energy strategy for Japan.

Generally, when a new product is created as a result of newly developed technologies, the users desire it be secure and safe. Specialists try to meet these demands and reassure the users. However, the meanings of "secure" and "safe" are different. The former expresses peace of mind, which is subjective, while the latter is a concept

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that can be defined objectively and scientifically. It is needless to say that people desire a product to be "absolutely safe"; however, it is not necessarily the case that the specialists' assurances of safety and security mean this demand has been met. The specialists should not assure safety in black and white terms. They should explain that every product is designed in terms of threshold values based on safety requirements, i.e., the design basis, and that there exists the possibility that accidents outside the scope of the design basis may occur. Furthermore, they should also explain that they prepare for such accidents, and that this makes the product "safe".

Conventionally, engineers are content to communicate with each other within their own societies and circles, but lack motivation to communicate with the public. However, the 1F accident has made it clear that the benefits and risk associated with a new product should be available to the public in an accurate and easy to understand manner. In short, they should learn the following two skills:

(1) Risk management: accurately predicting the risk and preparing for it.

(2) Risk communication: informing society of risks in a way that is understandable, with the aim of gaining society's acceptance.

For risk management, approaches have been developed in various fields of engineering. For example, probabilistic risk assessment (PRA) is applied in the field of nuclear engineering. Engineers should learn these approaches as part of their basic education.

As for risk communication, engineers have not yet tackled this problem earnestly because they are of the opinion that it is more a matter for experts such as social psychologists.

However, technology is now so extensively integrated into society that engineers need to be able to communicate effectively, i.e., develop the skills of engineering/science communication. Furthermore, organizations such as the JSME should send messages to the public that are well discussed and agreed upon, that is, through a voice representative of the entire organization. It is necessary for the JSME to systematize the process through which this is done.

*In Japanese, there is a word, "anshin", that is difficult to translate into English. One interpretation is "peace of mind", as used in this document. Furthermore, there is no word for "risk" in old Japanese; we have imported the word and its concept from English and write it as "risuku" in Japanese characters. However, even now people are not accustomed to dealing with and thinking in terms of risk. Most Japanese people are content to become "anshin" following the words of specialists or governments, instead of assessing the risk themselves.

5. Proposal IV To incorporate the lessons learned into our codes and standards, and foster engineers with the skills required to tackle disasters, and ultimately pass these lessons on to the next generation.

In order to apply the lessons learned from the Great East Japan Earthquake Disaster to mitigate the effects of earthquakes in the future, the committee would like to propose that the JSME promote the practice of incorporating the results of research into the codes and standards that the JSME contributes to setting.

The committee also would like to propose that the JSME foster specialists, especially young engineers, with the talent and skills necessary to tackle disasters and eventually hand these lessons down to the next generation.

Although there were many facilities and plants that sustained damage as a result of the Great East Japan Earthquake Disaster, it was found from the research of the WGs that some of them succeed in preventing a disaster because effective safety measures were taken in advance, based on the lessons learnt from previous disasters, or because they were constructed using the stronger earthquake-proof design outlined by the technical standards that were improved following the Hanshin-Awaji Earthquake. The proposals of the WGs have thus highlighted the importance of continually learning from disaster research and improving our codes, standards and manuals as a result.

Japanese engineers must be willing to examine and constitute codes and standards themselves instead of

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importing them from western countries. Most Japanese engineers are of the mindset that the codes and standards have been constituted by someone other than themselves, which is sufficient for them to follow the rules in Japan; codes and standards have actually been constituted by the Japanese government since the Meiji period. It is now the time for Japanese engineers to modernize their way of thinking. Furthermore, it is important that engineers working in the private sector, who understand the application of technology to the manufacturing process, lead the discussions with academic societies to arrive at new, up-to-date codes and standards. Conventionally engineers from industries have had difficulty to contribute to the setting of codes and standards because they may stand to benefit financially from certain outcomes. However, the committee recommends this no longer be the case and that academic societies should create an environment in which discerning engineers from the private sector can take part in discussing codes and standards without any prejudice.

On the other hand, it is necessary for academic researchers to apply the findings of their research to the setting of the codes and standard; this is an important way through which they can contribute to society. Most researchers are satisfied publishing papers in well established journals. They are not interested in improving codes and standards because it is laborious and they don't recognize it is as an important academic activity. Academic societies need to actively dissuade researchers from this point of view. Researchers should be aware that the results of research and technological development can contribute to society through incorporation into codes and standards. At present the motivation for such work is not high because doing so is not recognized in terms of career progression, compared with publishing papers. Therefore, it is necessary to create an environment in which academic society rewards such contributions.

The committee believes it is of the utmost importance to train and foster engineers, especially young engineers, to have the skills necessary to prevent or mitigate the effects of disasters that may happen in the future.

Torahiko Terada, a famous physicist in the Meiji period, pointed out in his book, "Tsunami and Human Beings", that the reason why people who experienced multiple tsunamis in their lifetime could not avert disaster lies in the fact that the intervals with which natural disasters like earthquakes and tsunamis occur are so long in comparison to the average human life, they didn't remember their prior experience of the disaster. He went on to say that it is important for people to try to remember such experiences in order to help avoid disasters in the future. While the frequency of earthquakes that damage machines and machine systems is once every several years or even once every few decades, the frequency of events like the Great East Japan Earthquake Disaster is much lower. It is said that earthquakes of this magnitude occur once every thousand years. Therefore, it is important to keep current the knowledge and lessons learnt from past events. To this end we must foster engineers, especially young engineers, to promote research for improving safety measures by continuously utilizing this knowledge, and ultimately hand it down to future generations. It is not enough to simply prepare manuals. Actual training is important to increase peoples' ability to cope with disasters.

The committee would like to propose that the JSME coordinate an effort from the academic, governmental and industrial sectors, and organize the results of the research obtained by the WGs into codes and standards that will help prevent and mitigate the effects of disasters to come. The committee also proposes that the JSME encourage the fostering and training of young engineers so that they gain the skills to tackle disasters in the future.

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Chapter 2
Features of the 2011 Tohoku Earthquake and Tsunami

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Abstract
A giant earthquake of moment magnitude (Mw) 9.0 occurred off the Pacific coast of Tohoku on March 11, 2011, and is the largest earthquake on record to strike in or near Japan. The huge tsunami generated by this earthquake struck the east coast along Tohoku, and left more than 19,000 people either dead or missing. The tsunami waves were also responsible for severe accidents at the Fukushima Daiichi Nuclear Power Plant, which further intensified the scope of the disaster. More than 120,000 houses and buildings were destroyed and more than 240,000 were partially collapsed. While plenty of buildings were damaged by the earthquake, a majority of the damage to buildings was caused by the tsunami.

Keywords : Moment Magnitude, Tsunami, Strong Ground Motion, Catastrophic Damage, Seismic Hazard Map, Earthquake Headqurter, Cental Disaster Management Council, Disaster Prevention Plan

1. Introduction

The earthquake of moment magnitude (Mw) 9.0, which struck off the Pacific Coast of Tohoku on March 11 2011 at 14:46 (Japan time),was the largest recorded in Japan's history. It was named the 2011 off the Pacific coast of Tohoku earthquake, hereafter called "the 2011 Tohoku Earthquake". The strong motions and tsunamis generated from this earthquake caused significant damage throughout wide regions from Tohoku to Kanto. Cabinet approval was given to name the disaster caused by the earthquake the "Great East Japan Earthquake." With the strong motions it generated, a maximum seismic intensity of 7 was observed at a station in Kurihara city of Miyagi Prefecture close to the hypocenter, while an intensity of upper 6 was observed over a wider area spanning the four prefectures: Miyagi, Fukushima, Ibaraki and Tochigi. Tsunami run-up heights up to a maximum of 40 m were also recorded around Miyako City on the Sanriku Coast, with waves reaching 10 m and higher along the approximately 500 km stretch of coast from Chiba to Aomori Prefectures. The coast along northern Miyagi through northern Iwate Prefectures in particular was hit by tsunami waves reaching 20 m and higher. Despite Iwate and Miyagi Prefectures boasting the world's most advanced tsunami countermeasures, those regions suffered catastrophic damage. More than 19,000 people were killed or lost, around 400,000 houses were fully or partially destroyed, up to 500,000 residents were evacuated, and the economic cost of the damage reached a staggering 16.9 trillion yen. One of the most substantial features of this great earthquake was the fact that around 90% of its victims perished due to drowning by the tsunami. It is this point in which it deviates significantly from the Great Kanto Earthquake (in which 90% of the victims died in fires) and the Great Hanshin Earthquake (in which 80% were crushed by collapsing buildings). Moreover, the accident at the Tokyo Electric Power Company (TEPCO) Fukushima Daiichi Nuclear Power Plant (hereinafter referred to as "Fukushima Daiichi Plant") was a direct result of the tsunami.

2. Outlines of the 2011 Tohoku earthquake

The Japan Meteorological Agency determined the hypocenter of the earthquake to be at latitude 38°6'12"N, longitude 142°51'36"E, approximately 130 km east-southeast of the Oshika Peninsula, at a depth of 24 km. Detailed analysis of aspects such as the seismic waves, crustal deformation and tsunami waveforms generated by the earthquake

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revealed that the rupture propagated for around 180 seconds over a wide area spanning approximately 500 km in length and 200 km in width, at the boundary of the North American Plate and Pacific Plate, which runs along the Japan Trench off the coast of Tohoku, and that substantial slipping occurred between the two plates, exceeding 50 m at its greatest. As the Pacific Plate sinks below the North American Plate, on which Tohoku, Japan is situated, at an annual rate of approximately 8 cm, strain accumulates. The cumulative strain over 300 to 600 years as tens of meters of slipping occurred was ultimately released, all at once, in this earthquake.

After the Great Hanshin Earthquake of 1995, the Government pursued the promotion of earthquake research, observation and disaster mitigation in Japan with serious determination, through the Headquarters for Earthquake Research Promotion (hereinafter referred to as the “Earthquake Headquarters”). Each year since 2005, the Earthquake Headquarters has published long-term forecasts of earthquake activity and the National Seismic Hazard Maps for Japan (Figure 1: HERP, 2010) [(1)], based on efforts including investigation of active inland and off-shore faults and examination of historical and geological records of subduction earthquakes. The long-term forecast for subduction earthquakes off the Pacific Coast of Tohoku that was released prior to the great earthquake divided the region into about six zones and predicted a 99% probability for an earthquake of around M7.5 off the coast of Miyagi Prefecture (off-Miyagi zone), 80–90% for an earthquake of around M7.7 south of the Sanriku Coast and east of the off-Miyagi zone (Southern Sanriku zone), a larger earthquake of around M8.0 presumed when generated by the combination of these two expected focal zones, off-Miyagi and Southern Sanriku, 7% or lower for an earthquake of around M7.4 off the coast of Fukushima Prefecture (off-Fukushima zone), 90% or more for an M6.7–M7.2 earthquake off the coast of Ibaraki Prefecture (off-Ibaraki zone), and around 20% for a tsunami earthquake of M8.2 near the Japan Trench from the coast of Sanriku to Boso. Since the hypocenter of the Tohoku Earthquake was located in the region between the off-Miyagi and southern Sanriku zones, where a high probability of earthquake occurrence had been predicted, we may regard the predictions of the location of earthquakes occurring as a partial success, and yet the rupture was not limited to that region. In fact, the rupture extended to all six of the divided forecast zones, from off-Iwate and Miyagi Prefectures and the Southern Sanriku zone, to off-Fukushima and Ibaraki Prefectures and near the Japan Trench from off-Sanriku coast to off-Boso Peninsula. Consequently, although the scale of the earthquake was predicted to be around M8.2 at its largest, it was in actuality M9.0. Considered in terms of energy, we find a discrepancy by as much as 15 times between the forecast and reality, which is quite a failure in the prediction of scale.

The Earthquake Headquarters has made its long-term forecasts for the source area of the Tohoku Earthquake, using only the historical earthquake activity data for the past 400 years, over which the level of accuracy is at its highest. In principle, it was not possible to forecast subduction earthquakes that exhibit long activity cycles exceeding 400 years. The problem has been known since before the Tohoku Earthquake struck, so investigative research on paleoseismicity and paleotsunamis commenced by examining tsunami deposits in order to extend the period for historical earthquake activity data, but the Tohoku Earthquake occurred before the results were released.

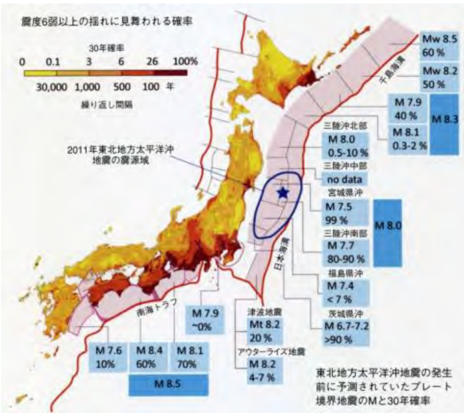

Figure 1. Long-term assessment of subduction earthquakes and National Seismic Hazard Maps (2010 version)

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3. Tsunami that caused catastrophic disasters

Data on the heights of tsunamis for 5,900 points along the Japanese coast were compiled and published by the Tohoku Earthquake Tsunami Joint Survey Group (Figure 2: TTJS, 2011)[(2)]. Tsunami run-up heights up to a maximum of 40 m were also recorded around Miyako City on the Sanriku Coast, in addition to which, tsunami waves were recorded at more than 20 m in height along the stretch of coast of approximately 200 km from northern Miyagi through northern Iwate Prefectures, and more than 10 m along the approximately 500 km of coast from Chiba through Aomori Prefectures. The tsunami also caused flooding in the Sendai Plain in Miyagi Prefecture, which penetrated 5 km inland from the coast.

The Tohoku Earthquake was an "unexpected," great M9-class earthquake, the likes of which had never previously been recorded in Japan, and yet, in terms of the tsunami, the Meiji Sanriku Earthquake that occurred on June 15, 1896 was accompanied by a huge tsunami that struck the Sanriku Coast, having a height that was roughly the same as that of the 2011 tsunami. The Meiji Sanriku Earthquake was by no means large in scale, at M7.2 based on the magnitude of strong ground motions, but it is known to have caused a huge tsunami that killed 22,000 people, primarily in Iwate Prefecture. This number surpasses the death toll of the Great East Japan Earthquake.

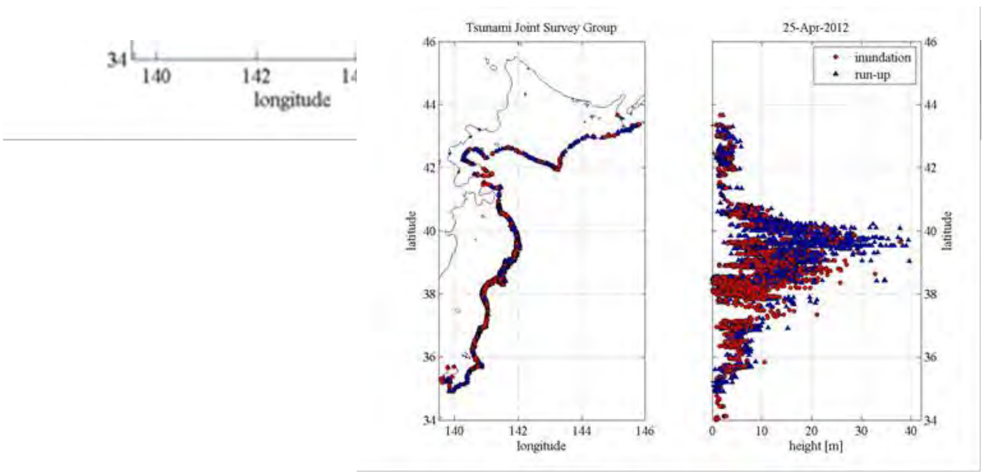

Figure 2. Results of tsunami survey by the Tohoku Earthquake Tsunami Joint Survey Group. Blue triangles indicate run-up height; red circles indicate inundation depth.

A tsunami warning for the Tohoku earthquake was broadcast at 14:49 by the Japan Meteorological Agency, 3 minutes after the earthquake occurred, predicting tsunami waves up to 6 m in Miyagi Prefecture, 3 m in Iwate and Fukushima Prefectures and 1 m along the Pacific Coast of Aomori Prefecture. The warning was transmitted on television and radio, as well as to the local authorities along the coast via a dedicated line, raising awareness among residents by disaster prevention wireless systems and other methods. Many people who felt the strong shaking caused by the earthquake fled to higher ground after receiving the warning. However, the predicted height of the waves was 3–6 m, so some people failed to evacuate as they had faith in the breakwaters, while others escaped to evacuation sites at low elevation, not far from the coast. Consequently, a great number of people lost their lives when the tsunami inundated the coast. The observational data of the Japan Meteorological Agency, which stated that the first waves of the tsunami were 0.2 m, has also been criticized for leading to delayed and cancelled evacuation by some. At 15:14, 28 minutes after the earthquake, the Agency revised its predicted tsunami heights to at least 10 m, 6 m and 3 m for Miyagi, Iwate and Fukushima, and Aomori Prefectures, respectively, based on data from GPS wave recorders situated on the seabed. Then, another 14 minutes later, at 15:30, it was determined that the tsunami waves along the Pacific Coast from Iwate Prefecture to the Boso Peninsula would be at least 10 m. The first warning update had been directly prior to the

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first tsunami waves reaching land on the Sanriku Coast. However, the strong ground motions from the earthquake had caused power outages over a wide area, and people had already started to evacuate, so the updated information did not adequately reach the inhabitants who lived along the coast (Imamura and Anawat, 2012)[3].

The Fukushima Daiichi Plant lost all of its power due to the strong ground motions and tsunami waves at around 15 m in height, and was unable to cool its reactors. This led to a catastrophic accident involving a core meltdown, hydrogen explosions and the release of radioactive material. The main facilities of the Fukushima Daiichi Plant were sited 10 m above sea level. In order to ensure safety against tsunamis, it was assumed that the height of tsunami waves would be 6.1 m, based on the "Tsunami Assessment Method for Nuclear Power Plants in Japan" by the Japan Society of Civil Engineers and assuming future incidents to be similar in degree as the earthquake that occurred off the coast of Fukushima Prefecture in 1938 (M7.5). In the long-term forecast by the Earthquake Research Committee, the possibility was raised that a tsunami earthquake like the Meiji Sanriku Earthquake could occur at any points along the Japan Trench, so TEPCO estimated that if such an earthquake were to occur off the coast of Fukushima Prefecture, the maximum height of the tsunami waves at the Fukushima Daiichi Plant would be 15.7 m. However, the fact that it was not known whether tsunami earthquakes had occurred in the area in the past meant that the possibility itself was thought to be low, and so no specific countermeasures were taken (Satake et al.2013)[4].

4. Characteristics of strong ground motions

The strong ground motions associated with the Tohoku earthquake were extended to the Kanto Region as well as the Tohoku Region; in fact, they were recorded at more than 1000 strong motion stations over almost the entire country (NIED, 2011)[5]. The fact that the peak ground velocity (PGV) and peak ground acceleration (PGA) of the earthquake attenuated with distance is roughly equivalent to the attenuation-distance decay observed in the 2003 Tokachi-oki Earthquake (Mw 8.3). Accordingly, although the moment magnitude of the present earthquake was 9.0, when considered based on the empirical attenuation-distance curves, i.e. Ground Motion Prediction Equations for the PGV and PGA of strong ground motions, it is actually around 8.3 (NIED,2011)[6].

Several wavepackets consisting of distinctive isolated-pulse-waves observed in the strong motion waveforms for this earthquake have been understood based on the forward modeling to be generated from five strong motion generation areas distributed over the source fault plane. These strong motion generation areas are found to the west of the hypocenter, located deep in the seismic fault and arranged along the down-dip edge. Meanwhile, inversion analyses by many authors using very long-period data such as crustal deformation and tsunami data have led to results that show a large slip area is present further east of the hypocenter, near the Japan Trench, where the source fault is shallow. These observations suggest that mega-thrust subduction earthquakes such as this have a period-dependent source model (Kurahashi and Irikura, 2013)[7]. This result provides important information for the prediction of strong ground motion for future mega-thrust subduction earthquakes.

5. Preparation for future large-scale earthquakes

In its capacity as headquarters for disaster-prevention matters, the Central Disaster Management Council, established in the Cabinet Office, formulated the Basic Disaster Prevention Plan, set out and implemented guidelines for disaster-prevention and emergency-response measures, guidelines for reconstruction and restoration measures, as well as a measure for the prevention of, and reduction in damage caused by, earthquakes and tsunamis in Japan.

In an effort to prepare against large-scale earthquakes and tsunamis following the Tohoku Earthquake, the Central Disaster Management Council has taken the lessons learned from the enormous loss of life and extensive material damage inflicted by a great M9 earthquake that could not be predicted, as an opportunity to deliberate on the largest

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category of earthquakes and tsunamis, taking into account all eventualities, based on paleoseismic investigation and other scientific findings. Meanwhile, the Council took the premise that tsunamis fall into two levels, specifically, tsunamis that occur with high frequency, and low height, but that nevertheless cause significant damage (L1 tsunamis), and the largest category of tsunamis, which occur at very low frequency, but cause enormous amounts of damage (L2 tsunamis). Its conclusion is that to protect residential properties and economic activity, as well as human life against L1 tsunamis, tangible, “hard” improvements are to be made, such as the installation of breakwaters, whereas for L2 tsunamis, the protection of human life is the foremost priority, and intangible, “soft” efforts such as the development of hazard maps, implementation of disaster-prevention training and designation of evacuation centers are required (CDMC, 2011)[8].

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Chapter 3

Damage to Machines and Equipment, and Good Practices for Seismic Countermeasures

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Abstract

Based on the investigations conducted by the JSME, it was found that the damage to mechanical structures resulting from the 2011 Great East Japan Earthquake was due to the movement of the ground, soil deformation and subsequent tsunami. Damage caused by the ground motion, such as that at the base of machines, the failure of pipe supports, the buckling of tanks and the failure of hook bolts in crane rails was found to be widespread. The soil deformation caused buried pipes to break and gantry crane rails to misalign. The tsunami also caused various damages, such as broken equipment due to collisions with floating objects and damage to tanks caused by the water pressure. Power system damage caused by electrical short circuiting also occurred. Although the earthquake caused a great deal of damage, seismic countermeasures taken in advance mitigated damage at some facilities. In this section, an overview of the damage to industrial facilities caused by the Great East Japan Earthquake is presented and the effectiveness of the countermeasures that were in place is summarized.

Keywords : Damage investigation, Industrial facilities, Damage due to strong seismic motion, Damage due to soil deformation, Tsunami damage, Seismic countermeasure

1. Introduction

A devastating earthquake of Mw 9.0 hit the Tohoku region, the north-eastern part of Japan, on March 11, 2011 (The 2011 Great East Japan Earthquake, hereinafter referred to as the GEJE). The earthquake and subsequent tsunami killed approximately 16,000 people and 3,000 more are still missing. The economic damage was estimated to be about 16.9 trillion yen not including the costs associated with the nuclear accident at Fukushima Daiichi Nuclear Power Plant (Cabinet Office, 2012). Industrial facilities, power plants, and research facilities were damaged, as were various kinds of mechanical equipment located at these facilities. The Japan Society of Mechanical Engineers (JSME) formed an investigative committee to study the seismic damage to mechanical equipment at these facilities to elucidate in detail the mechanisms through which the damage occurred and improve the level of preparedness for future earthquakes.

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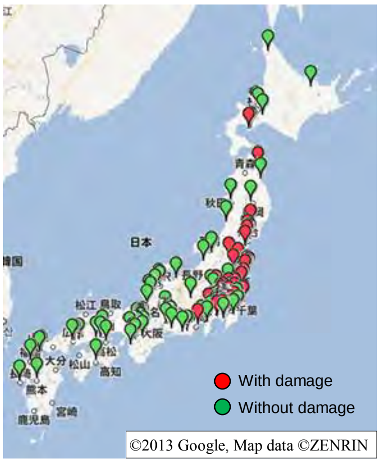
Working Group 1 (WG1) of the committee mainly conducted damage surveys of industrial facilities, including on-site investigations. In this section, an overview of the damage to industrial facilities and mechanical structures caused by the GEJE is presented and the effectiveness of the countermeasures employed is described.

2. Overview of the seismic damage to industrial facilities caused by the 2011 Great East Japan Earthquake

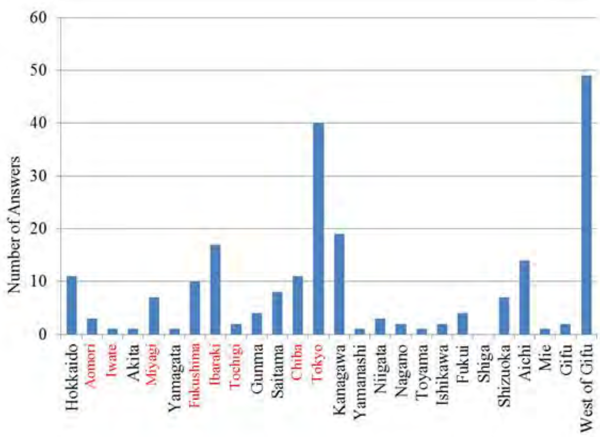
The JSME distributed a questionnaire to investigate the influence of the earthquake on industrial facilities about two months after the earthquake. The questionnaire was sent to about 1,000 organizations, and around 200 of them responded. Figure 1(a) shows a map of Japan and the questionnaire answers, and Fig. 1(b) shows the number of questionnaire answers for each prefecture. In Fig. 1 (a), the red marks denote damaged facilities and the green marks denote facilities that did not sustain damage. In Fig. 1 (b), the prefectures shown in red characters were the "disaster-stricken regions" where the Disaster Relief Act was applied. Although the questionnaire responses were mainly from the Kanto region and the numbers of answers obtained from the seriously tsunami-damaged areas in Iwate, Miyagi, and Fukushima were relatively small, some features of the seismic damage caused by the GEJE and other important knowledge was obtained from the various answers.

Based on the questionnaire and investigations of many sites, it was found that the damage to industrial facilities was mainly caused by one of the following causes or a combination thereof: strong seismic motion, soil deformation, and the tsunami. As for the damage caused by the movement of the ground, there were many cases at bases and supporting members of structures, pipes, cranes, shutters, and lifting machines such as elevators. Some damage was caused by the sloshing of liquids such as molten solder and spillage from liquid storage tanks. Troubles were reported that arose from machines slipping from fixed locations or being titled or disturbed from their upright/flat positions, even if they were not actually broken as a result. Such machines had to be adjusted and recalibrated after the earthquake. In addition, there were some cases in which evacuation was hampered by scattered tools, even when equipment damage did not occur. As for the effects of soil deformation, many cases of foundation damage due to liquefaction and damage to buried pipes were reported. In areas not devastated by the tsunami, problems mainly affected the vulnerable equipment or parts that had insufficient seismic capacity. In the tsunami-affected areas, however, all equipment, regardless of type, was damaged.

Very large areas in Japan were simultaneously affected by the GEJE. The total area of the "disaster-stricken region" to which the Disaster Relief Act applied amounted to more than 12% of the total area of Japan. Many organizations had problems continuing operation because both their primary and backup facilities suffered. Many facilities that were



(a) Seismic damage distribution for industrial facilities (as of June 15, 2012)



(b) The number of questionnaire responses by region

Fig. 1 Results of the JSME questionnaire

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relied upon to repair damaged machines or produce replacement machines also suffered from the earthquake, so a long time was needed for industrial operation to fully resume. In addition, the rapid recovery of industries was hindered by the stoppage and shortages of electrical power, water and fuel supplies. The questionnaire answers showed that the disruption of the supply-chain affected production activities in western Japan that were not directly affected by the earthquake. Large aftershocks frequently occurred after the main shock of March 11, most notably on April 7 and April 11, and often caused additional damage to industrial facilities. Several facilities suffered more severe damage due to the aftershocks than from the main shock.

It took from one to several days to determine the extent of the damage to many facilities in the disaster-stricken region. Though the questionnaire was distributed about two months after the earthquake, several organizations answered that they had not yet determined the full extent of the damage sustained. In addition to the damage to facilities, most organizations said that their employees had trouble commuting to work by both car and train after the earthquake, because of the low availability of gasoline in the first one or two weeks after the earthquake, and because of the disruption to public transportation caused by the planned blackouts.

Communication interruptions/convergence and electrical power outages occurred as a result of the earthquake. As a result many organizations said that securing means of communication was an important future task. Mobile phones and mobile text-messaging helped organizations contact their staff during the electrical power outage. It seems that private lines worked well as a way to maintain contact between main offices and branch offices, although some systems that relied on an electrical power supply were ineffective due to the blackouts. About 60% of the organizations who answered the questionnaire had prepared an emergency manual, and about 80% said that this manual was helpful to a greater or lesser extent in responding to the disaster, although a few of them said it was not helpful at all. The problems with the manuals were related to the estimated scale of the disaster, maintaining stocks of food, water and fuel, long-term power outages or shortages, and disaster training. Many organizations that did not have a manual answered that it was necessary to prepare such a manual soon.

The damage caused by the GEJE was varied in type and widespread as described above. In the following sections, the most common types of damage sustained by mechanical structures are discussed.

3. Damage to mechanical structures

3.1 Damage due to the strong seismic motion

Figure 2 shows the damage at the base of a circulation pump. The concrete base and cast iron base were broken, and the anchor bolts were deformed by the seismic motion. Figure 3 shows an example of the deformation of an anchor bolt, and Fig. 4 shows the deformation of a steel base of a FRP tank. In many cases, equipment installed on the roofs of buildings, such as air conditioning units, had collapsed or failed because the seismic response of buildings tends to be amplified at the top. Figure 5 shows examples of such damage. This kind of damage, which is related to bases and anchors, mainly occurred due to a lack of consideration of earthquake resistance when installing the equipment. Figure 6 shows damage to the anti-vibration bar of a boiler. The boiler was suspended from the upper position only in order to allow for heat expansion during operation; consequently the seismic response was large and the body of the boiler collided with the anti-vibration bar, damaging it.

Figure 7 shows the failure of pipe supports and Fig. 8 shows damage to utility pipes. The failure of the pipes occurred mainly at the pipe supports or connections with other equipment. The leakage of water from the damaged pipes often caused secondary damage such as moisture damage to books and documents or problems with electrical equipment. To prevent such secondary damage, it is necessary to consider the facility layout in the planning stage as well as the seismic resistance of the piping system. Another pipe-failure mode was related to soil deformation and is described in section 3.2. Figure 9 does not show pipe failure itself, but rather failure related to a pipe's seismic response. The different seismic responses of the pipes and the building caused damage at the inner wall.

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The buckling failure of tanks has been reported after previous earthquakes, such as the 1995 Kobe Earthquake and the 2007 Niigata-ken Chuetsu-oki Earthquake; this failure mode was also found to result from the GEJE. Figure 10 shows the buckling failure of a 2,000 m^3 water tank (Thermal and Nuclear Power Engineering Society, 2011). This

Fig. 2 Damage at the base of a pump

Fig. 3 Deformation of an anchor bolt
(Provided by JAXA)

Fig. 4 Deformation of the steel base of a FRP tank

Fig. 5 Failure of a water tank installed on a roof

Fig. 6 Damage to the anti-vibration bar of a boiler

Fig. 7 Failure of a pipe support (in-house hanging pipe)

Fig. 8 Failure of a utility pipe and water leakage
(Provided by JAXA)

Fig. 9 Damage to inner walls by pipes
(Provided by JAXA)

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failure was caused by the aftershocks on April 11 and 12. There were some tanks that did not sustain damage, despite being located in the same prefecture as the failed tanks. Thus, it is necessary to investigate the cause of these failures taking into account the characteristics of the seismic motion along with other factors. The damage investigations at hazardous material facilities were conducted and summarized by the National Research Institute of Fire and Disaster. According to their report, the damage caused by sloshing liquids occurred in the Tokyo Bay area and the Sea-of-Japan side of North Japan (Nishi, 2012).

Cranes and unloaders were also damaged by the earthquake and damage investigations were conducted by the Japan Crane Association (JCA) (Japan Crane Association, 2011). Figure 11 shows the number of damaged cranes with respect to crane type, revealing that it was mainly overhead cranes that were damaged by the seismic motion. Figure 12 shows a typical failure of an overhead crane. The hook bolts that held the crane rail deformed or fractured. Figure 13 shows another failure mode of an overhead crane. The failure occurred at the welding point at the suspension of the crane rail.

Fig. 10 Buckling failure of a 2,000 m^3 water tank
(Thermal and Nuclear Power Engineering Society, 2011)

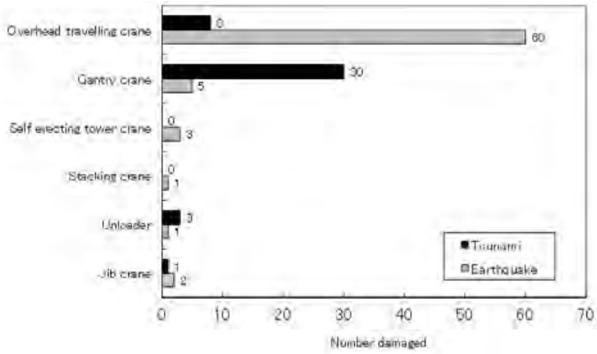

Fig. 11 Number of damaged cranes by type

Fig. 12 Elongation of a hook bolt

Fig. 13 Failure mode of an overhead crane (fallen rail)

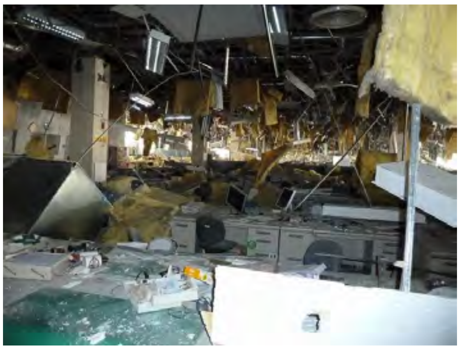

Fig. 14 Fallen ceiling materials

Fig. 15 Failure of cable racks

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Elevators are mechanical structures that require a high level of seismic safety. Typical damage to elevators included the jamming of cables, the deformation of rails, and derailing. The damage to elevators was investigated by the Japan Elevator Association (JEA) (Miyata, 2012) and the relation between the percentage of elevators damaged (damage ratio) and the applied seismic design guideline was analyzed. It was found that the damage ratio was about 3% for elevators constructed in accordance with the guidelines used before 1981, but only 2.36% for elevators constructed in accordance with the guidelines used from 1981-1998. The damage ratio of elevators constructed in accordance with the latest revision in 2009 was just 1.13%. It is clear that the damage was mitigated to some extent by both the previous and latest revision to the seismic design guidelines. In addition, an escalator reportedly collapsed, that is, became detached from its fixings in a large shopping centre in Miyagi Prefecture, but a detailed investigation of the incident has not yet concluded.

The ceilings and walls of factory buildings and equipment hung from the ceilings such as cable racks and air-conditioning units were also damaged. Figures 14 and 15 show some examples of these types of damage. Such incidents led to human injuries, secondary damage to machines, and hindered the resumption of business operations.

3.2. Damage due to soil deformation

During the GEJE, liquefaction was observed in many areas (Yasuda and Harada, 2011). Ports and embankments were also severely damaged by liquefaction, seismic motion, and the tsunami (Yoshida, et al, 2011, Murakami, et al, 2011). Much of the damage caused by soil deformation was observed in industrial facilities. Figure 16 shows a pipe support hanging from a pipe due to the subsidence of the surrounding soil. In this case, the pipe did not fail because the strength of the pipe itself was sufficient. Pipes which run out from buildings into the surrounding soil were often damaged by the relative displacement between the building and the soil. Figure 17 shows pipes fractured at the point of connection of the building and soil, due to the subsidence of the soil. Figure 18 shows a deformed quay wall and the misalignment of the unloader rail. In this case, the crane was unserviceable after the earthquake because it could not

Fig. 16 Uplift of a pipe support base due to ground subsidence

Fig. 17 Pipes fractured at the connection point of the building and soil

Fig. 18 Quay wall deformation and misalignment of the unloader rail

Fig. 19 Damage to road due to ground subsidence

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run on the deformed rail, although the crane itself was undamaged. There were many cases in which damage was observed at smaller facilities that surrounded larger or more important sites. This is mainly because the satellite facilities are set on different bases from the main facilities, for which less consideration is given to seismic countermeasures. Such instances were common in previous earthquakes also. Although not a mechanical structure, damage to a road in a research facility is shown in Figure 19. In this case large soil deformation slowed recovery, because the heavy machines necessary for making repairs could not be transported to the facility via the damaged road.

3.3. Damage caused by the tsunami

Many factories and plants are located on the coast because of the numerous advantages such a location offers in terms of the transportation of materials or products and access to coolant water. For this reason, however, many facilities were devastated by the tsunami, forcing the suspension of operation for a long time after the disaster. Although the number of cases investigated by the JSME committee was small, common types of damage caused by the tsunami were identified.

Typical occurrences were the breakage of equipment through collisions with floating objects, tanks being damaged or swept away (water, oil, gas), buckling failure of tanks due to buoyancy, and unloader wheels derailing. Power system damage resulting from short-circuiting of electrical lines also occurred due to tidewater flooding. Figure 20 shows the lifting-damage sustained by a 60-ton LPG tank (manufactured in 1974) due to its buoyancy. The sea was located at the left side of Fig. 20, and it seems that the anchor bolt was stretched by buoyancy and then deformed by the force of the tsunami arriving from the left. A 50-ton tank (manufactured in 1992) near the damaged tank was not damaged due to the larger diameter of its anchor bolts. The failure mode shown in Fig. 20 may be mitigated in the future by an adequate anti-tsunami design. Figure 21 shows tanks washed away by the tsunami and Fig. 22 (Tokyo Electric Power Company, 2011) shows the buckling failure of a water tank due to the pressure of the water. Figure 23 also shows the failure of a FRP tank supposedly caused by water pressure. An example of damage due to collisions with floating objects is shown

Fig. 20 Lifting damage to LPG tank by tsunami

Fig. 21 Tanks washed away by tsunami

Fig. 22 Buckling failure of a water tank due to the water pressure (Provided by TEPCO)

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in Fig. 24 (Japan Crane Association, 2011). This container crane had an isolation system at the bottom and was not damaged by the seismic motion. However, wreckage hit the cover of the device and deformed it. Salt damage also occurred due to tidewater flooding. In many cases, electrical systems and devices including power panels required inspection, cleaning, and replacement after the tsunami. In addition, the large amount of rubble left after the tsunami hindered the disaster-relief at industrial facilities (Thermal and Nuclear Power Engineering Society, 2011). The tsunami affected near-sea level facilities, but no damage was sustained by elevated sites. Thus, it is effective to install essential equipment in elevated areas.

Fig. 23 Failure of a FRP tank caused by the tsunami

Fig. 24 Damage due to collisions with floating objects (Provided by TEPCO)

3.4. Good practice

Although many industrial facilities and mechanical structures were damaged by this earthquake, the damage sustained by some facilities was mitigated by seismic countermeasures put in place before the earthquake. Many organizations took safety precautions such as fixing machines and furniture to the floor or building walls and preventing objects from falling from racks. Anchor bolts of a diameter sufficient to withstand seismic motion were effective for securing machines. As described in section 3.2, many pipes were damaged by the relative displacement between buildings and the surrounding soil. In such cases, flexible pipes such as those shown in Fig. 25 effectively overcame the problem. The application of base isolation systems or vibration control devices was also effective for reducing the movement of mechanical structures. Figure 26 shows an example of a vibration control brace in a facility building.

Many organizations said in their answers to the questionnaire that they had troubles due to the blackouts. In a factory that WG1 investigated, seismic shutoff valves were installed in flammable gas lines. These valves were designed to work mechanically, not requiring an electrical control, for such seismic events followed by electrical power outages. These valves worked effectively following the GEJE. The design of this factory also incorporated features that

Fig. 25 Flexible pipes

Fig. 26 Vibration control brace

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shutoff the flammable gas and vent the nitrogen gas in seismic events. Accommodating such features at the planning stage of future industrial facilities could prevent disasters to come.

Another good example of planning was seen in factories with raised walkways running along the outside of the buildings. The walkways prevented fractured wall materials from falling on persons and machines, and provided evacuation routes in addition to the corridors in the building. The additional access provided by the walkways aided in the resumption of operation at the factories. Of course, seismic designs in the initial facility construction plans are both essential and effective for mitigating the damage to mechanical structures caused by seismic motion, as are the elevator guidelines described in section 3.1. Equipment that was designed well in this sense sustained overall less damage during the GEJE. Reviewing past seismic damage and continuously rechecking the state of a facility is necessary and effective for improving seismic safety.

4. Recommendations for the seismic safety of mechanical structures

Based on the investigations into the damaged caused by the GEJE, the following recommendations have been made for mitigating the seismic damage to mechanical structures caused by earthquakes in the future.

(1) Promotion of seismic countermeasures
In order to prepare for possible future earthquakes such as the Tokai, Tonankai, and Nankai trough earthquakes as well as those occurring directly beneath the Tokyo metropolitan area, it is necessary to promote the implementation of seismic countermeasures in mechanical structures. It is also important to prepare emergency manuals and carry out emergency drills based on the manuals.

(2) Take measures to mitigate the damage caused by soil deformation
A lot of damage occurred to the bases of machines and buried pipes due to soil deformation resulting from liquefaction or subsidence. It is necessary to take measures to mitigate this damage.

(3) Preparation for tsunamis
A fundamental and effective countermeasure to tsunami damage is simply to install essential equipment at elevated locations. In addition to such countermeasures, it is also important to consider safety operations that are put into action when a does occur tsunami, for example, the safe evacuation of staff from the facilities.

