ISSN 8755-6839

SCIENCE OF **TSUNAMI HAZARDS**

Journal of Tsunami Society International

Volume 42 **Number 3** **2023**

EFFECTIVE TSUNAMI PROTECTION IN JAPAN - REVIEW AND DISCUSSION OF NEEDED MEASURES

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ABSTRACT

The 11 March 2011 Tohoku earthquake and tsunami, also known as the Great Sendai severe disaster and as the "Heisei" tsunami, occurred off the northeastern coast of Japan's main Island of Honshu, resulting in extensive destruction and the death of 22,000 people. Also, tsunami waves struck the Fukushima nuclear power plant on the coast, thus setting in motion a major accident and spreading long-lasting radioactive material in the ocean, with far-reaching impact on marine life in the North-West Pacific Ocean. Besides the large magnitude of the destructive earthquake, the main factors responsible for the great loss of life was due to the fact that existing tsunami protective countermeasures, such as seawalls, were inadequate in providing protection given the extreme height of the 2011 tsunami waves. The seawall was overtopped by these waves and large sections were destroyed by the accompanying debris flow, thus reaching further into the harbor. Subsequently, waves traveling up the river, transformed into a river-type of tsunami, overtopping river embankments, flooding the surrounding areas, and causing great loss of life and destruction, as in the past 115 years caused by great magnitude earthquakes and destructive tsunami events. These were: 1) The magnitude Mw=8.5 tsunami generating Meiji Sanriku earthquake of 15 June 1896 in Japan; 2) The magnitude Mw=8.4 tsunami generating Showa Sanriku earthquake of 3 March 1933 in Japan; 3) The magnitude Mw= Mw=7.7 Hokkaido Nansei-Oki tsunami generating earthquake of 12 July 1993; and 4) The magnitude Mw=9.4-9 Valdivia-Chile earthquake and tsunami of 22 May1960.

The present study examines Japan's government countermeasures in providing effective tsunami predictive and protection measures from such extreme and catastrophic tsunami recurrences in the future, and particularly against the threat of river tsunamis.

1. INTRODUCTION

The most significant aspect in taking effective tsunami protection measures is the accuracy of predicting the heights of expected waves and their potential extend of inundation. Recently, the Japanese government and the media announced that the accuracy of the tsunami height prediction ranges considerably from one half to as much as two times or more (Kinki District Transport Bureau, 2011; Pararas-Carayannis, 2014). For example, if the predicted height of a tsunami is 10 m, its actual height on the shore may vary from 5–20 meters, which indicates a rather broad range of four times in the inaccuracy of its evaluation. When the 2011 tsunami struck Japan, experts repeatedly stated "unexpected" occurrences about the damage that could be expected.

Given to the insufficient height of the existing seawalls, the tsunami could easily flow over them and afflict the residents near the coastline, who expected protection from the existing seawall and did not flee. The officially established narrow danger zone of the tsunami hazard map further aggravated the disaster, because the waves reached beyond the predicted range and affected residents seeking refuge in areas that were previously considered to be safe. Consequently, the inadequate height of the existing tsunami shelters acted as a fatal trap for many of the residents. Given such high vulnerability from extreme events, it is highly significant to have accurate data and information in order to ensure more effective protection for the people residing in coastal areas, and to safeguard against future recurrences.

The obvious question is on how the height of a needed protective seawall can be effectively determined, if the actual tsunami height ranges from 0.5–2 times of the predicted height? If the forecasts predict a tsunami of 10 meters in height, a 10-m-high seawall would be insufficient against a tsunami of 20 meters in height. In the past, seawalls were built in Japan based on estimates of tsunami heights that struck the coast (Yasunori et al. 2012**)**. However, such estimates of offshore tsunami heights often differ substantially from what actually can occur within an enclosed body of water of a bay or a harbor, due to many other reasons. For example, when tsunami waves reach closer to shore, they become compressed, their wavelengths are shortened, and their energies and heights may increase considerably due to the stage of the tide, effects of refraction or resonance, or due to combining with waves approaching from different directions. Thus, a tsunami wave which may have been only one meter or less in deep ocean, may increase in height to thirty to thirty-five meters when sweeping over the shore, and its run-up and inundation may be significantly greater traveling up a river, transforming into a river-type of tsunami (known as fluvial tsunami), reversing the river flow and overtopping existing embankments, flooding and abrading surrounding areas by carrying quantities of sediments. This occurred with the 11 March 2011 Tohoku tsunami, as discussed in greater detail by the present report.

