Chapter 6
Natural Disasters

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Abstract Natural disasters are damages to human lives or social activities caused by dangerous natural phenomena. This chapter quickly reviews the history of natural disasters, specifically for earthquakes and volcanic disasters, ground and sediment disasters, and water disasters, and discusses the mechanisms of how they break out and the typical damages they cause. Then the chapter explains predictions and countermeasures for disaster management.

Keywords Earthquake · Global environment · Ground disaster · Sediment disaster · Tsunami · Typhoon · Volcanic eruption

6.1 History of Natural Disasters in the Japanese Islands

6.1.1 Disaster Environments of Japan

Natural disasters break out when natural phenomena of earthquakes, volcanic eruptions, typhoons, heavy rain, or snow avalanches release large energy within short time periods to affect human living environments. Whether a natural disaster takes place or not depends on global environment, geographic conditions, sinking, lifting, and rising of tectonic plates and relative positions among oceans and land. The global environment is constantly changing; however, the time it takes to make visible changes is much longer than the average life span of human. This means that within a timescale of several tens of thousands of years, typhoons and earthquakes repeat at roughly the same locations.

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The islands of Japan, when compared to other regions of the earth, are surrounded by an environment where natural phenomena can easily cause disasters. The Pacific plate and Philippine Sea plate sinking under the ocean near Japan cause mega-thrust earthquakes. Tectonic plates that dive under Japan islands push the continental plates to cause inland crustal earthquakes at active faults. The sinking plates also produce magma underground and trigger volcanic eruptions.

Japan also sees a heavy average precipitation and the rain concentrates in the rainy season and typhoon seasons easily causing water disasters like flooding and storm surge. Furthermore, the Japan Sea between the Eurasian continent and Japan islands supplies plenty of moisture to the seasonal wind from the continent dropping heavy snow along the Japan seasides of the islands. The accumulated snow can cause snow avalanches and even landslides in early spring with rises of underground water levels.

6.1.2 Natural Disasters Up to the Mid-eighteenth Century (End of Edo Era)

With the geological conditions, we must say Japan cannot avoid outbreaks of earthquakes, volcanic eruptions, typhoons, and so on. These natural disasters have repeatedly attacked the islands since human started inhabitation on them. The ancient history books of Japan like *Nihon Shoki* (the oldest chronicles of Japan, Aston 1896) even noted such events. History books tend to record earthquake and tsunami damages over wide areas. Kyoto, which used to be the center of government administration and culture for a long time, has a large number of disaster records in its archives. “Nankai (south sea) trough earthquakes” break out in locations relatively close to Kyoto, and a number of disaster records have accumulated over the years.

The oldest Nankai trough earthquake on record is the 684 “Hakuho earthquake.” *Nihon Shoki* recorded damages that buildings collapsed over a wide area, tsunami waves washed away many boats, rice patches in the land of Tosa (now Kochi prefecture) went underwater with land subsidence after the earthquake, and hot springs in the land of Iyo (now Ehime prefecture) stopped coming up. These are typical damages with Nankai earthquakes with epicenters off the shore of Shikoku. Records show that earthquakes in Heian and Edo eras caused similar damages to the area. If we follow the timeline, we find that the earthquakes repeated in the same area every 100–200 years. The concept of plate tectonics in the 1960s clarified the mechanism of plate subduction causing large earthquakes to repeat in cycles. The entire world knows about Nankai trough earthquakes as a typical example.

Volcanic eruptions typically leave large amounts of volcanic ashes and lava on the ground surface. Affected areas often suffer over long times for removing the debris and from frequent soil disasters caused by them. Well-known volcanic eruptions are the 1707 Mount Fuji and the 1783 Mount Asama. When volcanos near the coast erupt, the sector collapse can cause tsunami. History books record major large-scale tsunami disasters at Oshima-Oshima in Hokkaido in 1741 and the 1792 Unzen Mayuyama collapse causing tsunami in the Ariake Sea.

Since the old days, people have made major civil engineering works to actively control water disasters. Singen-zutsumi (Kasumi Bank) in Kamanashi River in Yamanashi prefecture and project of shifting the Tone River flow to the east have traces of their major work still left today. Civil engineering works to manage water damages have the purpose of "flood control." Forcing rivers to reconfigure often have positive effects of promoting traffic, enhancing agricultural productivity, or building military barriers in addition to preventing disasters.