(4) Preparations for electric power outages
Electric power failure can occur on a large scale as a result of earthquakes. It is important to stock fuel for emergency power generators. With the assumption that there will be no power in emergency situations, fail-safe designs for emergency shutdown valves that contain hazardous or flammable material must not require electricity. It is also important to improve the reliability of the electric power grid and power stations during seismic events.

(5) Continuation of disaster prevention research for mechanical structures and ensuring damage survey data accessibility
Investigations into the damage sustained by mechanical structures due to natural disasters are fairly uncommon in the field of mechanical engineering. The JSME should support the members conducting disaster prevention research to foster young researchers in this field and ensure the data obtained by the damage survey is maintained and kept easily accessible.

5. Conclusion

The damage sustained by industrial facilities and mechanical structures in the 2011 Great East Japan Earthquake was summarized. From a questionnaire and many on-site investigations, we can conclude that the damage to industrial facilities was mainly caused by one or a combination of the following: strong seismic motion, soil deformation, and the

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tsunami. Although a great deal of damage occurred, seismically well-designed equipment did sustain less damage overall. In their questionnaire answers, many organizations said that their means of communication and provisions for electrical power outages/shortages should be improved in the future.

Though the damage caused by this earthquake was spread over a very wide area and various kinds of damage were observed, the authors focused on the damage to mechanical structures in the present work. In order to clarify the causes of this damage in detail, the relationships between the seismic motions, locations, structural characteristics and damages should be investigated in future work.

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The authors would like to acknowledge the institutions who allowed us to survey their facilities and answered the questionnaires. The authors are also grateful to Dr. Masaki Morishita of the JAEA and Dr. Yoshitaka Takahashi of Iwaki Meisei University for their contributions to several on-site investigations and discussions regarding the activities of WG1. The authors would like to thank the students of Fujita Laboratory at Tokyo Denki University for their contributions to the on-site investigations, and the students of Furuya Laboratory at Tokyo City University for their efforts in compiling the JSME questionnaire answers.

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Chapter 4

Understanding the Mechanism of Tsunami-induced Damage to Machines and Structures Based on a Discipline of Mechanics

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Abstract

This chapter describes an investigation and examination of the complicated mechanisms of damage to machines and structures caused by tsunamis. We attempted to understand the mechanisms of tsunami-induced damage from a bird's-eye-view in the case when civil and architectural structures, machinery and equipment are damaged and become unable to function, in addition to understanding a tsunami propagating from a seismic source. Toward this purpose, we studied actual phenomena that took place during the Great East Japan Earthquake (GEJE). Furthermore, we comprehensively examined the mechanisms of tsunami-induced damage that may occur in the future, and then aimed at obtaining useful knowledge towards future disaster prevention and mitigation. A vast quantity of recorded visual information on tsunami-induced damage during the GEJE was reviewed for the investigation and examination. Moreover, each member of Working Group 2 (WG2) performed his own field survey and simulation-based research. We then comprehensively examined those results.

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Keywords: Tsunami phenomena, Tsunami-induced damage, Machines, Structures, Computational mechanics, Tsunami proof design.

1. Introduction

We investigated and examined the complicated mechanisms of damage to machines and structures caused by tsunamis. Tsunami phenomena such as initiation, propagation and run-up might be basically discussed in specialized academic societies such as the Japan Society of Civil Engineers. However, we, as the Japan Society of Mechanical Engineers, attempted to understand the mechanisms of tsunami-induced damage from a bird's-eye-view in the case when civil and architectural structures, machinery and equipment are damaged and become unable to function, in addition to understanding a tsunami propagating from a seismic source. Toward this purpose, we studied actual phenomena that took place during the Great East Japan Earthquake (GEJE). Furthermore, we comprehensively examined the mechanisms of tsunami-induced damage that may occur in the future, and then we aimed at obtaining useful knowledge towards future disaster prevention and mitigation. A vast quantity of recorded visual information on tsunami-induced damage during the GEJE was reviewed for the investigation and examination. Each member of Working Group 2 (WG2) also performed his own field survey and simulation-based research. We then comprehensively examined those results.

1.1 Anticipated roles of an analytical scientific approach based on a discipline of mechanics

During the GEJE, we were shocked by the frightfully damaging power of the huge tsunami and felt powerless against the forces of nature. However, it is inevitable that a huge tsunami will again strike Japan, due to its proximity to plate boundaries. Therefore, it is imperative that scientists and engineers do their best to prevent and mitigate damage caused by huge tsunamis. For this purpose, we should first understand the mechanisms of tsunami-induced damage to machines and structures, and second establish measures to prevent and mitigate such damage.

Fundamentally, the propagation and run-up of a tsunami can be regarded as phenomena of fluids, while damage to machines and structures is a phenomenon of solids. Therefore, the tsunami-induced damage to machines and structures can be regarded as multi-physics phenomena of fluids and solids. It should also be noted that tsunamis caused by the dynamics of the earth result in far more complex and severe conditions than those anticipated when designing and operating machines and structures. A tsunami caused by the movement of plate boundaries propagates for hundreds to thousands of kilometers in the ocean, rushes to adjacent seas ranging from hundreds to thousands of meters, inundates stretches of coastal ranging from tens to thousands of meters in length, and finally damages machines and structures at the scale of centimeters to meters. This is a typical multi-scale phenomenon. Multi-physics and multi-scale phenomena are some of the latest scientific topics being studied. While research and development of methods to analyze and evaluate these phenomena have been ongoing worldwide, practical methods have not been established yet (JST CREST, 2009).

We believe that approaches based on a discipline of mechanics would provide us with a bird's-eye-view for understanding the mechanisms of tsunami-induced damage and essential solutions for preventing and mitigating this damage. This would also lead to a new area of study.

1.2 Roles of simulations for design scientific view based on a discipline of mechanics

A quantitative and reliable methodology for tsunami proof design of machines and structures is indispensable for seeking measures for preventing and mitigating tsunami-induced damage. For example, the mechanisms of and area damaged by a 5 m high tsunami and 15 m high tsunami differ considerably. Thus, different but concrete measures for protection against those tsunamis must be designed precisely.

Measures against tsunamis were enacted in several standards and guides even before the GEJE (JSCE, 2002, CAO, 2005). After the GEJE, several additional standards and guides were enacted, considering the actual damage caused by the huge tsunami. For example, the Guide for Setting Tsunami Inundation Assumption was revised by the Ministry of

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Land, Infrastructure, Transport and Tourism (MLIT, 2012a). The revised guide includes a simulation-based method for quantitatively assessing the tsunami inundation assumption. The Ministry of Land, Infrastructure, Transport and Tourism also published the Interpretation of Requirements to Structures of Tsunami Refuge Building and other documents, which contain a tsunami proof design method (MLIT, 2012b). The Atomic Energy Society of Japan published the Implementation Standard Concerning Tsunami Probabilistic Risk Assessment of Nuclear Power Plants (AESJ, 2011).

The conventional design of machines and structures usually employs relatively simple design formula and safety margins. However, it is very difficult to apply such a simplified formula for measures to prevent and mitigate tsunami-induced damage because different phenomena and factors are involved. Moreover, because tsunami-related phenomena are natural phenomena, the magnitude of a tsunami's influence has a much wider range of uncertainty, and it is difficult to set rational and sufficient design margins in a design standard. Consequently, direct computer simulation of the phenomena would be the most appropriate in terms of reliability. Simulation-based design is currently a well-accepted method for testing the crash worthiness and aerodynamics-related vibration and noise in automotive design. Such a trend could become indispensable in the tsunami proof design of machines and structures. For automotive design, the reliability of the method can be improved though accumulating verification and validation (V&V) of simulation results via comparison with experimental results. However, it is very hard to apply V&V processes to tsunami-related simulations.

2. Objectives and approaches

A tsunami ultimately causes various types of damage to machines and structures located in coastal areas as a result of the following process: (1) Generation of tsunami, → (2) Long-distance propagation in ocean, → (3) Propagation in adjacent sea, → (4) Arrival at coastal land and run-up. Below, the details of each process and related factors are described.

(1) The generation of a tsunami is influenced by earth-scientific factors such as the magnitude of the earthquake, and fracture characteristics of the fault and plate boundaries. In the GEJE, the superposition of two different tsunami sources generated a huge tsunami (Maeda, et al., 2011). Because tsunami generation is an earth-scientific phenomenon, it is very difficult to predict the magnitude of tsunamis accurately. Therefore, the prediction inevitably has a wide range of uncertainty.

(2) The long-distance propagation of a tsunami in the ocean is influenced by the topography of the ocean floor.

(3) The propagation of a tsunami in adjacent seas is influenced by the topography of the adjacent seafloors and the geography of the adjacent bays, capes and islands. In the offing of Fukushima, the seafloor in some areas features overhangs that extend away from the coast. Because of this unique geographical feature, some of the waves from the tsunami were reflected and focused away from the shallow area, which consequently increased the height of the tsunami (Sato, et al., 2012). On the other hand, in Matsushima Bay of Miyagi Prefecture, a number of small and large islands reduced the tsunami effects. Therefore, to understand the phenomena of (2) and (3), knowledge of oceanics and coastal engineering is very important. Compared with mechanical engineering, the prediction of such processes contains an uncertain band as well.

(4) The arrival and run-up of a tsunami are influenced by the characteristics of the land and sites, types of land use, and spatial arrangements of buildings and other outdoor structures. Therefore, knowledge of civil and architectural engineering is important. At TEPCO's Fukushima Dai-Ni Nuclear Power Plant facilities, seawater heat exchanger buildings were placed 4 m above sea level, while reactor buildings were placed 12 m above sea level. A tsunami wave with an estimated height of 9 m struck the sites. Sites 4 m above sea level were completely inundated, and seawater entered most buildings at the site. Important machines and electronic equipment were not damaged in one building because its door remained intact. On the other hand, because there was a slope at the south side of the site, the tsunami wave ran up the slope, reaching sites 12 m above sea level. Consequently, seawater entered some buildings at the site (TEPCO, 2011).

(4) The arrival and run-up of a tsunami is often characterized simply by the tsunami height. In reality, the tsunami should be characterized by the following five parameters: (a) Tsunami height, (b) Tsunami speed, (c) Inundation depth,

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(d) Inundation height, and (e) Run-up height, as schematically shown in Fig. 1. As described previously, these five tsunami parameters strongly depend on the multi-scale phenomena of (1)–(4) in a very complex manner.

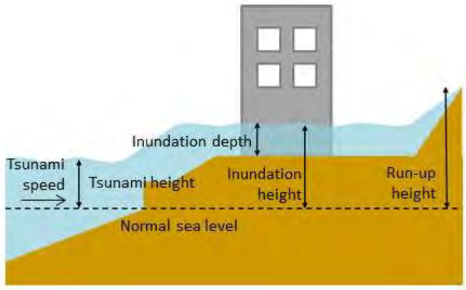

Fig. 1 Parameters describing a tsunami's features.

3. Damage to structures and functional loss of machinery due to tsunami

3.1 Characteristics of tsunami-induced damage and their categorization

Various objects damaged by tsunamis can be categorized into (A) tsunami protection structures such as tide embankments, (B) outdoor structures such as buildings and factories, houses, storage tanks and containers, and (C) machinery and equipment inside buildings and factories.

(A) Tsunami protection structures are often categorized as civil structures. Their seismic and tsunami strengths are expressed by their height, strength of the main body and strength of the foundation. These are related to seismic strength, tsunami strength and scouring. Seismic strength refers to strength against seismic vibration. Tsunami strength is strength against tsunami pressure. Scouring is a phenomenon such that the foundation of the tide embankment or sea wall is eroded by the eddy flow of the tsunami. Strictly speaking, this differs from the phenomenon such that tsunami water that overflows from the top of a tide embankment or sea wall erodes the backside of its foundation. Scouring causes a sudden decrease in tsunami strength.

(B) The strength of buildings and structures is related to seismic strength, tsunami strength and the water-tightness of windows, doors and penetrable portions (MLIT, 2012b). Buildings and structures are first heavily shaken by the earthquake, and consequently might be deformed and damaged. If they are built on newly reclaimed land, the land liquefies and their foundation is damaged and inclined. Subsequently, the tsunami strikes, and they are further damaged, inclined, and toppled by wave pressure, lift and backwash. Finally, the damaged buildings and structures are carried away. In the case of outdoor structures at power plants such as storage tanks that contain dangerous materials such as petroleum and liquefied gas, damage to these structures results in fires and explosions or the release of toxic gases into the atmosphere. Damage to these structures causes additional hazards. If we wish to protect the main body of buildings and structures, one approach is to open doors and windows to let the tsunami inside. On the other hand, if we wish to protect important machinery and equipment inside, we should carefully seal every gap in the doors, windows and penetrable portions, and employ water-tight doors and windows. In the latter case, the buildings and structures have to withstand the wave pressure and lift directly, so they must be designed accordingly and constructed very strongly. Because doors and windows are usually opened and closed in daily use, appropriate rules for their operation in the event of a tsunami should be established.

(C) Machinery and equipment inside buildings and structures are shaken by seismic loading, and are moved, deformed and damaged. They may also lose their function due to the severing of electric cables. In addition to such damage, when a tsunami enters a building, motors, electric supply boards and other electrically powered equipment without sufficient water-proofing might short circuit. If precision rotational devices such as pumps are inundated with seawater containing a lot of sand and mud, it is very difficult to completely clean up the sand and mud even by disassembly and washing, and it will take a longer time to recover their function. Machinery and equipment that are not completely cleaned up after being covered with seawater will rust. Moreover, if seawater containing a lot of sand and mud inundates the intake and outlet of seawater pumps, the intake and outlet become clogged and the pumps stop operating.

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The sand drift caused by a tsunami must also be assessed sufficiently. In summary, the driving forces behind tsunami-induced damage can be categorized into the following five types:

Type 1: Water coverage
Type 2: Coverage by seawater containing sand, mud and salt
Type 3: Deformation, fracture, floating, falling down, carrying away by massive amounts of water flowing at high speed (tens of meters per second)
Type 4: Impact, deformation and fracture by tsunami debris
Type 5: Scouring and sand drift

Once we understand the driving forces behind tsunami-induced damage, we know that preventing water-invasion by improving the water-tightness of buildings is important to protect machinery and equipment inside the buildings. At the same time, it is important to apply water-proofing to machinery and equipment inside the buildings or to set them in a sufficiently higher place to prevent water damage. A tsunami is not a simple increase in the height of water, but a massive amount of water (an incompressible fluid) traveling at a very high speed. That is why tsunamis have such damaging force. It is very difficult not only to design structures that can withstand the massive force of a tsunami, but also to take sufficient measures against it.

For example, spherically shaped storage tanks are good for containing highly pressurized fluid; however, they lack sufficient strength against local and/or non-symmetric external loading. Because a large amount of lift is applied to buildings and structures with high quality water-tightness, they are easily lifted unless they are well fixed to the ground. Some outdoor structures are only held to the ground by self-weight loading or ordinary bolts. These structures are easily lifted, toppled and carried away. Considering the complex effects of both seismic loading and a tsunami, the earthquake first breaks the support structures and damages the foundation due to liquefaction and then the tsunami strikes. Debris carried away by the tsunami impacts other structures and buildings. Therefore, it is not sufficient to consider only tsunami pressure, lifting force and water-tightness. It is also necessary to take into account impacts from tsunami debris, by considering the spatial arrangement of buildings and structures. Photo 1 shows a large ship that was sent crashing into a coastal factory by the huge tsunami following the GEJE (Yahoo! JAPAN, 2011).

Photo 1 A large ship that was sent crashing into a coastal factory by the huge tsunami following the GEJE (Yahoo! JAPAN, 2011).

3.2 Simulation: the method for quantitative analysis

As described previously, the mechanisms of tsunami-induced damage are very complex. The interaction between seismic loading and the tsunami makes the phenomena more complex. Because they are earth-scientific phenomena, it is very difficult to accurately predict both when they will occur and their potential magnitudes. Therefore, it is insufficient to establish measures for prevention and mitigation using only information on tsunami height. For example, if the Central Disaster Prevention Council declares that the estimated maximum height of a tsunami at a certain region is 20 m, would tsunami-related problems be solved by constructing a huge, 20 m high sea wall? The issue we are facing is not that simple. Constructing a 20 m high sea wall is costly, and the surrounding community is completely

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disconnected from the beautiful scenery of the coast. The lifestyle of people living near the sea is also significantly disturbed. Based on the inherent situation of the area, there are alternate measures, i.e., constructing a lower sea wall in order to prevent frequent but lower-height tsunamis, constructing a tsunami refuge building with sufficient height, tsunami strength and water-tightness, preparing a sufficient and workable plan of evacuation to higher ground, enhancing the seismic and tsunami strength of machinery and equipment, and preparing spare equipment at higher places for emergencies. This combination of multiple measures is much more useful. To do so, we have to understand well the seismic mechanisms and those of tsunami-induced damage. Based on this understanding, we could develop an assessment methodology for prevention and mitigation of damage to civil and architectural structures, machinery and equipment, and take multiple measures more appropriately. The actual simulations required are as follows.

(1) Simulation of tsunami generation and propagation (over long distances and near coastal areas)
(2) Simulation of tsunami run-up
(3) Simulation of seismic responses of structures, machinery and equipment, and that of damage assessment
(4) Simulation of water coverage, deformation and fracture due to the tsunami (pressure by massive water with a high speed, and lift)
(5) Simulation of transportation and impact of debris such as ships and containers
(6) Simulation of scouring and sand drift by the tsunami

4. Analyses and tsunami-induced damage and mitigation methods based on a discipline of mechanics

4.1 Coupling of three-dimensional fluid analyses and ocean tsunami propagation analyses

4.1.1 Objective

Various studies on tsunami wave source evaluation and ocean tsunami propagation have been performed based on non-linear long-wave theory (shallow-water theory) (Imamura, et al., 1988), inversion analysis (Satake, 1989) and so on. However, after the GEJE, which severely damaged critical infrastructure facilities, it was pointed out that previous tsunami analysis approaches were insufficient for evaluating the phenomenon, including the inundation of land. Regarding the evaluation of tsunami force, several formulas (Imamura, 1988) based on experiments targeting breakwaters have been developed. However, the methods for evaluating the tsunami force on terrestrial structures are not well established.

Tsunami analyses based on the non-linear long-wave theory have already been used by the Japanese government in the disaster prevention plan for estimating tsunami damage (MLIT, 2012a). In conjunction with that, it is highly desired to establish a practical method for predicting the tsunami force against terrestrial structures. In a two-dimensional model for ocean tsunami propagation analysis based on the non-linear long-wave theory, the variables to be calculated at grid points are the velocity vector and sea level. However, water pressure is not calculated directly. If we can use the coupling approach of ocean tsunami propagation analyses and three-dimensional fluid analyses (hereinafter referred to as the coupling tsunami analysis), it is expected that we will be able to evaluate tsunami forces and understand complicated tsunami phenomena in a terrestrial region.

In this section, we present a case study of the coupling tsunami analysis for the GEJE (Fujiwara, et al., 2012). Port Soma located in Fukushima Prefecture was selected as the object for the analysis.

4.1.2 Ocean tsunami propagation analysis for the GEJE

The Tsunami_N2 code developed by Imamura (Imamura, et al., 1988) is used for tsunami analysis based on the non-linear long-wave theory. This code is based on a finite difference method with a staggered leap-frog scheme.

The analysis region for ocean tsunami propagation analysis is a rectangular area about 1,000 km in east–west length and 1,700 km in north–south width including the wave source region of the GEJE and Port Soma, as shown in Fig. 2(a). The grid size was reduced in five steps from 1,215 m to 15 m from the ocean toward Port Soma. The terrain model was created based on the public data of the Japan Coast Guard, GSI, Marine Information Research Center, General Bathymetric Chart of Oceans and elevation data of Soma City. The distribution of the wave source model shown in Fig. 2(a) was adjusted based on the previous model (Fujii, et al., 2011).

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Figure 2(b) shows the distribution map of the tsunami sea level at 30 min after the earthquake occurrence. Figure 2(c) shows a comparison of the simulation waveform and GPS wave gauge observation of the Nationwide Ocean Wave information network and HAbourS (NOWPHAS). These waveforms are the raw unfiltered data. The simulation reproduces the observed waveform very well.

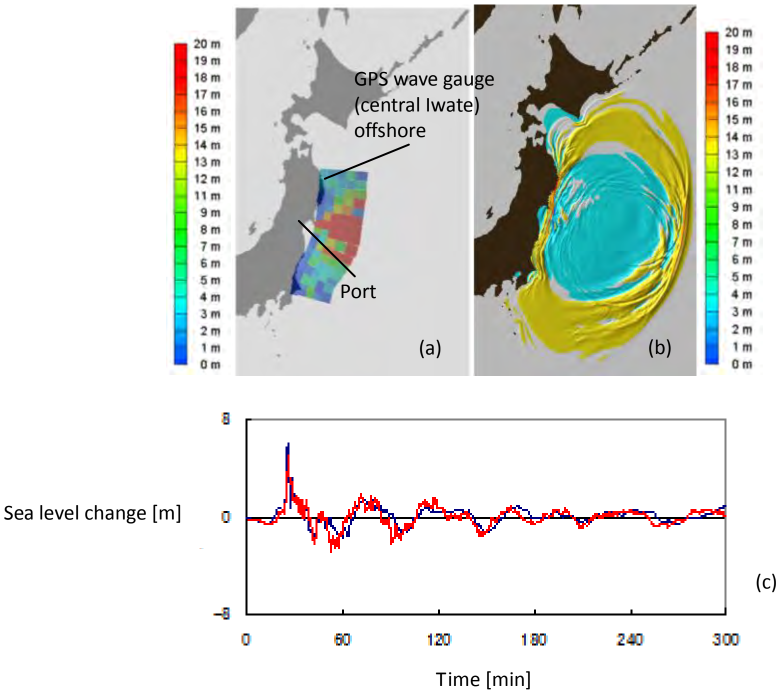

Fig. 2(a) Analysis region of tsunami wave propagation in ocean and tsunami source model, (b) Tsunami sea level distribution at 30 min after the earthquake occurrence, (c) Comparison between observed sea level (blue) and simulation result (red).

A tsunami source model is produced and optimized using the inversion analysis from many observed values of the tsunami. The waveform obtained by the ocean tsunami propagation analysis as a forward analysis is consistent with the naturally observed one. However, these results indicate that, once the exact wave source model is set, the propagation behavior itself of the ocean tsunami can be evaluated appropriately.

4.1.3 Tsunami simulation in Port Soma by three-dimensional fluid analysis

A commercial code, FINAS/CFD, using an unstructured grid of the finite volume method was applied for the three-dimensional fluid analysis. The governing equation of the three-dimensional flow is an expression of momentum conservation and mass conservation for incompressible fluid. The speed–pressure coupling method is the SIMPLEC method (Ferziger and Peric, 2002). Further, in order to express the free surface of the tsunami, the analysis space was modeled as a two-phase fluid flow of air and seawater based on the volume of fluid (VOF) method (Hirt and Nicholls, 1981).

In the three-dimensional tsunami analysis, due to the limitations of computational capacities, it is necessary to restrict the volume of the analysis region and the analysis time to a few minutes. The region of interest for three-dimensional fluid analysis of Port Soma has an area of 1200 m × 2220 m, indicated by the red box in Fig. 3. The land area of the region is 25 m high and the water area is 15 m high. The flow velocity vector and sea level obtained from the ocean tsunami propagation analysis were assigned to the interior of the analysis region as initial values. The time histories of the flow velocity vector and sea level obtained from the ocean tsunami propagation analysis were used for the outer sides of the analysis region as a boundary condition. For the analysis, we selected a 12 min period near the arrival time of the second tsunami wave. This is the time during which the sea level rose significantly, as shown in Fig. 4.

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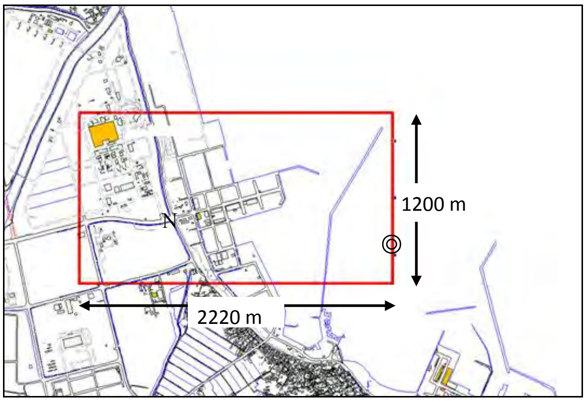

Fig. 3 Analysis region of three-dimensional flow simulation (Port Soma area).

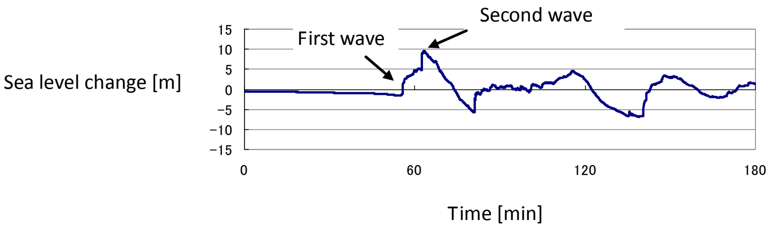

Fig. 4 Calculated time history of sea level change in Port Soma during tsunami. (The position is marked by "◎" in Fig. 3.)

A bird's-eye-view of the grid model for the three-dimensional fluid analysis is shown in Fig. 5. The grid model is based on the terrain model generated in the ocean tsunami propagation analysis. It was modeled in more detail for land structures and seafloor terrain. The cell size is 3 m in the horizontal direction, and 1 m in the vertical direction. The number of cells is approximately 8 million. This calculation was performed using the FOCUS supercomputer system (FOCUS, 2013). Forty-eight parallel computing cores (6 × 8 core node) were used, and the computation took 2 weeks.

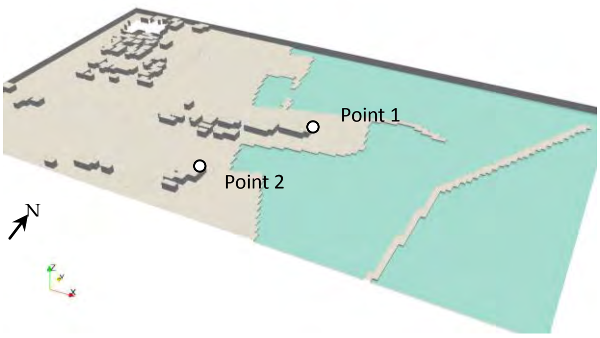

Fig. 5 Grid model for three-dimensional fluid analysis of Port Soma.

The bird's-eye-views of the calculated water surface at the time points are shown in Fig. 6. These water surfaces are obtained by plotting the iso-surfaces with an F value of 0.5 in the VOF method. Figure 7 corresponds to the time when the second wave of the tsunami flowed over the levee. At this time, a significant area of the land had already been flooded by the first wave, and the high second wave had arrived. Figure 6(b) is a bird's-eye-view when the second wave arrives at the front of the building on the pier. Point 1 is indicated in Fig. 5.

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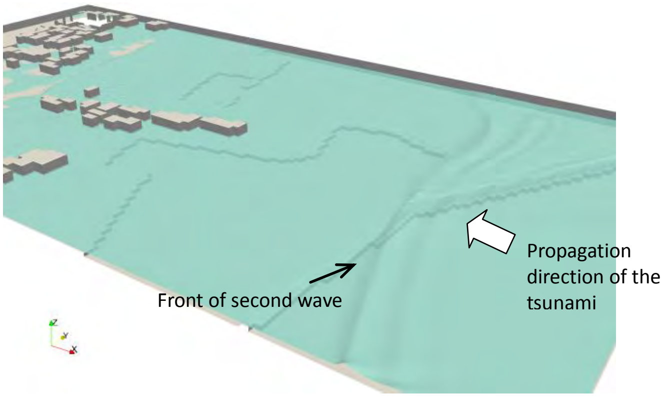
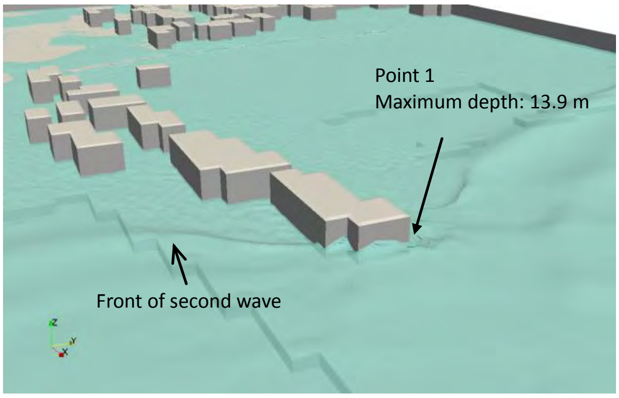


(a) 63.2 min: Second tsunami wave overflowing the levee.



(b) 64.0 min: Second tsunami wave reaches point 1.

Fig. 6 Bird's-eye-view of water surface.

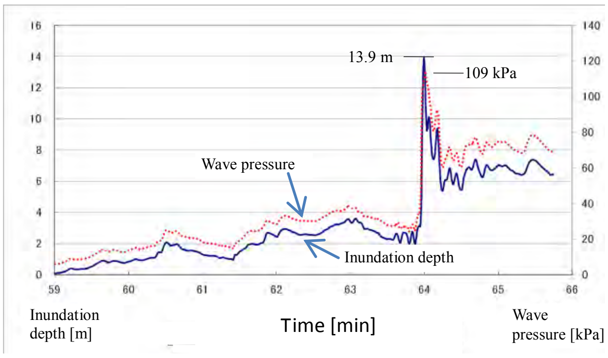


Fig. 7 Calculated time histories of flooding depth and wave pressure at point 1.

The time history of the wave pressure on the ground surface and that of flooding depth at point 1 (front of the building on pier tip) are shown in Fig. 7. The wave pressure and flooding depth have a similar shape. When the stage wave collides with the structure wall at point 1 at 64.0 min, the water surface instantaneously upsurges in front of the wall, the flood depth becomes 14 m and the depth decreases to 6 m a few seconds later. According to a field survey report (PARI, 2011), the vulnerable slate wall of the building at point 1 was destroyed, and the observed flood depth at the nearest point was 6.77 m. The analysis results are roughly consistent with these observations.

A tsunami analysis based on the non-linear long-wave theory was also performed in the port area, and compared with the three-dimensional fluid analysis. The time history and distribution of the flooding depth and sea level were nearly identical in both methods. This is a reasonable result because the terrain in the port is almost flat.

4.1.4 Conclusion and future work

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Due to the protection of critical infrastructure such as nuclear power plants against tsunamis, protective measures such as waterproofing of the building and installation of a flood barrier will be conducted from now on. To design such protective facilities, the wave force and flooding dynamics must be predicted more accurately. The coupling tsunami analysis is expected to meet this requirement. As shown in the examples described above, the three-dimensional fluid analysis can be considered to be a practical solution. However, further technological developments and the studies described below are desirable in order to apply the coupling tsunami analysis to safety evaluation and design.

(a) Standardization and validation of methods and models

To apply the design analysis, it is necessary to standardize the analysis methods and models to allow for quality control of the required levels. Numerical accuracy management and validation will then be required through comparison with observations and experiments (so called V&V). It should be noted that such an empirical approach covering both analyses and experiments has been conducted in the development of numerical wave waterways, CADMAS-SURF/3D (CDIT, 2010) for port facilities.

(b) Improvement of three-dimensional fluid analysis technology

In the three-dimensional fluid analysis required for the evaluation of critical infrastructure facilities, depending on the grid size and analysis area, the number of grid points easily exceeds several tens of millions. In some tsunami events, it may be required to analyze the event continuously for tens of minutes. These types of high-speed calculations for huge models will be required for practical use, and more sophisticated parallel processing techniques are desired. The use of very high-speed supercomputers such as the "K computer" will be considered as well.

(c) Analysis technology for shock wave pressure

In the fluid analysis dealing with incompressible fluid, the pressure caused by the momentum change when the tsunami collides against the structure can be obtained. However, generation and propagation of the sound pressure (shock wave) due to compressibility of the fluid cannot be evaluated. An explicit approach for fluid analysis considering the compressibility is required to deal with such a phenomenon. The computational load for compressible fluid analysis further increases, compared with incompressible fluid analysis. Advances in technology for very efficient calculation are required for this purpose. Moreover, the shock wave will cause a very large wave pressure instantaneously, but the impulse on structures will not be very large in general. Therefore, it is expected that the impact on structures is not critical. Coupled structural and fluid analyses will be required in order to evaluate this effect quantitatively.

4.2 Tsunami propagation from the open sea to the coast

4.2.1 Estimation of wave height and arrival time

The coastal areas of the Tohoku region suffered serious damage from the tsunami caused by the 2011 off the Pacific Coast of Tohoku Earthquake that occurred on March 11, 2011 (MLIT, 2011). Numerical simulations are used to develop disaster-prevention measures to deal with such tsunami disasters. They are also used to predict potential future tsunami disasters, to design disaster-prevention facilities such as coastal breakwaters and levees, and to predict tsunami attacks immediately after an earthquake occurs (Goto and Sato, 1993, Takahashi, 2004). The Central Disaster Prevention Council (CDMC, 2013) prepares basic disaster prevention plans and participates in the determination of important disaster-prevention matters. The Tonankai–Nankai Earthquake may cause considerable damage. Consequently, the council has been performing numerical calculations to predict wave height and arrival time when a tsunami reaches the coast.

4.2.2 Viscous shallow-water equations

As mentioned above, the tsunami generated by the GEJE caused serious damage to the coastal areas of the Tohoku region. Numerical simulations are used to predict damage caused by tsunamis. Shallow-water equations are generally used in numerical simulations of tsunami propagation from the open sea to the coast. This subsection focuses on viscous shallow-water equations and attempts to generate a computational method using finite element techniques based on the previous investigations of Kanayama and Ohtsuka (Kanayama and Ohtsuka, 1978).

In the numerical analysis of tsunamis, the viscosity term is often omitted (Ulutas, 2012). In this subsection, however, a computational method that includes the viscosity term is adopted because it enables more rigorous analysis

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to be performed, and the authors intend to include the viscosity term in future stress analysis of tsunamis.

Recently, the authors have found an interesting survey (Bresch, 2009) that deals with sound mathematical topics related to the viscous shallow-water equations.

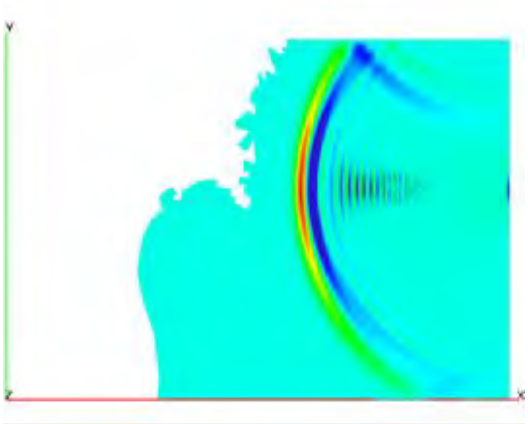

Fig. 8 Simulation of tsunami wave propagation off the coast of Tohoku.

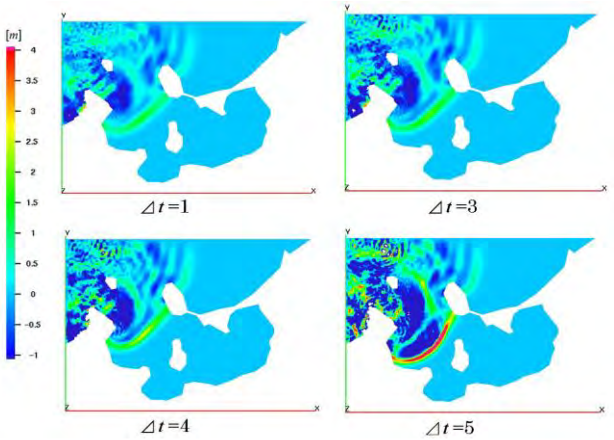

Fig. 9 Simulation results in Hakata Bay.

4.2.3 Setting of computational conditions

In general, a tsunami is excited in the following two ways. The first one is to consider the tsunami excitation as the initial condition of the water surface, but there is a lack of sufficient input information for such an artificial tsunami like that in Hakata Bay (Kanayama and Dan, 2014). The second one is to consider the tsunami excitation as the boundary condition of the water surface, as done in this subsection. The computational domain is not so wide that the above approach may be the only way.

It is also noted that 50 m at the open boundary for the Tohoku-Oki case may be too high. In the computation, the tsunami arrived at Oshika Peninsula after 20 min, and the highest wave height reached 15 m. These numerical results should be checked more carefully with data on the open boundary.

Figure 8 shows the ordinates of the water surface (water level) after 18 min. Because the computational domain is narrow, it looks as if there is a reflection from the northern boundary in Fig. 8. This type of artificial reflection can be removed by employing suitable boundary conditions on the open boundary.

In Fig. 9 of the Hakata Bay case, the time step size Δt was set to be 0.1 s. This time step size is unnecessarily small, because similar results can be obtained even if a time step ten 10 times larger is used for the same mesh data. Although a full non-linear stability analysis is very difficult, we believe that the present linear stability condition in (Kanayama and Dan, 2014) is useful. In fact, the similar stability condition of (Ushijima, 1983) in the case of $\theta = 1$ produces a good estimate of the 1 s time step in numerical experiments.

With open data (Tohoku University and JNES, 2013) and sufficient numerical analysis, estimation of the wave height and the arrival time should be improved.

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4.3 Issues related to prediction of long-distance propagation of tsunamis

When an earthquake occurs, the Japan Meteorological Agency issues a tsunami alert and warning before the tsunami arrives at the coast. The alert system employs a database-based method, and its insufficient accuracy has often been pointed out. The main reason of the inaccuracy is as follows. The database consists of a priori simulation of a tsunami's long-distance propagation for a variety of tsunami parameters. The parametric study cannot sufficiently cover every possible parameter space.

It is easy to solve such a tsunami's long-distance propagation problem based on shallow-water approximation by employing the latest high-resolution simulation method for hyperbolic equations. No supercomputer is needed. A tsunami simulation of a wide area shown in Fig. 10 can be simulated on 8,000 × 4,000 grid points with a 100 m width using multiple GPUs in tens of seconds (Acuna and Aoki, 2010). By increasing the number of GPUs, a linear speed-up can be attained as shown in Fig. 11. Figure 12 shows a snapshot of the real-time simulation of the tsunami propagation on 512 × 512 grid points using one GPU equipped in an ordinary notebook PC (Acuna and Aoki, 2011). This simulation includes the tsunami's run-up onto land.

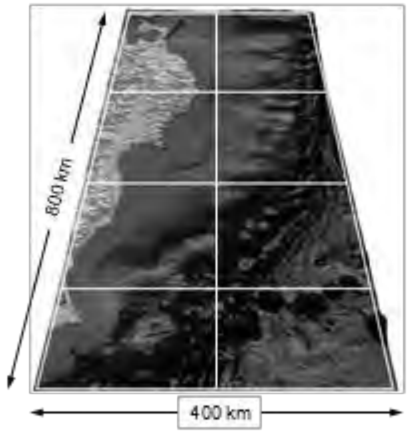

Fig. 10 Large region of tsunami propagation simulation off the coast of Sanriku.

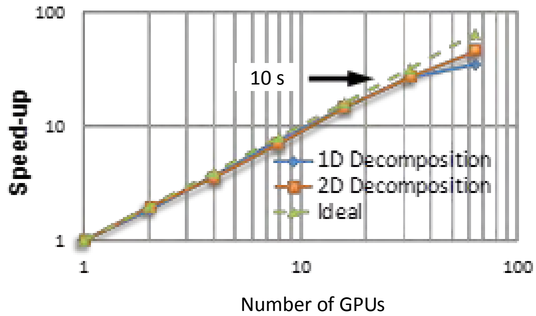

Fig. 11 Speed-up of computation time of tsunami propagation simulation for the number of GPUs.

An attempt to start calculating tsunami propagation right after an earthquake occurs was expected to drastically improve the accuracy of the alert for tsunami arrival at the coast. Although the anticipated area of the calculation of tsunami propagation is similar in size to the area shown in Fig. 10, it was found that such a calculation of tsunami propagation was not practically useful for a tsunami alert. The calculation of tsunami propagation is one of the initial condition problems for solving hyperbolic-type shallow-water equations. Therefore, the calculation must be started by inputting the displacement in shape of the seafloor during the earthquake. A current monitoring system of such displacement information cannot obtain very accurate information in such a short period of tsunami propagation. It is only possible to estimate an initial value from the observed arrival times of tsunamis at various coastal areas and the tsunami heights. Thus, the calculation is not useful for a tsunami early warning system. At least, it is indispensable to equip systems for monitoring the water level change in a wider oceanic area including seismic sources as soon as

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possible.

Not limited to tsunami propagation simulation, computational mechanics based on analyses of tsunami damage tend to be only case studies. It is very difficult to obtain general knowledge on damage mechanisms useful for disaster prevention and mitigation. Validation of such analyses is also difficult. In general, computational mechanics is a field of study in which responses (results) to applied forces (inputs) are analyzed. In many cases, we assume that the applied force is a controllable parameter in the simulation. However, in natural disasters, the assumption of applied force plays a much bigger role than the simulation itself. A conventional approach to computational mechanics does not work very well. To solve such problems effectively, it is necessary to develop an interdisciplinary approach to computational mechanics by collaborating with other fields of study such as earthquake science, soil mechanics, oceanology, earth science, civil engineering, information technology and social engineering.

