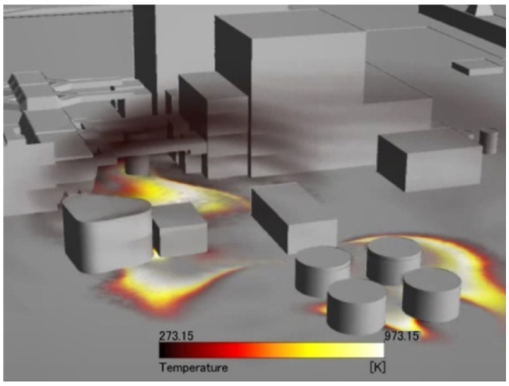
Disaster Prevention Simulation Technologies for Improving Resilience of Social Infrastructures



RIKUMA SHIJO[*1] JIRO YONEDA[*1]
TAKASHI OKAFUJI[*2] SADATO SUGIYAMA[*1]
YUTAKA FUJITA[*3] TOYOHARU NISHIKAWA[*4]

In recent years, natural disasters tend to create catastrophic damage because of climate change, abnormal weather, and so on. Therefore, disaster risk analysis and social infrastructure resilience need to be improved. Mitsubishi Heavy Industries, Ltd. (MHI) aims to contribute to building a safe and secure society by providing customers infrastructure products and services for improved resilience. MHI Research & Innovation Center has its own simulation technologies to predict infrastructure damage and formulate precautionary countermeasures to minimize the damage caused by various types of disasters such as floods, tsunamis, earthquakes, typhoons, fires and leakage/explosions. We are promoting the application of these technologies to actual infrastructures. This report summarizes such analyses and assessment technologies and presents examples of their practical applications.

1. Introduction

Meteorological disasters such as typhoon No. 15 and 19 in 2019 resulted in not only direct impact such as damage to buildings, power outage and discontinued operations, but also indirect impact mainly as a result of disrupted supply chains and logistics due to extensive flooding. The progress of global warming is expected to further increase the risk of natural disasters such as wind/flood damage caused by rainstorms or typhoons, as well as wildfires due to dry conditions. When stricken by these disasters, resilience (strength and recovery capability) becomes a critical issue in a sustainable society and corporate activities. However, when it comes to improving resilience, budgeting is an issue faced by ministries and agencies and municipalities, both of which have jurisdiction over cities, as well as by electric power and logistics companies supporting infrastructure and people's basic needs. Therefore, investment should be made efficiently, after risk assessment is properly carried out considering expected human casualties and economic losses. The risk level and the effects of precautionary countermeasures depend on the geographic and basin characteristics of the location of each infrastructure. Given such conditions, numerical simulation is considered effective in evaluating how these multiple factors can affect a specific facility. As shown in **Table 1**, we have performed disaster prevention simulations for electric power plants, chemical plants, bridges and wind farms, enabling us to gather the accumulated expertise. This report summarizes our disaster prevention simulations and presents their assessment examples for better resilience using specific terrain and infrastructure models by utilizing these simulations.

*1 Chief Staff Researcher, Fluid Dynamics Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.
*2 Chief Staff Researcher, Strength Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.
*3 Fluid Dynamics Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.
*4 Heat Transfer Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.

Table 1 Application examples of each simulation

Simulation type	Application example
Flood	Assessed the impact of a sudden rainfall on a new railway station and considered precautionary countermeasures
Tsunami	Haramachi Thermal Power Plant. Assessed the damage caused by the tsunami(1)
	NEXCO RI. Assessed the impact of tsunamis on bridges(2)
	Kesennuma Bridge. Considered precautionary countermeasures against tsunamis(3)
Earthquake	Assessed the buckling strength of nuclear power plant containment vessels and water storage tanks and considered reinforcement(4)
Typhoon	Nexco-West. Analyzed the air flow around the Himiyume-Ohashi Bridge(5)
	Used for the basic design of thermal power plants
	Examined the suitability of multiple types of wind turbines to the site
Fire	Assessed LNG pool fires
Leakage/explosion	Conducted the vent analysis for chemical plants
	Assessed LNG leak and explosion

2. What is disaster prevention simulation technology?

2.1 Overview of disaster prevention simulation technology

The features of MHI's disaster prevention simulation include: (1) resilience enhancement assessment packages covering not only a single disaster, but also various types, (2) the proposal of precautionary countermeasures by making use of our design technologies and expertise for steel structures and plant equipment in addition to damage prediction, (3) the assessment of the effectiveness of countermeasures by means of model experiments and large-scale three-dimensional (3D) simulations and (4) proven high reliability of simulation accuracy by comparing it with the results of model experiments and actual damage.

Figure 1 is a flow chart of assessment for disaster prevention simulation. Disaster prevention simulation is a method using a series of computations, which makes it possible to predict the severity of damage to infrastructure at the occurrence of natural or man-made disasters such as floods, tsunamis, earthquakes, typhoon, fires and leakage/explosions. This enables comparative assessment of the effectiveness of various countermeasures that are expected to enhance resilience. The scale of hazard can be chosen arbitrarily by setting, for example, time-series change in rainfall in the case of a flood, seismic intensity scale in the case of an earthquake and recurrence interval of formation in the case of a typhoon. As the input conditions for simulation such as terrain geometry and tsunami fault models are already in databases, simulation can be performed for any location by inputting the size and arrangement of structures of interest (e.g., plants, logistics centers and buildings). The simulation results can be output as a flood map in the case of a flood or tsunami, as forces acting on the structures or pressure contours in the case of an earthquake or typhoon, or as visualized images or videos of the pathway or area of spread/entry in the case of a fire or leakage/explosion. Thus, these simulations make it possible to understand damage and the effectiveness of countermeasures quantitatively.