6.1.3 Natural Disasters in the Mid-eighteenth Century (Meiji Era) and After

In the Meiji era, the government prepared disaster measures under a single national standard and also collected statistical data about disasters and started to form regulations about them. Since then, major earthquake disasters that caused 1000 or more fatalities occurred 13 times in the islands of Japan. Especially the 1891 Nobi earthquake, the 1923 Great Kanto earthquake, the 1995 Great Hanshin-Awaji earthquake, and the 2011 Great East Japan earthquake greatly affected earthquake measures after them.

Nobi earthquake was the first major disaster for modern Japan. The number of victims totaled 7273, and a large number of brick buildings and bridges built with imported Western technologies collapsed. This earthquake moved the government to establish the "Imperial Earthquake Investigation Committee" in 1892 to systematically study the mechanism of earthquakes and research ways of preventing earthquake disasters.

The Great Kanto earthquake was the worst earthquake disaster in Japan that killed over 105 thousand people. Severe fire damages took place in the cities of Tokyo and Yokohama, and the sum of fire-caused fatalities amounted to 90 thousand for the 2 cities. Cities during this time had wooden houses packed together with extremely high population densities. The disaster made people and the government realize the importance of city planning to keep some open space and wide roads, and schools next to public parks started to form with the reconstruction plans.

The Great Hanshin-Awaji earthquake was a major earthquake about 50 years after the 1948 Fukui earthquake. This earthquake marked a large number of building collapses, and over 80% of the deaths and missing immediately after the quake were caused by crush or suffocation. Water supply, electricity, and public transportation were cut off revealing the extreme vulnerability of urban areas against earthquakes.

The Great East Japan earthquake was triggered by the largest earthquake with Mw9.0 near the islands of Japan on record. The mega-thrust earthquake at the plate boundary caused extremely huge tsunami waves. After this earthquake disaster, earthquake measures on the table now generally assume earthquakes larger than those on records.

Since the Meiji era, the number of major volcanic eruptions is relatively small. The biggest was the 1888 Mount Bandai (Fukushima prefecture) mountain collapse that took lives from 477 people. One in recent years that we probably remember is the 2014 Ontakesan eruption with death toll of 63. During the 1986 Izu-Oshima eruption, the 2000 Mount Usu eruption, and the 2000 Miyake island eruption, the administration successfully evacuated the residents temporarily. Volcanic eruptions often come with early symptoms. The 2000 Mount Usu eruption caught much attention as a successful example of predicting volcanic eruptions.

During the time immediately after World War II, many weather-related and water disasters took place. The 1945 Makurazaki typhoon and the 1947 Kathleen typhoon attacked only 2 years apart, and each caused over 1000 dead and missing. The 1959 Ise Bay typhoon caused storm surges that attacked the zero-elevation area in Nobi Plain. This typhoon caused 5098 deaths and led to the regulation, “Disaster Countermeasures Basic Act.” The 1982 Nagasaki heavy rain, the 2000 Tokai heavy rain, and the 2011 Kii peninsula flooding followed. In recent years, the out-of-control land usage with urban area development magnified the damages, and economic damages spread to even wider areas with the destruction of supply chain; we started to see new facets of disasters that measure beyond damage to human bodies (Cabinet Office 2014).

6.1.4 Changes in Disasters Caused by Changes in Social Environment

Areas inhabited by people are rapidly growing with the growth in population (Christian et al. 2013). Japan, from the latter half of the Edo era to the early twenty-first century, saw rapid growth of population, and people kept moving onto landfills along the coast or carved out land where no one used to live. Also, with the development of globalization, supply chains in businesses are spread over large areas in and out of the country. Today, a fire in a single factory can cause effects that propagate throughout the entire world. Devastating natural phenomena like earthquakes catch our attention in terms of natural disasters; however, we also have to recognize that changes in people and societies are expanding the damages into other aspects that surround us.

6.2 Earthquakes and Volcanic Eruptions

6.2.1 Mechanisms of Earthquakes and Volcanic Eruptions

An earthquake is a phenomenon of underground bedrocks releasing a large amount of energy stored within them when they break in a short time period. Shifting of underground "faults" causes destruction of bedrocks, and the vibration from this shift transfers in the form of waves traveling over the surrounding ground shaking everything on the surface and underneath (Bolt 2005).