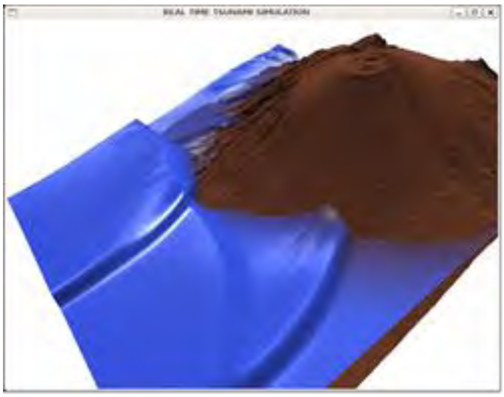

Fig. 12 GPU-based real-time simulation of tsunami propagation with run-up.

4.4 Estimation of hydrodynamic force

To estimate the impact force and impulse of a tsunami hitting walls or buildings, it is important to predict the non-linear motion and surface deformation of liquid, which are sometimes affected by the surrounding gaseous phase. In other words, it is necessary to observe the violent motion including the wave-breaking of the tsunami and to describe it as the flow field of free-surface flow. We can look back over the last two decades at the outstanding development of CFD techniques for the analysis of free-surface flow. Focusing on numerical methods with a fixed grid system, not only the convective schemes avoiding numerical diffusion of the VOF function (Hirt and Nicholls, 1981), but also the surface capturing methods without artificial smoothing of fluid properties around the gas–liquid interface have been proposed. With such a numerical method employing these techniques as piecewise linear interface calculation (PLIC)-VOF or constrained interpolation profile (CIP) (Yabe and Takei, 1988), the gas–liquid interface were captured sharply; that is, the jump of properties across the interface were captured within a cell.

For example, the results of an experiment and numerical simulation for a dam-breaking problem with a block (Koshizuka, et al., 1995) are shown in Fig. 13 (Himeno, et al., 2010). In the experiment, after the contact line of the liquid surface running on the bottom collided with the block, the water rose up over the block and reached the right wall. In the corresponding computation, both the liquid and gaseous phases were described by the Navier–Stokes equation for a homogeneous two-phase flow and numerically solved by the CIP based Level Set & MARS (CIP-LSM) code (Himeno, et al., 2010), in which the CIP scheme (Yabe and Takei, 1988) and the MARS method (Kunugi, 2001) are employed to solve the convective terms, and the level-set technique (Sussman, et al., 1994) is also utilized to obtain the shape of the interface. Compared with the experimental results, the shapes of the leaping water wave (a), the water bridge and the vapor room (b) were found to be reproduced clearly.

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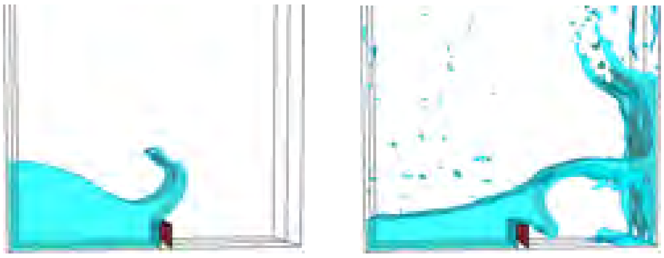
(a) 0.20 s (b) 0.50 s

Experimental results (Koshizuka, et al., 1995).



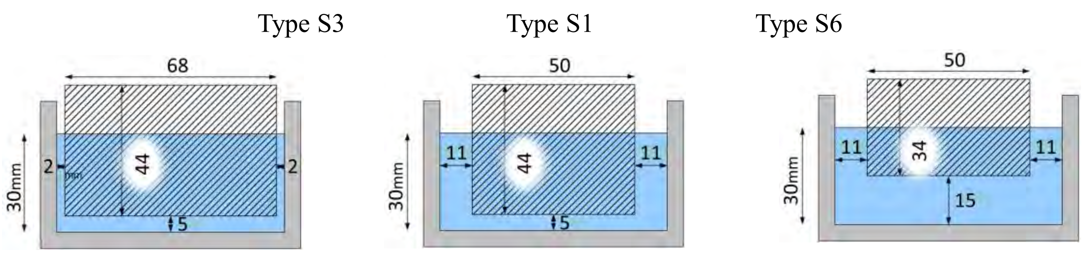
(a) 0.20 s (b) 0.50 s

Simulation results (Himeno, et al., 2010).

Fig. 13 Liquid motion of dam breaking problem with a block.

For another example of liquid collision, the experiment and the numerical simulation of the jet-sled decelerated by a water brake are shown in Fig. 14 (Nakata, et al., 2013). In the experiment, the sled on straight guide rails was accelerated by a model jet-engine up to a velocity of 20 m/s. Then, rushing into an open channel containing shallow water, the sled was decelerated to a stop. A rectangular plate was equipped at the front of the sled to receive the hydrodynamic force of water. In a series of experiments, several types of braking plate were tested. When focused on the splashing shape (a) and the braking force (b), the computations were found to give results in good agreement with the corresponding experiments.

Thus, the numerical analysis has the potential to provide helpful assessments of natural phenomena, which are difficult to measure and repeat experimentally in a cost-effective manner. Further improvements of the numerical method are expected to clarify various aspects of free-surface flows for the establishment of disaster-prevention or disaster-reduction technologies.



(a) Shape of open channel with breaking plate.

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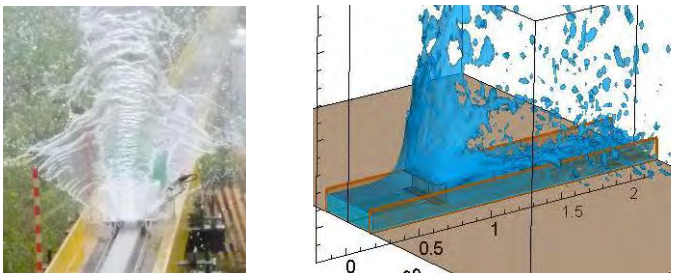
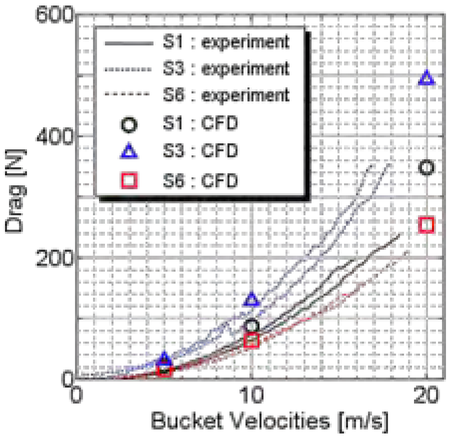


(b) Shape of splash after collision: Experiment (left) and simulation (right).



(c) Braking force acting on the braking plate.
Fig. 14 Braking force by liquid collision in an open channel.

4.5 Tsunami-scouring simulation

In the GEJE, damage by tsunami scouring was observed among a number of broken levees. Tsunami overtopping a levee turns to jet flow, which attacks the foundation of the levee. The jet flow scours the foundation, and then the strength of the foundation of a concrete levee is weakened and finally the levee collapses. Simulating this phenomenon precisely is very important to understand its mechanism and to find measures to prevent scouring-induced damage. We simulated the phenomena using the following simulation method that combines the smoothed particle hydrodynamics (SPH) method (Yagawa and Miyazaki, 2007) and the discrete element method (DEM) (Hakuno, 1997).

We employ the simple maker and cell (SMAC)-SPH method for simulating flow and the SPH elastic analysis for simulating solids. We first perform the flow simulation, and then we perform an elastic analysis using the calculated flow loading. Based on the stress and strain values, we subsequently perform fracture analysis (fracture judgment). When the stress value of the SPH particle in the soil foundation exceeds 100 MPa, the specific region is judged as fracture, and then the corresponding particle is converted into a free particle. The dynamics of the free particle is simulated using the DEM.

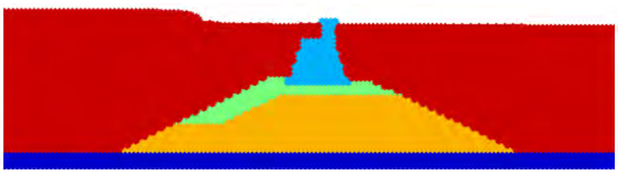


Fig. 15 A levee model for SPH-DEM analysis.

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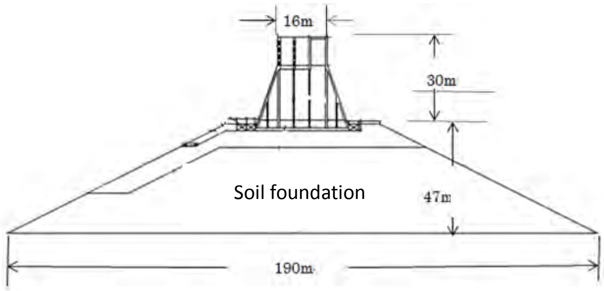


Fig. 16 A levee structure in Kamaishi Bay.

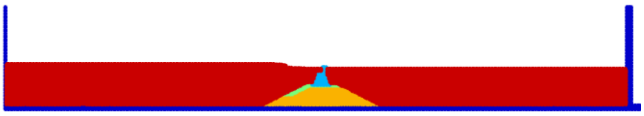
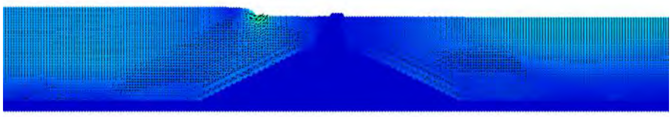
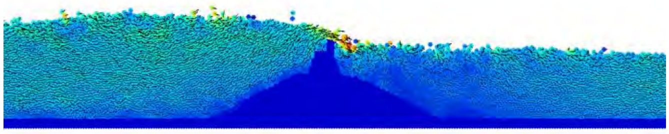


Fig. 17 A whole model for SPH-DEM analysis.

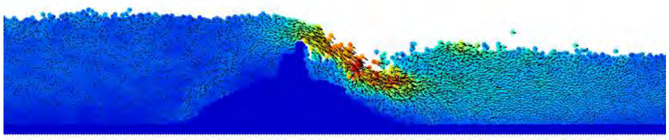
The DEM analysis is used for analyzing the flow of soil particles after the fracture of the soil portion. In this simulation, the fracture judgment criterion was set to 100 MPa for the purpose of demonstration. For a more realistic simulation, we need a precise study on the fracture criterion. In the DEM analysis, free soil particles are mixed with fluid particles. Figure 15 shows a two-dimensional simulation model of the levee built in the Northern portion of Kamaishi Bay. Figure 16 shows its cross-sectional view, while Fig. 17 shows the whole analysis model. The length is 1 km and the height is 40 m. The number of particles is 132,000, and the size of each particle is 0.5 m. The simulation results of the tsunami flow are given next. The jet flow overtopping the levee is qualitatively well reproduced. The jet flow delivers an impact force to the soil foundation of the levee. The SPH flow method calculates water pressure and impact load, which are used as external loads in the SPH elastic analysis. We can then evaluate the stress and strains generated in the particles of the soil foundation. Fracture judgment is performed using the calculated von Mises stress values. The particles judged as a fracture are then treated as DEM particles.



(a) Reading tsunami wave.



(b) Initiation of over flow.



(c) Appearance of slant flow.

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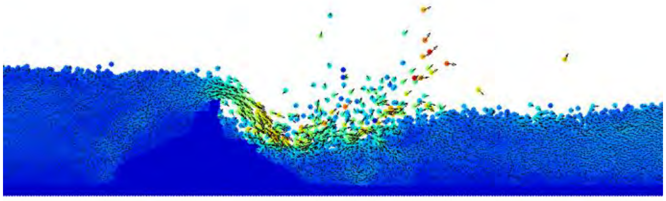
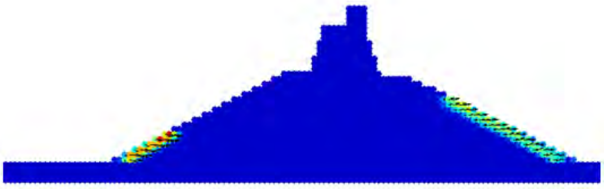


(d) Generation of flow attacking levee foundation.
Fig. 18 Flow analysis of a tsunami wave over a levee.

The forces impacting the foundation are included in the equation of motion. The pressure is then calculated implicitly by the SMAC-SPH method. The impact load caused due to jet flow is included in the Newton equation of motion assuming that a massive amount of fluid with a certain velocity attacks the foundation. Figure 19 shows the stress values that occurred in the soil foundation by fluid force. Because of this stress generation, the foundation is weakened and gradually fractures. Figure 20 shows the simulation results of coupling analysis between DEM particles modeling the foundation and SPH particles modeling fluid. Figure 21 shows the scouring effects on the soil foundation by the jet flow. Figure 22 shows an enlarged view of the scoured portion of the foundation.



(a) 30 s after overflow.

(b) 60 s after overflow.

(c) 3 min after overflow.
Fig. 19 Stress distributions at levee foundation.

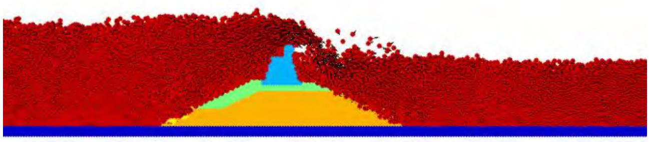


Fig. 20 A combination of the flow analysis and ground analysis.

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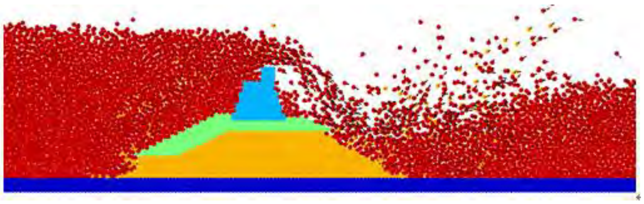

Fig. 21 Behaviors of flow and levee foundation.

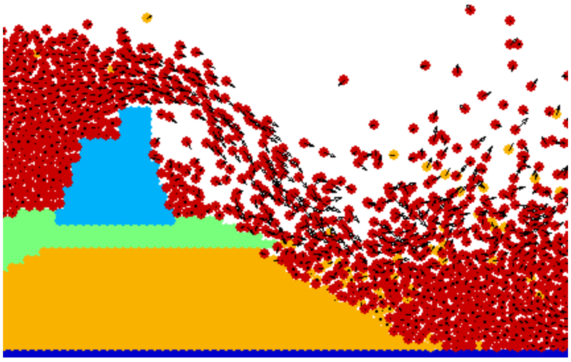

Fig. 22 Ground collapse by jet flow over levee.

4.6 Debris transportation simulation by tsunami

4.6.1 Objective

Debris exacerbated the damage caused by the tsunami that occurred after the GEJE. The origins of such debris are ships in ports, automobiles, destroyed buildings and houses, and so on. The evaluation of debris impacting buildings, structures and water-tight doors was found to be important for nuclear power plants. Such situations demand coupling analyses between debris and fluid during a tsunami's run-up, and the impact analyses of debris colliding with buildings and structures. If the deformation of debris is negligible, it is considered a rigid body in the analysis. The phenomena of a tsunami carrying debris can then be solved as fluid–rigid body interaction problems. This section reviews a state-of-the art particle method for such interaction problems.

The particle method is a simulation method such that the dynamics of continuum media are considered a collection of particles. Because the method does not need a mesh or grid, it can easily simulate complex behaviors of flow with a free surface. The state-of-the art review of particle methods in the field of civil engineering is given in reference (JSCE, 2012).

The following technologies are necessary to analyze tsunami run-up onto land with debris and its impact on buildings and structures.

(a) Large-scale and fast simulation based on particle method
(b) Fluid–rigid body interaction method
(c) Impact analysis and its validation

Issues with each technology are summarized in the following.

(a) Large-scale and fast simulation based on particle method
To simulate tsunami propagation realistically with an actual bathometry chart of the seafloor, an area of several kilometers wide must be calculated in tens of minutes. Moreover, current particle methods require a uniform spatial resolution. Assuming a tsunami height of several meters, we need to employ a spatial resolution that sufficiently resolves such a tsunami height. For example, if we employ a 1 m size particle for a 10 m high tsunami in a 1 km^2 area, the total number of particles reaches 10 million. Thus, we need to develop a large-scale and fast simulation for the particle method.

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Flow with a free surface can be regarded as incompressible if the flow velocity is sufficiently smaller than the sound velocity. Then a semi-implicit scheme is generally employed. A moving particle semi-implicit (MPS) method is a particle method that employs a semi-implicit method. Recently, a new method has been proposed. Here, the sound velocity is virtually set to be much slower than the real one, and a flow is solved as compressible flow using an explicit method (Shakibaeinia and Jin, 2010). Furthermore, if the Mach number, which is the ratio of flow velocity to the sound velocity, is set as 0.2, a critical time increment Δt determined from a numerical stability condition is found to be identical between the conventional semi-implicit method and the explicit method (Oochi, et al., 2010). The error of mass density caused due to the assumption of virtually lower sound velocity is within approximately 1% for the Mach 0.2 case (Oochi, et al., 2011). In the explicit method, the pressure can be calculated from the particle number density n as:

$$P_i = \frac{\rho}{n_0} c^2 \left(n_i - n_0 \right)$$

where n_0 is the reference value of the particle number density. The explicit method does not need to solve a linear equation system, being different from the conventional semi-implicit method. As described previously, an identical time increment can be employed. Thus, the calculation becomes drastically fast. The explicit MPS (Moving Particle Simulation) method is considered to be useful in tsunami run-up analyses.

Parallel algorithms for the explicit MPS method were then studied (Murotani, et al., 2012a). A two-layered parallel algorithm for a heterogeneous supercomputer was developed as well (Murotani, et al., 2012b).

We next show a three-dimensional tsunami simulation with actual, large-scale bathometric data of the seafloor using the explicit MPS method. Figure 23 shows a calculation model, which is a part of Ishinomaki City (4.0 km × 3.5 km). Its lower edge is the inlet boundary. The tsunami that occurred after the GEJE and then propagated from its source is calculated by solving a two-dimensional shallow-water equation, and the result is used in the explicit MPS analysis. The particle size is set as 2 m. The total number of particles is approximately 21 million. To simulate 25 min (1,500 seconds) in real time, the calculation time was 27 hours using 48 nodes (768 cores) of the Fujitsu FX10 supercomputer at the University of Tokyo. Figure 24 shows the simulation results. It reproduces well the situation such that the tsunami flows over a sea wall and runs up onto the land. The tsunami concentrates into the river end, and the tsunami inundated into a wider area along the river. However, the tsunami reached the edge of the calculation area, so that further run-up onto the upper area could not be calculated. We need to enlarge the calculation area, and increase the spatial resolution. The parallel calculation of the fluid–rigid body interaction to be described next is also needed.

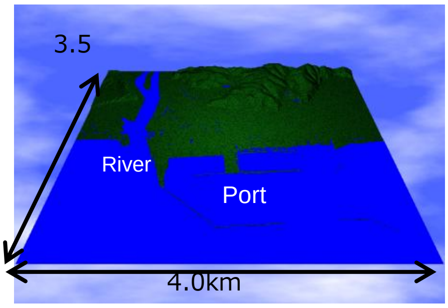

Fig. 23 Analysis setup of three-dimensional particle-based model for tsunami run-up in Ishinomaki City.

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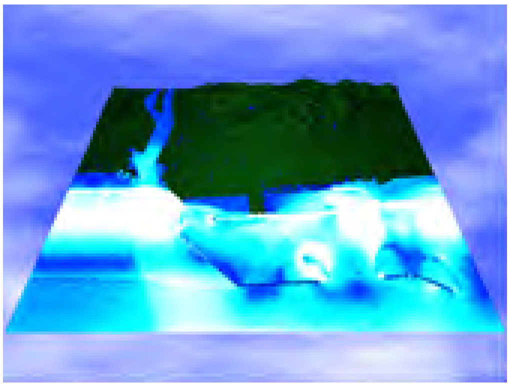
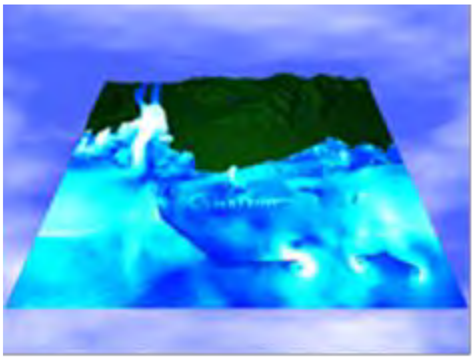
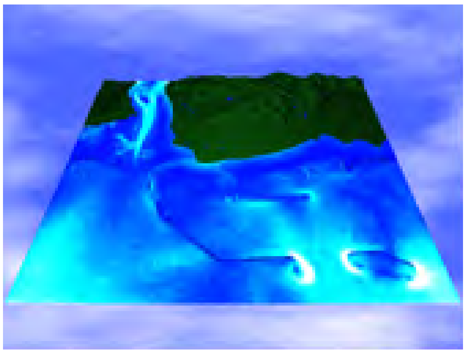


(a) 1,000 s



(b) 1,100 s



(c) 1,200 s

Fig. 24 Simulation result of tsunami run-up into Ishinomaki City.

(b) Fluid–rigid body interaction analysis

In the MPS method, by applying the Gaussian divergence theorem, an area integral of pressure on the fluid–rigid body interface can be transformed into a volumetric integral of the pressure gradient. Using this, we can perform a fluid–rigid body interaction analysis using the following simpler algorithm. Consider a calculation at some time step. We first perform fluid analysis without discriminating between fluid particles and rigid body particles. Next, for the rigid body particles, the rigid body shape is recovered in order to conserve the parallel and rotational movement of the rigid body (Koshizuka, et al., 1998). In this algorithm, we do not need to trace the fluid–rigid body interface explicitly. A number of rigid bodies can be treated in an identical manner. The method is suitable to simulate tsunami run-up carrying debris.

Next, we show some examples of the fluid–rigid body interaction analysis using the explicit MPS algorithm (Oochi, 2012). Figure 25 shows a part of Kamaishi City. There are seven ships in the port. Tsunami flow is modeled as a dam break for this demonstration. The ships are carried by the tsunami run-up onto the land. The calculation area is

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955 m long and 1,005 m wide. The real simulation period is 30 s, and the particle size is set as 1 m. The total number of particles is approximately 13 million. Figure 26 shows the simulation results. The ships are clearly transported by the tsunami. In the near future, we will calculate more debris in a much wider calculation region. We will also calculate the fracture of buildings and transportation of the broken buildings as debris.

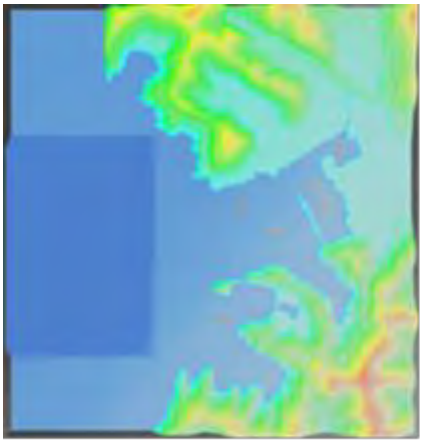
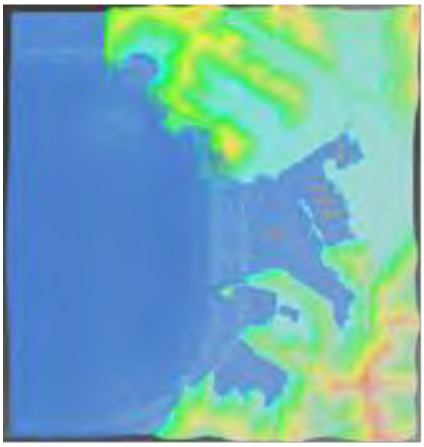


Fig. 25 Initial condition of fluid–rigid body interaction simulation.



(a) 10 s

(b) 20 s

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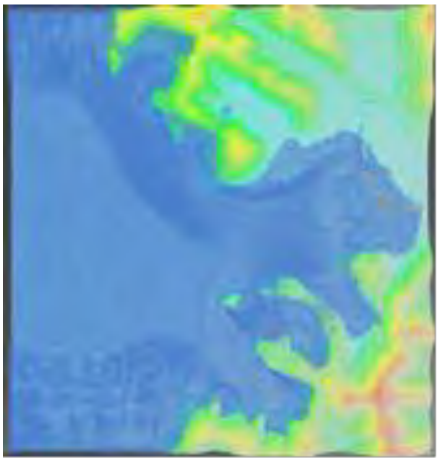

(c) 30 s

Fig. 26 Simulation results of tsunami run-up with seven ships.

(c) Impact analysis and its validation

After calculating the transportation of debris by a tsunami, we would like to calculate the impact of this debris on other structures. Through precise evaluation of the impact loading, we will quantitatively evaluate damage to buildings. In such a case, we need to validate the calculated impact loading by comparing with some experiments. Masuda et al. have been doing this type of research (Masuda, et al., 2012). Furthermore, to calculate the invasion of water into buildings, we need to apply a partially refined spatial resolution in such a region. This is one of our future research issues.

4.7 Two-way coupling analysis of tsunami and structure: water invasion analysis

4.7.1 Objective

Water-related disasters such as floods and tsunamis are fluid–structure interaction problems with free surface flow. In Japan, such water-related disasters occur frequently. It is very important to develop some simulation methods from the perspective of protecting machinery and structures. To do so, we first need to develop a method to simulate the fluid–structure interaction problem with free surface flow. Second, because a water-related disaster affects a wider area, it is necessary to develop a large-scale simulation method. There are very few studies from such a perspective.

The finite element method (FEM) has been widely used for structural mechanics problems. However, in general it is not very good at dealing with flow problems with free surface flow and moving boundaries. Various methods to capture moving boundaries and the free surface have been developed, including the VOF method (Hirt and Nicholls, 1981) and the Level Set method (Sussman, et al., 1994). Particle methods such as SPH (Yagawa and Miyazaki, 2007) and MPS (Koshizuka, et al., 1998), which deal with fluid flow in a Lagrangian manner, are good at dealing with free surface flow and moving boundary problems. The particle methods have also been extended to structural mechanics problems. However, because those use uniformly spaced particles, it is difficult to improve the spatial resolution locally. In the present section, we propose to use the MPS method for analyzing flow with a free surface, and to use FEM for structural analysis. We then combine both methods by employing a partitioned coupling method (Mitsume, et al., 2014).

4.7.2 Partitioned coupling analysis method

In this research, we employ a staggered-type two-way coupling method (Felippa, et al., 2001). In an analysis region with FEM, we set MPS wall particles and FEM nodes in an overlapped manner on the interface boundary, as shown in Fig. 27. Physical values are subsequently transferred between two regions. As for the interaction from fluid to structure, the pressure values of MPS wall particles calculated in the MPS fluid analysis are used in the structure domain as FEM nodal values. On the other hand, in the interaction from structure to fluid, the displacement values of the structure domain are transferred to displacement values of MPS wall particles.

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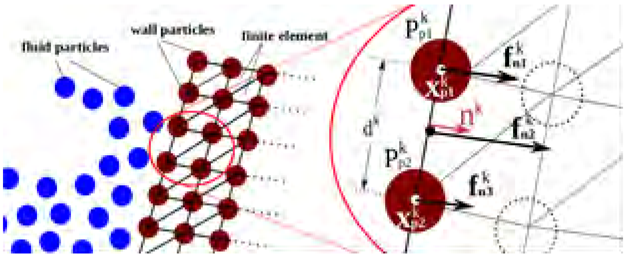

Fig. 27 Overlapping finite elements and MPS wall particles along the fluid–solid interface.

4.7.3 Verification of the method

To verify the MPS-FE method, one benchmark problem (Murotani, et al., 2012a) was solved. The problem was also solved by a space–time FEM (Walhorn, et al., 2005) and a particle FEM (Ryzhakov, et al., 2010) by other researchers. Figure 28 shows an analysis domain. Here, flow caused due to a dam break arrives and impacts an elastic wall. The material properties of the elastic wall are mass density ρ_s = 2,500 kg/m^2, Young's modulus E = 1.0×10^6 kg/m^2, Poisson's ratio $\nu = 0$, width of 0.012 m and height of 0.08 m. Material properties of the fluid are mass density ρ_f = 1,000 kg/m^3, dynamic viscosity $\nu = 1.0 \times 10^{-6}$ m^2/s, width of 0.146 m and height of 0.292 m. Gravitational acceleration is g = 10.0 m/s^2 and the time increment is $\Delta t = 1.0 \times 10^{-4}$ s. The elastic wall is subdivided into 40 × 6 sections. Second-order tetrahedral elements are employed. Small strain and large deformation analysis is performed. The fluid domain (column) is expressed with 146 × 73 MPS particles, and the particle space is 0.002 m. The explicit MPS method (Oochi, et al., 2010) is used for fluid analysis.

Figure 29 shows the time history of displacement of the top edge of the elastic wall in the x direction. Figure 30 shows several snapshots of the simulation results. Figure 29 shows a comparison of the present simulation results with other results (Walhorn, et al., 2005, Ryzhakov, et al., 2010). The time to collide and the peak value of the displacement of the MPS-FE method coincide well with the results of the particle FEM.

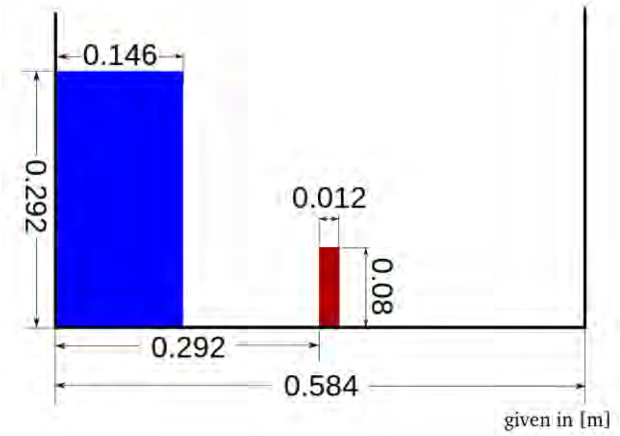

Fig. 28 Analysis setting of dam break problem with elastic obstacle.

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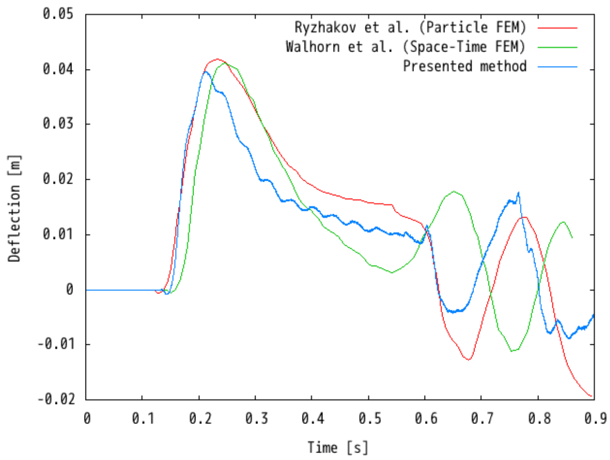

Fig. 29 Calculated time histories of displacement of the top edge of the elastic wall

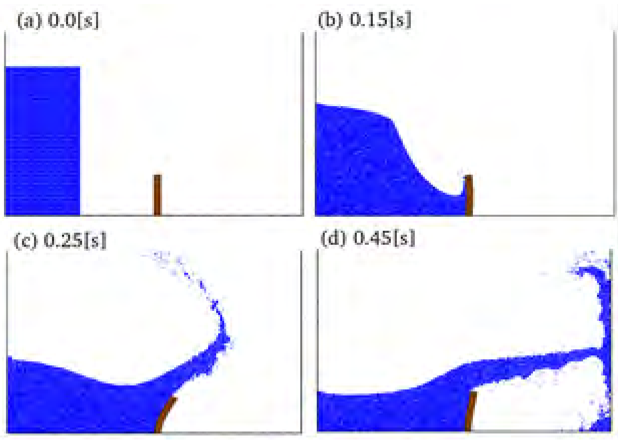

Fig. 30 Simulation results of fluid flow and deformation of elastic plate.

4.7.4 Water invasion analysis

Next, we performed a simulation of water-invasion right after the deformation of the elastic wall. Figure 31 shows the simulation results (Mitsume, et al., 2014). As for buildings containing important machines, their structure is built to be very strong, and furthermore water-tight doors might be equipped. In such cases, even though the structure itself is not destroyed and damaged, the water-tight door might be deformed by impulsive water pressure, and consequently water may enter the building causing damage to important machines. Therefore, this kind of simulation is very important to quantitatively evaluate the practical performance of water-tight doors.

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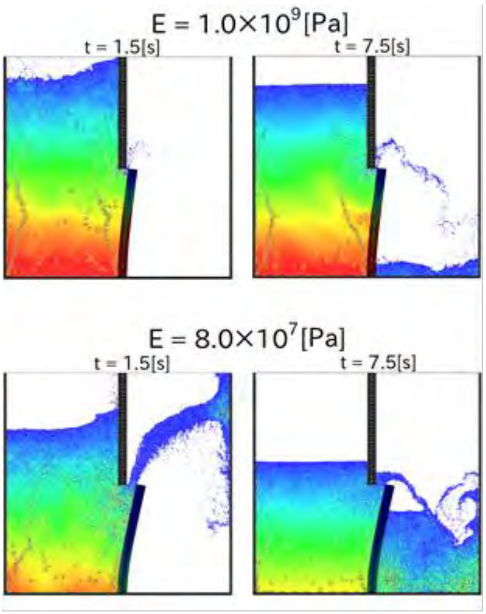

Fig. 31 Fluid invading simulation.

4.7.5 Future research issues

In section 4.7, we explained the MPS-FE method to analyze fluid–structure interaction problems with free surface flow. This method can solve basic water-invasion problems. To solve real problems, we need further development for treating large-scale and complex shape problems. Moreover, verification and validation of the method are also indispensable.

4.8 Behavior of steel-frame buildings upon collision with tsunami debris

4.8.1 Objective

The giant tsunami that occurred after the GEJE carried debris such as ships and cars upstream and caused additional damage to buildings in the area. For example, some buildings were irreversibly damaged, even though they were placed higher than the tsunami trace in Kesen-numa City, Miyagi Prefecture, as shown in Photo 2. It is thought that this damage resulted from large tsunami debris such as ships that were originally moored in the harbor (PARI, 2011b). The wave height of the tsunami that reached Kesen-numa harbor was approximately 6 m. Supposing that the wave velocity was 6–7 m/s, the force generated by the giant tsunami can be estimated as approximately 10 ton/m^2, which is sufficient to completely destroy buildings (NIRIM, 2011).

Photo 2 A ship washed up by the tsunami (Sankei Digital News, 2011).

Substantial effort has been made to estimate damage resulting from tsunami debris, even before the GEJE. Following the Indian Ocean tsunami after the 2004 Sumatra-Andaman earthquake, the Cabinet Office issued a report on the “Guidelines for Tsunami Refuge Building” (CAO, 2005) in 2005, and FEMA released the “Guidelines for

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Design of Structures for Vertical Evacuation from Tsunamis" (FEMA, 2008) in 2008.

In this section, some finite element analyses are carried out on a six-story, three-span steel-frame building being struck by a debris model mimicking a ship to investigate the mechanical effects of the impact force experienced by a building that remained standing after the seismic motion. This analysis is carried out using a collapse analysis code developed using the ASI-Gauss technique (Lynn and Isobe, 2007). The simulated seismic wave and fluid force are calculated from the height and maximum run-up height of the tsunami observed in Kesen-numa City (City of Sendai, 2012). Furthermore, the effects of the seismic motion, fluid force and impact force of the debris are compared between buildings constructed at different heights above sea level.

4.8.2 Numerical model and conditions

A six-story, three-span steel-frame building designed with a base shear coefficient of 0.3 is used as a numerical model. The span length and the floor height of the building are 6 m and 3.6 m, respectively. The floor load is set to 400 kgf/m^2. The specifications of the building are shown in Table 1.

Table 1 Specifications of the steel structure

Column

	Shape and dimension [mm]	Steel type
1, 2nd floor	□–400 × 400 × 19	SS400
3, 4th floor	□–400 × 400 × 12	SS400
5, 6th floor	□–300 × 300 × 9	SS400

Beam

	Shape and dimension [mm]	Steel type
1, 2nd floor	H-400 × 400 × 13 × 21	SS400
3, 4th floor	H-400 × 400 × 11 × 18	SS400
5, 6th floor	H-400 × 200 × 8 × 13	SS400

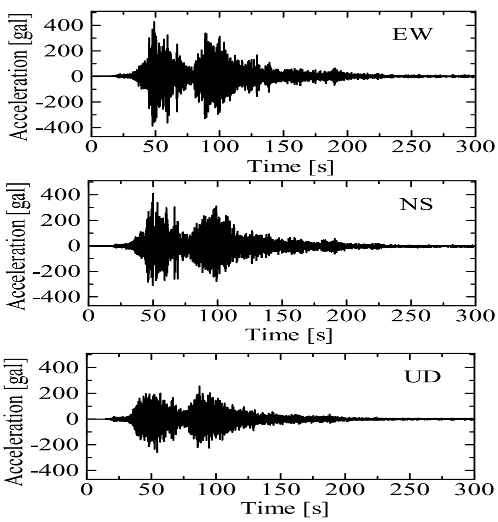

Fig. 32 Seismic wave observed in Kesen-numa City. (Data from 0–150 s is used as input.)

Damage to the building model under seismic motion is investigated by applying a Kesen-numa wave, as shown in Fig. 32, until 150 s from the beginning of the seismic activity. A buoyant force is then applied statically and a fluid

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force dynamically to the building and debris models, as shown in Fig. 33. The fluid force is calculated by assuming the maximum run-up height of the tsunami as $R^* = 21$ m and the tsunami height as $h = 15$ m, based on the data observed in Kesen-numa City (City of Sendai, 2012). Two building models are investigated, built at 9 m and 11 m above sea level.

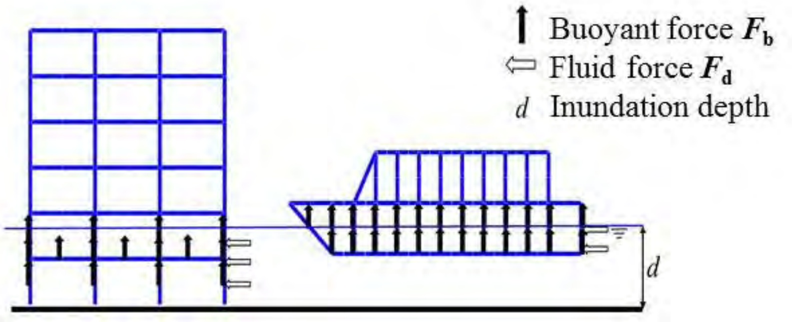

Fig. 33 Fluid force and buoyant force subjected to the building and tsunami debris.

The buoyant force that acts on a structure when the structure is partially or fully under water is expressed as follows.

$$F_b = \rho_s g V \tag{1}$$

Here, ρ_s is the density of seawater, g is gravitational acceleration, and V is the seawater volume displaced by the structure. The buoyant force acts opposite gravity, and may topple the building. In this analysis, buoyant forces generated in the volumes of the frame members of the building are applied to the nodes under the water level in the vertical direction. Similarly, the buoyant force equal to the weight of the ship is applied to the nodes under the water level in the debris model.

The fluid force composed of the pressure difference and the drag acting on a structure when the wave velocity of the tsunami is high, is given as follows.

$$F_d = \frac{1}{2}\rho_s C_d B (hu^2)_{\max} \tag{2}$$

Here, C_d is the drag coefficient, B is the width of the structure, u is the velocity of the tsunami wave, and (hu^2) is the momentum flux. The following equation can be used to approximate the maximum momentum flux value (NIRIM, 2011).

$$\left(hu^2\right)_{\max} = gR^2\left[0.125 - 0.235\frac{z}{R} + 0.11\left(\frac{z}{R}\right)^2\right] \tag{3}$$

Here, R is the run-up height of the tsunami used for the design, equal to 1.3 R^*, and z is the height above sea level. Fluid forces are applied to the underwater area on the tsunami side of the building and to the underwater area of the stern of the ship. The relationship between the height of the tsunami h, the level above sea level z and the inundation height d is as follows.

$$h = z + d \tag{4}$$

After applying the seismic wave, the buoyant force and the fluid force to the building, an initial velocity of 10 m/s is applied to the debris model (weight: 40 ton, length: 27 m, width: 6 m, height: 8 m, material: aluminum alloy) so that it collides with the building. The sequence mentioned above is seamlessly analyzed, and the behavior of the building is investigated in each sequence. The colors in the figure indicate the yield function value given by the following equation.

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$$f_y = \left(\frac{M_x}{M_{x0}}\right)^2 + \left(\frac{M_y}{M_{y0}}\right)^2 + \left(\frac{N}{N_0}\right)^2 \quad (5)$$

Here, M_x, M_y and N are the bending moments around the x-axis and the y-axis, and the axial force, respectively. The terms with the subscript 0 result in a fully plastic section in an element if they act independently on the cross section. The time increment of the dynamic analysis is set to 1 ms, and an implicit solution scheme using Newmark's β method is adopted in the analyses (β = 4/9 and δ = 5/6 are used to consider numerical damping).