2. FACTORS WICH ALTERED THE 11 MARCH TSUNAMI ON-SHORE AND INLAND RIVER TRANSFORMATION

Besides the overtopping and partially destroying sections of the existing coastal seawall, the 11 March 2011 Tohoku tsunami also inundated rivers and streams forming a bore (also known as a fluvial tsunami) that reversed their flows, causing extensive flooding and great damage to communities far inland. The series of waves that flooded, drained away and then re-flooded the land, a process which lasted long as subsequent waves arrived.

Such flooding of the coast and of up-river regions usually varies based on the direction of approach of the tsunami waves. If the tsunami approaches diagonally a bay-front, as often is the case, an existing cape usually blocks the full impact, thus resulting in smaller waves reaching the bay. Accordingly, small seawalls have been constructed to withstand the relatively smaller tsunami waves. However, we must evaluate a scenario in which a tsunami approaches directly the front of the seawall. Fortunately since 2011 and currently, the Japanese government has expanded efforts to implement tsunami countermeasures presuming that a tsunami of the same magnitude will recur again at a given location. This assumption is somewhat incomprehensive and can be ineffective in the bay-front tsunami impact scenario. The historic record documents such an outcome.

For example the Kitakami General Branch of the seawall, facing the mouth of the Kitakami River in Ishinomaki City of the Miyagi Prefecture, was constructed five years ago as a preventive measure for tsunami protection (Shimbun, 2011). This structure is situated on land and is designated as an evacuation site as extends up to a height of 6.5 m, which is 1 m higher than the highest tsunami water level, assumed at 5.5 m (Shimbun, 2011). However, this structure was completely destroyed by an enormous wave of height greater than 8 m in 2011. Among the 49 individuals who took refuge at this section of the branch, only three individuals—two adults and one child—survived (Shimbun, 2011). Teruyoshi Makino, 42, a city employee, stated, “The Evacuation was perfect, but the force of the tsunami exceeded the limit.” Based on past tsunami data, the Okawa Elementary School had been marked as a safe zone on the tsunami hazard map (Shimpo, 2011). Ishinomaki City had designated the Okawa Elementary School as a tsunami evacuation center, which was only 1m above sea level. On the day of the disaster, 74 students and teachers seeking shelter in the school grounds succumbed under the force of the tsunami waves. If this site had not been designated as a tsunami evacuation site, the individuals would have climbed the mountain behind and could have potentially survived.

Numerous other fatalities were recorded at sites that had been designated as “shelter zones” in the hazard map created with the tsunami height prediction model that was being used. However, at that time, the Japanese government had created a tsunami hazard map using the same method based on the assumption that most severe conditions of flooding had been considered in issuing such a “Tsunami Flooding Forecast Map”. This incorrect assumption and the hazard map that was issued were apparently inadequate in identifying “safe shelter zones”, that can safeguard individuals from such disastrous future events. Thus, studies were subsequently initiated for the purpose of developing an accurate

Method of predicting tsunami heights which can be used to create more effective and safer tsunami hazard maps and thus maximize the likelihood of survival. The tsunami prediction system currently employed by the Meteorological Agency is discussed as well in the subsequent section (JMA- Japan Meteorological Agency, 1999). The JMA methodology involves supposition of crustal deformation caused by earthquakes along known fault zones, and estimates of tsunami generative areas, as discussed in the following section.

3. NUMERICAL SIMULATION OF TSUNAMI WAVES – EXISTING FOCAL MECHANISMS OF THEIR GENERATION

The simulation for determining the focal mechanisms of tsunami generation by local or distant major earthquakes, as well as the heights and arrival times of tsunami waves on the coasts of Japan or anywhere else in the Pacific Ocean or elsewhere, can be broadly classified into two stages, one being a calculation of seafloor crustal deformation and another being the tsunami propagation and its height alterations due to refraction, diffraction, and maximum energy focusing.

The seafloor crustal deformation caused by earthquakes can be theoretically evaluated, based on assumption of the movement along major faults. The fault parameters can be estimated based on 1) the horizontal position and depth of the fault, 2) its size, 3) its orientation, 4) on its inclination, and 5) the direction and magnitude of the resulting slip.