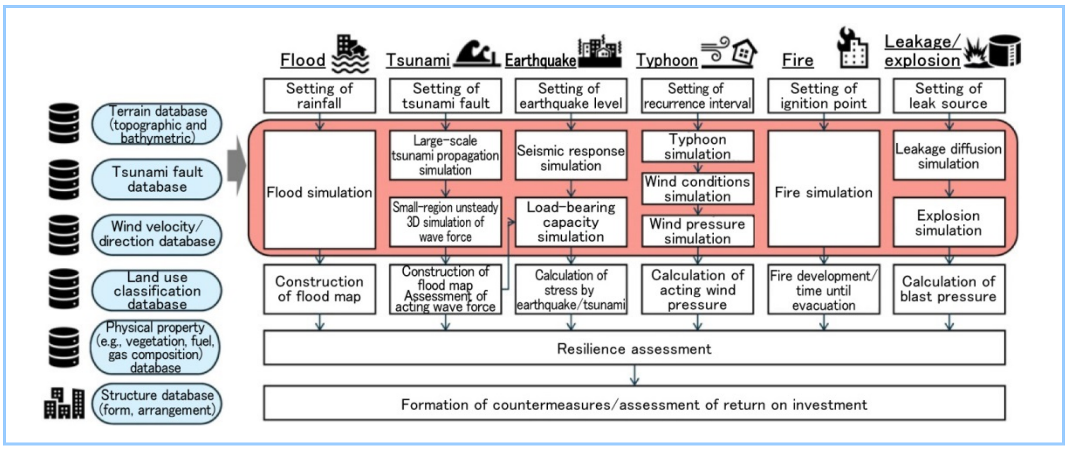


Figure 1 Flow chart of assessment for disaster prevention simulation

2.2 Simulation accuracy

As shown in **Table 2**, the accuracy of each simulation has been verified by comparing it with the damage of past disasters and the results of model experiments, thereby ensuring high reliability suitable for use in facility planning and design.

Table 2 Analysis accuracy of each simulation

Simulation type	Accuracy	Verification example
Flood	• Hazard map's flood depth being within 0.5 m	• Compared with the hazard map of the Hachiro River basin in Nagasaki (in-house assessment)
Tsunami	• Flood depth on the premises being within ±11% • Tsunami arrival time being within 0.5 min	• Compared with the actual damage to the Haramachi Thermal Power Plant by the tsunamis associated with Great East Japan Earthquake(1)
Earthquake	• Buckling load being within 10%	• Compared with the buckling deformation/load data obtained by the model experiments(4)
Typhoon	• Design wind velocity being within ±10% • Average wind pressure being within ±10%	• Compared with the data measured by the Nagasaki Local Meteorological Observatory • Compared with past wind tunnel experiments (in-house assessment)
Fire	• Reproduction of fire spread and smoke flow direction	• Compared with the actual damage caused by a fire incident at a logistics center and its investigation results(6)
Leakage/explosion	• Leaking gas concentration being within a factor of 0.5 to 2.0 • Flame propagation speed being within 20%	• Compared with the diffusion wind tunnel experiments using low-temperature methane gas (in-house assessment) • Compared with the large-scale experiments of hydrogen explosion (in-house assessment)

3. Application examples of MHI's disaster prevention simulation

In this chapter, assessment examples of resilience improvement using our disaster prevention simulation for modeled terrain geometry and infrastructure are presented.

3.1 Terrain/infrastructure models used for assessment and hypothetical disasters

The model case we created is terrain surrounded by the ocean and mountains with a river running through it (**Figure 2**). A power plant, a logistics center, a bridge and an urban area were arranged therein as virtual infrastructure. We assessed the damage to the infrastructure when each disaster struck this terrain and considered countermeasures that can be taken to enhance resilience. Because of space limitations, the presented assessment results of each simulation in this report pertain only to selected infrastructure: the urban area and power plant for the flood, the bridge for the tsunami, the logistics center for the typhoon, the power plant for the seismic load resistance, the logistics center and the urban area for the fire and the power plant for the leakage/explosion.

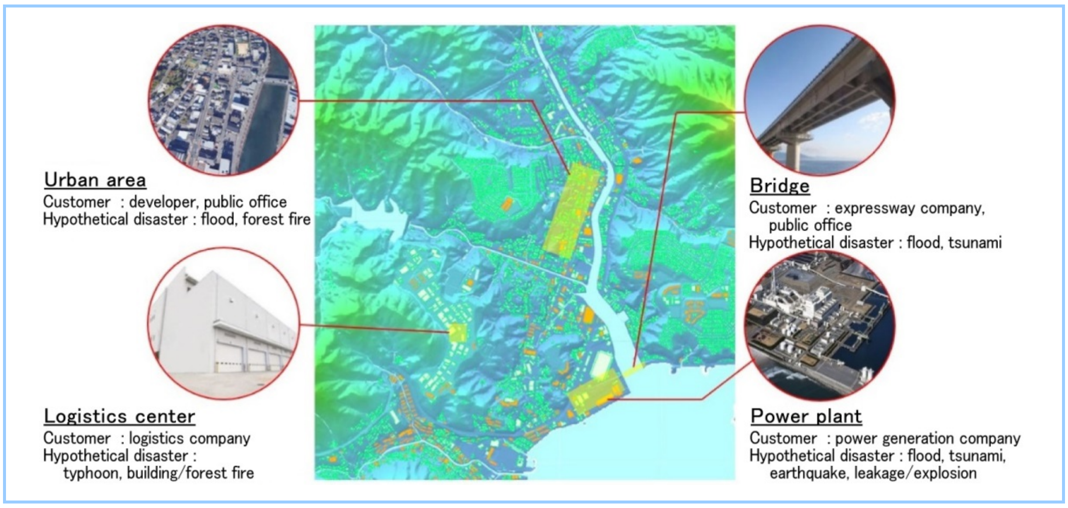


Figure 2 Infrastructure and surrounding geographic features for simulation

3.2 Simulation assessment examples

(1) Flood simulation

In recent years, the frequency of local heavy rains and the amount of flood flow are increasing markedly, mainly owing to global warming. To ensure the safety of people's lives and properties, the flood control management level has to be improved. The following is an example of assessment for resilience improvement by flood simulation using the aforementioned terrain model.

To include the influence upstream in the river and inundated areas around the river, the target area was set as 2.5 km (east–west) by 5.3 km (north–south). The terrain model was created using the digital elevation models (5-m mesh) of the fundamental geospatial data from the Geographical Information Authority of Japan and the land use tertiary mesh data (100-m mesh) obtained through the download service of the Japanese National Land Numerical Information. Flood behavior was calculated by unsteady and horizontal two-dimensional (2D) analysis while considering the roughness coefficient determined by the land use classification. The mesh size for calculation is 10 m and the time step is 0.1 s. **Figure 3** (left) shows the hypothetical hyetograph used for simulation. Based on the actual records of the past maximum rainfall in Nagasaki, Japan and in line with MLIT's guidelines[7], the hyetograph was elongated in such a way as to match the maximum total rainfall estimated based on the relationship between the duration of rainfall, the basin area of river and the maximum rainfall in the northern region of Kyushu. This amount of rainfall is comparable with that observed once every 1,000 years.