4.8.3 Numerical results

The deformation of the steel-frame building at the point of the maximum acceleration of the Kesen-numa wave is shown in Fig. 34. While some slight deformations can be observed in the building, the seismic motion is not large enough to critically damage the building. The building behavior under the buoyant force and the fluid force when it is located 9 m above sea level (thus the inundation height d = 6 m from Eq. (4)) and 11 m above sea level (thus d = 4 m) is shown in Fig. 35. The building located at 11 m above sea level is slightly deformed but does not collapse, while the building located 9 m above sea level is critically damaged. Figure 36 shows the behavior of each building when an initial velocity of 10 m/s is applied to the ship debris model in addition to the fluid force. Although there are some differences, collapse beginning from lower levels can be observed in both cases. The influence of the fluid force applied to the debris is confirmed to be larger than that of the impact force itself because the overall results do not significantly change when a low initial velocity is applied to the debris.

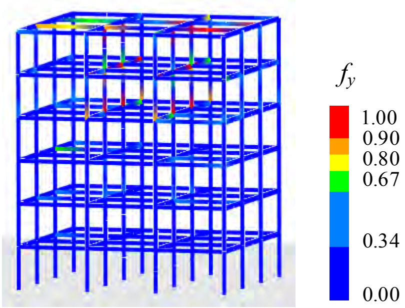

Fig. 34 Behavior of the building at maximum acceleration at 49.8 s.

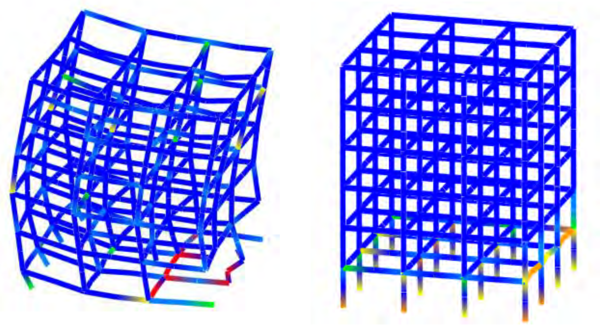

Fig. 35 Behavior of the building under fluid force and buoyant force
(a: 9 m above sea level, and b: 11 m above sea level).

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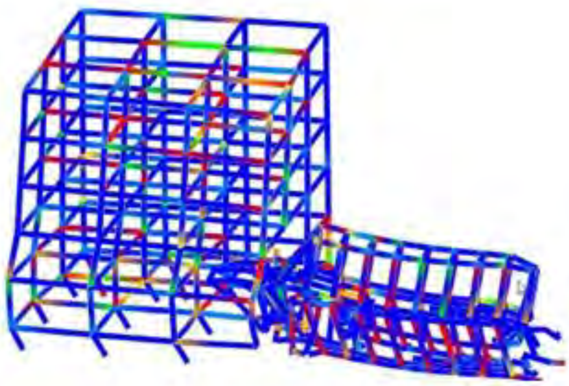
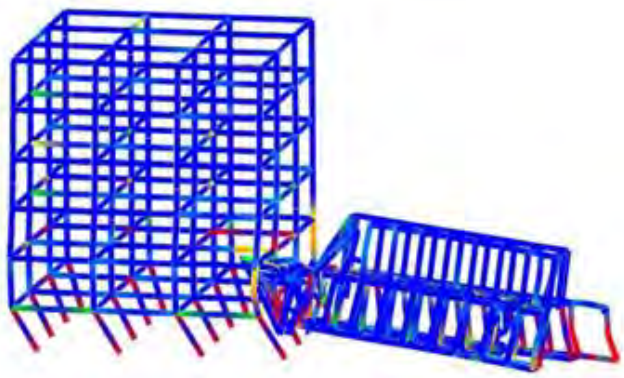


(a) 9 m above sea level.



(b) 11 m above sea level.

Fig. 36 Collapse of the building due to tsunami debris collision.

4.8.4 Conclusion and future issues

This section presented some numerical results on the debris impact and collapse behavior of a steel-frame building determined using the ASI-Gauss code. The effects of seismic motion, a buoyant force, a fluid force and an impact force on buildings located at different levels above sea level are compared. The fluid force is confirmed to have a large influence, and it may result in severe damage to the building at a lower height above sea level. Furthermore, the impact force of the debris also has a significant influence, and it may damage a building, even if the building has survived the tsunami itself. This indicates that the anti-collision and anti-tsunami considerations are of similar importance in the structural design of a tsunami refuge building. It may be necessary to investigate the dynamic behavior of buildings in tsunamis using more detailed data obtained from CFD simulations. We acknowledge the contribution of Mr. Yuan Qi Dong, a graduate student at the University of Tsukuba.

4.9 Evaluation by design engineering techniques

In the previous subsections, we show how to simulate the behavior of tsunami propagation and the deformation and fracture processes of machines and structures by using existing fluid mechanics and fluid–structure interaction methods. In this subsection, we describe a method for analyzing the chained impact of fluid and mechanical structures on a whole system.

Figure 37 shows a disaster scenario including debris caused by a tsunami, which has been proposed by Fujii and Imamura (Fujii and Imamura, 2010). Because this scenario involves a surging tsunami, their scenario must be combined with other analysis methods, such as failure mode and event analysis (FEMA) and fault tree analysis (FTA) in order to deal with the loss of functions of equipment or the whole system. We show an example of applying the FTA to the scenario of the loss of function of the system by a tsunami. At first, the loss of function of the whole system is set as the top event, and is deployed to intermediate events connecting to the top event. Moreover, the intermediate events

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are deployed to lower-level events until they are broken down to basic events, the failures of which can be evaluated directly. An example of the fault tree is shown in Fig. 38. All lower-level events are connected to upper-level events via an "AND gate", which means that an upper-level event occurs when all lower-level events occur, or an "OR gate", which means that an upper-level event occurs when at least one lower-level event occurs. In the case of the usual FTA, the top event probability is calculated from the fault tree and an individual basic event probability corresponding to the failure rate of each device. However, in the case of such events as tsunamis, they are very rare but cause significant damage. Therefore, applications of the conventional methods may not be sufficient. In reverse, it is appropriate to enumerate all conditions that cause the top event, to clarify the causal relationship between the loss in the whole system and external force due to tsunamis (such as wave power, buoyancy, impact force by debris) and inundation applied to the facilities and equipment, and to efficiently plan disaster prevention and mitigation based on those analyses. However, in the case of huge complex systems, such as industrial plants, it is not practical to break down into individual components and discuss their failure rate one by one. In order to realize the above-mentioned analyses in the future, it is necessary to clarify the relationship between tsunamis and the loss of function of the equipment with a batch of certain degrees.

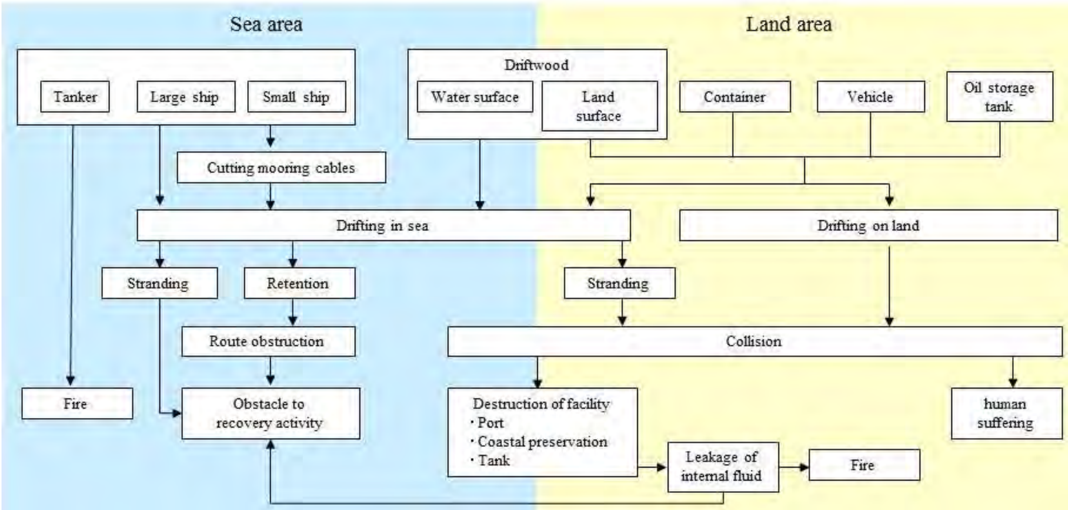

Fig. 37 Disaster scenario according to drifting bodies.

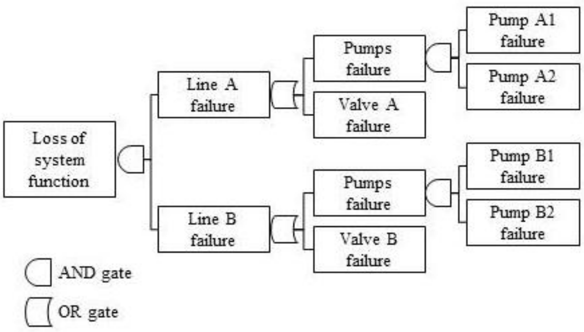

Fig. 38 Example of fault tree.

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5. Proposal to proceed with efforts to understand the mechanisms of tsunami-induced damage based on a discipline of mechanics

In this chapter, we investigated the complex mechanism of damage to structures and machinery caused by a tsunami. We, as the Japan Society of Mechanical Engineers, attempted to understand the mechanisms of tsunami-induced damage from a global perspective such that the effects on machines, civil structures and architecture are considered, in addition to understanding tsunami propagation from seismic sources. For this purpose, we studied various types of observed phenomena that occurred during the GEJE. Furthermore, we examine mechanisms of future tsunami-induced damage and aim at obtaining useful knowledge for future disaster prevention and mitigation. The methods employed for investigation and examination were to examine a huge amount of recorded visual information on tsunami-induced damage during the GEJE. Moreover, each member performed his own field study and simulation-based research. Based on this additional information, we performed a comprehensive examination.

Referring to the latest technologies, we perform simulations reproducing the mechanisms of tsunami-induced damage, and we investigate issues for future development.

It was found that real problems include various phenomena that exceed the state-of-the art simulation theories and models. Furthermore, it is very difficult to obtain input data for simulations and to verify and validate the methods. On the other hand, even though there are many difficulties, it is also clearly recognized that the simulation-based approach is very important and useful. Following such results, we summarize some proposals to make efforts to understand the mechanisms of tsunami-induced damage based on a discipline of mechanics.

(1) Tsunami hazards contain a large range of uncertainty. It is difficult to protect machinery and structures from tsunami-induced damage only using tsunami-protection structures such as sea walls and levees. It is very important to perform studies from the perspective of how to protect the functions of machinery and structures from tsunamis and how to design the protective measures and take appropriate actions. To do so, we need to precisely understand the mechanism of tsunami-induced damage. We then need to consider appropriate measures to protect them from tsunamis. The JSME should recognize these issues as one of their main targets, and as a whole, the JSME makes a big effort to do so and to implement the obtained results in our society.

(2) Various phenomena are related to the mechanisms of tsunami-induced damage. The range of damage caused by a tsunami is also very wide. In many cases, experimental approaches cannot be applied. Thus, computational mechanics plays a very important role in realizing proposal (1). On the other hand, current computational mechanics simulations can cover only a limited portion. There are a number of R&D issues in reproducibility, analysis scale, quantitative accuracy, computation speed, and practical application to prevention and mitigation design. By collaborating with other academic societies, the JSME as a whole should work hard.

(3) The results of proposals (1) and (2) are not only used to reproduce actual phenomena and to publish results in academic journals, but also implemented as tsunami proof design codes and guides for structures and machinery, so that our society can utilize the results in daily life.

(4) As described repeatedly, a tsunami does not occur solely. Structures, machinery and machines are first shaken by an earthquake, and then the tsunami strikes. Therefore, studies on complex mechanisms of damage from earthquakes and tsunamis should be accelerated.

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Report of JSME Research Committee on the Great East Japan Earthquake Disaster

Chapter 5

Application of Robot Technologies to the Disaster Sites

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Abstract
During the Great East Japan Earthquake disaster, Japanese rescue robots were used for actual disaster sites for the first time. Many robot technologies were used and tested mainly along the Sanriku coast and at the Fukushima Daiichi nuclear power plant (NPP). They were used along the Sanriku coast to inspect critical infrastructures, to search for missing persons driven underwater by the tsunami, to remove debris in the disaster sites, and to inspect buildings that were in danger of collapsing. At the Fukushima Daiichi NPP, unmanned construction technology was used to remove outdoor debris, and several military robots and rescue robots were modified for radiation monitoring, damage investigation, and removal of radioactive debris, and were used in the exterior and interior areas of the reactor buildings. In the evacuation centers, the therapeutic robots named “Paro” were introduced to more than 70 centers to provide psychological support to sufferers. The robots and robot technologies applied to the disaster achieved certain results. The results and trials of the practical applications, however, reveal new issues regarding the management of these robot technologies. In particular, at the Fukushima Daiichi NPP, there were no robots applicable to the disaster site immediately after the accident due to the unexpected severity of the accident. The site was contaminated with radiation and significant amounts of debris. In such a situation, both the tele-operation function and the ability to move on debris are required for robots. Professional operators and robust robots are also needed. However, such robots and operators do not exist in Japan. Thus, the government is strongly encouraged to technically and economically support anti-disaster robotics technologies.

Keywords : Rescue robot, Underwater vehicle, Tele-operation, Unmanned construction, Remotely operated vehicle, Military robot, Robot for nuclear power plant

1. Introduction

During the Great East Japan Earthquake disaster, Japanese rescue robots were used and tested. Along the Sanriku coast, several remotely operated vehicles (ROVs) were used to search for victims driven underwater by the tsunami, to inspect critical infrastructures, and to examine the bottom surface under the sea. A newly developed robotic construction machine and a rescue robot were used to remove debris at the disaster sites and to inspect a gymnastic hall that was in danger of collapsing in Hachinohe, respectively. They are now being used at the Fukushima Daiichi nuclear power plant (NPP) to remove debris in the interior and exterior areas of the nuclear reactor buildings, to monitor irradiation levels, and to inspect buildings. In the evacuation centers, the therapeutic robots named “Paro” were introduced to more than 70 centers to provide psychological support to sufferers. In the following sections, the details of the robots that were used and their results are reported with respect to the locations and purposes of use. Then, the problems extracted from the reports will be summarized from operational and technical aspects.

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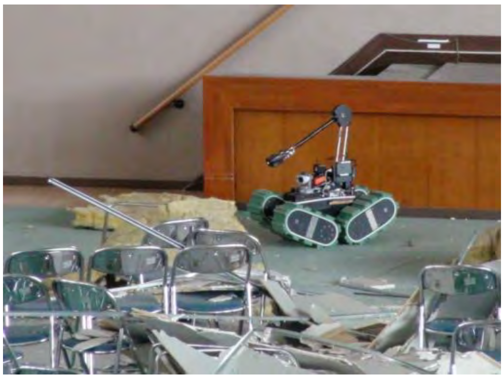
2. Robot technologies employed at the tsunami disaster sites

2.1 Robot activities along the Sanriku coast

The area devastated by the tsunami disaster was extensive and the amount of damage was unknown to the people in the other regions of Japan. The first robot activity that was employed at a tsunami disaster site began at a gymnasium that was in danger of collapsing seven days after the earthquake in Hachinohe. Prof. Matsuno from Kyoto University and his colleagues entered the disaster site from the northern part of the Sanriku coast on 18 March 2011 and tele-operated their developed mobile rescue robot "Kohga 3" to inspect the damage of the gymnasium, as shown in Fig.1. However, it was revealed that their robot was not able to locate survivors (Fig.2). On the other hand, it was revealed by their interview that the local governments along the Sanriku coast wanted an underwater investigation, since most of the victims died due to drowning. The local governments also wanted to conduct an underwater inspection of the damaged infrastructures and to investigate the amount of debris on the bottom surface of the harbors in order to ensure a prompt reconstruction of the damaged fishing harbors (Fig.3). Following a report by Prof. Matsuno on the robot activities and the investigation of the damage along the Sanriku coast, the Center for Robot-Assisted Search and Rescue (CRASAR) and International Rescue System Institute (IRS) collaborated and established a team to organize the operations for an underwater inspection. The operations began 18 April 2011 along the Sanriku coast. Prof. Hirose from the Tokyo Institute of Technology also began an underwater search for victims in the southern part of the Tohoku area on 19 April 2011. At the beginning of May 2011, the University of Tokyo Ocean Alliance and Mitsui Engineering & Shipbuilding Co., Ltd., surveilled the bottom surface of Otsuchi bay and found two victims. In the towns devastated by a tsunami, the new construction machine "ASTACO NEO", with twin hydraulic arms, developed by Hitachi Construction Machinery Co., Ltd., were employed to remove debris.



(a) Kohga 3 in the gymnasium (b) Operator controlling Kohga 3

Fig.1 Kohga 3 inspecting the gymnasium

(a) Shipbuilding yard in Kuji-shi (b) Noda-mura

Fig.2 Damages in the northen areas of the Sanriku coast

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Fig.3 Damages to Hachinohe port

2.2 Underwater investigation

One month after the earthquake occurred, underwater robots were employed to carry out an underwater investigation so that the lives of divers would not be jeopardized. AC-ROB, SARbot, and Seamor ROV were used to search for victims and to inspect the underwater portions of piers and bridges to assess the damage at Minamisanrikucho and Rikuzentakada from 19–20 and 21–23 April 2011, respectively. Anchor Diver 3 was used at Waraticho from 19–20 April 2011. These missions were conducted in collaboration with the IRS and CRASAR. The University of Tokyo Ocean Alliance and Mitsui Engineering & Shipbuilding Co., Ltd., investigated the amount of debris on the bottom of the sea around Otsuchicho from 28 April to 2 May 2011 and around Minamisanrikucho from 14 to 19 May 2011 by using the remotely operated underwater vehicle “RTV-100”. Several other surveillances of the sea-bottom surface were conducted following their investigation.

2.2.1 Minamisanrikucho and Rikuzentakata (Matsuno et al., 2012) (Murphy et al., 2012)

The ROVs that were used and their specifications are shown in Fig.4 and Table 1, respectively. SARbot is a commercial underwater vehicle developed by SeaBotix Inc. and was mainly used due to its portability and rapid setup/deployment. It is equipped with an enhanced color video camera, the Tritech Gemini 720i multibeam imaging sonar, an accurate GPS system, and a limb grasping mechanism. Seamor ROV was developed by Seamor Marine Ltd., and is equipped with high-resolution sonar and a grasper. AC-ROB is a small robot driven by a battery and captures video. It is similar to a thruster with a video camera and was mainly used to investigate tight places, such as under floating houses. In Minamisanrikucho, SARbot and Seamor were used to check if obstacles were present within 5 m of the water surface in the newly constructed area of the Minamisanrikucho fishing port. Since the clearness of the water was very poor (30–50 cm), a sonar sensor was used to locate large obstacles. As a result, there were no obstacles in the area that was checked. The amount of time that SARbot was in the water was 17 min on 19 April 2011 and 268 min on 20 April 2011, and that of Seamor was 178 min on 20 April 2011. In Rikuzentakata, SARbot, Seamor ROV and AC-ROB were used to search for victims. Since victims were assumed to be trapped by floating debris, as shown in Fig.5, the investigation was conducted under the floating debris or around the heaps of debris where divers had not yet searched. Such locations were very dangerous for divers due to the presence of hazardous materials in the debris, which also made the use of robots essential for the searches. No victims were discovered during these activities. The amount of time that SARbot was in the water was 193 min on 21 April 2011, 97 min on 22 April 2011, and 44 min on 23 April 2011, that of Seamor was 42 min on 22 April 2011, and that of AC-ROB was 35 min on 21 April 2011 and 20 min on 22 April 2011.

From 23 to 26 October 2011, the same team investigated debris that was large in size on the bottom of the sea, such as cars with gasoline, which is harmful for fishing. Two robots, SARbot and RTV-100, were used. As a first step, abstract data pertaining to the shape of the sea bottom for a wide area were collected by side-scan sonar attached to a survey boat. Then, the details of any suspicious object that was obtained by the abstract data were verified by using an ROV. ISR and CRASAR conducted the investigations and the data obtained by both were integrated into the same geometrical map, which was very convenient for staff of the local government and fishermen. More than 100 obstacles were found during the investigations.

ISBN 978-4-88898-244-3

Fig.4 Remotely operated vehicles (ROVs) that were used for the activities

Table 1 Specifications of the remotely operated vehicles (ROVs)

ROV	size (mm)	weight (kg)	tether length (m)	sensors	gripper	velocity (m/s)
SARbot	549×250×268	17.4	150	camera, sonar, GPS	○	3
Seamor	355×472×335	20	150	camera, sonar	○	3
AC-ROV	204×151×146	3	50	camera	×	1

(a) Floating debris driven by tsunami

(b) Image captured by the ROV under floating debris

Fig.5 Situation of floating debris

2.2.2 Wataricho (Huang et al., 2011)

Anchor Diver III, which is shown in Fig.6(a), was developed for the rescue activities of the Tokyo Fire Department by Prof. Hirose from the Tokyo Institute of Technology. It is equipped with a high-resolution video camera and 2D sonar, and driven by two thrusters. Anchor Diver III is connected to the operation site by a cable and can maintain its own position in tidal streams via the cable tension and thruster control, as shown in

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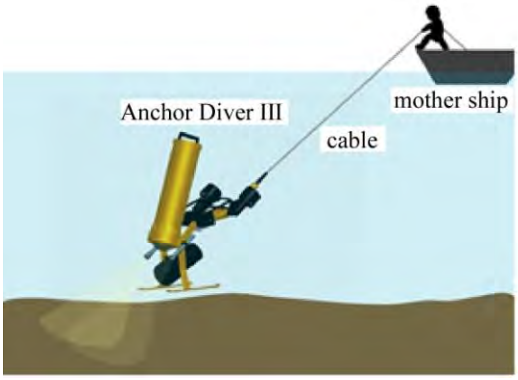
Fig.6(b). Since the direction of the thruster can be changed in the horizontal and vertical directions, the robot can move forward, upward, downward, and to the right and left, but the cable has to be rewound by the operator when the robot moves backwards. The shape of its main body is a cylinder, which is heavy at one end and light at the other. Therefore, the body always has a vertical orientation when in water. A sonar sensor and a camera are equipped on the heavy end of the body (the bottom end) and can continuously measure the bottom surface of the sea. Anchor diver III investigated an area of about 100 m^2 during a two day period. No victims were found during the investigation, but the conditions of the bottom surfaces of the ports were made clear.

(a) Photograph of Anchor Diver III



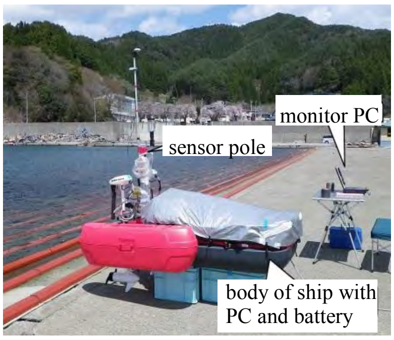
(b) Operation of Anchor Diver III

Fig.6 Anchor Diver III

2.2.3 Otsuchicho and Minamisanrikucho

The University of Tokyo Ocean Alliance investigated the bottom surface of Otsuchi bay and Shizukawa bay in collaboration with Mitsui Engineering & Shipbuilding Co., Ltd., from 28 April to 2 May and 14–19 May 2011, and found two victims. In Otsuchi bay, two remotely operated underwater vehicles (RTV-100 and RTV-100Mk2) and one autonomous surface vehicle (ASV), shown in Fig.7, were used. The length of the ASV was 2.1 m. The ASV can create maps of the sea bottom by using a GPS and its multibeam sonar. It can be autonomously controlled along a predetermined target path via its embedded computer. However, the ASV was not autonomously but remotely operated via a wireless LAN due to troubles with a controller. The map that was obtained is shown in Fig.8. An investigation by two ROVs was also conducted from a fish boat and it was found that a majority of the bottom surface was flat and that there was little debris. Two victims were also found. In Minamisanrikucho, only an RTV was used. The length of surveillance was about 12 hours and 14 locations were investigated.

(a) Remotely operated vehicles RTV-100 and RTV-100Mk2



(b) ASV

Fig.7 RTV-100, RTV-100Mk2, and ASV

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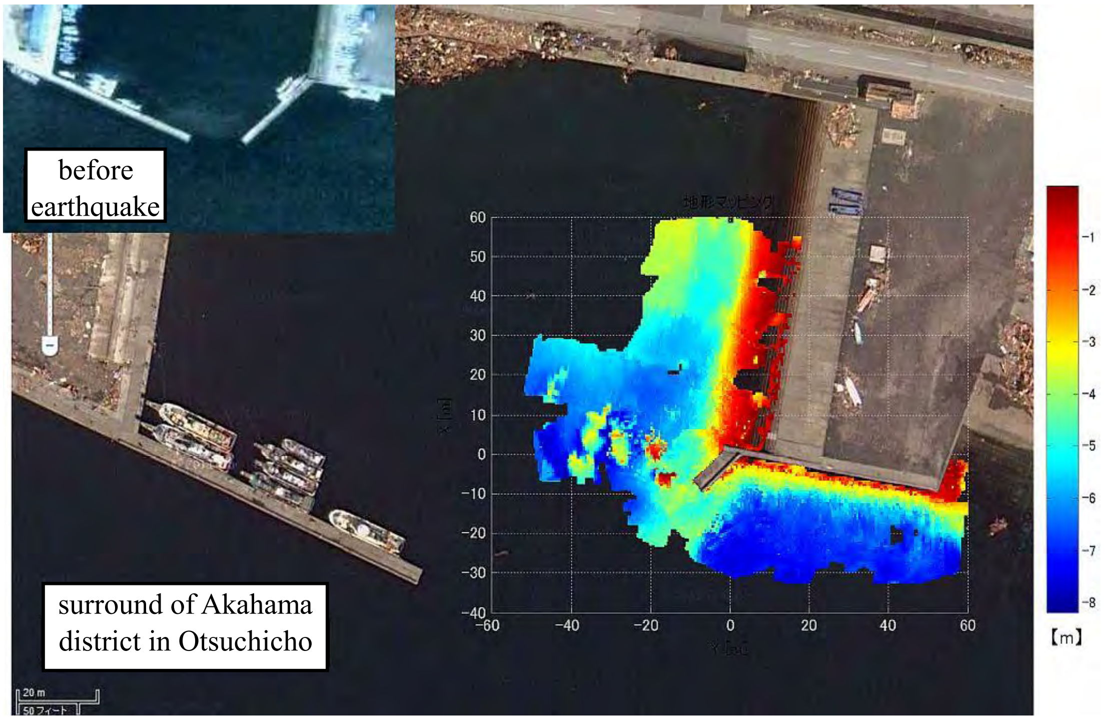

Fig.8 Bathymetry data obtained by the ASV. A photo of the area prior to the tsunami is shown in the top-left. Photos are from Google Earth (http://www.google.co.jp/intl/ja/earth/index.html).

During July 2011, the University of Tokyo Ocean Alliance conducted five visual surveys in collaboration with the Nippon Foundation and JF Zengyoren by using RTV-100 and the underwater vehicle “LEO”, which was developed by Tokyokyuei Corp. (Fig.9(a)). During the first four surveys, the boat shown in Fig.9(b) was anchored at a predetermined location and the sea bottom around this location was surveyed by the ROV. The depth was 40–70 m. During the fifth survey, the investigation was conducted using side-scan sonar equipped on a different boat and 60 anchoring points were determined in accordance with the measured data. Then, the surrounding area of the points was surveyed by the ROV the next day. This proved to be a very efficient method and most of the debris in an area of 3,300,000 m^2 was identified in just 4 days.

(a) Underwater vehicle LEO

(b) Fishing boat used for the investigation

Fig.9 ROV and the boat that were used in July 2011

2.3 Removal of debris

A new construction machine, ASTACO NEO, with twin hydraulic arms, as shown in Fig.10(a), was employed to remove debris and dismantle a portion of a damaged warehouse in Ishinomaki at the southern end

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of the Sanriku coast during May and June 2011. ASTACO NEO was developed during a project that was sponsored by the New Energy and Industrial Technology Development Organization (NEDO) (Yanagihara et al., 2009). One arm operates as the main arm that can be attached with commercial tools, such as 11-ton hydraulic shovels, and the other is a sub arm that can be attached with the newly developed versatile hand shown in Fig.10(b), which can grasp small objects at its finger tips and cut reinforcing steel at the base of its fingers. The degrees-of-freedom of the main arm is 5 and that of the sub arm is 9, both of which include their attachments. The main arm is controlled by the joystick on the right side and the sub arm is controlled by the joystick on the left side. The operations applied to the machine were completed smoothly and the robot was verified to have high efficiency. As another robotic technology, Smart Suit Light, which is a passive powered suit developed by Prof. Tanaka of Hokkaido University, was used to reduce the loads of the workers when removing debris (Imamura et al., 2011).

(a) Removing the doors of a damaged warehouse　　　　(b) Newly developed multifunctional hand

Fig.10 ASTACO NEO was used to remove the doors of a damaged warehouse

3. Robot technologies employed at the Fukushima Daiichi NNP

3.1 Robot activities employed at reactor No. 1 during the nuclear power plant accident

The hydrogen explosions of nuclear power units 1–4 affected a very wide area. Light debris was scattered along the road surrounding the power plant far from the buildings. Pieces of radioactive debris varying in size were also piled on top of cars and trailers around the reactor and turbine buildings, which disturbed the access of fire-extinguishing vehicles or concrete pumping tracks to the reactor buildings (Fig.11). Moreover, since it was strictly prohibited for workers to enter the buildings due to the high radioactivity, the amount of damage within the buildings was unknown. To recover from such an accident, it is essential to access the buildings and investigate the amount and type of damage; therefore, the development of many types of tele-operated robotic systems was urgently needed. However, there was no such robot in Japan applicable to the Fukushima Daiichi NPP immediately after the accident due to the unexpected severity of the accident. From the beginning of April 2011, unmanned construction technologies that were developed in Japan were used for the removal of radioactive debris outside of the buildings, which resulted in not only a clear accessible path to the buildings, but also a decrease in the level of airborne radiation. In April 2011, some U.S. military robots were modified for the Fukushima Daiichi NPP accident and were used to monitor the airborne radiation and to investigate the severity of damage. In June 2011, a Japanese rescue robot was utilized to investigate the interior of the reactor buildings. Currently, many robots have been developed in Japan and being used to remove debris, to monitor radioactivity or other physical parameters, and to inspect the damage to the nuclear reactors and buildings. Many more robot technologies related to the construction machines or rescue systems will be developed and used for the required tasks to decommission nuclear power units 1–4.

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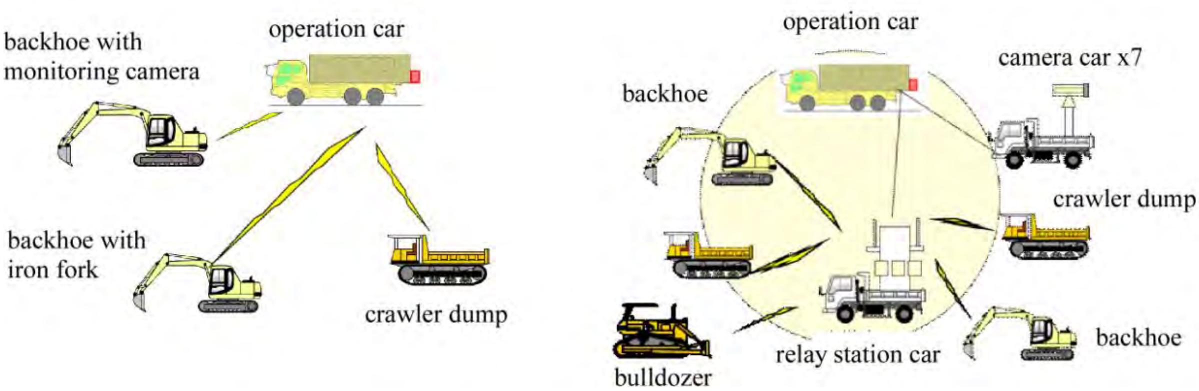
Fig.11 Debris that was scattered due to the hydrogen explosions

3.2 Removal of debris

Tele-operated construction machines modified for the disaster site were used to remove debris around the nuclear reactor buildings. At first, a backhoe with an iron fork attached to its tip, a crawler dump truck, a monitoring car with a camera, and an operation car were introduced as shown in Fig.12(a). The backhoe, dump truck, and monitoring car were tele-operated by operators in an operation car. Since the wireless communication range of this system limited the working distance to 150 m, it was impossible to use the system in high dose areas; thus, system 2 was introduced as shown in Fig.12(b). System 2 consisted of one operation car, one relay station car, seven camera cars, two backhoes, two dump trucks, and one bulldozer. The technologies installed in the tele-operation system were originally developed as unmanned construction technologies almost 20 years ago for the recovery activities of the evacuation of Mt. Unzen Fugendake and they have been continuously improved as construction robot technologies up until now (Yamamoto, 2007). At the time, there were about 20 skilled operators for unmanned construction machines in Japan, but it was impossible to place all the operators at the Fukushima Daiichi NPP, and the lack of operators was one of the most significant problems during the accident. It was also unclear whether the unmanned system would work well in high-radiation areas. If a machine became inoperable on an access road to the reactor buildings, the machine itself would have become a large obstacle that would seriously disrupt the recovery tasks. Despite these concerns it was determined to introduce the unmanned system into the disaster site.



(a) System 1 (b) System 2

Fig.12 Configurations of the unmanned systems used to remove debris

To collect the radioactive debris via the unmanned system, containers that were used in other nuclear power plants were modified for the grippers of the tele-operated backhoes so that they were able to open and

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close their flaps and used, but their radiation shielding ability was not high because they were designed for low level radioactive waste. All the debris was put into containers indiscriminatingly, as shown in Fig.13(a), and after being transported to the storage area, the containers were sorted according to the intensity of their radioactivity and stored as shown in Fig.13(b).

After introducing the unmanned system to remove debris, the level of the airborne radiation decreased. As the task became gradually easier, as shown in Fig.13(c), the applicable area became wider and almost 20,000 m^3 of debris was consequently removed from an area of 56,000 m^2. The system worked very well and the outdoor debris was almost completely removed by the middle of November 2011.

3.3 Pouring water into the pool of spent nuclear fuel

Just as the accident occurred, a periodic inspection was being conducted at reactor building 4, which had been eventually shut down. The pool of spent nuclear fuel on the top floor of the building was filled with the spent and unspent fuel removed from the reactor. A station blackout caused by the tsunami caused the water temperature in the pool to increase. If all the water in the pool had evaporated, most of the fuel in the pool would have melted down, producing levels of radioactivity so high that recovery would have been impossible. Therefore, pouring water into the pool was one of the most critical and urgent tasks immediately after the accident occurred. A modified concrete pumping track with a camera at the tip of the boom was used for the task and the water was successfully poured. It was then planned to continue this task remotely to reduce the radiation exposure of the workers, and three remote operation systems were developed. Fig.14 shows the entire system and the system configuration of Zousan 3, which consists of a concrete pumping track, an operation car, a monitoring camera car, and a relay station car. The three developed systems are similar, but they were not used in practice since the level of airborne radiation became low enough for workers to operate from the trailer when the systems were prepared.

(a) Remotely controlled backhoe

(b) Stacked containers

before removal of debris

3/May/2011

after removal of debris

14/May/2011

(c)Road between reactor building 2 and 3

Fig.13 Removal of debris by the unmanned control system

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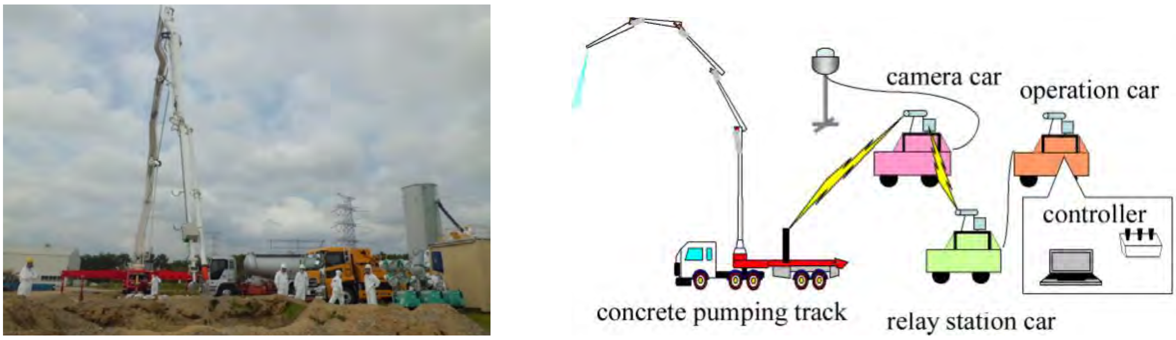

(a) The entire system (b) Configuration of the system

Fig.14 Remotely controlled concrete pump trailer

3.4 Radiation monitoring

A military robot, TALON, was provided to the Japanese government by DOE-INI on 14 April 2011 (Fig. 15(a)). TALON is equipped with a GPS and a radiation counter and can plot the obtained data on a geometrical map. The robot was expected to be used to monitor the outdoor radiation, but the roads were covered with debris, and the environment to operate the robot was very poor. Therefore, it was considered impossible to use only TALON. On the other hand, JAEA was developing RC-1 (Fig.15(b)), a truck on which a radiation shielding operation box is mounted. The shielding box has an 80-mm-wide steel sheet in front and operators can control the robots from inside of the box. TEPCO and JAEA developed a plan to transport TALON to the sites via RC-1 and tele-operate it from the box. In addition to the shielding box, a gamma-ray camera, laser range finder, thermo camera, radiation counter, and other small items were loaded into RC-1 as shown in Fig. 5.15(c). The gamma-ray camera displayed the intensity of the gamma rays by providing their corresponding colors on a screen, and it was very useful to locate the high-radiation debris around the large equipment hatch of reactor building 3 (Fig.16) and the exhaust air duct of reactor building 1. RC-1 and TALON were used on 5 May 2011. JAEA also developed another gamma-ray camera (γ-eye; Fig.17) that is more reliable than the previous one and a monitoring robot (J-3) that is based on RESQ-A, which was developed just after the disastrous nuclear accident in Tokaimura in 1999. To increase the radiation hardness and reliability, J-3 was remotely controlled via wiring and the motor drivers and the power source were placed in the shielding box. Due to this configuration, the radiation hardness increased 10^6 Gy. The motion range of J-3 was 50 m, which was determined by considering the weight of the cable that had a diameter of 20 mm and the maximum traction force of J-3. J-3 was loaded on to a new truck that had a shielding box and an air conditioner (RC-2), and was used to monitor gamma rays in reactor building 2 on 23 September 2011 (Kawatsuma et al., 2012).

Irradiation was also monitored at sea around the Fukushima Daiichi NPP by an unmanned surface vehicle (USV) (Fig.18), which can be autonomously controlled by using a GPS along a target path consisting of a series of given points on a map. Immediately after the earthquake, there was a lot of debris on the sea surface, and it was almost impossible to control the USV autonomously. Therefore, the USV was autonomously controlled, but the view ahead of the USV was also given to the operator on the ground. If an obstacle was found in the view, the operator sent the control command for collision avoidance to the vehicle. Then, the given command overrides that generated by the USV. To increase the robustness of the control system, four wireless communication systems were implemented (wireless LAN, FOMA, VSAT, and WIDESTAR) in order of priority. The length, width, and height were 6.0 m, 2.3 m, and 0.9 m, respectively, and its weight was 1.8 tons. The maximum velocity was 7 knots/hour and that during monitoring was 3 knots/hour, and the maximum sailing distance was about 100 km. In addition to the GPS compass and wireless communication systems, water samplers, a gamma dosimeter, and an acoustic doppler current profiler (ADCP) were equipped to the USV. TEPCO began operating the USV on 11 November 2011. The USV started at the Fukushima Daini NPP and sampled water at 26 points and measured gamma rays in real time off the coast of the Fukushima Daiichi NPP. The USV was unmanned, the total operation time was 3 hours and 40 min, and the sail distance was 40 km.