For an earthquake to break out, the bedrock has to be subject to continuous force, and it has to be sturdy enough to store the energy. Places that meet these two conditions are limited on the earth. Primary forces that deform the bedrocks are relative motions among the ten and some more tectonic plates that cover the earth (plate tectonics). Most earthquakes, therefore, break out near plate boundaries. Areas where oceanic plates dive under continental plates are susceptible to great earthquakes. Ground formations by molten rocks or magma are called volcanos, and the phenomena of magma bursting out to the ground surface, directly or indirectly, are called eruptions. Underground magma is subject to buoyancy caused by differences in its density with the surrounding rocks. Magma contains large amount of volatile material, primarily water, which separates out when the pressure drops to lower the magma density and generates the lifting force. If the magma contacts underground water near the ground surface, the water suddenly evaporates and causes steam explosion. Both great earthquakes and volcanic eruptions break out near band areas where tectonic plates sink. The reasons are sinking plates taking water deep down underground and the water lowering the rock's melting points to boost the generation of magma.

6.2.2 Earthquake Disasters and Their Transition

An earthquake shakes the ground, and artificial structures built on the ground surface and underground may suffer damage. The law of inertia tries to keep objects on ground surface where they stand, even when an earthquake moves the ground, and the objects receive force in the direction opposite from the ground movement. This force is inertia. If structures have insufficient strength to withstand inertia, they collapse and suffer damages. Inertia applies to underground structures, just like structures on ground surface. In addition, differences between movements of the ground and structures generate direct forces on the structures that can cause damages. Damages due to earthquake-caused ground movement include destruction of structures built directly above faults and those caused by earthquake-induced tsunami.

Intensities of the ground shaking are not uniform. The shaking tends to magnify on soft ground and apply large inertia on the structures. The ground properties also affect the cycle of the shaking. When the ground vibration property (natural frequency of ground) and that of the structure (natural frequency of structure) built on it coincide, resonance causes the shaking of the structure to magnify, and large inertia forces apply to the structures. The strength of structures is not uniform either. Even when stories of a building look all the same from the ground surface to high floors, the lower floors have to bear weights of the floors above them and have bigger columns and more reinforcement bars in them. When a strong tremor attacks a structure, the structure suffers damages first in its weakest point. For example, if a building has pilotis or columns to secure parking space on the ground floor, the relatively weakest ground floor suffers crashing damages.

We learned through lessons from the past major earthquakes that structures must have sufficient strengths so they do not suffer damages even in case of large inertia. The size of such inertia to assume during the design stage changes with time, and strengths of structures vary depending on when they were built. Their strengths also go down over time with degradation of the structures. In other words, sizes and strengths against inertia differ depending on location and structures, and large damages occur on structures with relatively insufficient strengths. This tendency applies not just to buildings like houses but also to bridges, subways, pipelines, oil tanks, and all other varieties of structures. Furthermore, secondary damages or their chain reactions can take pace, for example, with subway damage caused subsidence on the ground surface affecting nearby structures.

6.2.3 Predicting and Countering Earthquake Damages

Unfortunately, our current technologies cannot predict the sizes, locations, or timing of future earthquakes. Thus, we have to discuss countermeasures against estimated earthquakes that can cause large damages to the society once they break out. This process starts by estimating the ground shaking (reference earthquake motion) upon an estimated earthquake, projecting the damages to existing structures (evaluation of seismic capacity), and installing necessary strength (seismic retrofit). On the other hand, for structures to build in the future, designers design them to keep the level of damages within tolerance (aseismic design) in case of estimated earthquakes.

Mechanisms of earthquake occurrence shall be considered in the determination of the estimated earthquakes. Locations where bedrocks receive large forces must have caused a number of earthquakes in the past. If they continue to receive large forces, many earthquakes will occur in the future as well. Strengths of bedrocks also depend on sizes (magnitudes) of earthquakes; thus, magnitudes of past earthquake contribute to making estimations of sizes of future earthquakes.

In general, the shaking intensity reduces with distances to structures (attenuation). Therefore, assuming earthquake magnitudes allows estimating the ground shaking intensity with the distances from the structures of concern to the location of earthquake (location of the fault) and the properties of the ground where they are built (soil classification). The transmission of earthquake waves in the ground, however, is quite complex, and in recent years, more scientists estimate ground shaking at structural locations using sophisticated computational methods.

Once the ground shaking estimations are available, the magnitudes of inertia on the structure are found and comparing them to the structural strengths lead to estimating damages from earthquakes and their levels. If the analysis leads to intolerable damages, countermeasures are taken to enhance structural strengths by adding reinforcement, changing sectional configuration, or applying different materials.