Figure 3 (right) presents the time-series change in the flood depth. It in the urban areas increases with rainfall, resulting in a maximum of 2.05 m. On the other hand, the maximum flood depth in the power plant is 0.17 m, which does not pose a threat. We selected the following precautionary countermeasures to mitigate the damage caused by flooding to the urban area: the elevation of the river levee height near the urban area (by 3 m), the excavation of the river channel and the construction of a flood control basin (10 m in depth) upstream in the river. Their effects were then assessed. **Figure 4** (left) is the time-series change in the maximum flood depth in the urban area. The elevated levee is not effective. Because of the restrictions by the altitude of the estuary, the river channel is excavated until the riverbed altitude falls to 0.2 m, only reducing the maximum flood depth to 1.8 m. However, the construction of a 700-m square flood control basin enables the maximum flood depth to be lowered to 0.77 m. Figure 4 (right) compares the maximum flood depth between before and after the implementation of countermeasures, indicating that the suppressed rise of the river level by the flood control basin allows the precipitated rain in the city to be discharged into the river, thereby decreasing the flood depth in the urban area.

As described above, the risk of flood and the effects of countermeasures vary depending on the river basin and geographic characteristics. However, the use of a simulation makes it possible to identify potentially dangerous areas and formulate precautionary countermeasures for resilience improvement.

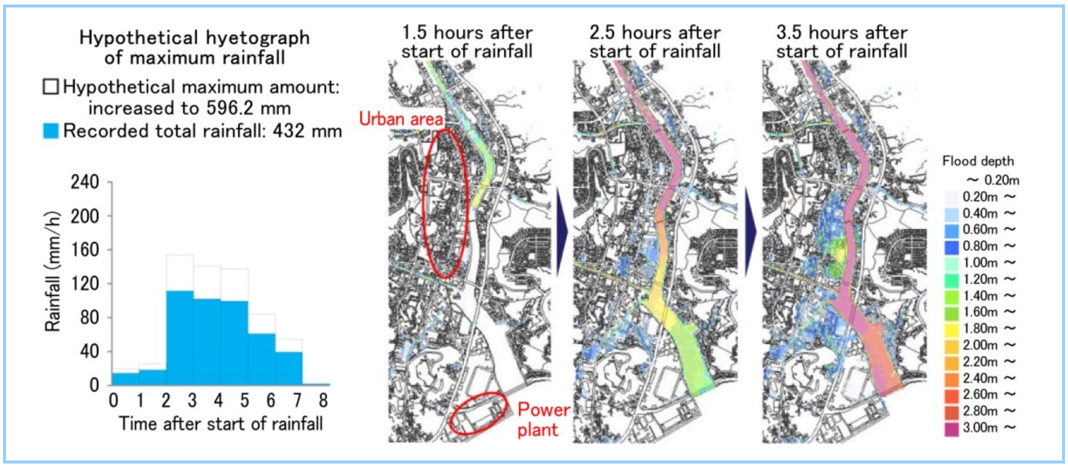


Figure 3 Flood risk assessment by flood simulation

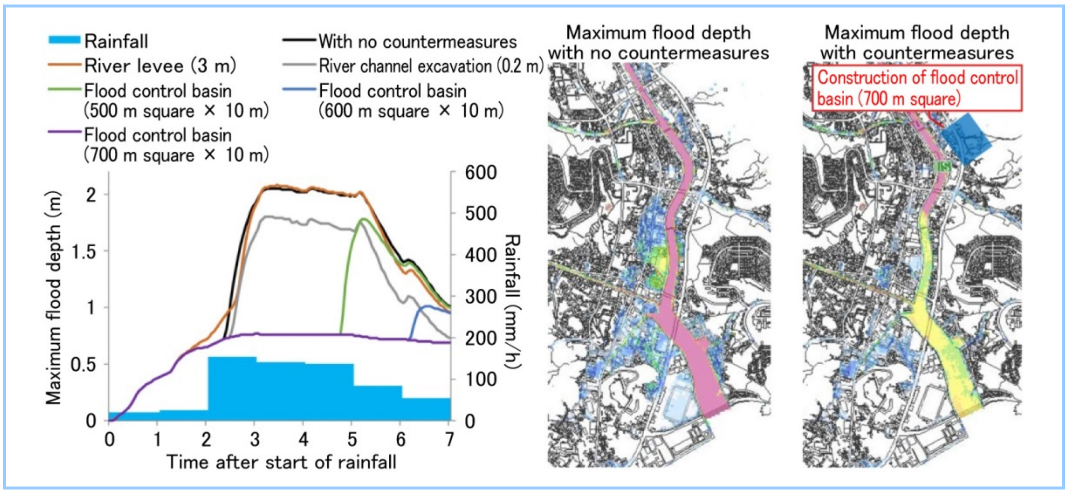


Figure 4 Consideration of precautionary countermeasures against flood by flood simulation

(2) Tsunami simulation

Historically, Japan was often hit by tsunamis associated with massive earthquakes. Especially on March 11, 2011, when an earthquake occurred off the Pacific coast of Tohoku, many structures were devastated by the tsunamis associated with the earthquake, which was much stronger than anticipated. With concerns about potential megathrust earthquakes such as one in the Nankai Trough, the risk assessment of damage caused by tsunamis to lifeline infrastructure and enhancement of their resilience are of increasing importance. We have developed a technology that can assess the behavior of tsunamis including their generation, propagation, run-up over coastal areas and wave force assessment[(1)(8)]. This technology was realized by the hybrid method in which large-scale tsunami propagation 2D simulation is combined with small-region detailed 3D simulation, as well as our marine vessel and oceanographic expertise of water channel experiments that can reproduce various types of waveforms. Presented below is an example of application of the technology to a bridge, by which the resilience to tsunamis was enhanced using the wave force reduction device.