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(a) TALON (b) RC-1 (c) RC-1 being loaded with several tools

Fig.15 Irradiation monitoring by TALON

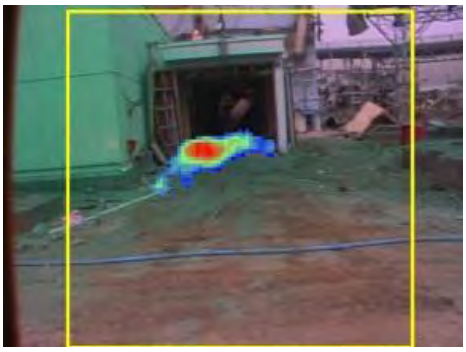

Fig.16 Image obtained by the gamma-ray camera around reactor building 3

(a) Remotely controlled robot J-3 with the γ -eye camera (b) γ -eye camera

Fig.17 Newly developed irradiation monitoring robot J-3

(a) USV (b) Operation site

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Fig.18 Unmanned surface vehicle (USV) used to monitor irradiation

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Fig.19 Packbot

Fig.20 Quince

3.5 Investigation of damage in the reactor buildings

For the monitoring and inspection, two Packbots (Fig.19), which are commercial military robots produced by iRobot Corp., were used to investigate the indoor damage of the nuclear reactor buildings after the middle of April 2011. One robot was controlled as a monitoring robot and captured images of the other robot via its camera, and the other robot was wirelessly controlled by the operator and was used to measure radioactivity, temperature, moisture, and so on. The robots also have a manipulator with (up to) eight degrees of freedom that can be used to open or close doors. These robots obtained valuable data pertaining to the indoor environment, but they were not able to go upstairs due to the steep inclination of the stairs. The rescue robot Quince (Fig.20) was developed by the IRS and began being used in July 2011. The mobile capability of Quince is very high, allowing it to climb stairs. In addition to the main two crawlers embedded in its body, Quince has a unique crawler mechanism that consists of two flippers with crawlers at the front and rear sides, which are similar to arms and legs. Quince is also equipped with a manipulator that has six degrees of freedom and is controlled via wires by operators. Before Quince was introduced to the Fukushima Daiichi NPP, the radiation hardness of the circuits included in the controller, the CCD camera, and the other sensors mounted on Quince were examined by irradiation tests at the Japan Atomic Energy Research Institute (JAEA) and Takasaki Advanced Radiation Research Institute in April 2011. The results showed that the laser range finder and CCD camera become inoperable at 124 Gy and 169 Gy, respectively, but all of the other semiconductors are still operable at 200 Gy, which indicates that Quince can operate for 5 successive days at 100 mSv/h with a safety rating of 10. After all other possible causes of failure were carefully examined, the staff at TEPCO began training to operate Quince in mid-April. On 20 May 2011, TEPCO determined that it was necessary to install a water gauge in the basement of reactor building 2 and to obtain samples of the contaminated water in this location. Quince was extensively modified according to these objectives and tested by TEPCO operators in reactor building 5 of the Fukushima Daiichi NPP, which was not damaged by a tsunami. On 24 June 2011, Quince was employed in reactor building 2 for the given missions, but they were not completed, because the difference in the width of the steps between the drawings of the building (92 cm) and the actual width (70 cm) was too narrow for Quince to turn on the stair landings. On 8 July 2011, Quince reached the second and third floors of reactor building 2 for the first time and monitored the air dose and sampled air dust. The operation screen for this day is shown in Fig.21, and the route taken by Quince is shown in Fig.22. Due to the great success of Quince, the extent of the damages to the buildings was clarified significantly.

Quince was also used to inspect the damaged buildings of Tohoku University in collaboration with a quad rotor helicopter (Pelican) and a rescue robot (Kenaf), which is the base robot of Quince, in July 2011 (Fig.23). A 3D map of the interior of the damaged building was also created (Michael et al., 2012).

3.6 Removal of debris from the reactor buildings

Some robots were used to remove radioactive debris and to clean the floors in the reactor buildings. The robot that was primarily used was a military commercial robot (710 Warrior) (Fig.24(a)) developed by iRobot

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Corp. In June 2011, 710 Warrior began cleaning the reactor buildings indoors. A cleaner is attached to the manipulator tip of 710 Warrior, as shown in Fig.24(b). iRobot Corp. provided two 710 Warriors: one with a heavy manipulator arm, and another with a universal vice with a hose clamp. The robot is a ground vehicle that utilizes tracks rather than wheels. The structure of the chassis consists of a drive mechanism paired with a flipper of the same size, the deck platform, and the base/arm coupling that is connected between the components. The heavy manipulator arm, universal vice, or any other payload can be installed on the deck platform. The chassis length is approximately 89 cm when the flippers are folded and the width is 54 cm (77 cm with flippers). The heavy manipulator arm has two links, but the deck platform, which can be lifted up and down and swivels forward and backward, provides a third link equivalent to an arm and an additional degree of freedom axis. The heavy manipulator arm is capable of lifting and handling approximately 99 kg. With a weight of approximately 200 kg, 710 Warrior has a mobility of over 12 km/h when the heavy arm is installed. It also has a radio and a wired communication mode when using the Operator Control Display Unit (ruggedized laptop PC), and can be operated by a hand controller. The use of 710 Warrior to clean the reactor building entrances was publicized in June 2011. The robot holds the dust collection nozzle and pulls the hose of the cyclone cleaner. It was used to review heavy shield transportation scenarios and to clean interior debris.

Fig.21 Operation panel of Quince

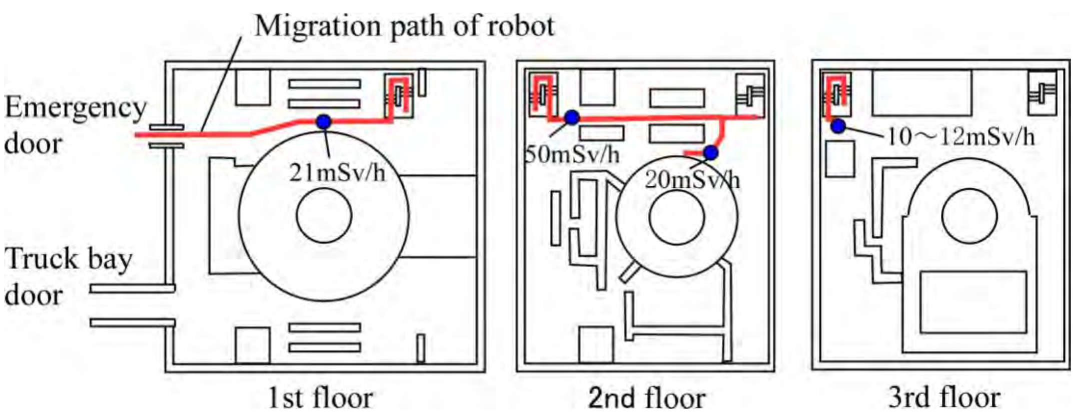

Fig.22 Root for inspecting the damage in reactor building 2 on 8 July 2011

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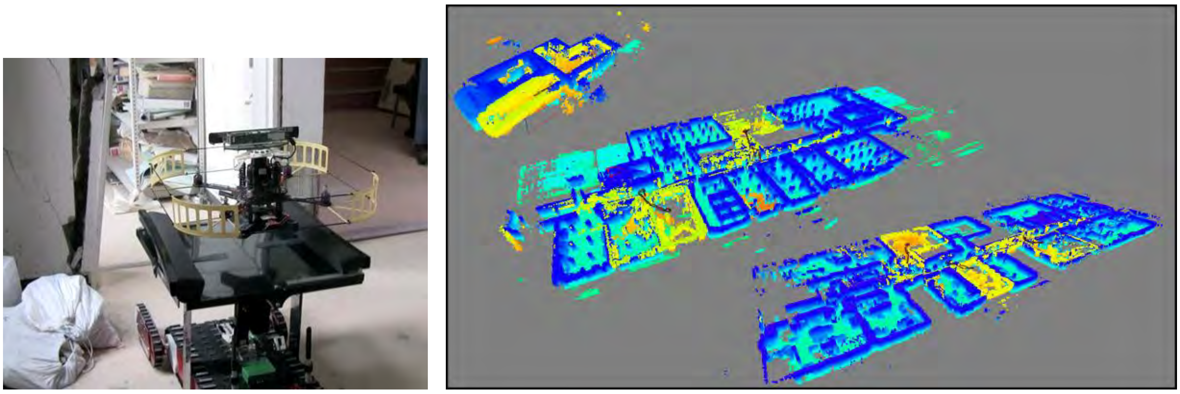

Fig.23 Inspection of a damaged building conducted in collaboration with Quince, Pelican, and Kenaf

(a) 710 Warrior (a) Quince and Pelican (b) 710 Warrior equipped with a cleaner
(http://www.tepco.co.jp/en/news/110311/images/110630_4.jpg)
Fig.24 710 Warrior that was used to clean the floors in the reactor buildings

(a) BOBCAT (b) BROKK
Fig.25 Remotely operated robots used to remove indoor debris

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Fig. 26 Paro in an evacuation center

Three other robots (TALON, BOBCAT and BROKK) (Fig.25) were used to remove debris around the heavy equipment hatch of reactor building 3. BOBCAT is a commercial unmanned construction vehicle developed by QinetiQ. BROKK is a remote controlled demolition robot for nuclear power plants; two BROKKs (BROKK-90 and BROKK330) were used. One was controlled via wires and the other was wirelessly controlled around the hatch.

4. Robot technologies employed at other sites

The therapeutic robots named Paro were employed at almost 70 evacuation centers to provide psychological support to sufferers. Paro is a robot seal developed for animal therapy (Shibata, 2012). Almost 2,000 PAROs have been sold in Japan since 2011 and 30% of them are used in medical and welfare houses. PARO was officially recognized by the Guiness Book of World Records as the most therapeutic robot, and has brought much consolation to sufferers in evacuation centers.

To assist in the reconstruction of daily lives in residential zones, the National Institute of Advanced Industrial Science and Technology (AIST) formed a consortium with corporations and applies life support technologies, such as energy and ICT services to temporary houses, to prevent elderly people from contracting major diseases caused by the lack of movement in Kesennuma.

5. Agenda and proposal for applying robot technologies to disaster sites

5.1 Agenda and proposal of a management system for anti-disaster robots

Along the Sanriku coast, underwater robots were mainly used to search for victims and to inspect infrastructures and the bottom sea surface. However, it should be noted that the number of activities and robots was too few for such a significant disaster. Most of the operators were university staff members and it was very difficult for them to approach the disaster sites due to the debris on the roads. Under such conditions, robots should be used as tools for the missions given by the members of the Self-Defense Forces or rescue teams of the Fire and Disaster Management Agency. The government is strongly encouraged to establish anti-disaster organizations that technically and economically support the operation of anti-disaster robotics technologies and the development of skilled robot operators.

For the Fukushima Daiichi NPP, robots were not initially applicable to the disaster site due to the unexpected severity of the accident and the difficulties of the task environments. The site was contaminated with radiation and had piles of debris. Therefore, both the tele-operation function and the ability to move on debris are required for robots. Professional operators and the robustness of the robots are also essential. However, such robots did not exist in Japan. On the other hand, there are many commercial military robots in the USA that can be easily operated, and it was much easier to introduce such robots to the sites than Japanese prototype robots. This is one reason why many of the robots that were initially used at the Fukushima NPP were from the USA. These facts also reveal the necessity of professional organizations to develop and operate anti-disaster robots.

5.2 Technical agenda and proposal for anti-disaster robots

It was very important that the robots were available for immediate use at the disaster sites. The robots that

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were used along the Sanriku coast had similar features, such as their robustness, portability, easy setup, and usability. These features are very important for anti-disaster robots. To create such robots, in addition to the development of technologies, the spiral improvement of robot technologies through repeated usage by actual operators is essential.

At the Fukushima Daiichi NPP, new objectives for the robots were continuously arising, and much modification was needed to complete their missions. To meet such requirements, robust base machines whose modifications for various missions are easily achievable are essential. A database of the available technical elements, the development of technical elements for an expected disaster or missions, and the coordinators for the developing robots for the given missions are also necessary. In particular, it was made clear that the robots require functions that allow them to access high, narrow, and underwater locations.

6. Conclusions

The Fukushima Daiichi NPP disaster was the first opportunity for most robotics researchers to apply their rescue robots to an actual large-scale disaster in Japan. Activities completed by using robot technologies were reported in this article and many robotics researchers joined various activities, such as damage investigations or recovery operations, and achieved some positive results. On the other hand, many critical issues pertaining to the management of technologies for anti-disaster robots and robots that performed insufficiently were also revealed, but all of the known facts are very valuable to improve the technologies of anti-disaster robots and to apply them to practical use. It is important to learn constructive lessons from as many experiences as possible.

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Report of the JSME Research Committee on the Great East Japan Earthquake Disaster

Chapter 6

Analysis of Traffic and Physical Distribution within the Disaster Areas

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Abstract

Traffic and physical distribution systems were widely and seriously damaged in the Tohoku area due to the earthquakes and/or tsunami. Many harbors and airports were damaged, and in particular, the Sendai airport was covered with water. In railway systems, infrastructures such as station buildings, railway tracks, rail catenaries, and pillars were widely and seriously damaged. However, the main structures were previously strengthened after the large earthquakes that occurred in Kobe and Niigata, so the damages to the railway systems caused by the earthquakes were not significant. Additionally, new systems such as the Earthquake Early Warning System were developed, which allowed the Shinkansen trains (known as "bullet trains") to be safely stopped prior to the strongest earthquake. In road transportation, roads and traffic signals were damaged, and numerous cars and trucks were carried away by tsunamis. Gas stations were also damaged, causing many cars to be unusable due to the lack of gasoline. A few days after the earthquake, Inter-NAVI information systems were available to drivers through car navigation systems, allowing them to determine which roads could be used, which was very useful for drivers. The "Kushinoha Sakusen" (teeth of comb operation) contributed greatly to the quick recovery of the roadways and logistics operations. As for physical distributions, supply chains were heavily damaged. Many factories of parts suppliers were damaged, so even though assembly makers were not damaged they could not procure parts and had to cease production.

Keywords : Air/Railway/Road Transportation, Earthquake Early Warning System, Inter-NAVI information System, Kushinoha Sakusen, Physical Distribution

1. Air Transportation

Most of the larger ports from Hachinohe in Aomori prefecture to Kashima in Ibaraki prefecture were damaged by the earthquakes and tsunami. However, the international and major ports recovered from the damages quickly. Hachinohe Port began contributing to disaster relief from March 12th and Ibaraki Port, the slowest to recover, resumed normal operations on March 14th (Ministry of Land, Infrastructure, Transport and Tourism, 2013). Several colliers crashed into the harbor, but no serious accidents, such as outflows of oil or large marine fires, occurred.

As for air transportation, a PTB ceiling collapsed, the windows of various airport facilities shattered, and radar facilities were damaged. Minor collisions between airplanes also occurred (Sato, S., 2013). The Sendai airport was seriously damaged by the tsunami, and 11 cracks formed in the runways and taxiways. Landing was impossible at the Sendai, Narita, and Haneda airports, which forced 100 planes to divert.

2. Railway Transportation

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As for railway transportation, infrastructures such as station buildings, railway tracks, rail catenaries, and pillars were widely and seriously damaged by the earthquakes and tsunami. The damages to the Shinkansen lines are shown in Figure 1. The area of damage was wider than that of previous large earthquakes. Many electricity columns were damaged, but there were no serious damages, such as collapsed bridges, due to the effective countermeasures that were put in place after previous large earthquakes. In total, it took 49 days for the lines to return to full operation, which was very quick compared to previous large earthquakes. Operations resumed between Tokyo and Nasushiobara on March 15th. The last line to restart was the line between Sendai and Ichinoseki, for which operations resumed on April 29th. Although 27 Shinkansen trains (known as "bullet trains") were being operated along the Tohoku line during the earthquake, all trains were able to decrease their speed and stop without any derailments or passenger fatalities. These effective actions were the result of the Earthquake Early Warning System, which was able to detect small P-waves before the large S-waves reached the railways and sent the information to the central operation center. However, one train that was being tested and operated at low speed derailed due to resonance between the basement and upper-roll motions.

The local lines of the JR East Company were directly affected by both the earthquakes and tsunami; however, the Shinkansen lines were not affected by the tsunami. The damages to the electricity columns

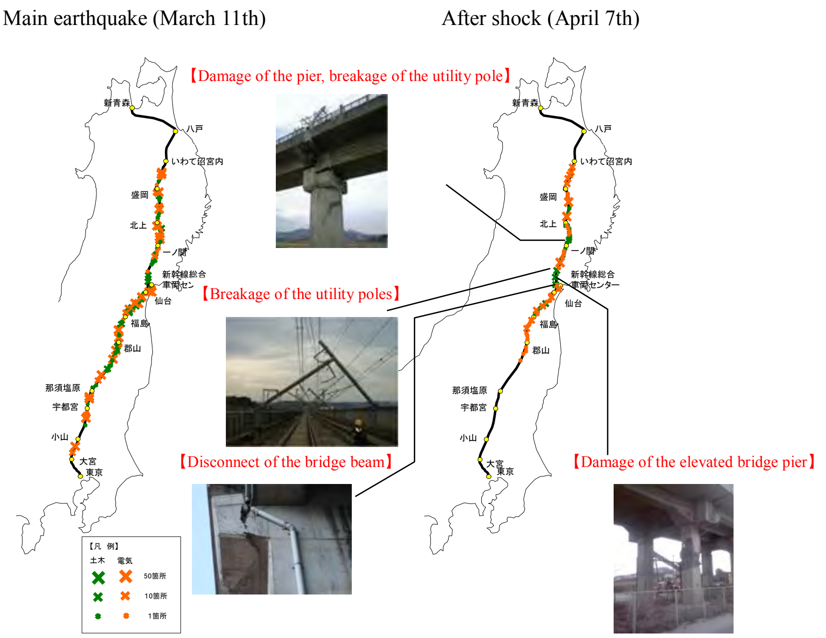

Fig.1 Damage of Tohoku Shinkansen line

Fig.2 Subsidence of embankment

Fig.3 Washed away of track

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were remarkable. Numerous damages, such as the misalignment of the rails (Figure 2) and train tracks that were completely destroyed (Figure 3), were seen in the damaged areas. Damages caused by the tsunami were very serious; not only were tracks washed away but 23 stations on seven different lines became unusable. Many trains were forced to stop between stations near the Pacific coast due to the earthquake. The passengers of 27 trains that were in danger of being affected by the tsunami (five of which were actually struck), were able to evacuate before the tsunami arrived.

In addition to the JR line, numerous tracks and stations were washed out in the North and South Rias lines, which is operated by the Sanriku Railway Company. The control room of the Sendai Airport line was flooded (East Japan Railway Company, 2011). The railway vehicles of the JR Freight Railway Company and tracks for the cargo that run toward the coast were also severely damaged (Tohoku District Transport Bureau, Ministry of Land, Infrastructure, Transport and Tourism, 2013a).

Damages to the elevated bridges and catenaries, liquefaction failure, and cracks were observed in the metropolitan area of Tokyo.

Although there were some severe damages, the following countermeasures against earthquakes that were previously established are considered to have functioned effectively.

1) Infrastructures were reinforced according to the new earthquake resistant standards.
2) Earthquake Early Warning Systems were introduced.
3) Derailment protection devices were equipped to railways.

3. Road Transportation

Highways had already been strengthened, similarly to the Shinkansen lines, so significant damage was not sustained. However, due to the tsunami, 870 km of damages were sustained by highways including 350 km of damage to the Tohoku highway, where numerous cracks formed in the road (Photo 6.3) and, in the worse case, a bridge support was damaged (Photo 6.4). The result was serious disruption to road transportation. Roads were repaired to allow temporary use for emergency vehicles by the morning of March 12th (East Nippon Expressway Company Limited, 2013).

As for normal roads, National Road 45, which is located along the Sanriku coastline, was severely damaged. Numerous cracks formed, some areas of the road were covered with water, and some bridges were washed away by the tsunami. Numerous damages such as cracks, fallen stones, and subsidence appeared on the other national roads.

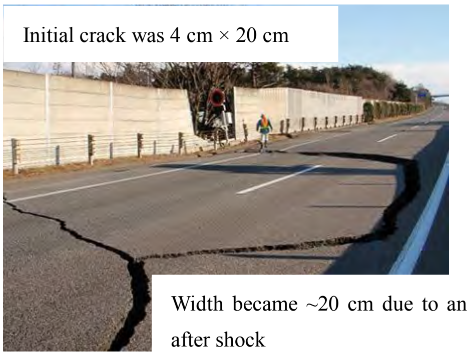

Figure 4 Cracks that formed in a road

Figure 5 Damage to a bridge support

During this earthquake, the "Kushinoha Sakusen" (Teeth of Comb operation) contributed greatly to the quick recovery of the roadways and logistics operations (Tohoku District Transport Bureau, Ministry of Land, Infrastructure, Transport and Tourism, 2013b). Figure 6 shows an outline of the Kushinoha Sakusen. To ensure a quick recovery for the heavily damaged areas near the offshore regions of the Sanriku coast, the

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Tohoku Highway and National Road 45, which run north-to-south and were not heavily damaged, were repaired first. Next, the roads that run east-to-west to the coastal areas were repaired. The other roads that ran along the Sanriku coastline were repaired last. These procedures were determined on the day of the earthquake, and 97% of National Road 45 was usable by March 18th.

As for the information of traffic near the damaged areas, real-time passable road information collected from car navigation systems was released on the Internet. This information was very useful for those who traveled to the damaged areas. The same information systems were introduced for large vehicles.

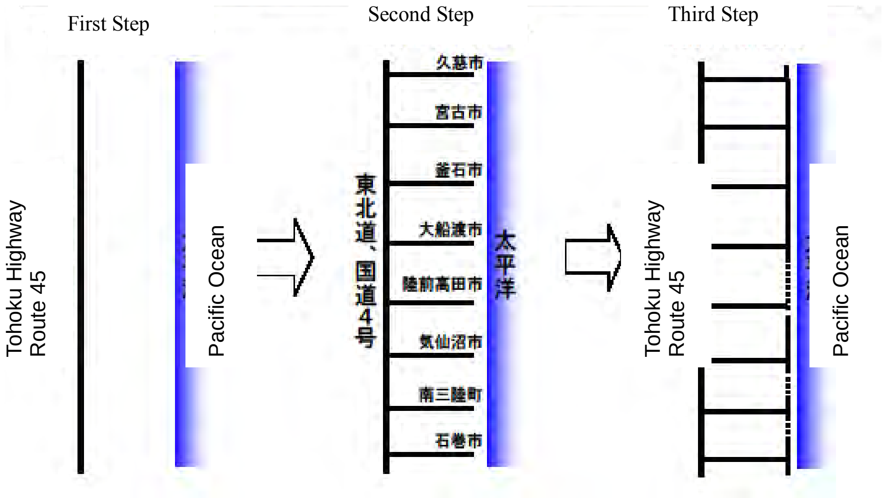

Figure 6 The “Kushinoha Sakusen” (Teeth of Comb operation)

4. Physical Distributions

As for physical distributions, the supply chains in Japan were severely damaged. Physical distribution contractors were affected, making delivery impossible. For companies with their production bases in the stricken areas, production ceased due to the damages to the factories or a rupture in the distribution channel. Moreover, many parts-supplier factories were damaged, so even though assembly makers were not damaged they were not able to procure parts and had to cease production. Not only the direct damages caused by the disaster, but also the subsequent scheduled blackouts had a large influence on the physical distributions. Thus, the brittleness of the supply chains was revealed by this disaster. In addition, fuel shortages in the stricken areas also became a huge problem. Even if the factories and roads had been repaired quickly, it would not have been possible to transport parts and products due to a shortage of gasoline. Special emergency trains that carried fuel to the stricken areas had to bypass the Tohoku line, since it was not usable (KEIDANREN, 2012).

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Chapter 7

Damages to Energy Infrastructures

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Abstract
Working Group 5 (WG5) was organized with support from the JSME Power and Energy System Division to investigate energy policies and to research and analyze various issues related to energy infrastructures, such as nuclear power stations, thermal power stations, hydroelectric power stations, power transmission and distribution systems, gas stations, and oil factories. In order to cover a broad range of topics, the four sub-working groups (A: Nuclear Power, B: Thermal Power, C: General Equipment of Energy Infrastructures, and D: Energy Policy) were established within WG5 from the standpoints of production, supply, and use of energy. The significant results obtained by each sub-working group are reported herein.

Key words : Nuclear power plant, Thermal power plant, Field survey, Energy system, Energy policy, Questionnaire survey

1. Damage survey of power plants

The Kanto and Tohoku regions along the Pacific coast were severely hit by the Great East Japan Earthquake on March 11 in 2011. Damage surveys of nuclear and thermal power plants were narrowed down to the affected area of the earthquake and tsunami. The surveyed power plants are listed in Fig. 1. Those are the five nuclear power plants, Higashidori, Onagawa, Fukushima Diichi, Fukushima Daini, and Tokai Daini, and the nine thermal power plants including the one pilot plant of integrated gasification combined cycle(IGCC), Sendai, Shin-sendai, Shinchi, Hara-machi, Hirono, Nakoso, Hitachi-naka, and Kashima. The field surveys were conducted at the underlined plants in Fig.1.

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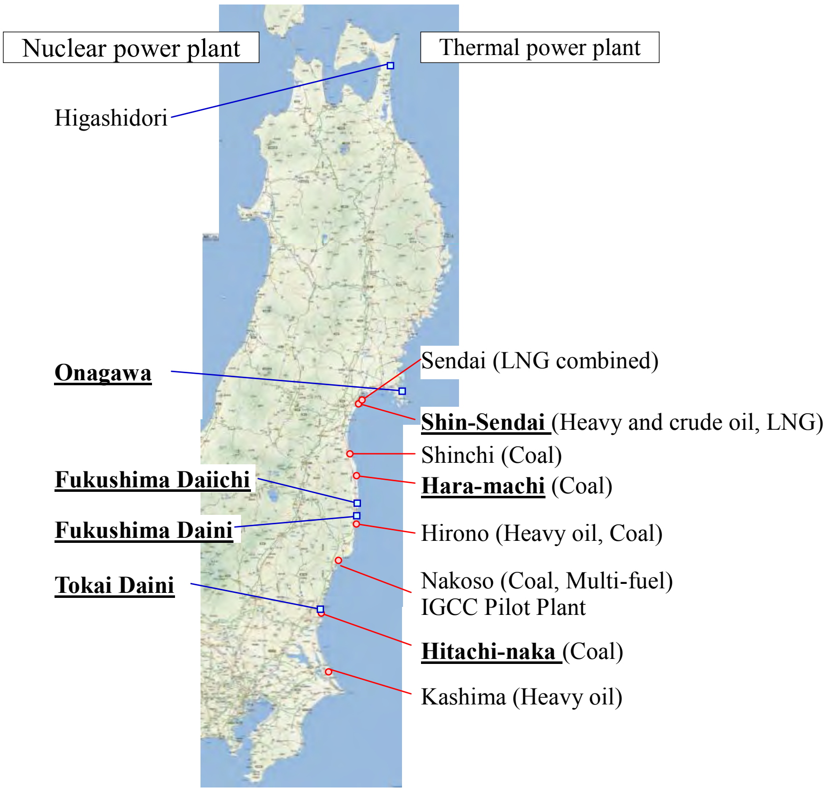

Fig. 1 Nuclear and thermal power plants in the Kanto and Tohoku regions along the Pacific coast.

1.1 Nuclear power plant

Figures 2 and 3 show the tsunami hitting the Fukushima Daiichi nuclear power plant and the reactor buildings damaged by the hydrogen explosion that was caused by the subsequent station blackout and core meltdown, respectively. Based on the results of the investigation and analysis of the accident at the Fukushima Daiichi nuclear power stations, the following important technical issues were recognized: (a) important equipment such as emergency batteries and emergency generators should be stored or located in water-resistant areas, and (b) power-supply cars and switchboards should be placed on higher ground. An investigation was also conducted on the accident management. First, it was estimated that the nuclear reactor core of unit #1 was under complete exposure before 18:00 JST on 11 March 2011 (Aritomi, 2012). This implies that there was only a very limited amount of time during the accident management to avoid serious outcomes, such as the release of radioactive materials into the environment. Furthermore, it was considered that the persons in charge at the site, the central office of the Tokyo Electric Power Company and the headquarters of the Japanese government, did not adequately recognize the aforementioned serious situation. Understanding the spatial and temporal development of the events expected after the occurrence of an accident and the information of the plant status are the basis used to take appropriate accident management procedures. Therefore, instrumentation systems to determine the plant status should be available under any circumstances. During the past 40 years, since unit #1 of the Fukushima Daiichi nuclear power plant began full operation, various experiences and effective safety measures pertaining to a possible nuclear power plant accident, including TMI-2, have accumulated (U.S. NRC, 2002). Additionally, the outcomes of the researches on severe accidents carried out by the Japan Atomic Energy Agency (JAEA) and Japan Nuclear Energy Safety Organization (JNES) were reported (Nariai, 2011), but the knowledge obtained from these was unfortunately not used sufficiently for “kaizen” or for the improvement of the existing nuclear power plants in Japan. In the investigation report of the TMI-2 accident that was published over 30 years ago, it was already pointed out that when new knowledge is obtained, it should be applied immediately to existing plants to extract new important issues, maintain the effort for kaizen, and to re-examine the institutional design (President’s commission on the accident at Three Mile Island, 1979). In addition, unit #1 was developed by the General Electric Company as a turnkey project; in other words, unit #1 was not developed by JSME. In view of this, it may be obvious that it was of particular importance to thoroughly investigate the previous accidents at nuclear power plants and the outcome of severe accident research to improve the safety features of nuclear power plants in Japan. As a

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response to the September 11 attacks, the United States Nuclear Regulatory Commission (US NRC) pointed out the possibility of a nuclear power station blackout caused by terrorism and requested a countermeasure be taken to ensure that the cores can be cooled under any circumstance (US NRC, 2012). It is of our deepest regret that we did not follow such a measure, but this will certainly be in place for future operations.

Many important lessons were also learned from the events that occurred at the nuclear power plants (NPPs) other than the Fukushima Daiichi nuclear power plant. At the Tokai Daini nuclear power plant, the Japan Atomic Power Company increased the height of the wall surrounding the seawater pump and improved the water-tightness of the penetration sections; these measures were taken before 11 March 2011 in response to a map that showed where flooding caused by a tsunami was expected, as provided by Ibaraki Prefecture in October 2007. As a result of implementing these countermeasures, two out of the three seawater pumps for the emergency diesel generators were able to avoid the flooding caused by the tsunami (Fig. 4). The Fukushima Daini nuclear power plant was struck by a tsunami that was higher than expected, but a cool shutdown was achieved by prompt operations, which included the implementation of temporal electric cables and the transportation and placement of alternative pump motors (Fig. 5). This confirmed the importance of preparing backup systems, creating manuals for accident management, and ensuring the use of alternative equipment. In the Onagawa nuclear power plant, an electrical short circuit occurred in a high-voltage power panel and caused a fire, which threatened the seismic class-S equipment. As for the Fukushima Daiichi nuclear power plant disaster, the seismic class-S equipment of the nuclear power plant units that were investigated was not damaged due any of the earthquake motions. Thus, it can be considered that the precautionary measures taken for earthquake motions were appropriate. However, a re-examination is required for the possibility that the functionality of the class-S equipment was influenced by the damage of the class-B and/or C equipment caused by the subsequent fires. Another notable event occurred at the Onagawa nuclear power plant. During this event, although the tsunami height was less than the ground height, several pumps were flooded due to the tsunami, which caused the emergency diesel generators to fail. The top of the box containing the tide indicator was blown off due to the increase in sea level caused by the tsunami. As a result, the reactor building was connected to sea to cause the flooding of the reactor building by the sea water (Fig. 6). The box top was very weak because the tide indicator was added after the nuclear power plant began operating without taking the risk of flooding into careful consideration. This is an important example that shows that meticulous attention is needed when implementing countermeasures to ensure water-tightness.

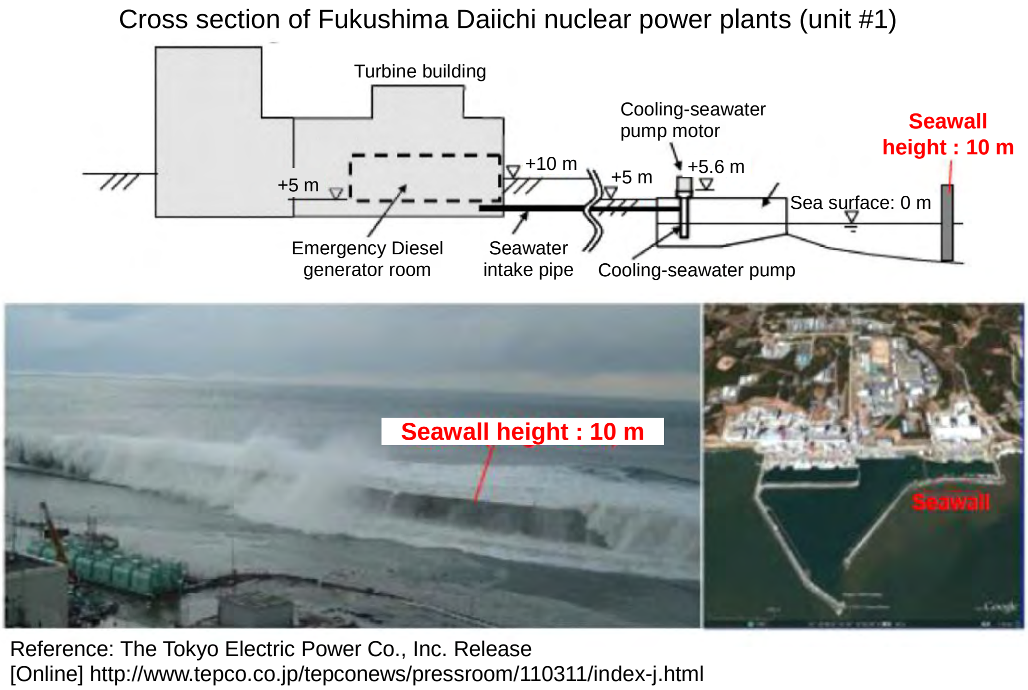

Fig. 2 Layout of the seawall and an image showing the tsunami hitting the Fukushima Daiichi nuclear power plants.

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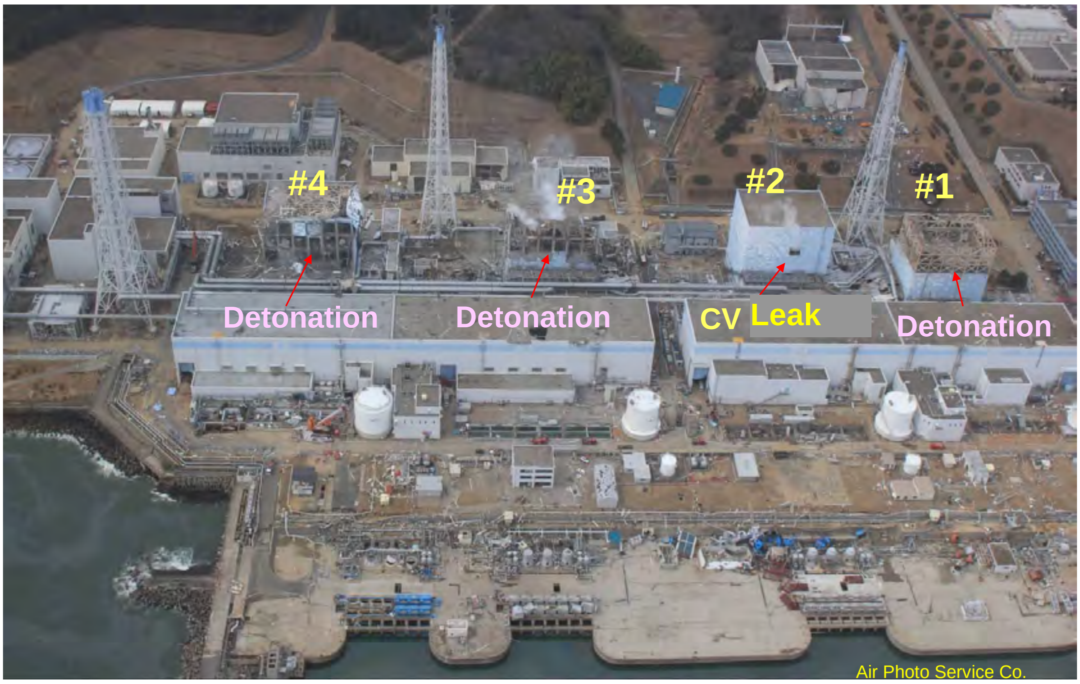

Fig. 3 Reactor buildings of the Fukushima Daiichi nuclear power plants after the occurrence of the hydrogen explosions (Courtesy of Air Photo Service Co.).

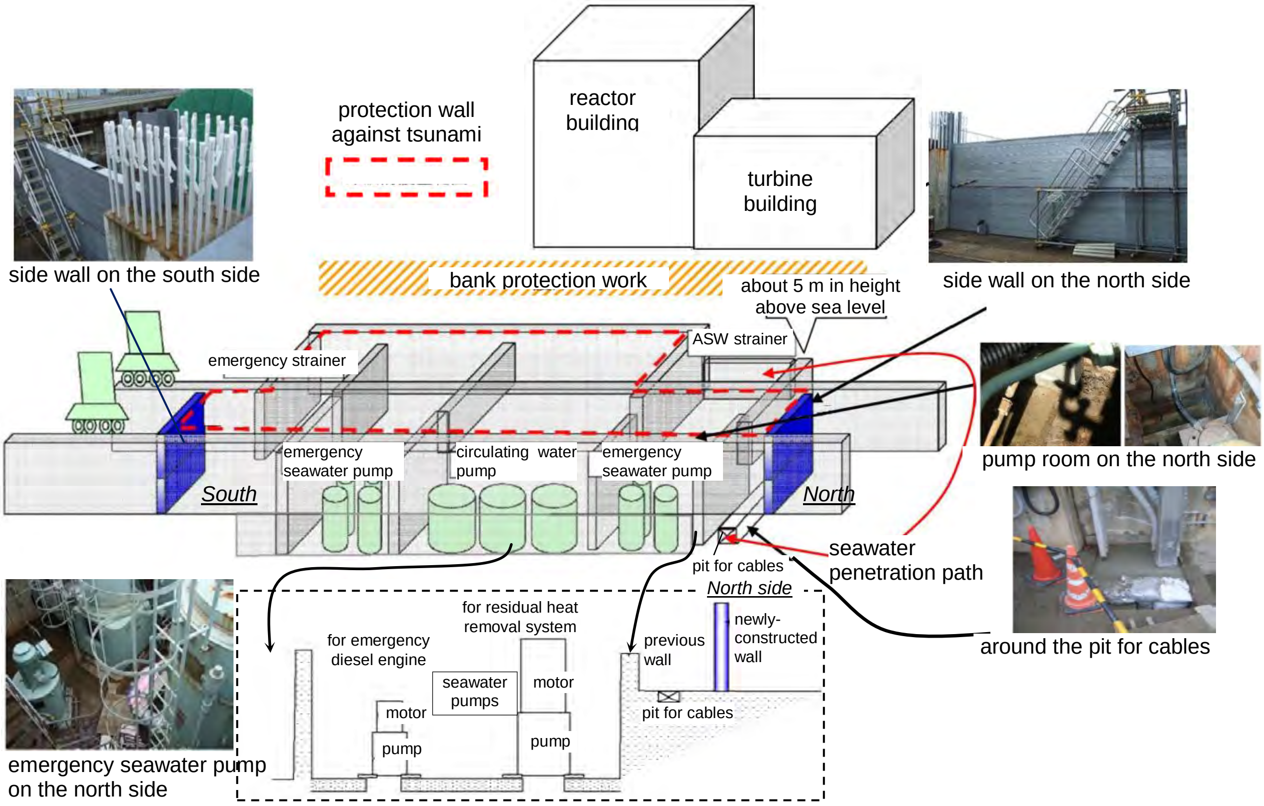

Fig. 4 Layout of the seawater pumps for the emergency diesel generators at the Tokai Daini nuclear power plant (The Japan Atomic Power Company, 2011).

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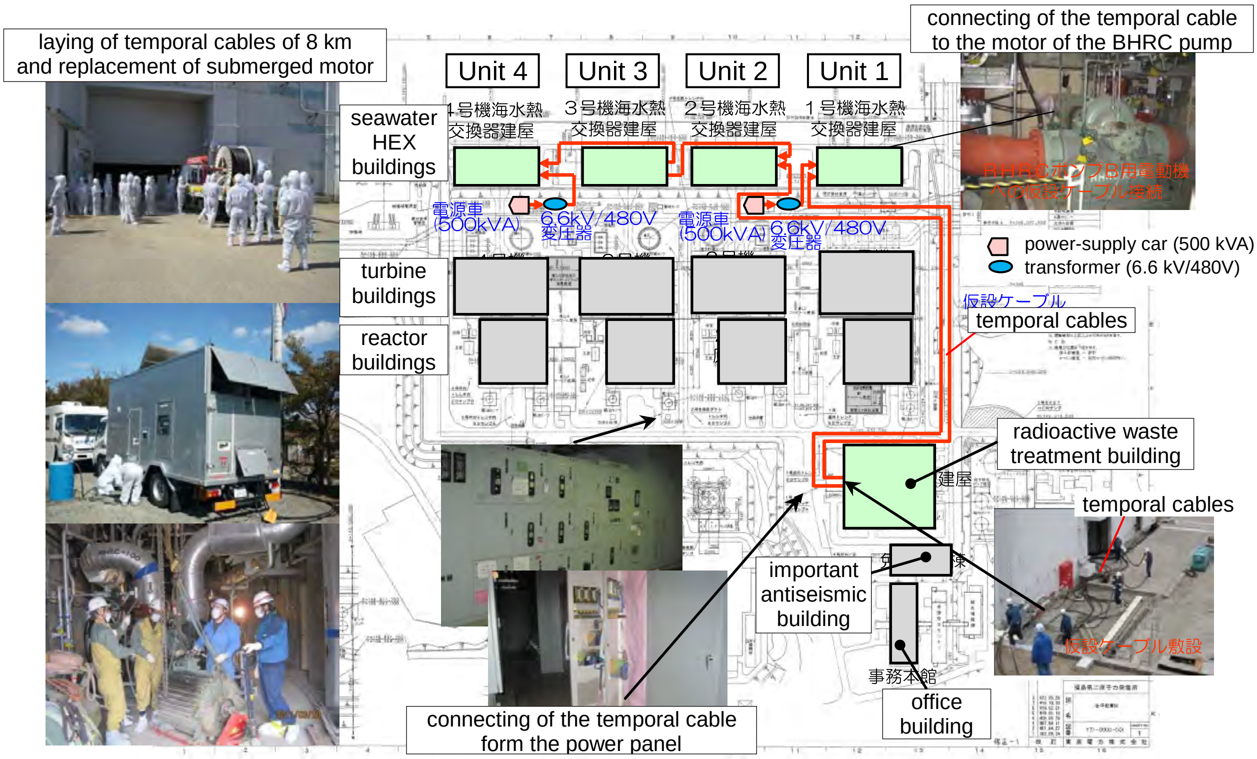
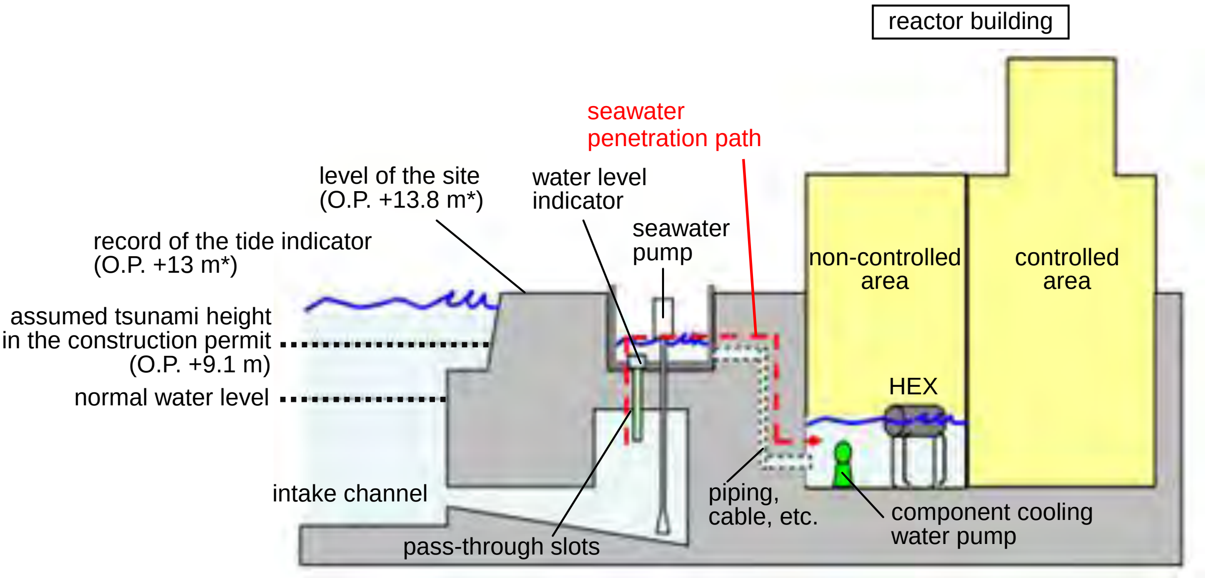


Fig. 5 Layout of the temporal electric cables and the transportation and placement of the alternative pump motors at the Fukushima Daini nuclear power plant (Tokyo Electric Power Company, 2012).