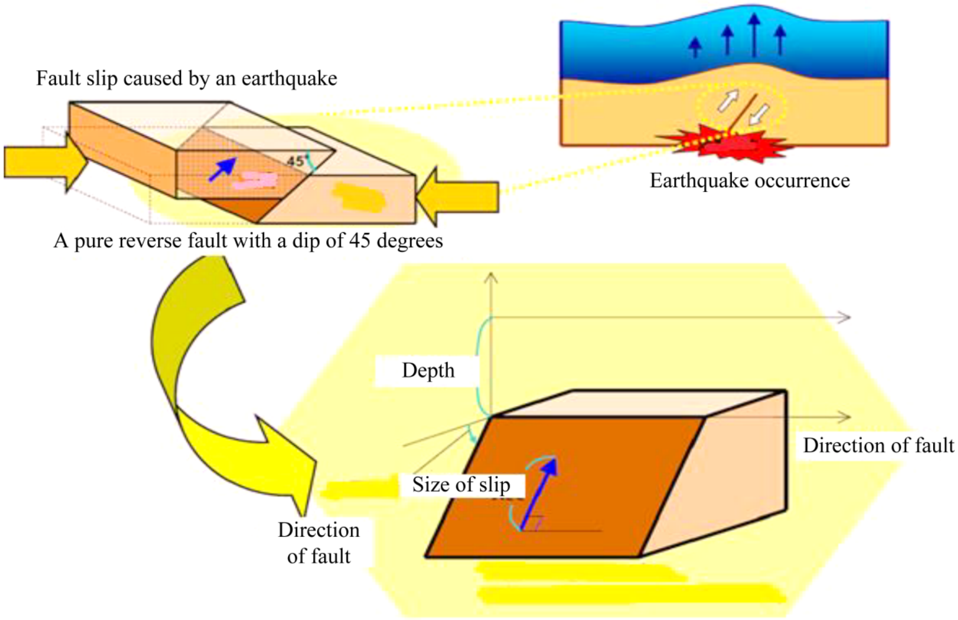

Fig. 1 Schematic of earthquake source faults causing tsunami

The direction of the fault can be determined from the data of known past earthquakes. The horizontal position, depth, and size of the fault along with the magnitude of slip, can be estimated from the magnitude. In addition, the inclination and slip direction of the fault can be set as being a pure reverse fault with a maximum inclination of 45° (Fig. 1 above), which corresponds to the generation of the largest possible tsunami. Accordingly, this study conducted extensive simulations to ensure adequate prevention and mitigation response to earthquakes of any size at any location, which could generate tsunami waves, and which particularly impact on Japan. Figure 1 is a schematic of such undersea earthquake source fault movement, which could generate a destructive tsunami based on maximum source displacements and focusing of propagation

In particular, this study considered approximately 1,500 faults in the horizontal direction at six distinct depths varying from 0 and 100 km and four magnitudes. Thereafter, a tsunami propagation calculation was applied.

However, the tsunami height calculation may be scientifically incorrect, as there may be other earthquake parameters, factors and deviations which may not have been considered. One such deviation can be clearly seen from the logarithmic graph of Figure 2 where the average slip in meters of a seismic fault is plotted in terms of an earthquake's seismic moment (Miyakoshi Lab EtAl, 2015)