Figure 5 gives a series of processes consisted of the assessment of tsunami wave forces to the formulation of precautionary countermeasures, and the evaluation of the effects. Firstly, large-scale simulation of tsunami propagation covering a radius of several hundred kilometers was performed using the nonlinear long wave theory in order to predict the height, velocity and flow direction of tsunami waves rushing toward the target coastal area with a bridge. Secondly, using their time-series data (i.e., regarding height, velocity and flow direction) as the boundary condition, small-region unsteady 3D simulation was performed by the volume of fluid (VOF) method for seawater-air two-phase flow, whereby the tsunami force acting on the bridge was calculated. The several kilometer area around the bridge was analyzed. By setting the mesh size to as small as 0.1 meter near the bridge, the wave force was accurately predicted. The results indicate that there is a risk of the bridge drifting away after its bearings are fractured if no countermeasures are taken. Through the experiments in which tsunami waves were reproduced using water channel with a sliding-type wave generation plate, we developed a device that can reduce the wave force (a fairing). As it turned out, it was confirmed that the drifting away of the bridge can be prevented by employing wind fairings to reduce tsunami wave force.

The aforementioned simulations and experimental techniques enable appropriate countermeasures to be implement after the level of priority is determined based on the risk of damage caused by tsunamis to the infrastructure. This can help to efficiently formulate precautionary countermeasures against tsunamis.

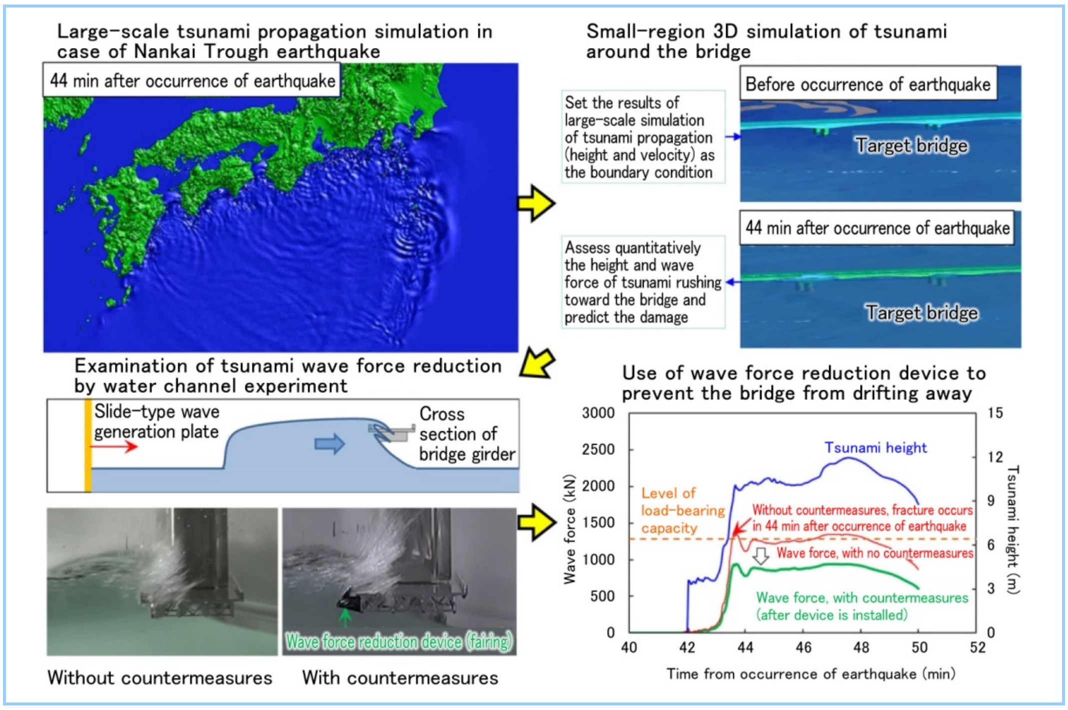


Figure 5 Enhancement of bridge resilience by tsunami simulation and water channel experiments

(3) Typhoon simulation

Buildings are designed to withstand a storm with a recurrence interval of 50 years (an event that occurs once every 50 years on average), causing no damage to the main components for structural strength. In the case of a storm with a recurrence interval of 500 years, buildings are designed not to fall down or be ruined. However, as the increase in the intensity of typhoons owing to global warming is of recent concern, it is important to predict the damage caused by a large typhoon and enhance resilience. The following is an assessment example to improve the resilience of a logistics center through a typhoon simulation.

Firstly, in this method, a virtual typhoon is formed based on the probability distribution of statistically-processed past typhoon data and random numbers. By "(1) typhoon simulation", the wind velocity and direction over a flat terrain when hit by the virtual typhoon are calculated. Secondly, by "(2) wind conditions simulation" with a geographical model, the wind velocity and direction at the location of construction are calculated. Finally, by "(3) wind pressure simulation" with a modeled building, the wind pressure acting on the building is estimated. By combining these three simulations and repeatedly calculating the impact of typhoons formed in a period of 10,000 years, the long-term prediction of damage caused by typhoons becomes possible.

Figure 6 gives the simulation results of a wind velocity of a recurrence interval of 1,000 years. The wind pressure acting on the south side wall increases because of the strong wind blowing from the sea toward the construction site on the typhoon's approach. This pattern of wind velocity, direction and pressure is observed in all of the 10 highest wind velocities of virtual typhoons formed in a period of 10,000 years. This indicates that the enhancement of south-side wall resilience is especially important.

In this target logistics center, as shown in Figure 2, a large shutter is installed on the wall. If broken, the damage is not limited to the shutter itself, but leads to secondary damage including breakage of facilities and stored items inside the center. It may take a long time to recover the center. Possible precautionary countermeasures include changing the building arrangement design if still at the stage of planning, or introducing windbreak nets if already in operation. **Figure 7** depicts the instantaneous wind pressure distribution and the maximum instantaneous wind pressure acting on the shutter at wind velocity of a recurrence interval of 1,000 years. The maximum instantaneous wind pressure on the shutter exceeds the wind pressure resistance level in the original building design. However, the figure also indicates that it can be reduced below the wind pressure resistance level, if the building arrangement is changed or windbreak nets are installed.

The aforementioned simulation technology makes it possible to identify potentially dangerous components of a building and formulate precautionary countermeasures for resilience improvement.