6.2.4 Volcanic Eruptions and Their Transition

Phenomena that cause damages from volcanic eruptions include drop of volcanic rocks, deposition of volcanic ash, pyroclastic flow, lava flow, outburst of volcanic gas, and so on. Debris bursting out from volcanos are at high temperature and flow down from the volcano body toward lowland with large energy. When these “flows” reach areas where people live, they cause volcanic eruption damages. Different viscosity of magma causes different scenes of damages. Volcanos with less viscous smooth magma often squirt out lava flows. Those with high viscous magma tend to have explosive eruption with large amounts of volcanic ashes and cause pyroclastic flows. The caldera of Mount Aso in Kyushu is the sign of the huge eruption with debris scattered over distances of several hundreds of kilometers.

At times, the same volcano can show different types of eruptions. For example, the 864 Jyogan eruption of Mount Fuji caused lava flows, whereas the Hoei eruption in 1707 burst out volcanic ashes and pumices from a crater that opened on the volcano side. Debris accumulated around a volcano are unstable and can cause the volcano body to collapse upon earthquakes or small eruptions. The 1888 Mount Bandai eruption and the 1980 eruption of Saint Helens in the USA are such examples. The 1985 eruption of Nevado del Ruiz in Columbia suddenly melted volcano-top glaciers all at once and caused huge lahars that took 23 thousand lives.

Large-scale volcanic eruptions, in addition to the direct damages described above, are known to cause global climate changes. Volcanic gas and ashes from large eruptions reach the stratosphere to block solar energy from reaching the earth surface. This lowers the average temperature over the entire globe and causes poor crop harvest and food shortage. Eruptions of Laki in Iceland in 1783, Tambora in Indonesia in 1815, and Mount Pinatubo in the Philippines in 1991 are typical examples of such damages.

6.2.5 *Predicting and Countering Volcanic Eruptions*

Before volcanos erupt, the rise of magma toward the earth surface often causes abnormal phenomena. Administration has established organizations for disaster prevention by evacuating people beforehand by detecting signs of eruptions through constant monitoring of bedrock movement, electromagnetic changes, abnormal heat generation, volcanic gas, and so on.

The Japan Meteorological Agency constantly monitors 50 volcanos among the 110 active ones throughout the country. The Cabinet Office of the Government of Japan has established “Volcano Disaster Management Councils” for 38 of the 50. Each council consists of prefectural and local government officials, meteorological observatory personnel, the Sabo (Soil Erosion Control) Department, and volcanologists to discuss evacuation at times of no threats to prepare against eruption. These volcanos have eruption alert levels to announce eruption warning and forecasts in coordination with local evacuation plans.

At the time of the 2000 Mount Usu eruption, the work of Professor Hiromu Okada of Hokkaido University (at the time) known as the “home doctor of Mount Usu” succeeded in predicting the eruption and evacuating the residents in the area (Okada 2007). At the time of the 2014 Ontakesan eruption, however, the size of precursors was small, and the prediction failed leaving 63 dead or missing. It was the worst volcano disaster in Japan after World War II.

6.3 Ground and Sediment Disasters

6.3.1 *Types of Ground Disasters and Mechanisms of Their Occurrences*

There are two types of ground disasters: those that break out on plains and landfills and others that take place in hills and mountainous areas. The former type includes subsidence due to consolidation of clay ground, wide area subsidence caused by extraction of groundwater, and liquefaction of sandy ground. Landslides caused by earthquakes and heavy rainfall are of the latter type. Although different in nature from these types, the new concerns of underground disposal or storage of industrial waste including radioactive nuclear waste are, in a broad sense, also ground disasters.

Soil that make up the ground has the structural skeleton formed by solid grain particles contacting one another and pore filled with air or water or in cases with oil. Ground disasters break out when pore water that fills pore inside the grain particle formed structural skeleton changes within the ground. Structures built on clay ground change the load inside the ground, and pore water is squeezed out over a long time period causing ground subsidence. When pores filled with water reduce their volumes due to pumping out of the groundwater, ground subsidence also takes place. Liquefaction, on the other hand, is caused when the earthquake force takes away resistance in loosely packed sandy ground filled with water and turns the ground soil into a liquid-like state. The earthquake shakes the ground giving rise to the pore water pressure, and the soil particles lose their contacts with one another disintegrating the particle-formed structure, and the particles start to flow in the form of muddy water.