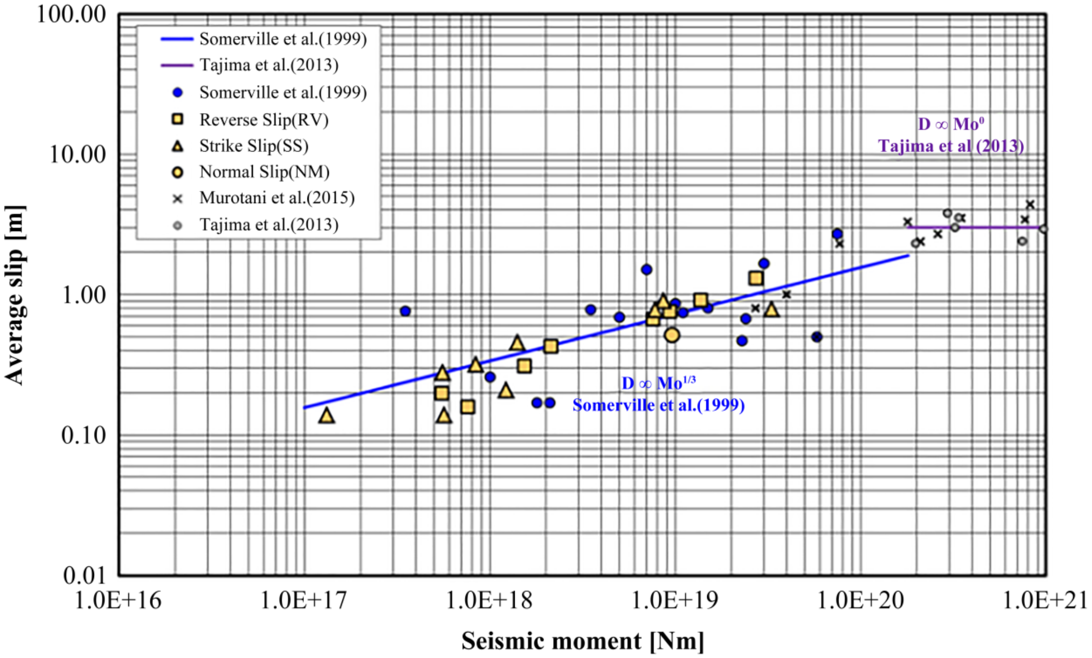

Fig. 2 Average slip in meters of a seismic fault in terms of an earthquake's seismic moment *(Miyakoshi Lab Et Al, 2015).*

The straight line passing through the center of the previous seismic data in Figure 2 represents the formula reported by Somerville (1999). The average slip (m) at any seismic moment (Nm) can be calculated using this formula.

Notably, the tsunami height calculated from the average slip (m) represents an average tsunami height; therefore, a fundamental mistake would be made when using this formula, which yields an average value, for cases where the maximum value matters (e.g., tsunami). As depicted in Figure 2, the seismic moment is 8.0E+19 Nm and the average slip is 2.8 m, which is 2.2 times the calculated value of 1.3 m. Using the formula, the corresponding tsunami height is calculated to be 1/2.2 of the previous actual tsunami height.

This is an example in which the actual observed value considerably deviated from the calculated value because of the small amount of data. With more data, we can derive more accurate results. The concept of using a regression equation to obtain an estimated mean with the maximum value, such as an earthquake or tsunami, is fundamentally incorrect. In this calculation, the average slip corresponds to an average value, and the tsunami height calculated using the average slip denotes the average tsunami height.

Moreover, the tsunami height cannot be determined only by using the average slip. Even for the same slip amount, it varies considerably depending on its slow or rapid movement. Thus their source tsunami height calculations are wrong. Based on these numbers, they simulated the tsunami propagation process.

3.1 Terrain Tsunami Amplification

The tsunami height varies considerably depending on the topography near the coast. In addition, the tsunami waves may continue to inundate on land. Waves are converge in places with special topography, such as the tip of a cape or the rear side of a V-shaped bay, which necessitates special caution. A tsunami can surge further owing to the repeated reflections and can result in remarkably high waves by overlapping with multiple waves. Consequently, the first wave is not necessarily the biggest and the subsequent waves may be higher. In shallow water, the wave speed diminishes and the wave height increases. Moreover, complex variations can occur, such as waves over shallow water that overlap on those advancing in deep water.

However, as the tsunami propagation process is a physical phenomenon, it can be predicted according to scientific laws. Specifically, the sea surface is classified into meshes for calculation, with 15 m mesh near the coast. The precise calculations were enabled by the increased computer capacity and calculation speed.

Overall, the "prediction accuracy of tsunami height of 0.5–2 times" does not vary, because the predicted height of the first tsunami wave is incorrect. Thus, we intend to enhance this "prediction accuracy of tsunami height of 0.5–2 times" to mitigate the tsunami damage. Certain studies have suggested, "escape training" as a tsunami countermeasure (Sugiyama and Yamori, 2019). In case of an under sea earthquake, escape training predicts the height of the tsunami that will impact the coast based on the magnitude and location of the earthquake. Accordingly, a safe evacuation route can be communicated to the public via mobile phones. Recently, this has been implemented in evacuation drills in various places. However, the inaccurate predictions of tsunami height at 0.5–2 times is grossly uncertain. The safe evacuation routes for an expected tsunami height of 3 meters ceases to be safe if the tsunami wave height exceeds 3.5 meters. An individual can drown even under an excess height of 50 cm. As 3.5/3.0 = 1.17 times, individuals can succumb under a tsunami that is ≈20% higher than the predicted/expected height.