O.P. (Onagawa peil) is 0.74 m lower than T.P. (Tokyo peil).
* The levels are taken into account the earthquake deformation (about -1 m).

Fig. 6 Image showing how the building next to the nuclear reactor building of unit #2 flooded at the Onagawa nuclear power plant (Tohoku Electric Power Company, 2011).

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1.2 Thermal power plant

On-site surveys and hearing surveys using questionnaires were conducted by Group B on eight thermal power plants and one pilot plant of the integrated gasification combined cycle (IGCC) in the Kanto and Tohoku regions along the Pacific coast that were damaged by the earthquake and tsunami. The causes and degree of damage were investigated.

The summarized results of the questionnaires that were provided during the investigation are shown in Tables 1 (a) to (c) for each cause of damage. The level of damage is classified into four levels. Level “A” indicates no damage, “B” indicates minor damages that can be repaired by only replacing a few parts, “C” indicates severe damages that require many replacement parts, and “D” indicates that the facility is no longer usable. Table 1 (a) shows that the main facilities of the thermal power plants were robust enough to withstand the shock of the earthquake. Although the boilers were damaged by the shock of the earthquake, which included damages to the hydraulic anti-vibration equipment and the deformation and formation of cracks in the super heater, evaporator, and economizer, the damages were only minor. The tsunami devastated the thermal power plants along the coast. In particular, the Hara-machi coal-fired thermal power plant was devastated by an enormous tsunami that had a height of about 18 m. An office building was flooded to the ceilings of the third floor. The electrostatic precipitator was also flooded, and the buoyancy force acting on destroyed the basement and the connecting induced draft fan to demolish. Despite such devastating damages, the Hara-machi power plant started to commission its second plant on 3 November 2012 and its first plant on 28 January 2013. A station blackout due to the tsunami caused the other plants to experience extreme difficulties. A steam turbine was not operable after it came to an emergency stop. Another steam turbine was damaged because its lubrication oil system was not functioning. However, these damages on the steam turbines are considered to be only minor. On the other hand, a thermal power plant on an artificial island experienced liquefaction and subsidence. Although the soil liquefaction affected conveyor belts and pipelines, the damage was repairable by rearranging the support legs. Main buildings and facilities were not damaged due to their foundation pile. All investigated thermal power plants except the Hara-machi thermal power plant began operating within a year after the disaster due to dedicated efforts.

The following list states what can be taken from the experiences of the disaster.

a. Emergency evacuations

Emergency evacuations during the earthquake and from the tsunami were effective. However, there was an unfortunate case of human loss during a secondary disaster response. Guidelines and drills of an emergency evacuation for a secondary disaster are required.

b. Ensure emergency communications are provided

A portable satellite telephone is the most effective tool during disaster conditions. However, its battery needs to be charged for it to be used continuously.

c. Emergency power systems

There was one in which an emergency power supply did not function, since the room with the control rack was flooded; however, the power generator and batteries were safe from the flooding caused by the tsunami. Thus, it is strongly recommended to place the emergency power source on the turbine floor with its control rack. A power source for startup must also be kept at this location. An emergency power supply is required not only for facility conservation, but also to protect the staff.

d. Fires in electric systems

There was one case in which the electrical room in a service building was on fire. The ignition source may have been a spark in the terminal or frictional heating caused by the shock of the earthquake. Consideration on the use of flame retardant materials will be required to prevent the ignition and dispersal of fires.

f. Floating objects due to the tsunami

There was a case in which a windbreak net prevented floating objects, such as automobiles and containers, to flow into a yard. Since automobiles often become causes of fire, parking lots for automobiles must be on higher ground or surrounded by a windbreak net.

g. Improvement in quake resistance for fixed components

There were cases in which ceiling panels collapsed in a central control room and an accident occurred due to the

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collapse of a grating floor. The structures of these fixed components need to be improved.

h. Improvement in the water-tightness of buildings

Roll-up doors were easily damaged due to the increase in water pressure caused by the tsunami. Instead of roll-up doors, watertight doors should be used for electrical rooms.

Table 1 Damage conditions classified by their cause.

(a) Shock of the earthquake

Components	1	2	3	4	5	6	7	8	9
Facilities for fuel supply	A	A	A	A	B	A	B	A	B
Gas turbine and its accessories	B	-	-	-	-	-	A	-	-
Boiler and steam lines	B	B	B	C	B	B	A	B	B
Steam turbine and its accessories	B	A	B	A	B	A	B	A	B
Facilities for cooling water	A	A	A	A	B	B	A	B	A
Facilities for air supply and flue gas exhaustion	A	B	A	A	B	B	A	B	A
Facilities for the receiving and transmission of power, and emergency power system	A	A	A	A	B	A	A	A	A
Other components									
Buildings and facilities	B	B	B	B	B	B	B	A	A
Communication facilities	A	B	A	A	A	A	B	A	A
Dock and road	A	B	A	B	C	A	A	A	A

(b) Tsunami

Components	1	2	3	4	5	6	7	8	9
Facilities for fuel supply	B	B	D	D	D	C	B	C	A
Gas turbine and its accessories	B	-	-	-	-	-	A	-	-
Boiler and steam lines	B	B	B	C	A	A	B	A	A
Steam turbine and its accessories	A	C	B	C	C	A	A	A	A
Facilities for cooling water	B	C	C	C	D	C	B	A	A
Facilities for air supply and flue gas exhaustion	A	B	B	D	B	A	B	A	A
Facilities for the receiving and transmission of power, and emergency power system	B	B	C	D	D	C	A	A	A
Other components									
Buildings and facilities	B	B	C	D	B	A	B	A	A
Communication facilities	B	B	C	C	A	A	B	A	A
Dock and road	B	B	C	C	C	B	B	B	A

Table 1 Damage conditions classified by their cause.

(c) Liquefaction and subsidence

Components	1	2	3	4	5	6	7	8	9
Facilities for fuel supply	A	A	B	A	A	A	A	C	A
Gas turbine and its accessories	A	-	-	-	-	-	A	-	-
Boiler and steam lines	A	A	A	A	A	A	A	A	A
Steam turbine and its accessories	A	A	A	A	A	A	A	A	A
Facilities for cooling water	A	A	A	C	A	A	A	A	B
Facilities for air supply and flue gas exhaustion	A	A	A	A	A	A	A	A	A
Facilities for the receiving and transmission of power, and emergency power system	A	A	A	A	A	A	B	A	B
Other components									
Buildings and facilities	A	A	A	A	A	A	A	A	A
Communication facilities	A	A	A	A	A	A	A	A	A
Dock and road	A	B	A	A	C	A	A	C	B

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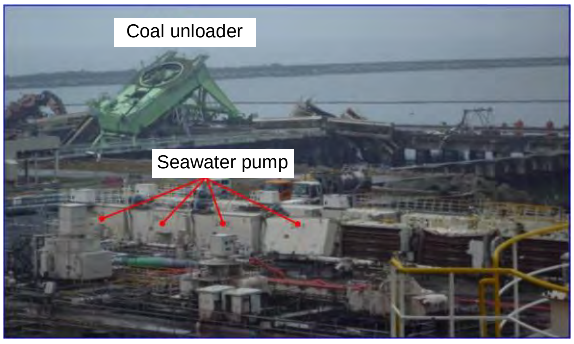


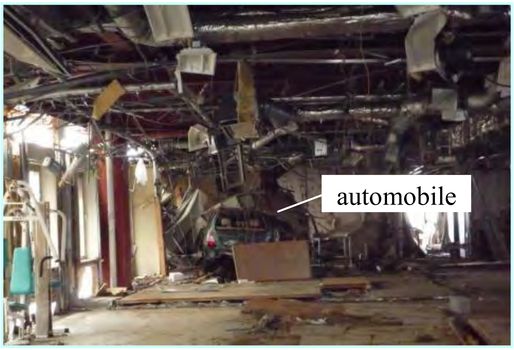
(a) Damaged coal unloader and sea water pump.

(b) Damaged light and heavy oil tanks.

(c) Damaged concrete wall.

(d) Damages to unit #1.

(i) Wall facing the sea.



(ii) The 2nd floor.

(e) Damaged service building.

Fig. 7 Damaged facilities of the Hara-machi thermal power plant.

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2. General Equipment of Energy Infrastructures

Group C covers topics of the general equipment of the energy infrastructures, and an investigation summary of this group is listed below.

(1) The lessons learned from the 1995 Great Hanshin-Awaji Earthquake

The damage ratio of the electric power transmission facilities to the transformation facilities arising from the 2011 Great East Japan Earthquake (M9.0) has been reduced after reviewing the technical standards, which were based on the Great Hanshin-Awaji Earthquake, for electrical equipment. However, the 2011 Great East Japan Earthquake was different from the disasters with an earthquake that had an epicenter near large cities. From this point of view, the damages and consequences of previous disasters have been taken into consideration and the design policy on the technical standards does not require many significant changes. However, a further study on the design basis by accumulating actual data of the damages will be expected.

Table 2 Summary of the damage ratio of the power station and facilities of TEPCO.

Electric power transmission and transformation facilities (N of damages / N of total facilities)			
Earthquake intensity	Overhead transmission lines	Underground transmission lines	Transformation facilities
7	0 / 21	0 / 0	0 / 0
6	33 / 6271	4 / 202	74 / 1490
5	8 / 24263	26 / 3512	30 / 6898
Maximum damage ratio of the distribution facilities			
Overhead power lines		Underground power lines	
Supports 0.2%		Maintenance holes 21%	

(2) Importance of preparation in terms of “disaster mitigation”

Earthquake countermeasures put in place previously have been effective to a certain extent, especially against seismic motion. However, severe damages have been caused by remarkable intensities of liquefaction or the unexpected severity of tsunamis. Infallible countermeasures for a great tsunami caused by a great earthquake with a magnitude of nine are almost impossible. In fact, in terms of the design policy on electrical equipment against great tsunamis with heights of 15 m or more, it is important to prepare redundant or distributed backup systems for severe damages that need to be quickly repaired, because technical matters go beyond the realistic mechanical designs of equipment, such as a high anchorage strength or high waterproof performance. With regard to the energy infrastructures that cannot be moved to higher grounds, such as oil refineries or LNG bases, there is no countermeasure against great tsunamis within an affordable cost. Thus, energy service providers have no other alternative but to take business continuity plans (BCPs) based on “disaster mitigation” preventing human loss and minimizing disaster damages. From the viewpoint of disaster mitigation for energy infrastructures, the following issues are important:

- To control incidents before severe accidents occur
- To prevent local damages from expanding to other areas
- To minimize nationwide aftermaths by stopping operations of energy services
- To restore facilities as soon as possible by taking precautions against severe damages

(3) Securing diverse energy sources

It is necessary to secure both usual and emergency energy sources, because Japan frequently experiences natural disasters. In particular, electric power supplies rank as the first priority for lifelines. Therefore, in addition to securing energy stations equipped with onshore self-sustainable power sources, it is important to develop mobile power stations from ships to onshore facilities and emergency guidance and communication frameworks, as shown by the previous great tsunamis. Furthermore, it is necessary to secure storage stations and supply chains of emergency fuel and to deregulate or revise any relevant laws. For example, relaxation of regulations under the Fire Defense Law that will allow an increase in fuel storage capacity and consequently extend the operation time of emergency power generation facilities, especially in emergency evacuation centers, should be considered when developing effective countermeasures.

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3. Energy Policy

After the 2011 Great East Japan Earthquake Disaster, the energy policy of Japan was discussed. Sub-working group D attempted to confirm the important issues of the energy policy based on a broad investigation of the basic stances and opinions of mechanical engineers and researchers in order to consider the directionality in rearranging the scientific data and knowledge regarding the energy infrastructures and future scenarios. From 1 August 2011 to 30 October 2011, a questionnaire survey was provided on the JSME website to JSME members that were registering to the power energy systems division as first to third priorities, and 320 answers were returned. As for their age, 15% of the respondents were in their 30s, 21% were in their 40s, 30% were in their 50s, 21% were in their 60s, and the remaining 13% were in another age group. Engineers and researchers comprised 50% of the respondents and 16% were university teaching staff, which reflects the characteristics of the personnel composition of the division. The questionnaire was composed of the following ten main categories: (1) the progress of science and the status of comfort and convenience, (2) energy supply structures and commitment to nuclear power in the future, (3) alternative energy of nuclear power and commitment to renewable energy, (4) concentration and dispersion of urban functions, (5) expectations for the smart grid, (6) preparation for large-scale power outages or rolling blackouts, (7) cooperation with the neighboring countries in terms of energy infrastructures, (8) how to deal with large natural hazards, (9) direction of energy policies and future technological developments, and (10) robust energy infrastructures that are significantly at risk.

The results of the questionnaire revealed the thinking process of the engineers and researchers and their ideas regarding the energy issues. The perspectives that are important when discussing and determining the future energy policies of Japan were considered based on the following viewpoints:

- Involvement of energy and civilization after the Industrial Revolution
- Changes in the structure of energy consumption in Japan
- The state of energy in Japan after the 2011 Great East Japan Earthquake Disaster
- Possibility of replacing nuclear power with renewable energy
- The difference between Japan and foreign countries regarding power conditions (comparison with the power conditions of Germany)
- Impact of the conversion of energy structures on society

The above results of the questionnaire were taken into consideration and are summarized as follows:

(1) Important viewpoints when considering an energy policy

Japan relies on imports for most of its resources, and it is difficult to output as much energy as the neighboring countries do, unlike those of Europe, and nuclear power is responsible for the base load of power that supports the industry. The current situation of Japan needs to be understood to clarify the difference between Japan and other countries, and to recognize them correctly.

(2) Impact of the conversion of energy structures on society and the roles of engineers

A rapid full conversion to renewable energy or the conversion to thermal from nuclear power can cause an extremely serious future impact on society, such as an increase in fuel procurement costs, an increase in power generation costs, and a reduction in the production capacity of the industry due to power shortages, which can lead to companies being traded to overseas owners and the oppression of people's lives due to a decrease in income and employment. The conversion can also make it difficult to achieve the objectives regarding global warming, to contribute newly developed technology to the emerging countries that use nuclear energy (see Fig. 8), and to contribute nuclear non-proliferation, which can lead to the loss of trust among the international community. Providing scientific explanations to people is one of the most important missions of the academic society. Those who are responsible for conducting risk communication to the public, such as mass communication, should understand their position in society, and they need to recognize a way to disclose correct information and how to form a bridge between engineers and society.

(3) Towards the future construction of energy in society

Future power constitutions can have a significant impact on the fate of nations that have few resources, including

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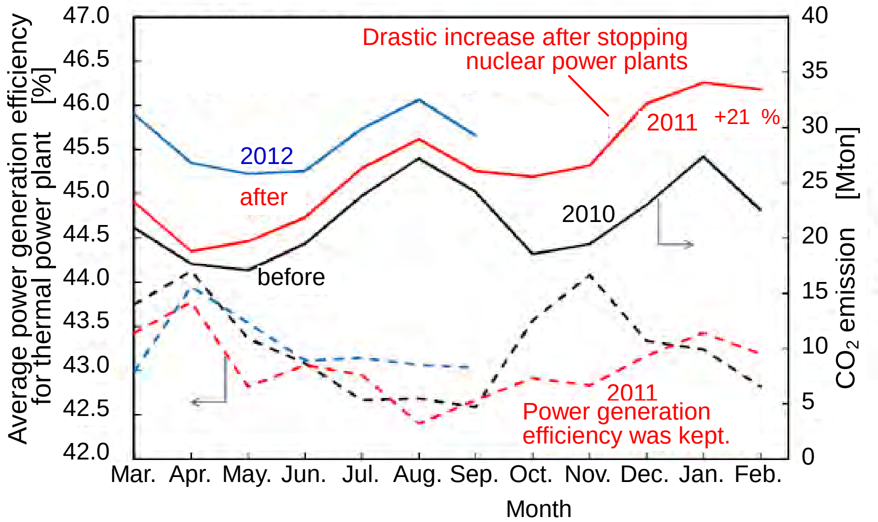
the lives of people and society, and they should be determined after a careful discussion that takes into careful consideration the scientific knowledge and evidence without being influenced by simple cost estimations and emotional discussions. We should study various complex issues, such as ensuring long-term energy security, the impact of the industry, economy, and employment on social life, and the impact of global warming, from a variety of viewpoints. Both industrial growth and the improvement of human life should be achieved, and it is necessary to ensure that the safety measures of nuclear power are sufficient. Furthermore, it is important to build an optimum energy supply system that includes the appropriate development of renewable energy that takes the characteristics of the power generation systems of the existing nuclear and thermal power plants into consideration.



These data were obtained from "Electricity Statistics Information" published by the Federation of Electric Power Companies in Japan.

(Average power generation efficiency) = (total power generation amount) ∕ Σ[(comsumption × heating value) for each fuel]

(CO_2 emission) = Σ[(comsumption × CO_2 emission coefficient) for each fuel]

Fig. 8 CO_2 emission and power generation efficiency before and after the earthquake.

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Chapter 8

Nuclear Codes and Standards Issues and Future Perspectives

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Abstract

Working Group (WG6), titled "Nuclear Codes and Standards Issues and Future Perspectives", focused its investigation on the impacts of the 2011 Great East Japan Earthquake, which was followed by a devastating tsunami, on the nuclear power plants (NPPs) located along the northeastern Pacific coast of Japan. The objectives of WG6 were to survey the damages of the NPP facilities that were caused by the earthquake and tsunami and the subsequent consequences (accidents), to examine and analyze the causes of these damages and accidents within the ability of the JSME as a professional society, to conduct a root cause analysis of the damages and accidents and to give considerations on the relationship between the codes and standards issues, and to analyze cases where countermeasures against the earthquake and tsunami worked well and to obtain insights from the analysis. In order to determine the root causes of the Fukushima Daiichi NPP accident and to determine the roles that the codes and standards have in developing safety enhancement measures to prevent future accidents, WG6 conducted studies on the following three viewpoints

Viewpoint 1: Reasons why the accident at the Fukushima Daiichi NPP was unpreventable

Viewpoint 2: The roles of the codes and standards responding to Severe Accidents (SAs)

Viewpoint 3: The adequacy and issues of the current seismic design technology

Based on these studies, WG6 created a set of tangible recommendations on what the future nuclear codes and standards should be to enhance the safety of NPP facilities.

Keywords: Fukushima Daiichi accident, Nuclear safety regulation, Design basis, External hazards, Codes and Standards, Risk management, Seismic design

1. Introduction

Working Group (WG6), titled "Nuclear Codes and Standards Issues and Future Perspectives", focused its investigation on the impacts of the 2011 Great East Japan Earthquake, which was followed by a devastating tsunami, on the nuclear power plants (NPPs) located along the northeastern Pacific coast of Japan. The objectives of WG6 were to survey the damages of the NPP facilities that were caused by the earthquake and tsunami and the subsequent consequences (accidents), to examine and analyze the causes of these damages and accidents within the ability of the JSME as a professional society, to conduct a root cause analysis of the damages and accidents and to give considerations on the relationship between the codes and standards issues, and to analyze cases where countermeasures against the earthquake and tsunami worked well and to obtain insights from the analysis. Based on the studies that were conducted, WG6 created a set of tangible recommendations on what the future nuclear codes and standards should be to enhance the safety of NPP facilities.

As a first step, WG6 conducted a fact finding survey on the impacts of the earthquake and tsunami on the typical nuclear power stations located along the northeastern Pacific coast of Japan, which included the Fukushima Daiichi NPP (Tokyo Electric Power Co.), Onagawa NPP (Tohoku Electric Power Co.), and the Tokai Daini NPP (Japan Atomic Power Co.). This survey was primarily constructed based on the information available in the public domains and utility

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reports.

Next, in order to determine the root causes of the Fukushima Daiichi NPP accident and to determine the roles that the codes and standards have in developing safety enhancement measures to prevent future accidents, WG6 formulated the following three viewpoints:

Viewpoint 1: Reasons why the accident at the Fukushima Daiichi NPP was unpreventable

Viewpoint 2: The roles of the codes and standards responding to Severe Accidents (SAs)

Viewpoint 3: The adequacy and issues of the current seismic design technology

Then, WG6 conducted an extensive survey study and investigation based on these three questions. Through the investigation and discussion among the members, several issues, perceptions, and concerns were raised relating to these viewpoints, which were finally put together as a set of recommendations and proposals by WG6.

2. Impacts of the earthquake and tsunami

Table 1 summarizes the outline of the impacts of the 2011 Great East Japan Earthquake that was followed by a devastating tsunami that affected the NPPs located along the northeastern Pacific coast of Japan.

Table 1 Summary of the Impacts of the Earthquake and Tsunami on the NPPs

Plant Site	PGA of EQ gal*1	Tsunami Height m	Plant Protective Response		
			Reactor Shutdown*3	Core Cooling *4	Containment
Higashidori	17 / 450 *2	> 4	Success	Success	Success
Onagawa	573 / 512	13	Success	Success	Success
Fukushima Daiichi	550 / 438	14–15	Success	Failure*5	Failure*5
Fukushima Daini	277 / 428	7	Success	Success	Success
Tokai Daini	225 / 400	5.4	Success	Success	Success

*1 Representative value of the peak ground acceleration (PGA) of the earthquake at each plant site

*2 Design value / Observed value

*3 Automatic reactor shutdown (scram)

*4 Structural integrity of the reactor cooling system, secured emergency power supply, and ultimate heat sink

*5 Units 1–3. Unit 4 experienced an outage and units 5 and 6 reached the cool shutdown state safely

The following can be noted after reviewing Table 1:

- The PGA exceeded the design value at the Onagawa and Fukushima Daiichi NPPs, while the PGAs at the other sites were lower than their design values.
- The Fukushima Daiichi NPP was struck by a series of huge tsunami waves that had heights as high as 14–16 m, which significantly exceeded the design tsunami wave height of 5.4–5.7 m. The other sites were also struck by tsunami waves, but their heights were not larger than their design wave heights.

At the Fukushima Daiichi NPP station, although all the offsite power was lost, three operating units (units 1–3) were successfully shutdown by the automatic scram system that detected the earthquake. However, the overwhelming tsunami inundated deep into the plant facility, disabling the emergency diesel power supply and all AC power, and these units fell into the state of a long-term station black out. As a result, the reactor core cooling capability was lost, the reactor cores were severely damaged and melted, and hydrogen explosions occurred. Furthermore, an SA occurred, which caused a large amount of radioactive material to be released into the environment.

On the other hand, at the NPP stations other than that of the Fukushima Daiichi NPP, all of the operating units were automatically shut down after the earthquake was detected and the functions of the emergency power supply systems were maintained in spite of partial loss of the offsite power at some stations. The reactor cooling capability of these units was maintained and all units reached a safe cool shutdown state, and the safety of the reactors was secured. In addition, no significant damage due to the earthquake load has been reported on the structures, systems, and components important for safety.

As for the Fukushima Daiichi NPP accident, several organizations conducted thorough investigations and have

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issued detailed reports; these organizations include the Government of Japan (2011, 2012), the National Diet of Japan (2012), and IAEA (2011).

3. Insights regarding the three viewpoints

3.1 Viewpoint 1: Reasons why the accident at the Fukushima Daiichi NPP was unpreventable

To simplify, the direct cause of the Fukushima Daiichi NPP accident may be attributed to the fact that the facility was struck by a devastatingly huge tsunami that had a height that significantly exceeded the design basis. Naturally, there is a question on the adequacy of the design basis of the Fukushima Daiichi NPP regarding tsunami heights. As another important cause of the accident, there was no supposition for the possibility of a tsunami exceeding the design basis. Therefore, no countermeasures were taken against a tsunami event that exceeded the design basis. Adequate risk management was also implemented. It was unclear to as why the risk management was neglected. Some important issues that are immanent in the fundamental management systems, the preparedness of the owners to secure safety, and the roles of the nuclear safety regulation system are as follows:

- there was a lack of attitude to promptly and flexibly apply new knowledge to facility and equipment improvement and regulatory requirements;
- the arguments on nuclear safety often tended to lapse into the dualism of “safe or dangerous”, which acted as an obstacle to the incentive for improvement;
- there was a lack of objectives that could have been constantly pursued to enhance safety, and although the regulatory requirements and the codes and standards were the “minimum” requirements that needed to be observed, there was a tendency to recognize that only satisfying the requirements was sufficient;
- risk information was utilized not to “determine vulnerabilities and to improve”, which is its primary purpose, but instead for “demonstrating safety”; and
- there was a lack of will to focus on the international trends in safety regulations, such as the activities conducted by IAEA and US NRC, and to achieve international harmonization in terms of the regulatory system.

Reflecting on the lessons learned from the Fukushima Daiichi NPP accident, fundamental changes were made to the government’s nuclear safety regulation, which include the following:

- inclusion of SAs into the scope of the nuclear safety regulation (prior to the Fukushima accident, the SA management was implemented by owners’ voluntary efforts);
- introduction of the “back fit” regulation where any amended requirements based on new knowledge are applied to the existing fleets of the NPP; and the
- introduction of a limitation of 40 years for the lifetime of a NPP as a measure for aging plants.

While questions may arise on the adequacy of scientific and engineering basis of the 40-year lifetime limitation, it is expected that an effective and efficient nuclear safety regulation system can be implemented and operated based on scientific rationalism. Then, in addition to appropriately recognizing and moving forward on the issues mentioned above, efforts that are also important on the systematic documentation of the regulatory requirements to secure regulatory transparency and the training and education for the professionals of the nuclear safety regulation to gain high level of expertise are needed.

3.2 Viewpoint 2: The roles of the codes and standards responding to the severe accidents

The Main Committee on Power Generation Facility Codes of JSME, established in 1998, develops and publishes various codes and standards mainly related to the structural integrity of mechanical components in NPP facilities. The typical codes and standards include the material code, design and construction code, the welding code, and the fitness for service code. These JSME codes are counterparts, in a sense, of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Codes, Section II (material), Section III (construction), Section V (welding), and Section XI (ISI). The nuclear codes and standards of JSME have been applied to the nuclear safety regulations of the existing fleets of the domestic and newly built NPPs after technical assessments had been conducted and endorsed by the regulatory authority.

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The important points for exploring the role of the codes and standards reflecting the Fukushima Daiichi NPP accident and the reorganization of the nuclear regulatory system may include the following:

1) Development of codes and standards for the SA conditions; and
2) Continued and enhanced utilization of the codes and standards of private sectors via regulatory authority.

3.2.1 Codes and standards for severe accidents

The scope of the current codes and standards include design basis accidents (e.g., the Loss of Coolant Accident (LOCA)). SAs such as core meltdowns have been defined as beyond design basis events (BDBEs), and have been out of the scope of the current codes and standards. This corresponds to the fact that in Japanese nuclear regulations, the SA issues, such as those associated with the development of an accident management program, were not included in the regulatory scope, but rather left for the owner's voluntary safety effort or activities. However, after the Fukushima Daiichi NPP accident, the Japanese nuclear regulations have been completely restructured, including their organizational aspect, making the SA measure the most important regulatory issue.

On the other hand, the Fukushima Daiichi NPP accident revealed the notion that nuclear power plants should be designed and equipped with the necessary equipment so that the safety of the plant is secured by ensuring that the safety functions of shutting down the plant, cooling the core, and containing any radioactive material are operating properly, even when the plant is exposed to a severe threat of external events (earthquakes, tsunamis, hurricanes, etc.) exceeding the design basis. The codes and standards for embodying such plant designs and equipment installations are needed, as schematically illustrated in Fig. 1.

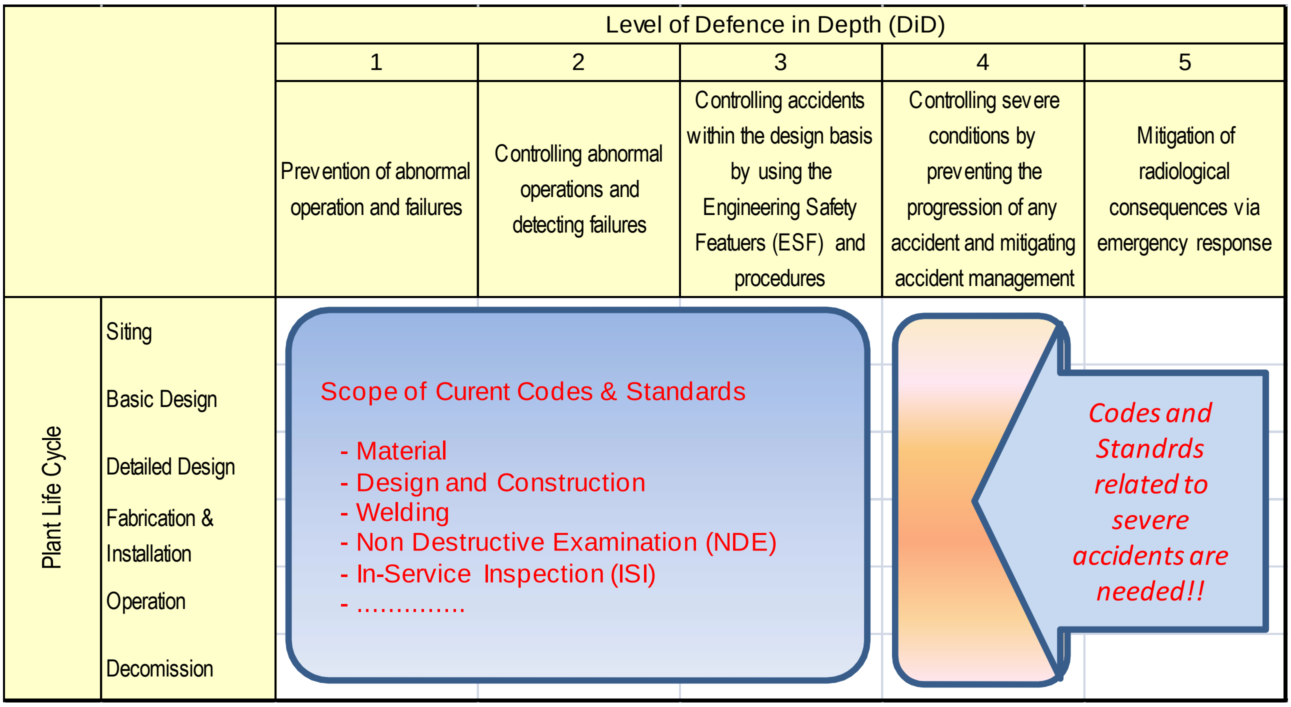

Fig. 1 Scope of the current and necessary codes and standards with respect to the level of the accident

Codes and standards are need for the SAs that are outside the scope of JSME, and thus the three major Standards Development Organizations (SDOs) of Japan (JSME, the Atomic Energy Society of Japan (AESJ), and the Japan Electric Association (JEA)) are working together under the framework of the "Nuclear Codes and Standards Consortium" to draw an overall picture of the necessary codes and standards for the SA measures. It is noted that in this effort of systematic development, an overall view of the entire picture is critical, as is schematically shown in Fig. 2.

In the Main Committee on Power Generation Facility Codes of JSME, as part of the effort for developing the needed codes and standards for this new area of SA measures, work is underway to develop guidelines that are

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considered to be of the highest priority when restarting the existing plants in Japan.

One guideline is the "Severe Accident Management Design Guideline for External Events", of which the purpose and scope are as follows:

- to provide guidelines or a common basis as references for the utility operators when they develop or refine their accident management programs;
- the guideline provides SA preventing measures by implementing alternative equipment and/or original equipment;
- the guideline also provides SA mitigating measures and strengthening measures for SA management programs; and
- the guideline currently applies to Boiling Water Reactors (BWRs)

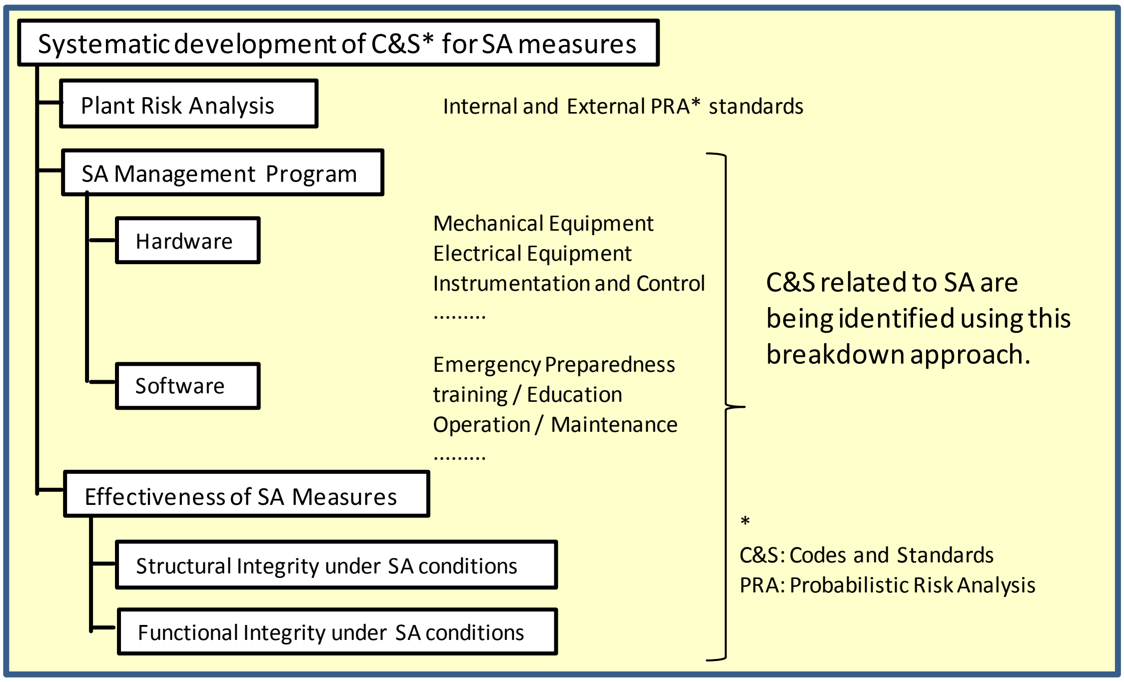

Fig. 2 Systematic development of codes and standards for SA measures

The external hazards that are considered include earthquakes, coastal flooding due to tsunamis and high tides, river flooding due to the collapse of a dam or river bank, windstorms such as typhoons, hurricanes, and tornados, heavy snowfall and very low temperatures, landslides and avalanches, fine particles such as volcanic ash, offsite fires, and the combination of earthquakes/coastal flooding, earthquakes/river flooding, and earthquakes/offsite fires.

The guideline requires the following functions to be secured for the SA prevention measures:

- Reactor cooling capability via a high-pressure injection system
- Reactor cooling capability via a low-pressure injection system
- PCV venting
- RPV depressurization capability
- Long-term reactor cooling capability
- Spent fuel cooling capability

The guideline also requires the following functions to be secured for SA mitigation:

- Capability to cool debris and the containment vessel (CV)
- Capability to prevent CV failure due to over heating/pressure

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- Capability to prevent CV failure due to damage caused by debris
- Capability to prevent hydrogen explosions
- Decrease in radiation exposure and control of the release of fission products

Another effort is also underway to develop the "Guideline for a Structural Integrity Evaluation of Containment Vessels under Severe Accident Conditions". Here, the basic idea is that keeping the boundary (barrier) function of the containment vessel intact under SA loads is of significant importance to suppress the uncontrolled release of radioactive materials into the environment. Furthermore, its fundamental purpose is to provide guidelines for structural analysis methodologies and failure criteria for structural integrity evaluations under SA loading and SA environments. In this guideline, the loads that are taken into consideration include over pressuring and overheating due to core meltdown in a SA. The failure modes include the following:

- ductile failure or damage to the containment shell
- severe wall cracking at geometrical discontinuities (e.g., reinforced openings)
- buckling of a torispherical, ellipsoidal head by external pressure
- buckling of penetration bellows by internal pressure
- loss of leak tightness at bolted flanges

A detailed three-dimensional elastic-plastic finite element analysis will be applied and a strain-based failure criterion for ductile failures will be provided.

The Main Committee on Power Generation Facilities Codes has a close cooperative relationship with the ASME Boiler and Pressure Vessel Code Committees. In fact, a number of JSME code engineers have participated in several of these ASME committees and their sub-tier groups as members or officers. It should be noted that a cooperation framework between JSME and ASME has also been established for the effort of developing necessary codes and standards for SA measures. The guidelines depicted above were presented to ASME at their draft state and ASME provided a number of useful comments to JSME.

3.2.2 To continue and enhance the utilization of the codes and standards of the SDOs

The nuclear codes and standards of JSME were applied to the nuclear safety regulations of the existing fleets of the domestic and newly built NPPs after a technical assessment was conducted and endorsed by the regulatory authority. This framework, which is called the "performance-based regulatory rules and application of the codes and standards developed by SDOs", has been in effect since 2006 in Japan. In regard to this framework, there were concerns that the provision of detailed technical rules by the government regulator had sometimes caused a delay in updating the rules with the latest technical knowledge, and as a result, it was difficult to promptly and flexibly apply the advanced technologies (the detailed technical rules were also within the regulatory rules prior to 2006).

Academic societies, such as JSME, provide an arena where the most excellent scientific knowledge and technologies are gathered, and where utilizing this excellent expertise to enhance nuclear safety is one of the most important roles. By developing, updating, and maintaining the codes and standards for the detailed technical rules by the academic societies as SDOs, the regulatory body is able to focus its regulatory resources on truly important safety regulatory issues. Considering these aspects, it is recognized that the utilization of the codes and standards of the SDOs and third party certifications, such as a design conformity assessment and weld inspection, should be further promoted, which will lead to the optimal allocation of limited regulatory resources to important safety issues.

3.3 Viewpoint 3: The adequacy and issues of the current seismic design technology

As was mentioned earlier, although earthquake ground motions that exceeded the design basis were observed at some sites (e.g., Onagawa), failure, damage or loss of the functionality of the structures, systems and components important to safety have not been reported, except for the Fukushima Daiichi NPP units, where inspections are not able to be conducted due to the accident. In this context, it can be considered that the current seismic design technology for mechanical components and the related seismic design rules adequately functioned.

Furthermore, there were cases in the past in which NPPs were hit by earthquakes whose peak ground motion exceeded the design basis. Typical examples include the Onagawa station that was hit by the Miyagiken-oki earthquake in August 2005, and the Kasiwazaki-Kariwa station that was hit by the Niigataken Chuetus-oki earthquake in July 2007. In these cases, the plants were safely shutdown soon after the earthquakes were detected. Detailed inspections

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were conducted in each plant unit after each earthquake and it was determined that there were no significant damages and that the structures, systems, and components important to safety did not malfunction. The current seismic design technology seems to have also functioned. The seismic analysis methods were sufficiently conservative (e.g., elastic analysis with a low damping factor) and the seismic design criteria, such as the allowable stress limits, were also sufficiently conservative.