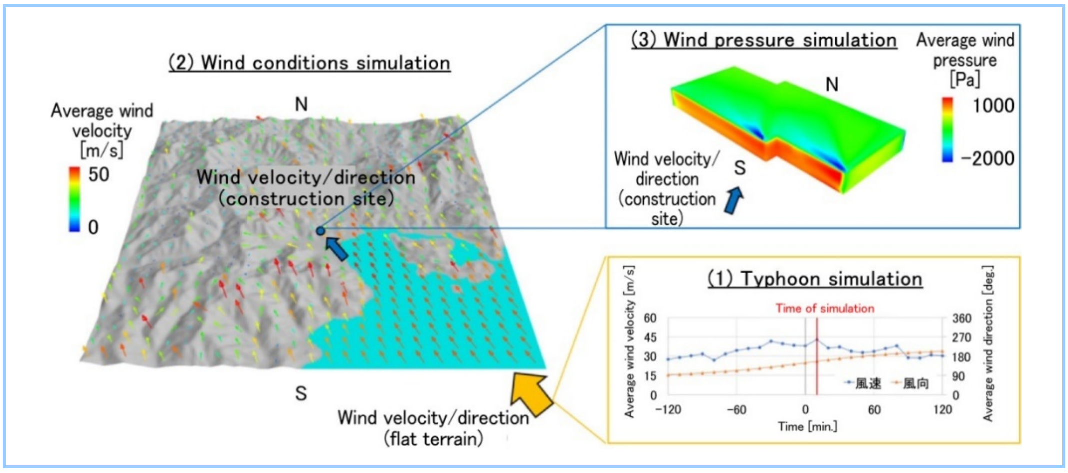


Figure 6 Wind damage risk assessment by typhoon/wind conditions/wind pressure simulations

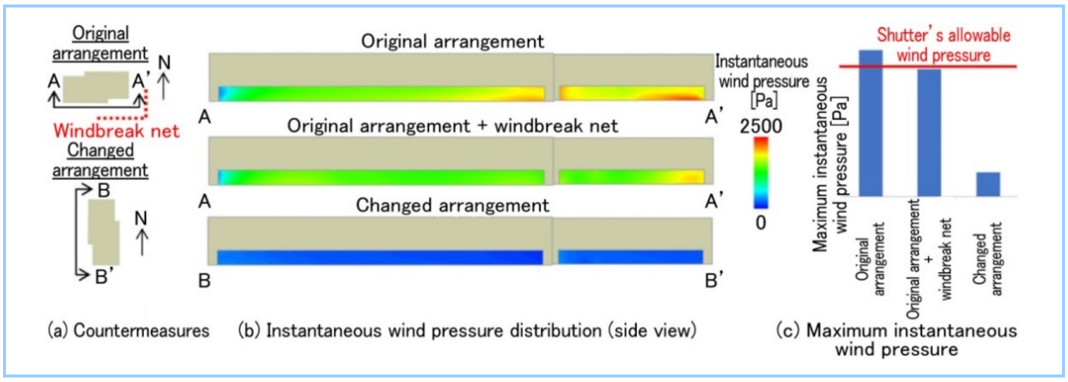


Figure 7 Consideration of reduction of wind pressure acting on shutter

(4) Simulation of load-bearing capacity in the event of an earthquake and associated tsunamis

In recent years, strong earthquakes with a seismic intensity of 6 or higher stuck Japan several times, causing damage to many critical infrastructures such as power plants. For example, according to the reports of the Fire Research Institute (currently, the National Research Institute of Fire and Disaster) of the Fire and Disaster Management Agency[(9)], seven cylindrical storage tanks were buckled by the Great Hanshin-Awaji Earthquake (January 17, 1995). In some of the tanks, leakage of the contents was also observed. In 2011 off the Pacific coast of Tohoku Earthquake, (March 11, 2011), in addition to the earthquake itself, the flood resulting from the associated tsunamis caused serious damage to structures. At the Haramachi Thermal Power Plant located along the coast, the out-of-plane deformation and the buckling were observed in the side shell plates of the heavy oil tanks [(10)].

In this report, elasto-plastic buckling analyses were applied to a large cylindrical storage tank (approximately 30 m in diameter and 20 m in height) installed outdoors in a power plant to evaluate the buckling load-bearing capacity against seismic load and hydrostatic pressure caused by flooding, and to confirm the effectiveness of reinforcement against buckling. The addition of stiffening rings were adopted for the improvement of bending buckling based on the large-scale buckling tests in the previous study[(11)], although increase of the side shell thickness by replacing the shell plates can be another option. The stiffening rings have the advantage in cost reduction and period shortening of reinforcement work, and workability improvement (e.g., applying automatic welding) compared to the replacement of the tank shells. As the stiffening rings are also effective for improvement of external pressure buckling strength, these can be adopted as countermeasure against both earthquakes and flooding.

Figure 8 gives the simulation results of load-bearing capacity against seismic loads. A fully-filled cylindrical water tank without reinforcement withstands the load (fluid pressure) calculated by the seismic response simulation using the horizontal acceleration specified by the Standard for Seismic Design of High Pressure Gas Equipment (Level 2) [(12)], but bending buckling occurs at the lower part of the tank in the case of the seismic acceleration caused by the seismic intensity 6 upper (1,000 Gal). By applying stiffening rings, the buckling strength was improved by 19% due to prevention of bending buckling at the lower part of the tank was prevented, and the tank can withstand the seismic load of intensity 6 upper. As the buckling strength is adjustable by changing the arrangement and the number of stiffening rings, a suitable reinforcement structure can be proposed in accordance with the required load-bearing capacity. The simulation of load-bearing capacity against tsunami flooding was also conducted. Referring to the records of past events[(1)], the flood height in a virtual plant site is set to 13 m, and the external pressure by the hydrostatic pressure was applied to the empty tank from the bottom to the flood height as shown in **Figure 9**. The tank without reinforcement was buckled by an external pressure much smaller than the hydrostatic pressure induced by the 13-m flood height. In the case of the tank with stiffening rings, the buckling area of the tank shell was limited by these rings, and the buckling pressure was increased by a factor of 5.6. As a result, the tank has the sufficient buckling capacity against 13m flood height. These verified simulations of load-bearing capacity can provide reinforcement to enhance resilience of structures.