Current tsunami warnings are issued over a wide area based on tsunami heights with poor accuracy. Hence, the number of people who rely on tsunami warnings to evacuate is decreasing, and the damage caused by tsunamis is actually increasing.

A tsunami warning for a specific area should be issued based on a more accurate tsunami height prediction. However, it is impossible presently to improve the accuracy of tsunami height prediction with current methods. After an initial tsunami wave strikes a shore, and an accurate measurements of its height and travel direction are made, issuing a prompt warning for the areas where the tsunami will be reaching next is necessary.

Thus in order to establish a more effective warning system, local government agencies should have quick access to data from seafloor seismometer and tsunami measurement network devices as soon as possible in order to measure the tsunami height, and thus issue a reliable tsunami warning only to the affected areas (NEC, 2013). Therefore, it is important to regain people's trust in tsunami warnings otherwise the resulting tsunami impact and destruction will increase significantly. Thus government authorities should create new tsunami countermeasures, recognizing that the current countermeasures are inadequate and may actually increase the damage.

Nonetheless, the actual scenario is more concerning. The initial height of a tsunami impacting on land is nearly impossible to accurately predict as it can be affected by a slight changes of water depth, land topography, an earthen wall of ~1 m height, or an artificial hill. Upon visiting the disaster area of Natori City devastated by the 2011 tsunami, the author noted two two-story wooden buildings constructed adjacent to each other on a field. Surprisingly, one building suffered no damage, whereas the ground floor of the other building—located 5m away—was devastated by the tsunami. Notably, a 1-m-high earthen wall separated the fates of these two building by blocking and diverting the tsunami direction. Unfortunately, such minor obstacles cannot be incorporated into a simulation program.

Additionally, concrete buildings in densely populated cities are structures that act as barriers and can considerably affect tsunami impact with enhancement of wave heights and gains in momentum. An example of such occurrence was broadcasted seven years after the 2011 disaster, by an NHK special television program under the title: "Kawatsunami: Unknown Truth in Seven Years of the Earthquake" (NHK Special, 2018). According to the report, the tsunami reached the Kitakami River by traveling up to a speed of 40 km/h, causing 74 fatalities at the Okawa Elementary School – which had been designated as an evacuation center – and causing 68 fatalities in the Magaki district, which was situated 5 km inland from the sea. The tsunami followed the meandering course of the river; slamming and breaching the riverbanks by a height of 2 meters, and inundating an area up to 1 km inland.

The facts presented in this broadcast demonstrated that the embankments couldn't prevent tsunami damage. Thus, the strengthening of coastal dykes does not help at all. If a river flows through the town, the tsunami can flow through the river and impact the river embankment. On the day of the 2011 disaster, 600 times the average amount of seawater flowed into the Kitakami River, thereby increasing the river discharge to a speed of 40 km/h. This signifies that even a weak tsunami is dangerous if a river is flowing with extensive amounts of added water from the sea. The water in the river is pushed back by the tsunami and rises in height, thereby creating a massive river tsunami.

On that same day, the tsunami disintegrated 190 km out of the 300-km-long seawall on the Sanriku coast (Yasunori et al. 2012), because its waves created a debris flow that lifted up the sludge and sand from the seabed. As such, river tsunamis can readily destroy river levees.

In Tagajo City, Miyagi Prefecture, a river tsunami traveled up the river in the city and impacted a building district, resulting in 188 fatalities. If buildings block the tsunami flow, the height of the water level increases. Thereafter, the flow concentrated in the gaps between the buildings, increasing its speed even more by a Bernoulli effect. The tsunami flowed specifically fast in areas with sturdy buildings and exceeded 30 km/h at maximum. Furthermore, the tsunami traveled along the road, such as a waterway, and entered the city area while turning the alley. It collided with a concrete building and altered its direction, thereby creating a complicated damaging flow.

Fumihiko Imamura, a professor at the International Research Institute of Disaster Science at Tohoku University, analyzed this Tagajo tsunami and determined that the structure of the city exacerbated the damage. Professor Imamura stated that “The density of buildings is very high, and the tsunami becomes very strong, so I think this can be called an urban torrent. There is no way to escape, and no time to escape.”