Onagawa station was also hit by the 2011 Great East Japan Earthquake, and to visually investigate the impact of the earthquake and tsunami on the facility, an IAEA team of international experts conducted a survey to contribute their results to an IAEA database, which is being compiled by the International Seismic Safety Centre (ISSC), to provide knowledge about the impact of the external hazards on nuclear power plants to the member states (Fig. 3). According to the team's initial report (IAEA, 2012),

> *"Onagawa, facing the Pacific Ocean on Japan's north-east coast, was the nuclear power plant closest to the epicenter of the 11 March 2011 magnitude 9.0 earthquake that struck Japan and resulted in a devastating tsunami. The plant experienced very high levels of ground shaking—among the strongest of any plant affected by the earthquake—and some flooding from the tsunami that followed, but was able to shut down safely. In its draft report the team said that 'the structural elements of the NPS were remarkably undamaged given the magnitude of ground motion experienced and the duration and size of this great earthquake'."*

This may also imply that the current seismic design technology is adequate.

Fig. 3 Field investigation by IAEA (upper left and right: survey of the flooded areas; lower left: survey at the front of flood barrier (tsunami survey))

However, these plants were not allowed to restart until after some time. A major reason for this delay is attributed to the fact that the methods and procedures for the structural integrity evaluation of the structures, systems, and components affected by the seismic loads exceeding the design basis were not well prepared. There were also no established restarting criteria.

Among the important issues that need to be investigated in the area of seismic design, efforts need to be made towards the understanding of the ultimate structural integrity limits of components and piping and the ultimate functional limits of active components against the seismic load. The Fukushima Daiichi NPP accident showed that, inherently, there is a very large uncertainty in the severity level of natural hazards and the importance of risk management against natural hazards whose severity levels exceed the design basis. In this context, designing the structure, systems, and components against the seismic load of the design basis may not be sufficient. It is important to conduct an evaluation regarding to what extent the structural and functional integrity of the structures, systems, and components can be maintained against a seismic load exceeding the design basis (real design margin). For this purpose,

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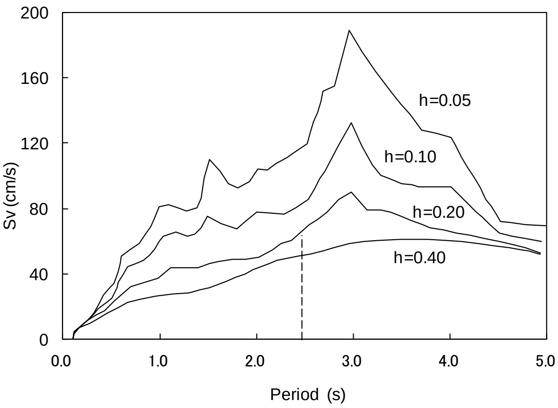
standard methodologies for an ultimate structural integrity evaluation in the exceeding range of the design basis and corresponding criteria are expected to be developed. Inelastic (elastic-plastic) seismic response analysis methodologies and failure criteria based on strain are needed.

Rules and criteria should also be developed and provided to judge when a NPP that has experienced an earthquake exceeding its design basis can be restarted. In order to judge whether the earthquake that hit a plant exceeded the design basis or not, further studies on the governing earthquake ground motion parameters (indices) that have good correlation with the structural damages and failures are needed. The current seismic design methodology is based on the design against seismic inertia force, and therefore the maximum acceleration is used as the primary indicator for the level of an earthquake. However, the maximum acceleration may not always be the contributing measure for the physical value that relates to the structural failure. Conversely, there are cases in which the relative displacement induced by an earthquake or the maximum velocity that is related to the energy of an earthquake is the governing parameter for the structural failure. In fact, in the gas industry, the spectral intensity (SI), which is the integral of the response velocity spectrum of an earthquake within a certain period range (Fig. 4a), is used as the major index for the damageability of earthquakes. It is shown that there is a good correlation between the damage and failure of buried gas pipelines and the SI value. The US NRC requires that, according to Regulatory Guide 1.166, evaluations should be made by using both the response spectra and the cumulative absolute velocity (CAV) to judge whether an earthquake that hit a NPP exceeds the design basis or not (US NRC, 1997). Here, the CAV is the integral of the absolute velocity time history of an earthquake ground motion (Fig. 4b). Studies are needed to determine the appropriate parameter that can indicate whether an earthquake can affect NPP facilities from the viewpoint of structural and functional integrity, and while including the applicability of the SI and CAV.

$$SI = \frac{1}{2.4}\int_{0.1}^{2.5} S_V dT \ (h = 0.2)$$

Sv : Velocity response spectrum
T : Natural period (s)
h : Damping factor



$$CAV = CAV_i + \int_{i}^{i+1} |a(t)|\,dt$$

Summation of the time integral of the absolute acceleration in the range where the maximum value of acceleration exceeds the threshold.

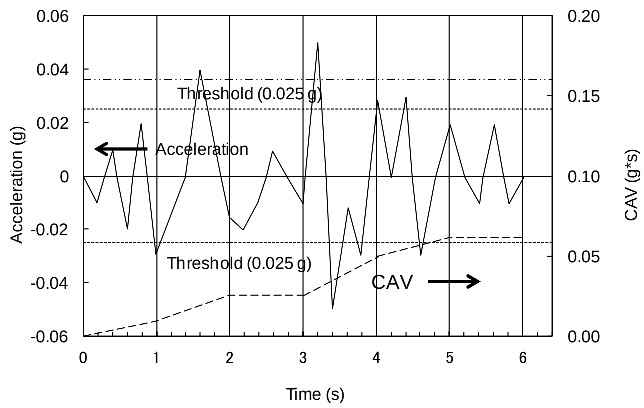


Fig. 4 Definitions of the (a) SI value and (b) CAV

4. Recommendations

WG6 conducted an extensive survey and investigation based three differing viewpoints, as outlined above. Through the investigation and discussion among the members, several issues, perceptions, and concerns were raised relating to these viewpoints. Based on these insights, WG6 developed five recommendations as given below. These recommendations are towards the regulators, the owners and the industry, general public, and codes and standards development bodies.

Recommendation 1: Improving nuclear safety based on the concept of risk

Improving the safety of NPPs should be pursued constantly and continuously. To make these activities effective,

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introducing and applying the concept of risk is essential for safety evaluations or as countermeasures to improve safety.

For the issues regarding nuclear safety, the attempts to distinguish between safe or dangerous should stop, and calm and philosophical discussions should be made based on scientific knowledge and facts. JSME is expected to deliver a proper message to society and the public with such a perspective.

Recommendation 2: Expectations for nuclear safety regulations

As for nuclear safety regulations, a systematically constructed set of safety requirements should be implemented with scientific rationality based on the state-of-the-art technology and high level perspectives. For this purpose, utilization of the codes and standards of the SDO and third party certifications, such as design conformity assessments and weld inspections, should be further promoted, which will lead to the optimal allocation of limited regulatory resources to important safety issues. Transparency, objectivity, and fairness are required for safety regulations and thus the systematic documentation of regulatory requirements open to the public is recommended. It is also important to create an atmosphere where open and flat discussions can be made about the safety regulations among the stakeholders, regulators, owners, industry, SDOs, and the academia. Awareness on the international trend of nuclear safety regulations is also essential to update domestic regulations.

Recommendation 3: Owners with a sense of safety

The owners of NPPs should have a basic attitude with a sense of safety and should continuously revisit and update their design basis and safety evaluation of their plants, including external hazards, with the latest scientific and engineering knowledge. In addition, after carefully considering the large uncertainty of the severity of external events, the owners should be well prepared for situations that exceed the design basis. The owners should be aware that the regulatory requirements and the requirement by the codes and standards are the minimum safety requirements, and should maintain a basic attitude to continuously improve the safety of their plants, since they are directly responsible for the safety of their facilities.

Recommendation 4: Issues with codes and standards

The SDOs should refer to the lessons learned from the Fukushima Daiichi NPP accident and the subsequent researches and investigations, and after collaborating with each other, they should clarify the new role and perspective of the codes and standards to prevent and mitigate SAs caused by severe external events. The codes and standards that are required for this need to be developed in a timely manner and with high priority.

When developing the codes and standards of the SDOs, it is important that the SDOs cooperate and collaborate amongst each other and hold dialogues with a regulator, while recognizing the complementary relationship between the performance-based regulation and technical rules of the codes and standards.

Recommendation 5: Seismic design

The ultimate failure limit of structures and components against seismic loads need to be understood, and the safety margin that is currently accepted in the seismic design methodology and criteria should be quantified. Based on this class of knowledge, structural evaluation methodologies and corresponding failure criteria against severe seismic loads exceeding the design basis should be developed by applying state-of-the-art knowledge and technologies. Systematic and consolidated studies with such a perspective are expected to be conducted.

Rules and criteria should also be developed and provided to judge whether a NPP that has experienced an earthquake exceeding its design basis should be restarted. In this regard, studies are needed to determine the appropriate parameter that can indicate whether an earthquake can affect NPP facilities from the viewpoint of structural and functional integrity.

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Report of the JSME Research Committee on the Great East Japan Earthquake Disaster

Chapter 9
Crisis Management for Earthquakes, Nuclear Power Plant Accidents and Other Events

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Abstract

Focusing on the crisis management implemented, the Fukushima Daiichi Nuclear Power Plant disaster, the measures taken by the East Japan Railway Company (JR East), and the shortage of PET-bottled beverages were examined. Regarding the Fukushima Daiichi Nuclear Power Plant, reports published by various bodies have been reviewed to determine the appropriate actions that should be taken after a tsunami strikes. Our study revealed that the disaster could have been prevented if well-structured crisis management procedures were put in place prior to the earthquake. Although the severity of the tsunami was beyond any expectation, the damage caused to the electrical system supplying power to the cooling system should have been predicted, because the nature of the damage was very similar to that addressed in B.5.b. (Code number of Nuclear Regulatory Commission). On the other hand, JR East successfully stopped the Tohoku Shinkansen trains and the trains that were in service did not derail. JR East also successfully evacuated passengers from five trains, which were later washed away by the tsunami after the evacuation. The success of JR East is attributed to its efforts after the Chuetsu Earthquake. Furthermore, our investigation on the shortage of PET-bottled beverages immediately after the earthquake revealed that the standardization and multi-source supply of components are important in business continuity plans.

Keywords: Crisis Management, Fukushima, Shinkansen, Business Continuity Plan (BCP), Supply Chain

1. Introduction

The Japan Society of Mechanical Engineers (JSME) organized a committee to conduct investigations and formulate proposals regarding what lessons mechanical engineers should learn from the 2011 Great East Japan Earthquake. As a result, six working groups that mainly focus on studies based on traditional mechanical engineering were created. However, it was soon recognized that studies based on the viewpoints of the social or human aspects of the disaster should also be made. Accordingly, a seventh working group was created to study the problems with crisis management after the earthquake.

This working group focused on the following three points: (1) to identify the causes of the accidents at the Fukushima Daiichi Nuclear Power Plant (NPP) from the viewpoints of crisis management, (2) to analyze the successful actions taken by the East Japan Railway Company (JR East), and (3) to show the importance of a social system in terms of anti-disaster measures. To achieve these objectives, candidates of various backgrounds were selected as members of the working group. They were not necessarily experts in nuclear engineering, railroads, or designing manufacturing

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facilities, although they each had some type of engineering background. Therefore, the studies do not fully address specific design problems. It should be noted that the objective of this working group was to identify, from the viewpoint of crisis management, more general conditions that will be accepted as safe by society for various technologies.

2. Viewpoints when Discussing Crisis Management

When translated into Japanese, the distinction between crisis management and risk management is sometimes unclear. Some say that carrying an umbrella in case it rains is risk management, while buying one after it starts raining is crisis management. Following this example, to identify a shop selling umbrellas before going out would be risk management, and actually buying one at that shop is crisis management.

In this chapter, we will first describe how people acted in response to the earthquake and tsunami. Then, we will consider whether other actions would have been more favorable, and for such instances, we explore what prevented such actions from being carried out. In many cases, we have found that not only tangible matters, but also intangible matters such as training, rules and regulations, laws, and political culture have prevented the favorable actions from being carried out. These situations are related to risk management. Accordingly, our studies were initially based on crisis management and are concluded with proposals regarding risk management.

3. Fukushima Daiichi NPP

3.1 Review of the Accident Sequence

(1) Situations Caused by the Accident

When we discuss risk management, we need to first clarify what inconvenient situations were caused by the accident. The process, at the same time, will identify which of these situations should have or could have been prevented with risk management.

The exact causes may differ depending on how the Fukushima Daiichi NPP accident is viewed. From the viewpoint of future safety measures, it should be pointed out that the valuable surrounding land and ocean have been contaminated after the accident. The contamination was the result of our failure to “contain” radioactivity; containing is the most important of the three principles for nuclear power generation, i.e., “stop, cool, and contain”. Our failure to “contain” the radioactivity also led to problems with the evacuation of local residents.

It is clear that the failure to “contain” the radioactivity was the result of the failure to “cool”. Even after successfully attempting to “stop” the reaction by fully inserting the control rods, the decay heat from fission products raised the core temperature. “Cooling” means to release the fission heat to the outside and failure to do so will disable the “containing” function. In the worst case scenario (abandoning the nuclear reactor), the damage would be limited to the reactor core only if the “containing” function was successful. Thus, when managing the risks of NPPs, one should always be aware of the ultimate target of “containing”.

During the Fukushima Daiichi NPP accident, for example, the CV temperature reached 300°C, which melted the resin seals of flanges and electrical wire feedthroughs. Then, hydrogen gas carrying radioactive material was released into the building and exploded in units 1, 3, and 4, which discharged the radioactive material high into the air. Furthermore, in units 1 and 3, some of the radioactive material travelled through the water in the bottom of the suppression chamber of the CV and was vented into the air. Unit 2 released the largest amount of radioactive material, which was speculated by some experts to have leaked through the bellows, but the point of leakage has not yet been confirmed. Regardless, a significant amount of radioactive material leaked into the air from unit 2 without going through water. The fallout was the worst during the morning of 15 March 2011 after the hydrogen explosion of unit 4. A thick contaminated plume was discharged from unit 2, dispersed to the northeast of the Fukushima Daiichi NPP towards Iitate-mura, and the contaminated material of the plume fell to the ground as rain. Significant amounts of radioactive material continued to be released after 15 March 2011 from units 1, 2, and 3, without going through the CV water. The material stopped being released towards the end of March 2011, when the accident was nearly contained. In addition, cooling water leaked out from the CV to the basement of the buildings. Some of the contaminated water made its way to the ocean.

TEPCO announced in May 2012 that the total amount of radioactivity was 900 peta becquerel (PBq; peta is the

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prefix for 10 to the 15th power). This figure was obtained by converting the Cs137 release to the Iodine equivalent, adding the results to the I131 release, and following the International Nuclear Event Scale (INES) method. However, both NISA and JAEA announced that the total amount was 480 PBq. The amount of release due to the Chernobyl accident was 5,200 PBq; thus, the amount of release due to the Fukushima Daiichi NPP accident was 9 to 17% of that of the Chernobyl accident.

The above TEPCO announcement broke down the radioactivity release as follows: about 5 PBq from the hydrogen explosions of the reactor buildings, about 1 PBq due to venting from the CV, and about 900 PBq (i.e., almost 100% of the entire release) escaped from the CVs to the buildings and then to the atmosphere without being transported through water. After watching the hydrogen explosions on television and hearing about the venting, the majority of the public had the impression that the explosions and steam venting released the largest amount of radioactive material; however, the quantitative analysis contradicted this misconception. When the hydrogen explosion occurred at unit 4 at 06:14 JST on 15 March 2011, we thought that the worst was over, since units 1 and 3 had also already exploded. However, after the explosion of unit 4, the largest release of radioactive material was yet to come.

Many on-site workers were exposed to the radiation. The Diet Investigation Committee [12] reported that 167 workers experienced an exposure of more than 100 mSv, and six of them experienced an exposure of 250 mSv or higher. Despite this severe accident, none of the workers or local residents were severely injured. Although some hospital patients passed away during the evacuation for reasons other than exposure to radiation, the respect for life and the emergency evacuation was in a sense a success. However, as of 15th May, 2014. the contamination has not allowed 258,219 evacuees and out-migrants to return to their residential areas, since these areas can still expose a person to an annual dose of 20 mSv. The changes in lifestyle and surroundings, including the loss of friends and family, place a heavy burden on the minds of the evacuees.

(2) Progression of the Accident

a) References

The overall study we are conducting has detail records of the Fukushima NPP accident by a number of workgroups (WG), thus, WG7 will only cover the summary of the accidents. The following is a list of available reports.

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[3] What should we learn from the severe accidents at the Fukushima Dai-ichi Nuclear Power Plant –Final Report, Team H2O Project, Dec. 21, 2011, http://pr.bbt757.com/eng/pdf/finalrepo_111225.pdf

[4] Fukushima Investigation, Research Investigation Report, Rebuild Japan Initiative Foundation, Mar. 11, 2012, Discover 21, Inc. (in Japanese)

[5] TEPCO Interim report of Fukushima Nuclear Accidents Investigation Committee, TEPCO, Dec. 2, 2012, http://www.tepco.co.jp/en/press/corp-com/release/11120205-e.html

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[14] Special Report on the Nuclear Accident at the Fukushima Daiichi Nuclear Power Station, Nuclear Energy Institute, http://www.nei.org/resourcesandstats/documentlibrary/safetyandsecurity/reports/special-report-on-the-nuclear-accident-at-the-fukushima-daiichi-nuclear-power-station
[15] Estimation of Radioactive Material Released to the Atmosphere during the Fukushima Daiichi NPS Accident, TEPCO, May 2012, http://www.tepco.co.jp/en/press/corp-com/release/betu12_e/images/120524e0205.pdf
[16] The Final Conditions For Restarting Nuclear Power Plants, "Fukushima Daiichi" Accident Investigation Project Final Report, Kenichi Omae, July 2012, Shogakukan (in Japanese).
[17] Technical Report: Fukushima Accident Summary (Aug. 19, 2011), R. Yoshioka, K. Iino, Association for the Study of Failure. http://www.shippai.org/images/html/news559/FukuAccSummary110819Final.pdf

In August 2012, TEPCO released videos of the teleconferences that were held during the accident to the media, and in October 2012, they were made available on TEPCO's homepage. Although individual names and some portions of the images are censored, they provide viewers with footage showing the high tension on site at the time. In total, they are several hours long, but all that can be seen and heard are reports from the field being transmitted to the headquarters. The headquarters, on the other hand, continued to send inquiries and demands for information. Suggestions and advice were not provided by the headquarters or the design and maintenance manufacturers (Hitachi and Toshiba). Such information could have been provided via a different route; however, decisions were probably being made by the field engineers during the first few days.

These videos revealed that during the accident, engineers collected 12V batteries from cars for reading sensors and operating valves and even announced they were in need of cash to purchase them from hardware stores. It took them as long as 6 hours to assemble the batteries into the electrical circuits. These troubles contributed to the delay in releasing the reactor pressure. The videos also show that when the engineers started to inject cooling water into the RPV from the fire engines, they had to rely on the seawater from the tsunami that was left inside the pits; pumping water from the ocean was not that easy.

In November 2013, TEPCO released images from a boat-mounted camera that showed the water leakage from the suppression chamber of unit 1. We currently cannot access the reactor due to high radiation; however, as we collect more evidence from the remaining reactors we will gain more insight and understanding of the accident. We will not rush to conclusions and will carry out a thorough investigation into what happened with the accident.

b) Outline of the Light-water Units

The progression of the accident can be better understood by first explaining how units 1, 2, and 3 of the Fukushima Daiichi NPP operated. Fig.1 outlines the primary equipment of unit 1 and Fig.2 outlines that of units 2–5.

During normal operation, fuel bundles were placed inside the RPV, which was surrounded with water that was used to moderate the neutrons and cool the fuel. The fuel heated the water, which evaporated into steam that traveled through the main-steam line to reach the main turbine. The steam hit the turbine blades to rotate the turbine rotor, which then turned the electric power generator. The main condenser condensed the steam discharged from the turbine chamber to water to feed it back to the RPV. The condenser was cooled by circulating seawater.

Upon emergency, control rods were inserted from the RPV bottom into the reactor core to stop the nuclear fission reaction. Simultaneously, the RPV was isolated from the main-steam line. Nuclear fission products in the RPV generated decay heat even after the fission reactions were stopped and the fuel temperature would continue to increase. Nuclear reactors have systems to remove this decay heat; an IC was used for unit 1 and an RCIC was used for units 2–5.

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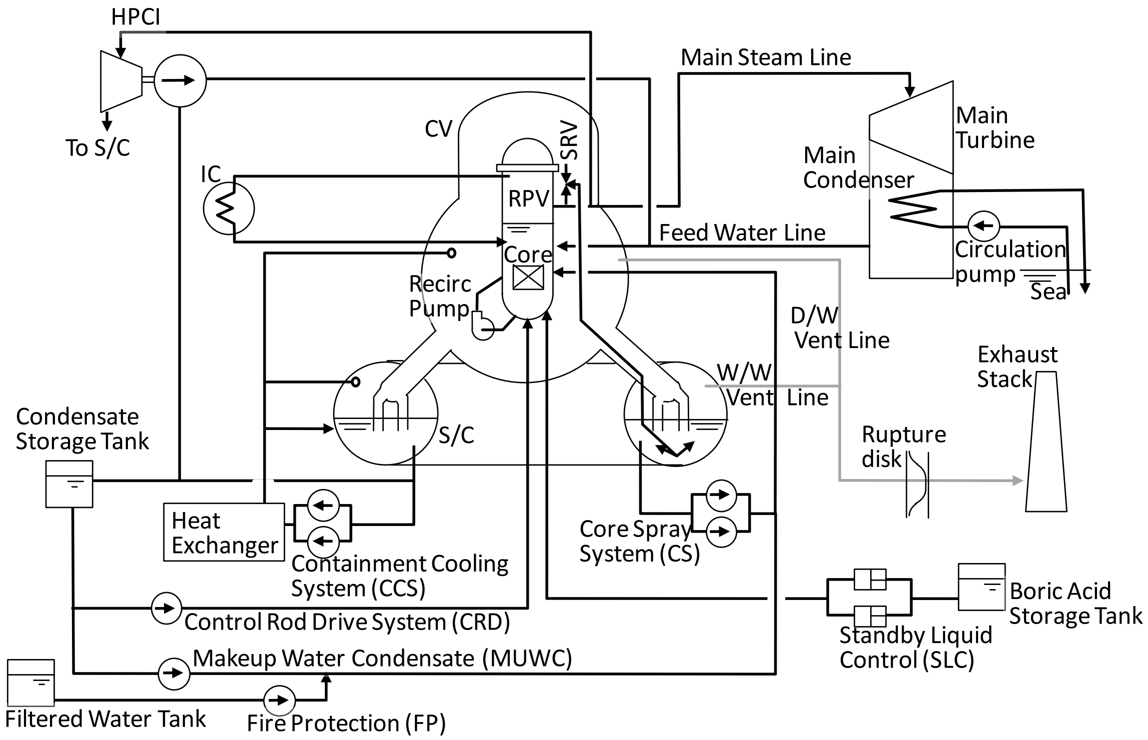

Fig.1 Outline of the primary equipment of unit 1 of the Fukushima Daiichi NPP.

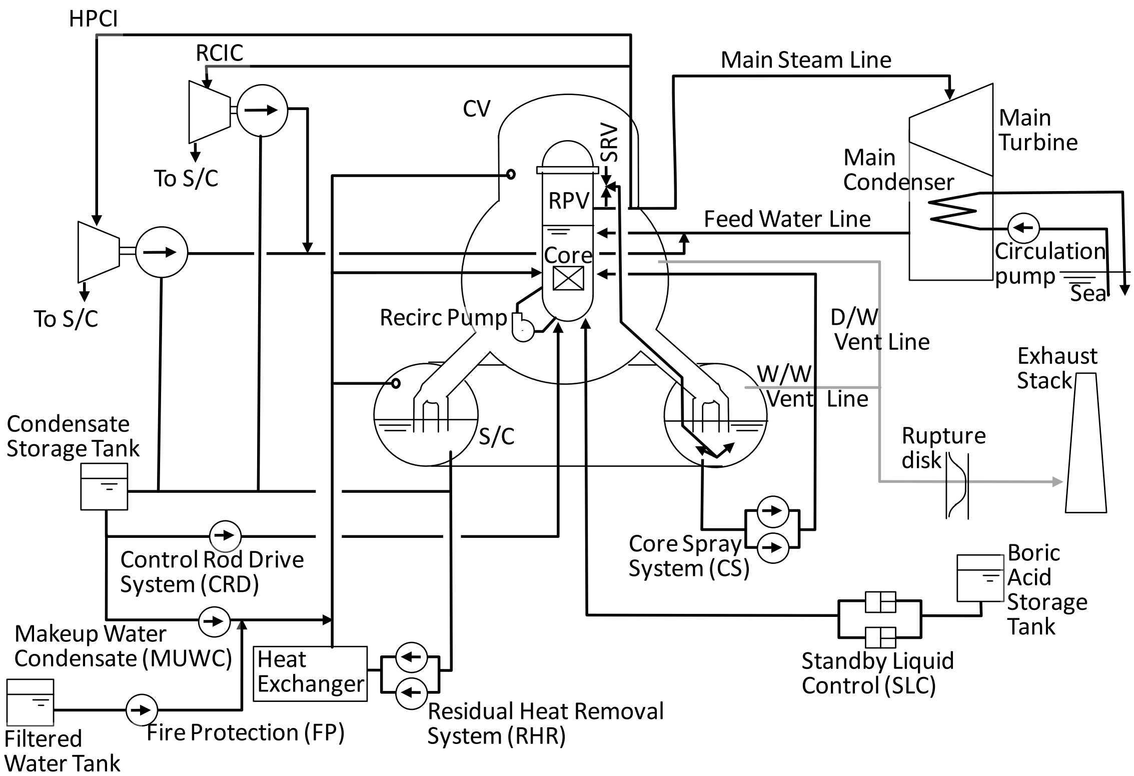

Fig. 2 Outline of the primary equipment of units 2–5 of the Fukushima Daiichi NPP.

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The IC operated without the help of a pump to condense steam from the RPV to water, which gravity carried back to the RPV. The coolant that condensed steam in the IC heat exchanger was stored separately as water. The cooling water evaporated into steam and was discharged to the outside of the reactor building; thus, when in use, the IC required its cooling water to be refilled in order to maintain its cooling capacity. When cooling water was filled to its maximum storage level, the IC was able to condense steam from the RPV for 8 hours. In contrast, the RCIC and HPCI pumps were driven by turbines that were turned by steam from the RPV. The IC and RCIC did not require electrical power sources; however, if the RPV steam pressure dropped, the IC and RCIC would stop operating

In addition to the above cooling systems, each reactor comprised a water condensation system (MUWC) and a residual heat removal system (RHR), which were driven by electrical pumps. The fire protection systems (FC) were driven either electrically or by diesel. The pressure within the RPV reached about 70 atm; however, the CV maximum allowable pressure was about 5 atm. The diesel pump driven by the FP pressure reached about 6 to 7 atm, and that of the fire engine reached about 8 atm.

c) Progression of the Accident towards a Cold Shutdown State

The equipment of both the Fukushima Daiichi and Daini NPPs suffered a number of tsunami damages. The DC power at the Fukushima Daini NPP was maintained throughout the tsunami and the plant managed to restore its AC power within 2 days. Restoration efforts were carried out under harsh conditions; however, thanks to the preparations and training that were followed in accordance with the accident management (AM) plans, severe accidents were avoided at the Fukushima Daini NPP.

The Fukushima Daiichi NPP, on the other hand, lost all its electrical power sources except for the DC power at unit 3, which was eventually lost after 2 days. At the Fukushima Daiini NPP, the valves were controllable from within the central control room, whereas the operators of the Fukushima Daiichi NPP had to climb to the physical locations of the valves or switchboards to supply the compressed air or direct the electrical power. These delays in valve operation led to the release of radioactive material from the Fukushima Daiichi NPP.

At both plants, engineers attempted to reach a cold shutdown state by following scenarios (i) through (vi); however, different procedures were followed at the Fukushima Daiichi NPP.

(i) Start the emergency diesel generators after an earthquake

Both the Fukushima Daiichi and Daini NPPs were able to fully insert their control rods within 1.6 seconds after the earthquake occurred, which was before the tremors from the earthquake ceased. Offsite power sources were lost immediately after the earthquake; however, the emergency diesel generators (D/G) began operating. The IC and RCIC systems began operating to cool the fuel rods in the RPVs.

The Diet Report [12] speculated that the earthquake caused damages to the reactor or piping before the tsunami struck, whereas the Cabinet Report [1] [2] concluded from their actual temperature, pressure, and radioactivity measurements that the damages did not take place until after the tsunami struck.

(ii) Use the emergency D/G, DC power, and switchboards after a tsunami

Seawater from the tsunami poured into the Fukushima Daiichi NPP through the doors and windows of the turbine buildings. The emergency D/G, DC battery, and switchboard functions were lost, except for the DC power at unit 3. Units 5 and 6 of the Fukushima Daiichi NPP and units 1–4 of the Fukushima Daini NPP had at minimum an emergency D/G, DC battery, or a switchboard to operate the valves and pumps. Units 5 and 6 of the Fukushima Daiichi NPP had an air-cooled emergency D/G and were luckily shut down for maintenance. Simply increasing the number of emergency subsystems is insufficient for the large systems comprising a power plant unit; they require a number of diversified safety subsystems that operate under different principles.

Eventually, the Fukushima Daini NPP recovered from the severe damage; however, at the time, all of its seawater pumps were lost due to the tsunami. It took two days of hard work to connect temporary power cables directly to the pumps. The Fukushima Daiichi NPP took similar efforts to make use of the switchboards that were repaired; however, the repeated hydrogen explosions did not allow any progress to be retained. The accident, which reached a level of catastrophic severity, was partly due to the multiplicity of simultaneous accidents with multiple reactors.

(iii) Initiate cooling with high pressure steam from the RPV after a tsunami

Units 4, 5, and 6 of the Fukushima Daiichi NPP were shut down for maintenance and did not have an urgent need for cooling. After the earthquake, the IC of unit 1 of the Fukushima Daiichi NPP was started, and the RCICs of units 2 and 3 were started. The RCICs of units 1–4 of the Fukushima Daini NPP were started after the tsunami struck. If the

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plant had lost all of its AC power as the Fukushima Daiichi NPP did, a meltdown would have occurred within 3 hours, since the units were unable to start their high pressure cooling systems.

An IC works by forcing high pressure steam into water cooled pipes in order to condense the steam to water and by then letting the water flow back into the RPV under gravity. A RCIC turns a turbine with the high pressure steam to drive a pump that forces water inside the CV or from outside tanks into the RPV at high pressure. Both the IC and RCIC do not require AC power. The concept is to allow cooling whether emergency electrical power is available or not. These systems, however, have valves on their piping, and the valves on the IC of unit 1 were designed to close upon power failure (fail-close), whereas those on the RCICs of the other units were designed to fail-as-is. After the earthquake, operators started the RCICs of units 2 and 3 of the Fukushima Daiichi NPP and thus their valves remained opened to cool the reactor core after the tsunami had struck.

In contrast, unit 1, without its IC after the tsunami, experienced a severe accident. Within three hours, the RPV water level decreased enough to expose the fuel rods, and the inner and outer surfaces of the Zircaloy cladding (tube that houses the stacks of fuel pellets) were oxidized. The oxidized films had high melting points and the cladding melted from the inside. As the tubes deformed, the oxidized surface films could no longer hold their shape and broke. The fuel pellets inside the rods cracked into fragments [17] and the radioactive material fell to the RPV bottom and further down into the CV. As the fuel rods disintegrated, zirconium reacted with oxygen in the surrounding water and produced about 1 ton (nearly 10,000 cubic meters) of hydrogen gas. Half a day later, the hydrogen gas exploded.

(iv) Arrange piping to inject low pressure cooling water into the RPV and start cooling

The type of IC and RCIC described above can inject cooling water into the reactor even when the pressure is 70 atm; however, they are driven by high-pressure steam and will stop running when the reactor pressure drops. The RCIC in unit 2 ran for 3 days and that in unit 3 ran for a day, followed by the HPCI that worked in a similar manner for another half a day.

While the high-pressure cooling systems were operating, methods of injecting cooling water without the use of AC power were required for the Fukushima Daiichi NPP. At the plant, the engineers injected cooling water at several atmospheres into the RPV by using fire engines and diesel driven pumps from the outside through piping for the fire protection system (FP). These procedures were not planned in advance; thus, the workers in the field had to connect the pipes on the spot. The work proved to be difficult; for example, for unit 2, the workers built a cooling water route from the FP to the RPV via the RHR. This route had an AC-powered motor operated valve (MOV) with a diameter of 24 inches. The valve could have been opened within 24 seconds if the AC power was available, however, without it, 10 workers took turns in turning the heavy valve manually and this labor took an entire hour to complete.

The plant manager at the Fukushima Daiichi NPP decided to rely on fire engines at 17:12 JST, an hour after the tsunami, as an alternate method of water injection. The AM of TEPCO, however, did not have such plans, and the search for water inlets and the layout of hoses for the first time further delayed the cooling of the reactors.

(v) Open the SRVs to reduce the RPV pressure and vent valves to reduce the CV pressure

In order for the low pressure cooling systems in (iv) to operate, the high pressure steam in the RPV has to be released into the CV and then released into the atmosphere to lower the RPV pressure. Fig..3 shows the structure of the main steam safety relief valve (SRV). When the main-steam line pressure rises to an abnormally high level, the pressure on the valve lifts it from the seat and the steam is released into the SC. Manual activation requires energizing the solenoid valve to bring nitrogen gas into the cylinder to push the piston up and the lever mechanism lifts the valve off its seat. This solenoid valve is activated by DC 125V.

The air operated (A/O) vent valve from the SC to the vent line is structured similarly to the SRV, except instead of a cylinder/piston and lever action, compressed air pushes a diaphragm up to lift the valve. Manual activation of this vent valve also requires DC-powered solenoid activation.

When the compressed air and DC power were lost due to the tsunami, the field workers had to prepare high pressure gas and somehow apply DC power to the solenoids to bring the gas under the piston or diaphragm to activate these valves. During the accident, workers collected compressed gas bottles and portable compressors, and for DC power, 12V automobile batteries and small 2V batteries stacked in series were used. When the gas or battery power was drained, the valves would close and the field workers had to repeatedly assemble their temporary valve activators. Thus, the process of relieving pressure was slow and the extra time that the high pressure systems provided was wasted. Then, the hydrogen explosion at unit 1 set back the pressure relief efforts at unit 3, and when the top floor of the reactor

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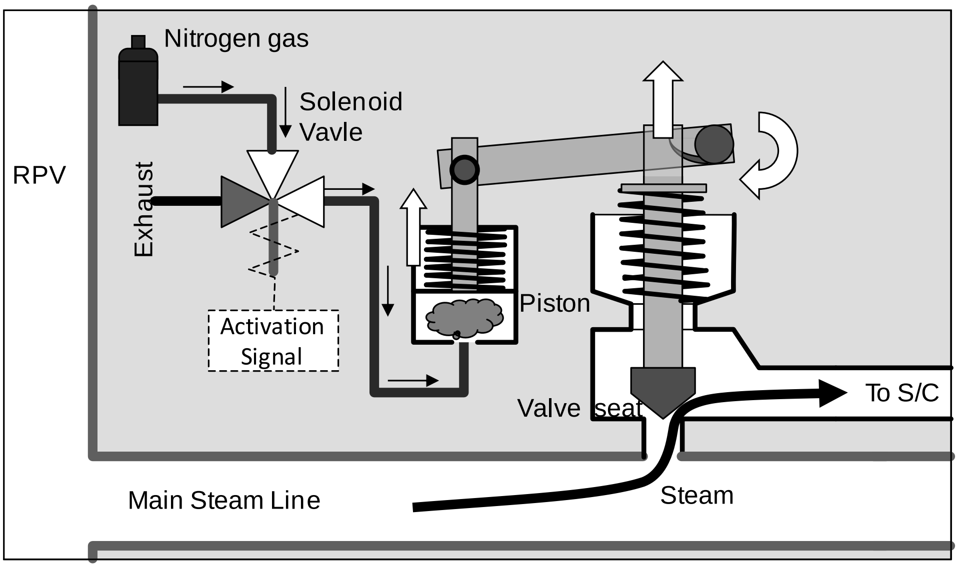

Fig..3 Safety relief valve.

building at unit 3 exploded, the recovery efforts for unit 2 were set back.

(vi) Circulate cooling water through the heat exchangers to release the heat into the sea

Injecting water from a low pressure system into the reactor would have prevented the meltdown; however, to reach a cold shutdown state, high-temperature steam and water had to run through the heat exchangers to release the heat into the sea. Contaminated water accumulated in the reactor buildings of units 1–3, probably due to cracks in the RPV or CV. To cool and filter the contaminated water, recirculation systems were built on outside of the reactors to reach a cold shutdown state. The contaminated water, unlike cooling water under normal conditions, had directly contacted the fuel and contained a large amount of radioactive material. The water had to go through a zeolite-filled filter tank to capture the cesium and other radioactive materials. The filter tanks are not reusable and the used tanks continue to accumulate in Fukushima.

3.2 Scenario of avoiding an accident

(1) The severe accidents were avoidable

Units 5 and 6 of the Fukushima Daiichi NPP and units 1–4 of the Fukushima Daini NPP successfully reached a cold shutdown state; in other words, they followed the scenarios to avoid severe accidents and succeeded. Fig. 4 shows this scenario, i.e., to run the high pressure cooling systems for about 1 day and to gain some extra time, open the SRVs and vent valves to reduce the reactor pressure to run the low pressure cooling systems, then while the low pressure systems are running, continuously remove the heat with the prepared heat exchangers and circulation routes.

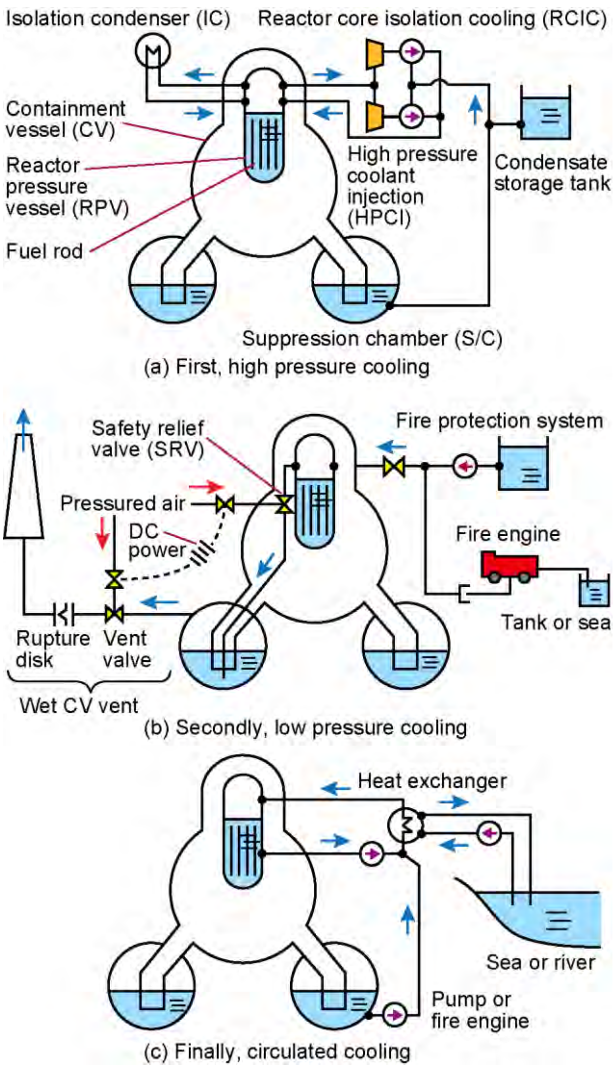

Fig..4 Scenario of a successful cold shutdown.

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Unit 1, however, failed to operate its high pressure cooling system (IC) and did not succeed. Units 2 and 3 did not succeed when they failed to open their SRVs and vent valves. The Fukushima Daiichi NPP manager gave orders to prepare to initiate low pressure cooling with fire engines 1.5 hours after the tsunami; however, the high pressure cooling system of unit 1 had already stopped and the core had already been exposed.

(2) Would there have been less loss if all the right decisions were made?

Although the operations that were being carried out at the Fukushima Daiichi NPP were similar to those at the Fukushima Daini NPP, the media speculated that human errors were made by the operators during the critical points of the accident. We do not intend to blame individuals, and would rather like to discuss why the engineering team, which included off-site engineers, failed and did not cooperate with one another. When Apollo 13 lost one of its oxygen tanks and was in danger of not returning to Earth, ground-based engineering was used to create mock-up trials with the same elements and conditions to devise ways to ensure survival and to send instructions to the spaceship. This is the type of teamwork that is needed for NPPs.

a) Could the IC at Unit 1 have been restarted?

The IC of the Fukushima Daiichi NPP had the capability of cooling the RPV without a pump. Its capacity was sufficient because after the earthquake and before the tsunami, operators ran them with partial capacity to avoid a sudden cooling of 55°C per hour or faster. Such rapid cooling could cause RPV damage due to thermal stress.

Unit 1 had two IC systems (A and B). Each system had two lines: the upper line where the RPV steam traveled to the IC and the lower line that passed the IC condensed water back to the RPV. Each line had a 125V DC operated valve on the exterior of the CV and a 480V AC operated valve in the interior of the CV. The valve on the exterior of the CV had a manual handle, but the one on the inside did not.

Just before the tsunami hit, both systems had only the DC-operated valves on the exterior of the CV on the lower line closed and all of the other six valves were open. When the tsunami caused an SBO, the IC system safety sensors lost their “safe” signal and all eight IC valves closed. The reasoning for this closure is to keep the IC offline, because if a signal is lost, an accident is likely to be the case, and without identifying the accident, it is safer to keep the RPV isolated from any external system that may have been damaged. The engineers called this “fail close” behavior “fail safe”. A later investigation, however, revealed that all four valves in the CV were not fully closed.