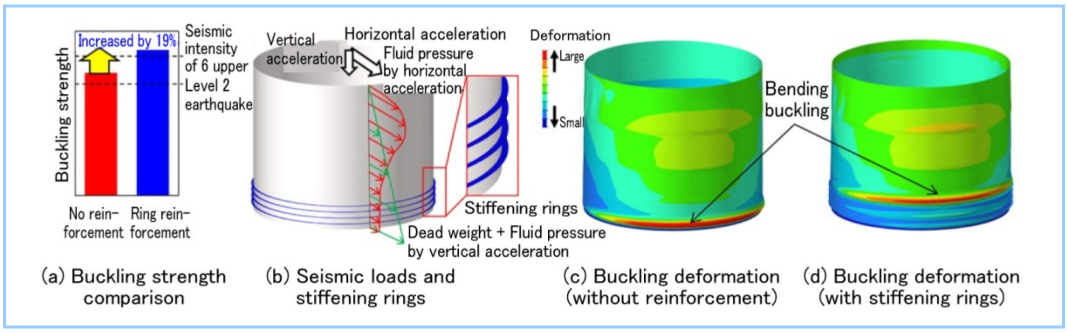


Figure 8 Consideration of possible reinforcement structures of large cylindrical storage tank against buckling by earthquake

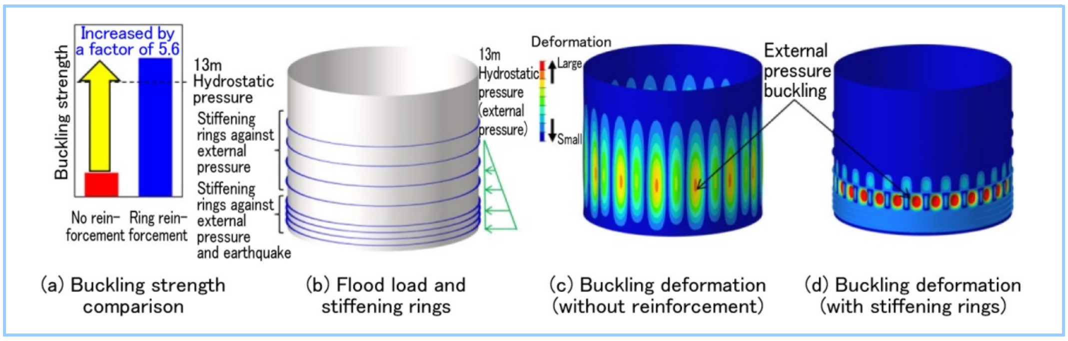


Figure 9 Consideration of reinforcement of large cylindrical storage tank against buckling by tsunami flooding

(5) Fire simulation

[1] Indoor fire simulation

Indoor fire may be caused as a result of human error or an electric short circuit. As buildings are designed as per the Fire Service Act or Building Standards Act at the time of construction, the necessary facilities such as fire doors and sprinklers are supposed to be considered appropriately. However, if a fire accident occurs and first aid firefighting or initial firefighter response fails, serious damage would be caused. In fact, in the incident of a fire at a logistics center in 2017[(6)], the first attempt to suppress the fire using sprinklers and fire extinguishers failed. Furthermore, some of the fire doors did not work because of the short circuits caused by the fire. It took 12 days for the fire to be finally extinguished. The resulting damage was the second and third floors of a three-story building being almost burned down.

Based on this incident, we modeled a zone where the fire occurred in the logistics center (**Figure 10**) and performed a fire simulation. In the fire simulation, the fire dynamics simulator (FDS) code(13) was used to conduct the 3D unsteady flow and combustion analysis. As shown in **Figure 11** (left), before the implementation of countermeasures, the smoke detector responded when the smoke concentration exceeded 10% in 150 seconds after the occurrence of fire, which led to sprinkler activation. However, flames had already developed by then and fire extinguishing was not possible. For resilience improvement, an early flame detection camera with image analysis technology was introduced, which supposedly allows sprinklers to be activated two minutes earlier. We assessed how this time difference in activation can change the spread of fire by using fire simulation. The results indicate that, if this measure is implemented, the fire can be extinguished by first aid firefighting before the flames developed (Figure 11, right). As described above, the use of a simulation makes it possible to check the effectiveness of countermeasures in advance, leading to minimization of the damage or securing evacuation time.

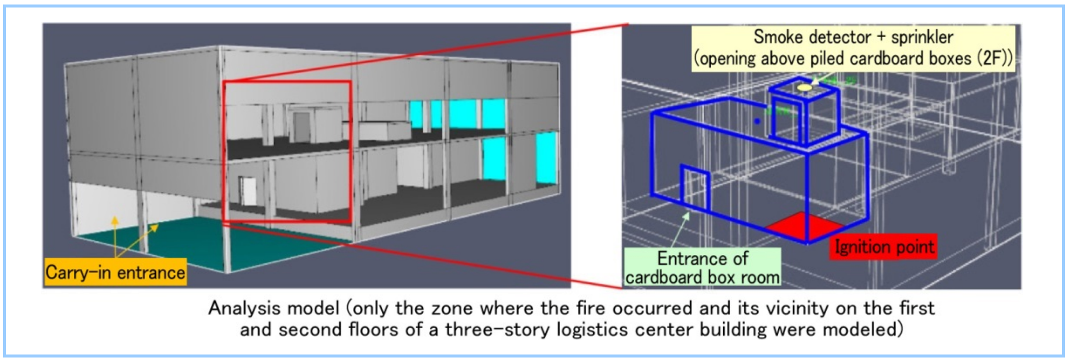


Figure 10 Target zone of fire simulation analysis

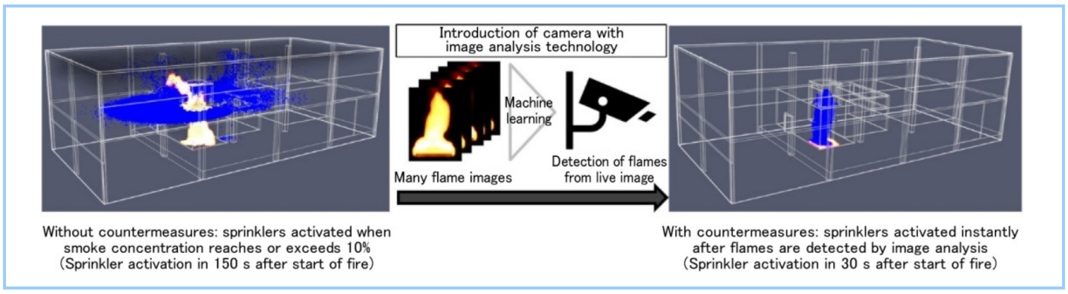


Figure 11 Verification of effect of early detection with image analysis technology by fire simulation