Almost 30,000 rivers flow through the islands of the Japanese archipelago. The investigations and research on the threat of river tsunamis are progressing where the kind of dangers exist. A massive earthquake along the Nankai Trough is forecasted in the near future. According to the national government’s assumptions, tsunamis will hit cities across the Japan immediately after the violent tremors. Amid this threat, Osaka Prefecture is becoming increasingly concerned regarding river tsunamis, because 174 rivers flow through Osaka, and it has a population of 8.8 million residents.

In 2012, the government announced that the expected flooding areas in Osaka Prefecture were limited to regions near the coast. However, the prefectural government presumed a situation in which the river embankments and water gates fail to function, thereby creating its own estimates. The results revealed that the area of the flooded area extended to more than three times the official national assumption.

According to simulations conducted by experts, the tsunami waves can penetrate up to 2 km from the mouth of two rivers, with increasing water level near the tsunami confluence. In particular, the tsunami overflowed into areas housing commercial facilities. In case of a river with a gentle slope, the tsunami reached as far as 12 km from the river’s mouth. Upon crossing the embankment, experts suggest that the tsunami will flow into the low-lying residential areas.

According to the Osaka Prefectural government, in the worst-case scenario, the number of victims would increase to 130,000, which is more than ten times the national government’s estimate. Overall, Tokyo faces the greatest danger in Japan. In the 1600s, when Ieyasu Tokugawa built the Edo Castle, he reclaimed the sea to create the town of Edo by digging vertically and horizontally to carry supplies by boats. The Edogawa, Arakawa, and Sumida rivers flow through the city of Tokyo.

The flood control for the five wards of Koto has been combining Sumida, Koto, Adachi, Katsushika, and Edogawa (Koto 5 Wards Large-Scale Flood Countermeasures Council, 2022). Owing to the simultaneous occurrence of floods and storm surges, the river collapses at multiple locations, including on both banks of the Arakawa River, eventually inundated almost the entire Koto Ward. The population within the inundated area reached approximately 2.5 million. Approximately 440,000 residents will have to be evacuated from their homes, as the buildings will be completely submerged. In contrast, the number of evacuation centers in the five wards of Koto is approximately for 490,000 residents, who cannot be accommodated. In the worst-case scenario, floodwaters can remain inundated for more than two weeks, and residents will be forced to stay in a harsh environment for a long time without gas and water supply. Thus, early rescue is required to prevent damage from the vertical evacuees, but if one million residents have to be evacuated (half of the population of the inundated area), the boats owned by the Kanto police, fire departments, and the Self-Defense Forces will be employed. Regardless of full mobilization, the rescue operation would involve more than two weeks.

Nonetheless, this is only an evacuation plan, and the repair of embankments as well as the discharge of the enormous quantity of water flooding the land have not been specifically considered, which forms the scope of a future research. The destructive power of tsunamis is incomparable to storm surges and floods. Even if a weak tsunami hits Tokyo Bay, the sludge from the bottom will be swept up, and the tsunami will intensify with as it merges with the Arakawa, Edogawa, and Sumida rivers. In particular, river levees in Tokyo are thin and can be easily destroyed by tsunami laden with sludge due to the high land prices. The number of victims will surpass the number of 130,000 fatalities predicted for Osaka Prefecture. Notably, the Koto 5 Ward Crisis Management and Disaster Prevention Division is unaware of river tsunamis flowing up rivers.

CONCLUSIONS

Knowledge and understanding about the complicated nature of the tsunami hazard is imminent for effective protection countermeasures. The recently introduced method of escape training may prove to be ineffective. In case a weak tsunami impacts Tokyo or Osaka, a wide area will be flooded by a river tsunami, and economic activity will cease for several years. Although the economic center of Osaka is located higher than the mean sea level, the center of Tokyo's economy is situated below the sea level. Moreover, the current communication network, power grid, gas, water, and other facilities are based on underground tunnels. Thus, draining of floodwater will require months of time. Four years ago, Osaka started to prepare against the threat of river tsunamis. However, no such effort has been yet adopted by the Tokyo government. Thus, adequate efforts must be undertaken to ensure protection against the potential tsunami hazard.

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