The problem in terms of accident management was that none of the field engineers or the off-site engineers realized that the IC systems both stopped after the SBO. We later learned that the Fukushima Daiichi NPP simulator that was used to train the operators did not include an IC (it was only installed at unit 1), and the standard process at the Fukushima Daiichi NPP to counter high RPV pressure was to only activate the SRVs. The two IC systems at unit 1 of the Fukushima Daiichi NPP were never operated since the reactor began operating in 1971.

A later investigation revealed that the “fail close” logic upon SBO closed all eight IC valves; however, the AC 480 V valves inside the CV did not fully close, because the AC driving power was lost before they were fully shut. The on-site engineers were confused, because they tried opening the DC powered valves on the exterior of the CV and saw some steam escape from the IC discharge lines that vented to the outside of the reactor building; however, they were worried about high temperature damage to the IC piping, and closed the valves.

It is understandable that the on-site engineers misinterpreted the IC valve status while in the chaotic control room, but what about the off-site engineers or manufacturers of the plant? No one remembered the “fail close” logic that should be implemented with the IC valve system to warn the operators on site. If they had received such advice, the on-site engineers could have scrambled to collect DC batteries or even manually turned the handles to open the IC valves located on the exterior of the CV.

b) Could the HPCI of Unit 1 have been restarted?

Unit 1 also had an HPCI system, which would have been able to turn a turbine with high pressure steam to drive a pump to inject cooling water into the RPV. After the tsunami, however, the unit was out of DC power to control the HPCI turbine and its lubrication pump for the bearing was inoperable as well.

c) Why was the HPCI of Unit 3 stopped without confirming a reduction in pressure?

The RCIC of unit 3 stopped on 13 March 2011, the day after the tsunami, at 11:36 JST. The RPV water level decreased and the HPCI started automatically. The HPCI ran for about 14 hours before it was manually stopped at 02:42 JST on 13 March 2011. The plan was to relieve the high RPV pressure with SRVs while the HPCI was running;

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however, the chief operator stopped the HPCI without confirming the action with top level management. When the operators later tried to pop the SRVs, the DC power was exhausted and the valves did not open. The stopped HPCI could not be restarted either and this was when the unit started its way towards core exposure and meltdown.

Later at 09:36 JST on 13 March 2011, the SRVs and vent valves finally opened and the fire engines succeeded in injecting water into the RPV with lower pressure; however, the core had already been damaged.

d) Why did the cooling water source for the RCIC of Unit 2 change?

The RCIC of unit 2 was operating at the time of the SBO and it kept running without being controlled. At about 12:30 JST on the 14 March 2011, however, it lost its water injection function, probably due to the high water temperature in the SC. When the water temperature increased on the pump suction side, cavitations in the water lowered the water injection capability.

The RCIC was first running with water from the condensate storage tank; however, the water source switched to the SC between 04:00 to 05:00 JST on 12 March 2011. At this time, the condensate storage tank was still about 30% full. Without the RHR to remove heat in the SC, relying on SC water to cool the core would raise the internal temperature and pressure. When the RCIC ceased to operate, the SC reached 149°C and 0.49 MPa.

This question should also have been addressed by the off-site engineers and manufacturers. However, low pressure coolant injected from the fire engine made it in time for unit 2; thus, the switched water source had no direct affect on the fuel damage. However, the progression of the accident could have been different if there were any further delays in the water injection from the fire engine.

e) Was the fire engine running out of gas while cooling Unit 2 an oversight?

When unit 3 exploded at 11:01 JST on 14 March 2011, the RCIC for unit 2 stopped and the top of the core of unit 2 began to be exposed above the water level at 17:17 JST. Immediately after this event, the news reported that the pressure of the RPV of unit 2 decreased and was followed by the injection of low pressure water via a fire engine. Later news, however, reported that the water level dropped at 18:22 JST, exposing the full length of all the fuel bundles. This news was then followed by a surprising fact that the fire engine that was used to inject the seawater was inoperable due to an insufficient supply of gas.

f) Did reinforcing the blowout panel fixture lead to the hydrogen explosion?

While units 1, 3, and 4 experienced hydrogen explosions, unit 2 did not experience a hydrogen explosion. The blowout panel on the reactor building of unit 2 popped open at 15:36 JST on the 12 March 2011 when unit 1 experienced its hydrogen explosion. The 5 m^2 opening allowed the hydrogen gas to escape and the gas never accumulated to a level that would have caused an explosion.

The Cabinet Interim Report (pg. 214 of [1]) stated that TEPCO, following the case in which the blowout panel popped open at the Kashiwazaki-Kariwa plant and efforts failed to contain the air inside the reactor building during the 2007 Chuetsu Offshore Earthquake, made design changes to strengthen this panel on its Fukushima NPPs.

As we mentioned earlier, the release of radioactive material due to the hydrogen explosion was small; however, the explosion affected other works underway to control the plant. Similar to the following problem associated with a rupture disk, the efforts to "contain" a small amount of radioactivity led to explosions that delayed the work efforts.

g) Why were the rupture disks in place?

The venting line had two vent valves in series and a rupture disk before the line reached the exhaust stack. A rupture disk is commonly used in chemical plants to completely shut off the flow inside a pipe. The disk, however, ruptures when the pressure difference on its two sides exceeds its set point. Its completeness overcomes the limitation with regular valves with valve seats that always have the possibility of allowing small leakage. The original GE design called for either a double valve configuration or one with a rupture disk. The Japanese plant adopted both to have two regular valves and a rupture disk. The set point, however, was at twice the CV pressure limit, causing great difficulty in venting the CV. The rupture disks, after all, were not needed.

(3) What was the cause of the accident?

a) Tsunami

In a sense, it is true to say that the accident would not have happened if the tsunami did not hit the NPP. It is also true that TEPCO failed to take precautions against such a great tsunami despite the studies that have been conducted in the past 10 years and results obtained regarding the 869 Jyogan tsunami. At the same time, if the other events with

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similar chances of occurrence are taken into consideration, we would have to plan against volcano eruptions, fires, airplane crashes, meteor strikes, terrorist attacks, war, mud slides, and so on. The fact is NPPs have to take precautions against events that are extremely unlikely to occur.

b) SBO

During this accident, the Fukushima Daiichi NPP succeeded in “stopping” the reaction, but failed to “cool” the reactor, and as a result it also failed to “contain” the radioactivity. The cause of this failure is considered to be the SBO.

What we should learn from this accident, however, is the fact that there always will be events that are Beyond Design Basis (BDB). In preparation, we needed to prepare multiple layers of protection and to determine what countermeasures to take for any possible sequence of events.

In contrast, the nuclear industry and regulation denied the need to prepare measures against an extended (30 minutes or longer) SBO. The real cause was not the SBO, but the failure to plan for an extended SBO.

c) Lack of preparation and training for an emergency

TEPCO and the Government of Japan are to blame for this accident, since their preparations and training against severe accidents were poor. They should have invested more in preparing and training for an accident to lower the risk of such a disaster. However, training was conducted on how to share electricity between adjacent units and alternate water injections through FP; however, this training was certainly not sufficient. Foreign countries such as the US and Switzerland have 125 V batteries and nitrogen gas bottles on hand-pulled carts that can be easily transported.

NRC’s B.5.b. [11] requires preparations that include having hand operable valves, transportable alternate pumps, alternate water level and pressure sensors, and a way of filling the fuel pool using gravity. Such preparations would have made a great difference in this accident. The government report pointed out that NISA received explanations about the B.5.b from the NRC, but ignored the information stating that terrorist attacks will not take place in Japan.

The most critical type of preparation and training needed for this accident was to “relieve the reactor pressure within 1 hour and inject low pressure cooling water into the RPV”. The units could have reached a cold shutdown state if only this process was conducted successfully. Unit 1 with its IC stopped, however, would not have had enough time to relieve the reactor pressure, and its core would have been partially damaged even if preparations were made.

(4) Design interference of the “cooling” and “containing” functions

Decay heat is like a smoldering fire in that a significant amount of heat is released. The generation of heat immediately after a shutdown is about 7% of the reactor thermal output, which drops to about 0.6% in one day and to 0.2% in one year. If we take unit 1 as an example, and assume a value of 460 MWe and a power generation efficiency of 30%, the thermal power would be 1,530 MWth, and the decrease to 0.6% after 1 day would be 9,200 kW. If we were to remove this decay heat with the vaporization heat (540 cal/g) and sensible heat (80 cal/g to heat water from 20°C to 100°C) of water, 12.7 tons of water would need to be poured every hour into the RPV. This would be possible since a regular fire engine can discharge 2 tons of water every minute at about 10 atm. The only problem is that the RPV pressure would be as high as 70 atm.

This is why the RPV pressure needs to be lowered. A nuclear reactor has a double shell structure with the RPV and CV and the RPV pressure needs to be released into the CV. However, this increases the CV pressure and temperature, and the CV pressure has to be released into the atmosphere. This process cools the fuel rods through vaporization of the cooling water, and ultimately uses the atmosphere as a heat sink. Since contaminated steam is released into the air, this process fails to meet the function of “containing” the radioactivity, even though the amount of material that would be released would be small. Thus, such a process can only be allowed for emergency situations such as the Fukushima accident.

The Fukushima Daiichi NPP, however, failed to follow the above emergency scenario, because it first failed to “cool” the reactor. This failure caused the fuel cladding to melt and the cooling water came into direct contact with the fuel pellets. Then, when the highly contaminated steam and water escaped the CV, they contaminated the land, sea, and air.

The above discussion showed that the functional requirement of “cooling” interferes with that of “containing”. During the Kashiwazaki-Kariwa NPP accident in 2007, a small amount of radioactive material was released from the condenser of unit 7 through the exhaust stack. The release of radiation made the news and caused turmoil among the public. The media also exaggerated the effects of water splashing out of the fuel pool of unit 6; however, the

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radioactivity spill was equivalent to 9 liters of water from the Miasa hot springs (known for its radium rich springs). The Fukushima Daiichi NPP accident was so severe that venting the CVs finally spreading the radioactive debris, was considered to be reluctant. The delays in venting were caused by the technical difficulties that were discussed above. We must, however, recognize that the "fail close" design of the IC valves for unit 1 and the rupture disks on the vent lines interfered with the efforts to quickly reduce the pressure to ensure low pressure cooling was applied to the reactor cores. We are not particularly opposed to the idea of filtered venting. However, the coverage by the media confuses the idea of containing radioactivity under normal circumstances with what actions to take during serious emergencies. During a serious emergency, the design function of "cooling" must have priority over the function of "containing" and we may have to review the designs to confirm if the systems are designed in such a way. This severe accident should not be repeated and the knowledge gained from its consequences should be implemented in an effective manner.

3.3 Proposals Concerning Crisis Management at NPPs

(1) Departure from Absolute Safety

The internationally accepted definition of safety is "freedom from unacceptable risk". However, a widespread opinion in Japan is that we should seek absolute safety when NPPs are involved. It is true that Japanese people fear the use of nuclear energy. As Japan is currently the only country to have been attacked with atomic bombs, the people have specific emotions related to the use of nuclear energy. In addition, television programs aired shocking scenes of the hydrogen explosions during the Fukushima NPP accident, which caused people to fear atomic energy more.

However, such technology cannot be utilized if absolute safety is a requirement. In addition, as the Fukushima NPP accident demonstrated, once "absolute safety" is mentioned as a method to persuade people, no true measures for realistic safety can be taken, because taking such measures would prove that those who mention "absolute safety" are stretching the truth. Regardless of whether they are for or against the utilization of nuclear energy, anyone should accept the internationally accepted definition of safety, and discuss whether the remaining risks are acceptable after all efforts have been made to reduce the risks accompanying the use of nuclear energy. Therefore, we propose that "absolute safety" should not be the sought after standard when considering the safety of NPPs.

(2) Distinction between "Beyond the Design Basis" and "Beyond Conceivability"

Immediately after the accident, the phrase "beyond conceivability" became very popular. The phrase was used to state that TEPCO should not be held liable because the accident was "beyond conceivability". However, the phrase "beyond conceivability" does not literally mean that no one was able to conceive such a situation. In fact, TEPCO was aware of information pertaining to the Jogan Earthquake, which caused a disastrous tsunami. Nevertheless, TEPCO decided not to take any action, because the information about the earthquake was not certain.

When a person adopts a design basis, they usually know that the probability that an accident could occur beyond any expectation is not zero. In that sense, they conceive an event or occurrence beyond the design basis. However, if one assumes that nothing will happen beyond the design basis, actions will not be taken against any situation that could occur. Even after the Fukushima NPP accident, people still expect that accidents will not occur beyond the design basis. Therefore, pressure is exerted on regulatory bodies so that the regulatory standards will be raised. If a report says that a tsunami with a height of 15 m is expected, regulations will be made to ensure that it is mandatory to build a wall higher than 15 m.

However, what should be taken from the Fukushima NPP accident is that we should be prepared for anything beyond the design basis. Even if a tsunami with a height of 18 m is expected, a wall could be as low as 15 m if countermeasures are taken for a tsunami that comes beyond the wall. Therefore, we propose that the design basis should not be correlated with conceivability. When a design basis is adopted, the possibilities of what could happen beyond it should be taken into consideration.

(3) Scenario for the Remaining Risks

If one accepts that an accident could occur beyond the design basis, then they should assess the remaining risks of the design basis. For this purpose, a scenario is necessary. The Fukushima NPP accident has provided sufficient material for such scenarios.

Using the reactor of unit 1 as an example, an investigation revealed that its HPCI system became unusable immediately after the tsunami struck. The cause was that the direct current power supply failed, which further caused the electric valves and lubrication pumps to be inoperable. Even under the conditions of an SBO, the direct current power supply would not automatically fail. However, the water of the tsunami soaked the direct current elements,

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which caused them to be unusable. In such a scenario, if an element fails, another element will back it up. If that element fails, another element will back it up. In short, failures that occur one after the other should be taken into consideration. By repeating this process, one will reach a point where there is no longer an unacceptable risk. Therefore, we propose that a method to create such a scenario should be developed.

(4) Learn from the Past

After the Chuetsu-oki Earthquake, JSME formed a committee to study regulatory actions to determine whether the successful survival of the Kashiwazaki-Kariwa NPP was a result of implementing effective regulations. However, the committee reached no meaningful conclusion, because most of the experts were only willing to state that the "Stop, Cool, and Containment" procedure was successfully completed.

Nevertheless, experts have pointed out certain areas that need improvement. Some of the examples are as follows:

- Prevent office lockers, ceiling lights, etc., from falling;
- Provide an emergency power supply for necessary locations;
- Improve the condition of emergency vehicle access roads; and
- Use flexible joints for the buried pipes of the fire protection system and other emergency systems.

Unfortunately, however, the safety measures taken after the earthquake are mostly focused on the anti-earthquake strength of various structures. In addition, there were many cases where existing structures were found to be safe, because the improved calculation of a stress-strength analysis determined the safety margins to be sufficient, and no actual structural changes were made.

The Chuetsu-oki Earthquake occurred on 16 July 2007, which was well after the September 11 attacks. Therefore, the government should have known the importance of crisis management for NPPs, because they received the B.5.b from the US. Nevertheless, the Kashiwazaki-Kariwa NPP accident did not enhance efforts in crisis management. Conversely, many experts used the accident as evidence to persuade the public that the NPPs of Japan were absolutely safe. It also seems that the Fukushima NPP accident did not change this view. Experts, including those from regulatory organizations, still focus on the strength of the structures. Their efforts are to enforce rules that require protective walls to be constructed higher than any tsunami that may come in a thousand years. Therefore, we propose that the shortcomings of the disaster relief efforts that were made after the Chuetsu-oki Earthquake be taken into consideration.

(5) Role of Legal Framework

The Act for the Regulation of Nuclear Power Plants and Related Facilities empowers the Minister of the Economy, Trade, and Industry to issue orders to entities operating NPPs. To the best of our knowledge, two orders were issued during the Fukushima NPP accident. One order said, "Regarding the reactor of unit 1 of the Fukushima Daiichi NPP, appropriate measures, such as filling the reactor vessel with sea water, should be studied, and the soundness of the reactor should be secured." Another order required that water should be promptly poured into the used fuel pool of the reactor of unit 4.

We can only simply wonder whether these orders had any effect. Usually, administrative orders are issued when those that need to be regulated do not voluntarily take measures that are necessary for public safety, since there are some disincentives against taking such measures. However, the measures that TEPCO were instructed to carry out were not completed due to technical difficulties; there was no lack of willingness on their part.

Administrative orders are necessary when the operating body of a NPP is hesitant to perform a task that is technically possible but politically difficult to conduct. In the political culture of Japan, early venting is one such example. During the Fukushima NPP accident, early venting would have prevented the meltdown of the nuclear fuel. However, early venting could have been a target of criticism, because it intentionally discharges small amounts of radioactive materials. In such a situation, an administrative order should make it easy for the operating body of the plant to take the necessary measures. Therefore, we propose that an effective legal framework should be created to improve the administrative regulations of NPPs.

(6) Contamination of Radioactive Materials

Due to the Fukushima NPP accident, the areas of land around the NPPs are contaminated with radioactive material. People were evacuated from these areas and many still live in temporary housings far from their homes.

The land needs to be cleared from this radioactive material before the evacuees can return to their homes, but there is a disagreement to what extent this process should be taken. Scientists suggest that the LNT model and the principles of ALARP or ALARA should be adopted. For laymen, however, this suggestion is somewhat misleading. The phrase

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"as low as reasonably practicable (or achievable)" is often interpreted as "as low as possible", and environmentalists suggest that the contaminated soil should be removed as much as possible. However, such a viewpoint leads to a more difficult question: after the contaminated soil is removed, where should it be disposed to? No area is willing to accept such soil. It seems that the effects of low radioactivity are overestimated and the effects of stress caused by the evacuation are underestimated. Although the LNT model should make it possible to conduct a risk-benefit analysis, it is very difficult to allow people to accept its true meaning. Therefore, we propose that a better method of balancing the risk of low radioactivity and the benefit of early soil removal should be developed.

4. Reponses of JR East to the Earthquake and Tsunami

4.1 Tohoku Shinkansen, Commuting Railways around the Tokyo Metropolitan Area, and Local Lines along the Sanriku Coastal Line

(1) Tohoku Shinkansen

When the earthquake occurred, 18 trains were in service, and one train was operating at a speed of 270 km/h. The early detection system for earthquake motions successfully responded to the occurrence of the earthquake and all trains came to an emergency stop. Derail prevention rails successfully prevented all the trains that were in service from derailing. There were no passenger injuries that were reported.

The successful management of these trains is mostly attributed to the well-prepared countermeasures of JR East; however, we would like to point out some of the fortunate conditions. One is that the Tohoku Shinkansen line runs parallel to but at some distance from the coast, and because the seismic center was in the Pacific Ocean, the train was far enough for the early detection system to work in a timely manner. Another is that only a few people were on the platform of Sendai station, since the earthquake occurred soon after the train departed. We should take these fortunate conditions into consideration.

(2) Commuting Railways around the Tokyo Metropolitan Area

(a) Overview

The Yamanote Line of JR East provides some examples of the problems that are likely to arise after an earthquake. The following three problems can cause railway services to be suspended:

- An upheaval of the railway tracks;
- Displacement of the insulators for the overhead wires; and
- Detachment of the overhead wires.

(b) Timeline of the Decision not to Resume Operations

The earthquake occurred at 14:46 JST. Inspection teams were organized immediately and 12 parties (24 members) were allocated to inspect the railway tracks and related facilities. The Yamanote Line has a circular route that is 34.5 km in length and its inspection started at 15:40 JST. An upheaval of the railway track was discovered at 18:05 JST, and an announcement was made to the public and mass media at 18:20 JST that all JR lines would not resume service that day.

Some criticized the decision and timing of the announcement, but we consider that it was unavoidable. The upheaval of the railway track could have caused serious accidents, and the restoration process for such damages is lengthy. In addition, many commuting lines run radially from or across the Yamanote Line. Therefore, the decision not to resume all commuting train services was reasonable. Although the unavailability of the JR commuting train services caused many people to spend the entire night at their offices, a better decision could not have been made under such circumstances.

(c) Resumption of Service

Many workers were needed to repair the damaged railway track, but transporting them to the site was very difficult because many of the roadways were congested. It took more than 2.5 hours to transport the workers and materials. The restoration efforts commenced early the next morning and finished at 06:58 JST. Preparations were then made to resume service. The Yamanote Line resumed service at 08:36 JST. Considering the amount of traffic and the continuous efforts throughout the night, we consider that the best efforts were made.

(3) Local Lines along the Sanriku Coast

Following the occurrence of the earthquake, the trains came to an emergency stop and passengers were evacuated to places of refuge. In addition, 27 trains were located between stations. Five of those trains along the Sanriku coast

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were swept away thereafter by the tsunami. However, since the employees of the railway company successfully guided the passengers to the places of refuge, none of the passengers were injured or became missing. Some of the employees, at their own judgment, followed the advice from older passengers who knew the nature of a tsunami. Such examples demonstrate the importance of training and the use of independent judgment.

The area along the Sanriku coastline has been struck by tsunamis many times in the past. The elderly passengers proved that the lessons learned from the previous tsunamis were beneficial. The successful evacuation from the trains demonstrated the importance relaying such experiences from generation to generation.

4.2 Proposals Concerning Countermeasures against Future Great Earthquakes

(1) Lessons from the Successful Examples

The success of JR East should of course be appreciated. However, it is very likely that another earthquake will hit the Tokaido area. Many conditions that existed with the 2011 Great East Japan Earthquake will not exist in that area. The Tokaido Shinkansen mostly runs along the coast where the amount of time between trains is much shorter. Thus, there are many passengers on the platforms at all times. These conditions would make it more difficult to stop the trains safely without any accidents. Therefore, studies should be conducted carefully to gain insight and knowledge from the success of JR East.

(2) Prevention of Social Disorders

When the safety of a railway is considered, the passengers in the trains are usually the main priority. However, the 2011 Great East Japan Earthquake revealed the importance of the safety of railway stations. When commuting trains are suspended, people tend to stay in or around the stations. However, a great earthquake is often followed by aftershocks, and once a station is hit by an earthquake, cracks may form in the walls and an aftershock may cause broken pieces to fall. Taking such possibilities into account, JR East ordered people to keep away from the station buildings. Although using a station as refuge building is not realistic, it is important to provide passengers with reasonable safety when they are in or around stations and waiting for services to resume.

The 2011 Great East Japan Earthquake has taught us that stopping trains to avoid accidents is not the goal for the crisis management of railway services. As the principal mode of public transportation in Japan, railways should provide reasonable safety measures for passengers that have come to the stations and have been told that all trains are out of service.

5. Necessity of a BCP as Shown by the Shortage of Beverages Bottled in PET Containers

5.1 Facts about PET Containers

Many buildings such as marine produce processing plants and the distribution centers of the pacific coast, retail stores like shopping centers and specialist stores, a group of food wholesale distribution centers in the Iwanuma industrial park adjacent to the Sendai airport, a group of factories near the Sendai port, the Fukushima NPPs, and a group of factories at the Kashima Industrial Complex were covered with water as a result of the tsunami. Buildings disappeared without leaving any trace of evidence and many of the other buildings were devastated by the force of the tsunami. For example, an ironworks in Iwate was covered with water and mud, and port facilities were badly damaged. A beer factory near Sendai port was directly damaged by the tsunami; four storage tanks collapsed and the production line was badly damaged. At the distribution center in the Iwanuma industrial park, the warehouses were washed away by the tsunami and the frozen food from the storage containers was scattered throughout the area.

Moreover, in many factories, ceilings collapsed and facilities were either completely destroyed or rendered unserviceable by the seismic motion. The physical distribution center stopped functioning because the products and raw materials on the shelves and the automatic warehouse collapsed. A significant amount of time was needed to shutdown and repair the machines, which made many factories and the physical distribution center unsure when their lines would resume normal services.

After the Fukushima Daiichi NPP accident, the head of water purification for the Tokyo Water Department announced that iodine 131 was detected in the water samples at the water supply plant in Kanamachi on 23 March 2011, and the levels of which were twice the levels that are considered safe for babies and infants. Although Kanamachi is roughly 200 km south of Fukushima Prefecture, where the Fukushima Daiichi NPP is located, the water from the Line River to the Edo River flew into the water purification plant.

After the government sent out an alert that households, hospitals, and daycare centers should not allow babies and infants to drink tap water, people began to panic and bought bottled water at supermarkets and convenience stores. The

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metropolitan area had a water shortage and there were many people who asked their friends in the Chukyo or Kansai areas to buy and send them bottled water. The large beverage manufacturers ran at full capacity to meet the consumer demands, but their limit was reached. This had a negative effect on companies' turnovers because bottled water is a less profitable item than soft drinks; pricing became more competitive as a result. Moreover, the demand for PET bottles (plastic bottles) and their caps exceeded the supply. In particular, colored caps and caps with logos were not able to be produced.

The annual production of bottle caps was about 24 billion, and 90% of them were produced by three major companies. The manufacturing facilities at the Ishioka and Utsunomiya factories, which produce 40% of the bottle caps, had to stop production because of the earthquake and they could not keep up with the demand for mineral water. Usually, the color of the cap and the logo is different for different brands or product images. Thus, the setup at each facility has to change (e.g., the production line has to change every time the color is changed in accordance with the request of the customer) and production efficiency is low. Therefore, the manufacturer proposed to unify all the PET bottles with plain white caps. The Japan Soft Drink Association accepted the proposal, which then eliminated the shortage of bottle caps.

In a general supply chain, tier two companies supply tier one companies, tier three supplies tier two, and so on. In the context of this study, the companies are supplying parts and materials to the factories. The structure of a supply chain can be seen as a tributary that gives off branches to upstream sectors in a wide river. For example, an automobile consists of 2000 to 3000 parts. It begins with the material processing of thousands of small to medium sized components by various enterprises, which are eventually assembled into a car by the car company. However, recently, products such as semiconductors, which need dedicated facilities and clean rooms for the fabrication of their materials, require a production structure in which particular companies assume specialist roles. This type of structure is called a barrel or diamond structure and improves productivity and reduces costs.

When the 2011 Great East Japan Earthquake occurred, the Ibaraki plant in Hitachinaka City, Ibaraki Prefecture, which manufactured microcomputers for automobiles, suffered damages. The machines were severely damaged and the building with the clean room was damaged, which caused the plant to shutdown, since cleaning operations could not be carried out. The company that produced this microcomputer had a global share of 45%, and 25% of this was manufactured in that factory. Many other automobile parts were manufactured in the plants in the Tohoku region and parts became out of stock due to the damages sustained. Therefore, automobile assembly plants in Japan, including those in Hiroshima and Kyushu that were not directly damaged, had to stop operations and automotive factories in Europe were also subsequently forced into lengthy shutdowns. This led to a disruption in supply chains across the world.

5.2 Recommendations regarding the BCP

(1) Risk avoidance via decentralization and standardization

The 2011 Great East Japan Earthquake showed the importance of the plants in the Tohoku region and their ability to affect global economic activity. Automobile parts are not always manufactured in the Tohoku region, and it was beyond any prediction that the plants that were shutdown would affect the automobile factories across the world. Many people criticized this incident even though the 15 m tsunami that destroyed the back-up generators at the Fukushima Daiichi NPP was unexpected.

The companies in the global manufacturing industry did not have any stocks, because they were actively introducing new Toyota production systems. After this disaster, people were troubled by the low stock values; furthermore, during times of competitive pricing, the stock interest rate is a large financial burden on companies. Companies are expected to continue using the just-in-time system, which is likely to advance the decentralization of business operations, such as production, supply, and distribution, to avoid risks. For example, the plants that pursued higher efficiency by gathering distribution bases stopped functioning and they could not produce or sell items, because the raw materials and products fell from the racks of the automatic warehouses. Therefore, some companies considered distributing their physical distribution base to several places and having a simple rack warehouse where damages can be overcome manually. Furthermore, some companies distributed databases by introducing cloud computing and moved their suppliers to the western regions of Japan or to a location outside of Japan. Movements are being made to distribute the production bases to different locations, but the danger of

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technology leaks needs to be taken into consideration.

On the other hand, they promote the standardization and communalization of the operation systems for vehicular control systems in the automobile industry and the Ministry of the Economy, Trade, and Industry plans to promote the communalization of automobile parts following this disaster. They will focus on the cases in which vehicle factories stopped operation not just in Japan but worldwide, which disrupted the supply chain for vehicle parts. They have also already begun the standardization and communization of specific parts. There is increasing interest in such collaboration even though there is a risk of decreasing the motivation to improve the quality of parts and reduce costs, because the element of competition between the parts manufacturing companies would be removed.

(2) Reconsidering the performance of the BCP

In 2008, each company created a BCP in case they experienced an emergency. Some companies authenticated the standards of the global BCP management (BS 25999-2007). A plant that produces laptops in Date City, Fukushima, suffered damages because of the disaster. There is a company that can transfer operations to a factory in Shimane Prefecture in accordance with its BCP. Many companies confirmed the safety of their employees when the 2011 Great East Japan Earthquake occurred; however, it was impossible to continue operations due to the damages to the facilities and supply chain disruptions. The BCP was supposed to work on specification of priority business, a consultation of service level, alternatives of global business center, agreement for the employee and education, but the BCP did not work because tsunami waves that were higher than expected hit the coastal zones, surpassed the embankments, and caused devastating damage.

(3) Reducing the Risk of Power Outages in Supply Chains via Decentralized Power Generation

During the Great East Japan Earthquake Disaster, the destroyed supply chains caused setbacks when attempting to deliver products to the markets. Generally it can be said that industrial processes deal with supply chains that consist of many companies. Even if a company is not directly affected by electrical power outages, operations may become impossible if other companies upstream in the supply chain are without electricity. As a result, the final product cannot be manufactured.

From this point of view, this study investigates the possibility of sustaining the operation of supply chains through the inclusion of decentralized power plants. Factories in a supply chain are sometimes located in a single power supply system or in multiple power supply systems. Simplified mathematical models were employed in this study to evaluate the probability of a sustainable power supply throughout the entire supply chain.

(a) A Supply Chain within One Power Supply System

The supply chain consists of one assembling factory to which parts and materials are supplied by N additional factories. In this section, one power supply system provides electricity for all the factories of the supply chain as shown in Fig. 5(a). Each factory has its own distributed power plant, which has a certain capacity to maintain the power supply in case the power supply system stops working. It is assumed that the probability of a power supply outage is P_0, where the suspending probability of the distributed power plants is P. When the supply chain relies on only the power supply system, which is regarded as a reference, the probability of malfunction of the supply chain is equal to P_0.

Here, P_1 represents the malfunction probability when the factories have distributed power plants. There are two cases where the supply chain is sustainable: one is that the power supply system is working, and the other is that the distributed power plants are all operating when the power supply system stops. This probability is expressed as follows:

$$P_1' = 1-P_0+P_0(1-P)^{N+1}$$

Then, the malfunction probability can be described as follows:

$$P_1 = 1-P_1' = P_0[1-(1-P)^{N+1}] \qquad \text{eq. 1}$$

The ratio of this probability to the probability of the reference case is defined for an index as follows:

$$R_1 = P_1/P_0 = 1-(1-P)^{N+1} \qquad \text{eq. 2}$$

This index indicates that the ratio does not depend on the reliability of the power supply system.

Fig. 6 shows a numerical example where P_0 is assumed to be 0.1% and P is considered to be larger than P_0, i.e., P=0.1–1.0%. The following can be derived from the results.

- When all factories are equipped with distributed power plants, the malfunction probability of the supply chain is

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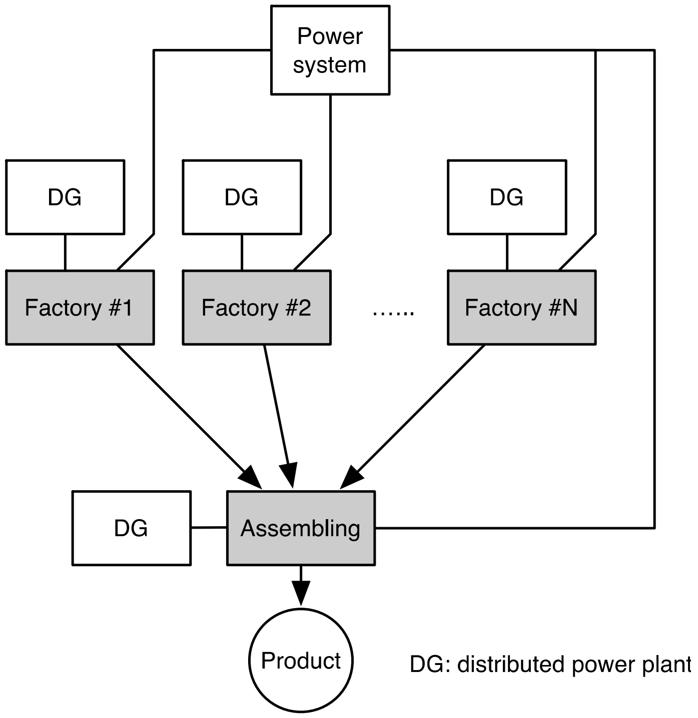
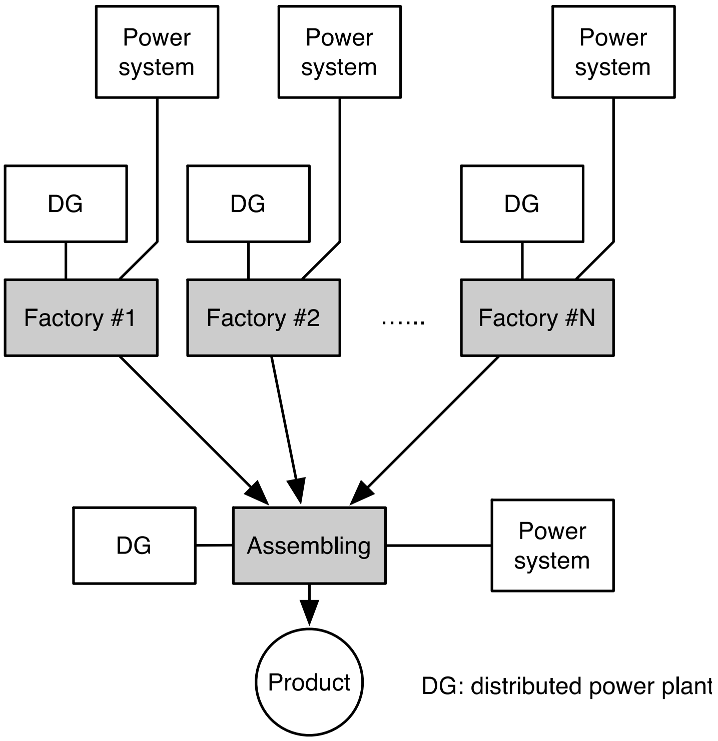
significantly reduced compared with that of the reference case.
- The malfunction probability increases as the number of factories increases.



(a) The case of one power supply system.



(b) The case of multiple individual power supply systems.

Fig. 5 Schematic of the power supply flow in the supply chain.

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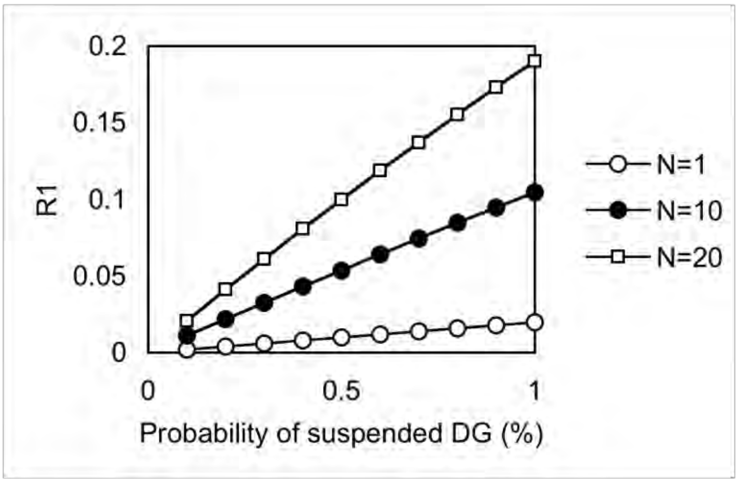

Fig. 6 Malfunction probability when using one power supply system.

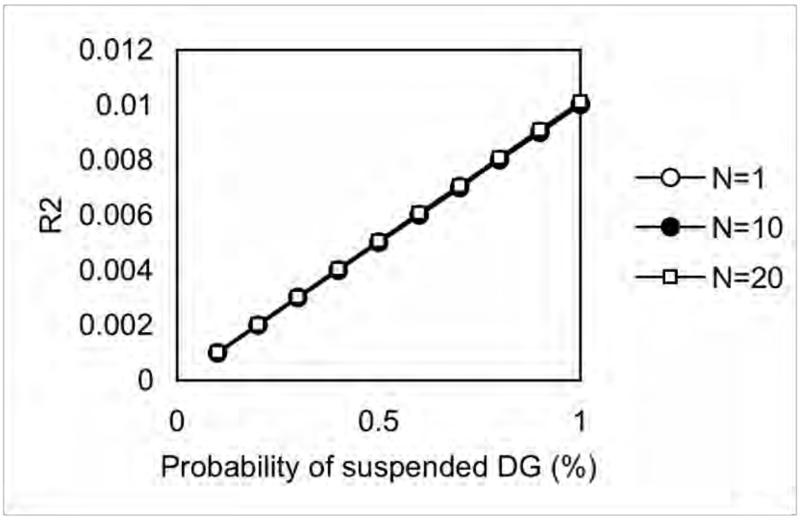

Fig. 7 Malfunction probability when using multiple power supply systems.

(b) A Supply Chain with Multiple Power Supply Systems

In this section, it is assumed that each of the factories in the supply chain is located in different power supply systems. Fig. 5(b) illustrates the schematic flow of electricity for this case.

As a reference, the probability that the supply chain is sustained without distributed power plants is considered, which implies that all of the power supply systems are in operation. The probability can be expressed as follows:

$P_2' = (1-P_0)^{N+1}$

Hence, the malfunction probability can be represented as follows:

$P_2 = 1-P_2' = 1-(1-P_0)^{N+1}$ eq. 3

When either the power supply system or the distributed power plant for each factory is available, the supply chain can operate. The following expression describes the probability that all factories are operating:

$P_3' = (1-P_0P)^{N+1}$

The malfunction probability is denoted as follows:

$P_3 = 1-P_3' = 1-(1-P_0P)^{N+1}$ eq. 4

An index is defined as the ratio of this probability to that of the reference case as follows:

$R_2 = P_3/P_2 = [1-(1-P_0P)^{N+1}]/[1-(1-P_0)^{N+1}]$ eq. 5

Fig. 7 depicts a numerical example with the outage probability of power supply systems, P_0, which is

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commonly assumed to be 0.1%. The results consequently imply the following.

- Incorporating distributed power plants in the supply chain is very effective to reduce the malfunction probability, i.e., less than 0.01 in terms of the R_2 index in the example.
- The malfunction probability does not depend on the number of factories in the supply chain.

The analyses suggest that when distributed power plants are installed in the supply chain, the malfunction probability can be decreased quite effectively regardless of the conditions of external power supply systems; that is, one power supplier or multiple power suppliers provide electricity for each factory of the supply chain. In other words, it is not enough for only a portion of the supply chain to be equipped with BCP measures when attempting to ensure the sustainability of the entire supply chain. In order to reduce the risk of malfunction, in terms of a continuous power supply, it is important to have backup power plants in all factories in the supply chain.

6. Proposals from the Viewpoint of Crisis Management with regard to Safety Measures

6.1 Safety Measures and Crisis Management

When designing machines, three steps are usually taken to ensure that they are safe. First, they are designed to be inherently safe. Second, safety guards, alarm buzzers, or other measures are used to avoid accidents. Finally, information regarding residual risk is provided to users.

These three steps may be useful for designing large-scale systems such as NPPs. However, placing too much emphasis on the first step is not appropriate, especially when the causes of the accidents can only be predicted based on probability. For example, the height of the largest tsunami that could possibly reach a NPP during its lifetime cannot be precisely predicted. Therefore, no NPP can be inherently safe, regardless of the height of its protection wall. Even in such a situation, the design basis should be reasonably chosen, but one should always be aware that an event beyond the design basis could occur.

Accordingly, when a design basis is chosen, one should first consider what kind of accident an event beyond the design basis could bring about. Then, a chain, or a cascade, of prevention measures should be put in place. Such measures should include well-structured crisis management procedures. In this sense, designing crisis management procedures should be conducted when designing a large-scale system. The safety of a large-scale system cannot be achieved only by implementing the design basis.

6.2 Definition of Safety and Risk Communication

The internationally accepted definition of safety is the “freedom from unacceptable risk”. Under this definition, whether a large-scale system is regarded as safe or not depends on the recognition of an acceptable risk by the public.

As mentioned above, after a design basis is chosen and a chain of accident-prevention measures are taken, there will be one remaining risk. If that risk is acceptable, the system is safe. However, if the public does not regard that risk to be acceptable, the system would not be regarded as safe. In this regard, it should be noted that people tend to regard a risk as unacceptable if it is unfamiliar. Therefore, once a system is designed and the designer determines it as safe, they should persuade the public that the remaining risk is acceptable. This is why risk communication is important in developing new technologies. Without appropriate risk communication, no new technology can be accepted by the public. Therefore, engineers should incorporate the basic concepts and techniques required for risk communication into their skill set.

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