[2] Wildfire simulation

While often taking place in the U.S. or Australia, wildfires can also occur in Japan as shown by the incident of a forest fire in Ashikaga City, Tochigi in 2021. As the cause of wildfires is often related to human errors such as careless smoking, prediction is not possible. Once the fire spreads, it is difficult to extinguish. Therefore, the key of first stage lies in quickly gathering information about how the fire spreads for safe evacuation.

In this assessment, we assumed that a fire started on a mountain with a campsite and performed wildfire simulation under the hypothetical weather conditions (with a constant wind direction) to examine how the fire spread toward a logistics center or urban area. If there is error in the prediction of wind direction, damage area may be overlooked and the risk of delay in evacuation may be increased. Therefore, the fire spread was predicted considering the uncertainty of wind direction. In the wildfire simulation, a cellular automation method is employed for the progress of an event. In this method, whether the fire spreads to the adjacent cells is determined by conditional and probabilistic branching, so quicker calculation is possible compared to physical models to solve the heat balance. By making use of this advantage, we considered that the predicted wind direction has an occurrence probability distribution based on the normal distribution and performed/ arranged simulations using various patterns of wind direction. This enabled us to develop a method that can show the range of fire spread in every elapsed time by a fire arrival probability distribution (**Figure 12**, left). With this method, the logistics center is evaluated that "it may be subjected to the fire in 24 hours with a probability of 27%" (Figure 12, right), where is not affected by the fire when simulated with a constant wind direction. Thus, it becomes possible to provide probabilistic information in real time, helping to secure evacuation time and prevent delay in evacuation.

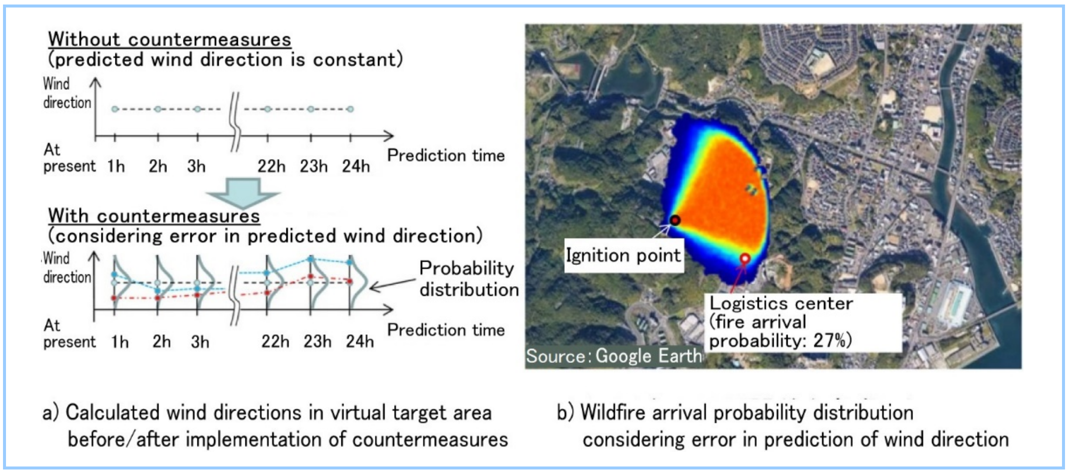


Figure 12 Wildfire simulation considering uncertainty of wind direction predictions

(6) Leakage/explosion simulation

A leakage/explosion incident can be caused either accidentally (e.g., plant operational mistakes, aging degradation or impairment) or intentionally (e.g., terrorism). In either case, early detection of abnormal conditions and minimization of damage are necessary according to the concept of resilience.

In this assessment, we performed the leakage/explosion simulation on the assumption that gas leaked from a propane tank at a virtual plant and a fire started after the flammable gas filled the surrounding area. For simulation, FLUENT, a general-purpose fluid analysis code, was used. The leakage simulation was performed by 3D unsteady flow analysis, followed by the explosion simulation using a progress variable model. As shown in **Figure 13**, the results indicate that propane gas filled the area around the leaking tank. It is also indicated that, after ignition, point A in the plant is subjected to high blast pressure and temperature. To protect critical facilities even in the case of an explosion and enable quick recovery, we simulated and assessed the effect of a protective wall installed in advance in front of point A, as shown in **Figure 14** (left). The results indicate that the pressure at point A at the time of explosion is reduced to about 1/3, significantly lowering the load on the building (Figure 14, right).

Conventionally, each tank or building is assessed at the design stage regarding pressure resistance, etc., in accordance with the relevant guidelines. Using these simulations makes it possible to assess the influence of tank/building arrangement at the design stage as well, which can lead to resilience improvement of the entire plant.