On slopes, earthquakes and heavy rain trigger sediment disasters. The next section discusses types of sediment disasters and how they happen. The groundwater flow that fill pore raises concerns about dispersion and diffusion of contamination from underground waste.

6.3.2 Types of Sediment Disasters and Mechanisms of Their Occurrences

Sediment disasters is a collective term for debris flow, landslides, hillside collapses, and so on that are caused by the movement of earth and soil. Debris flow is a flow of mud with high content of rocks and stones, and it is called a mudslide when the flow mainly consists of finer mud, sand, and pebbles. Debris flows can be caused by hillside collapses induced by heavy rainfall or riverbeds with stones and soil suddenly lifted by increased river flows that push them all downstream. Although theory about physics of debris flows have been clarified, predicting when, where, and how big they will be is difficult. Landslides and hillside collapses are phenomena of big chunks of soil and rocks sliding down with gravity. Landslides, in general, are mild slopes moving slowly, however, over wide areas. In many cases, grounds that slipped in the past often start sliding again. Special land configurations called landslide formations can form on ground surfaces. Hillside collapses, like cliff collapses, are relatively smaller, and they are concentrated collapses of steep slopes on mountainsides caused by heavy rainfall or earthquakes. Hillside collapses break out during the rainfall or within a relatively short time from the end of rain; however, landslides often continue for long times even after the end of rain. Understanding them takes not just knowing infiltration of rainwater but also long-term flow of groundwater.

Soil and rocks on slopes receive strong sliding forces from gravity trying to push them down the slopes induced temporarily by earthquakes or added weight with rainwater infiltration. On the other hand, vertical movement from earthquakes can lower the vertical stress, and rainwater infiltration can raise the pore water pressure to lower the effective force on the structural skeleton of soil particles. These phenomena lower the frictional resistance at the "slip plane" between the stable layer of slopes and chunks of soil and rocks. When the sliding force overcomes frictional resistance at the slip plane, a landslide or a hillside collapse breaks out.

The huge landslide at Xiaolin Village in Kaohsiung Taiwan in August 2009 triggered attention to deep-seated landslides. Differently from shallow landslides of slope surfaces with weathered depositions, deep-seated landslides are major collapses that take bedrocks at deep underground with them. Shallow landslides occur with heavy rainfalls in short time periods, and in contrast, deep-seated landslides break out when the accumulated rainfall reaches 400–500 mm over long time. During the September 2011 Kii Peninsula heavy rain, deep-seated landslides took place over a wide area in Nara and Wakayama prefectures, Japan, and caused serious damages.

6.3.3 Ground and Sediment Disasters

Main damages caused by ground and sediment disasters are the following. Subsidence causes structure to tilt, generates steps on the ground, and increases the risk of flooding. Liquefaction causes structures to sink or tilt and can cause underground structures to come up to the ground surface. Levees can sink or their bodies can shift to the side. Landslides can cause loss of lives or properties and can destroy houses.

In recent years, people are more concerned about compound disasters like earthquake, liquefaction, and tsunami all occurring at the same time, or heavy rain causing landslides and flooding. During the March 2011 Great East Japan earthquake in Japan, the earthquake caused liquefaction, and coastal structures like seawalls or river levees lost their functions when the tsunami hit the area to mark huge damages. The September 2011 heavy rain in Kii Peninsula caused huge landslides that blocked rivers and formed natural dams. There was high risk of these natural dams collapsing that would have caused major outburst floods in the downstream areas.

6.3.4 Preparations for Preventing Ground and Sediment Disasters, Measurement, and Monitoring

Measures for ground and sediment disaster prevention include both hardware and software. Hardware measures against debris flows include embedding soil retaining structures to stop collapse of unstable slopes and prevent lumps of earth from moving, or building soil-blocking dams in the downstream of rivers to stop debris flows or to lessen their energies. Software measures, on the other hand, include enforcing regulations that restrict housing development in areas where sediment disasters are likely (e.g., Act on Promotion of Sediment Disaster Countermeasures for Sediment Disaster Prone Areas 2000); informing residents with sediment disaster hazard maps about areas with risk of debris flows, landsliding, and hillside collapses; or issuing ground and sediment disaster warnings so residents can brace or make early evacuations. Hardware preparations so far have made large contributions in reducing ground and sediment disasters. In recent years, however, reduction in investment to public projects caused by the shrinking economy is causing administrations to shift their efforts into software. Of course, software alone cannot prevent these disasters. Especially the battle against extreme weather conditions, said to be caused by global warming, requires more efficient and effective measures by combining hardware and software measures in a balanced way. For liquefaction, a number of construction methods have been proposed and implemented including dispersing increased pore water pressure, lowering underground water level, or stiffening the ground.

Measurements and monitoring of ground and soil movements like debris flows, landslides, and hillside collapses are extremely important in predicting disaster they cause and in making early warnings and evacuations. Methods in practice include monitoring displacement and deformation of moving soil and measuring physical quantities about groundwater like water content in hillsides or pore water pressure. A large number of methods for such measurements and monitoring have been proposed; however, what and where to make measurements and monitor for the best results have not been clarified. We need to continue making measurements and collect monitoring data and analyze the data to set control standards and to reach solutions for these threats by the nature.

6.4 Hydrosphere Disasters

6.4.1 Mechanisms

Water-caused disasters like tsunami, storm surge, or flooding are called hydrosphere disasters. They are all natural phenomena that involve huge quantities of water with great energy; however, the mechanisms of their occurrences vary. Tsunami is a phenomenon that propagates a rise or subsidence of sea surface with gravity working as the restoring force. A landslide or a volcanic eruption can cause tsunami, but about 90% of them are caused by earthquakes. When a tropical cyclone like typhoon grows, the low pressure sucks up the ocean surface, and the violent wind blowing toward the coast pushes the seawater to cause storm surge. Flooding is the phenomenon of heavy rain from a typhoon or a front gathering to rivers and their sudden rises in water level pouring out into the cities.

A lump of water quickly moves in the horizontal direction than in the vertical, and all hydrosphere disasters are explained as waves with long wavelengths compared to the depth (in case of a flooding, the flood area is wider compared to the inundation). When the wavelength is 25 times or more of the water depth, the wave is called a long wave, and the governing equations (equations that describe the governing physical laws) are as follows:

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \tag{6.1}$$

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{D}\right) + \frac{\partial}{\partial y}\left(\frac{MN}{D}\right) + gD\frac{\partial \eta}{\partial x} + \frac{gn^2}{D^{7/3}}M\sqrt{M^2+N^2} = 0 \tag{6.2}$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}\left(\frac{MN}{D}\right) + \frac{\partial}{\partial y}\left(\frac{N^2}{D}\right) + gD\frac{\partial \eta}{\partial y} + \frac{gn^2}{D^{7/3}}N\sqrt{M^2+N^2} = 0 \tag{6.3}$$

where η is the water level; M and N are the discharge fluxes in x and y directions, respectively (which express the strengths of flows in the horizontal direction); D is the total water depth (sum of water depth and water level; inundation depth in case of flooding); g is the acceleration of gravity; and n is Manning's roughness coefficient (for the magnitude of friction at the bottom).

The first term of Eq. (6.1) is the rate of water level change with respect to time, and the second and third terms are the rates of discharge flux changes with respect to space. Equation (6.1) is the continuity equation derived from the law of mass conservation, and it expresses that spatial change of flow causes the water level to go up or down. The first terms in Eqs. (6.2) and (6.3) are the rate of flow flux change with respect to time, the second and third terms are the rate of discharge change with respect to space along the flow components, the fourth terms are the change of pressure with respect to space, and the fifth terms are the sizes of bottom friction. Equations (6.2) and (6.3) are the equations of motion in the horizontal directions derived from the law of conservation of momentum, explaining that the flow varies with spatial differences in flow or pressure and it decays with larger friction at the bottom.

Calculating Eqs. (6.1) through (6.3) with the computer allows simulating hydrosphere disasters. In fact, they are the equations that the central and local governments use in estimating damages and producing hazard maps. These three equations with multiplications and divisions of variables are based on the theory of nonlinear long waves and apply generally to deep ocean and to land. Tsunami warnings, however, only need predictions of waves that reach the coastlines, and nonlinear terms for shallow sea and on ground are neglected.