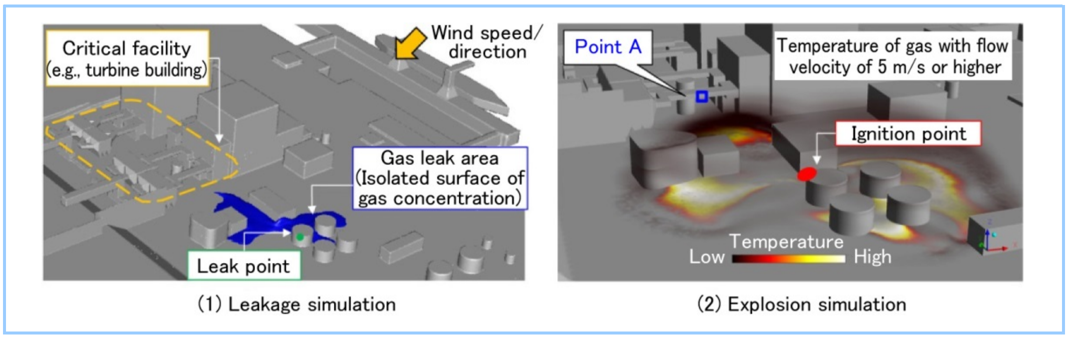


Figure 13 Leakage/explosion simulation results

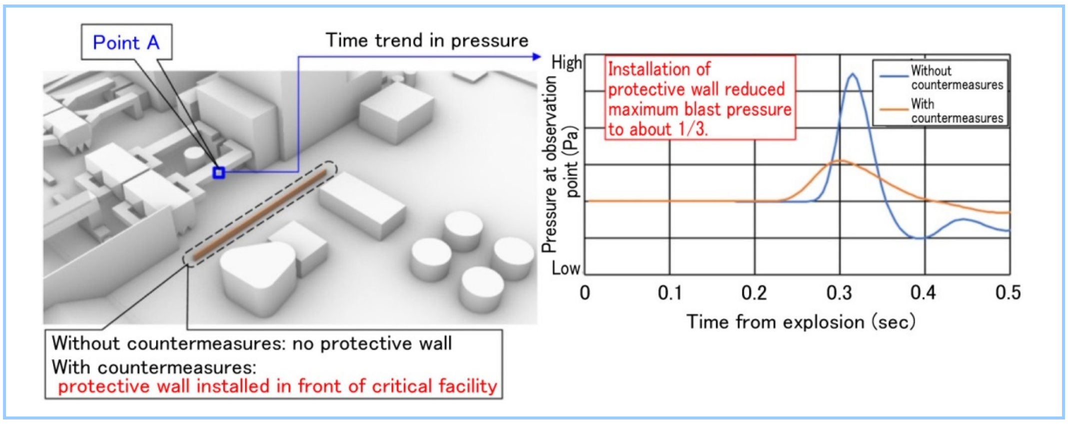


Figure 14 Consideration of blast pressure reduction by installing protective wall

3.3 Hazard visualization examples

We are constructing a disaster risk visualization system that makes it possible to understand the risk of damage to the infrastructure owned/managed by customers and decide whether any precautionary countermeasures are necessary. Given below is an example of our visualization application for tsunami hazard, which is conducted on a web-based application.

Regarding an earthquake of the Nankai Trough, the probability of the occurrence of which in the next 30 years is projected to be as high as 70-80%(14). Then, we have performed large-scale tsunami propagation simulation covering all areas on the Pacific coast with multiple possible fault cases and have created a database. As shown in **Figure 15**, customers can choose any location on the map and see wave propagation videos of relevant tsunamis and their quantitative data such as maximum flood depth and arrival time from the database.

While continuing to construct a visualization system for other disaster prevention simulations as well, we will add a 3D visualization capability to this system using our virtual reality (VR) system(15). By visualizing from various angles how a catastrophic event progresses while encompassing the structures in the target area, we will develop simulation systems that can provide more realistic understanding of an event and evacuation.

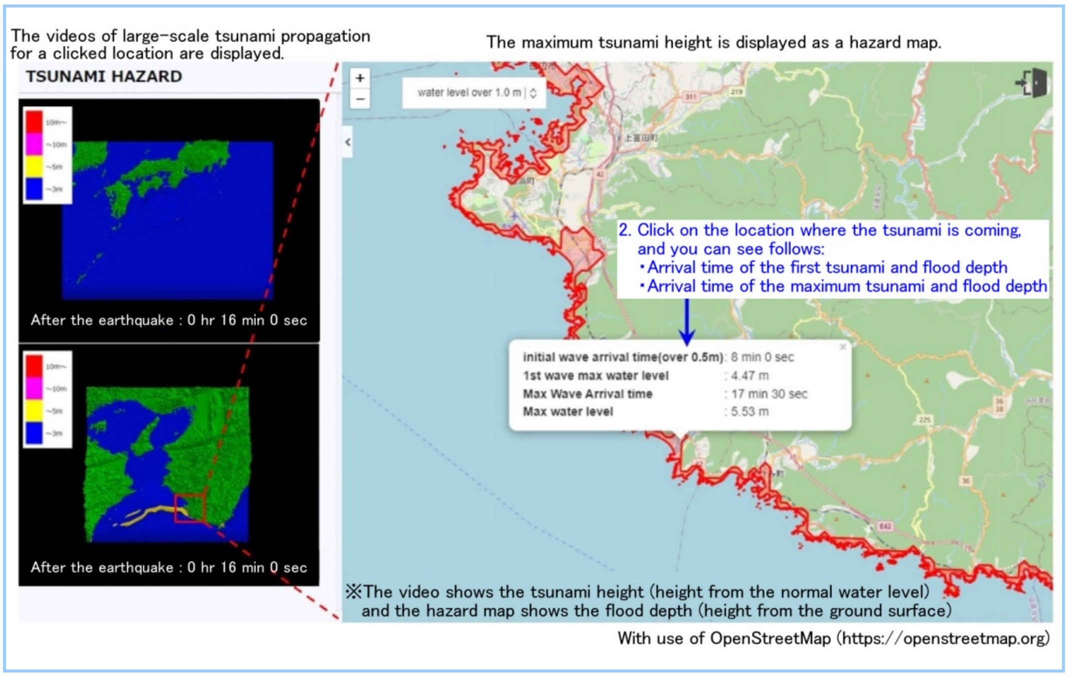


Figure 15 Tsunami hazard visualization example

4. Conclusion

Using terrain and infrastructure models, we used the disaster prevention simulation to assess the damage caused by hypothetical natural or man-made disasters such as floods, tsunamis, earthquakes, typhoons, fires and leakage/explosions and enhance resilience. Some of the assessment examples are presented in this report. With these technologies, it becomes possible to identify potentially dangerous areas and formulate precautionary countermeasures for resilience improvement, which can help to construct safe and secure cities and disaster-resilient infrastructure.

As global warming progresses in the future, the hazard level is expected to increase. We will continue to develop technologies that can contribute to realizing a sustainable society and corporate activities by improving the resilience of infrastructure in both Japan and overseas.

* The maps provided in Figures 2, 3 (right), 4 (right) and 5 of this report were created using the digital elevation models and land use tertiary mesh data from the Geographical Information Authority of Japan.

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