6.4.2 Scenes of Damages

Tsunami damages take different forms depending on where they take place. In general, tsunamis that were generated near the coast like the tsunami caused by the 2011 Off the Pacific Coast of Tohoku earthquake (Tohoku tsunami) are called near-field tsunamis, and those that reached long distances where the earthquakes were hardly sensed, like in the case of 1960 Chilean tsunami, are called far-field tsunamis. The two types are distinguished in disaster mitigation. Near-field tsunamis attack the coastal area within several minutes to several hours to cause large human damages. Far-filed tsunamis that travel across the Pacific Ocean attack a wide area with long-wavelength waves to cause large damages to the fishery industry. The coastal topography also affects tsunami damages. A ria coast has complex jagged interface between land and water, and although tsunami waves may amplify locally, the steep land in the back often limits the inundation to the coast. For flat land, tsunami waves may amplify a little because of the simple coastline; however, the wide flat land lets the waves reach far inland. For example, Tohoku tsunami inundated a wider area in Fukushima prefecture and destroyed more buildings than in Iwate prefecture with higher waves. Rivers have less resistance and friction to damp the tsunamis, and they can run up to upstream regions and cause damages to residents that are usually not worried about tsunamis.

Storm surges cause different magnitudes of damages depending on the typhoon routes and geography. Strong winds blow counterclockwise in the perimeter of typhoons, and the right side of the moving typhoon suffers from the circling wind and forward movement. Typhoons near Japan move from southwest to northeast generally. Thus, bays that face the south have openings that winds can attack and suffer big storm surge. This effect caused huge inundation damages to, for example, Tokyo bay at the time of the 1949 Kitty typhoon, Ise Bay during the 1959 Ise Bay typhoon, and Osaka Bay with the 1961 second Muroto typhoon. Global warming weakens the upward flow of air that causes typhoons, and predictions say that their number will drop. Warm vapor that is the energy source of typhoons, however, increases, and there is the risk that once they are born, they may be larger and stronger.

Global warming caused larger and stronger typhoons that will increase the rainfall with higher risks of flooding. When towns are flooded by river, flows going over the banks or destroyed levees are called fluvial flooding, whereas, flooding caused directly by rainwater and insufficient pumping or draining are called pluvial flooding. The primary cause of fluvial flooding is upstream rainfall. Thus, even when there is small rainfall in towns, flooding can take place and persist for an extended time. Inundation depths suddenly rise with fluvial flooding; thus, quick evacuation is important. Not evacuating the area or attempting to after the flooding started can cause human damages. In recent years, there is more pluvial flooding in urban areas. The inundation depths growing gradually with pluvial flooding cause less human damages; however, flooding over a wide urban area can cause large economic damages.

6.4.3 Damage Mitigation

Countermeasures against hydrosphere disasters start with assuming the external force and estimating the damages they cause. Based on these basic data, hardware and software countermeasures are implemented. Many of the countermeasures are common to all forms of hydrosphere disasters. Tohoku tsunami influenced the countermeasures against storm surge and flooding, so in the following, we will discuss mainly about countermeasures against tsunami.

Hardware preparations of building structures like seawater walls, river levees, and water gates aim at preventing water from entering residential areas. In designing structures, the designer needs to define the external force, and before Tohoku tsunami, it was the largest in history. The idea was reasonable that huge external force applies in cycles; however, the precondition was that human knows the biggest in history. Tohoku tsunami, however, showed us the fact that our limited records of history do not teach us what the largest in history was. The fact that we had a misunderstanding of knowing the biggest in history was a factor in causing huge damages beyond our forecast. With this lesson from Tohoku tsunami, we since then have set two levels of tsunami expectations: “level 1 tsunami” height with tsunamis that frequently occur from our data and maximum “level 2 tsunami” height with physical possibility even beyond our experience. Hardware preparations against level 1 tsunami aim at protecting resident’s lives and properties, and for level 2 tsunami, the preparations also involve software to protect people’s lives.

Damage estimation before Tohoku tsunami was about inundation damages, i.e., about the behavior of water. Tohoku tsunami, however, opened our eyes to all sorts of tsunami damages including building destruction, floating objects, disaster debris, and geographical changes with sand transportation. Evaluations are starting about these phenomena that accompany inundation damages.

Software preparations target properly informing the residents about risks that come with disasters and encouraging them to take proper action upon their breakouts. Evacuation is especially important in case of hydrosphere disasters, and a number of hardware preparations are also in process, like double levees (raised roads) that proved effective at the time of Tohoku tsunami, coastal protection forests, evacuation buildings and lifesaving hills for temporary evacuation, and strong seawater walls. At the time of Tohoku tsunami, the tsunami warning, indispensable for starting evacuation, underestimated the size and was a factor in causing expanded damages. Since Tohoku tsunami, therefore, enhanced monitoring and new numerical models are in the process of being in place.

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