FLOW GEOMETRY OF OVERFLOWING TSUNAMIS AROUND COASTAL DYKES

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Japan has a long stretch of coastal dykes along its shoreline to protect against many types of coastal disasters. The 2011 Tohoku Tsunami caused serious damage to these coastal dykes along the long coastaline. One of the main reasons of the coastal dyke failure was overflowing tsunamis. Thus, after the 2011 Tohoku Tsunami, many studies on coastal dyke failure due to overflowing tsunamis have been conducted. The present study aimed to analyze the basic hydraulic characteristics of overflowing tsunamis on coastal dykes. First, the characteristics of overflowing tsunamis on coastal dykes observed during the 2011 tsunami were described using field data. The field data showed that there were different types of overflowing tsunamis during the 2011 tsunami and these types could be related to coastal dyke failure. Then, flow geometry were discussed based on the classification presented by Hom-ma (1940). Finally, the relationships between the hydraulic characteristics of overflowing tsunamis around coastal dykes (velocity field and pressure profile) and coastal dyke failure were discussed in detail by means of both laboratory investigations and numerical experiments.

Keywords: tsunami; 2011 Tohoku Tsunami; coastal dyke failure; overflowing tsunami; laboratory investigations; numerical experiments

INTRODUCTION

Japan has a long stretch of coastal dykes along its shoreline to protect against tsunamis, storm surges, high waves, and coastal erosion. The 2011 Tohoku Tsunami caused serious damage to these coastal dykes along the Pacific Coast of the northeastern part of Japan. According to the Ministry of Land, Infrastructure, Transport and Tourism (2011), 190 km out of total 300 km of coastal dykes in three most affected prefectures (Iwate, Miyagi and Fukushima) were completely or partially destroyed due to the tsunami.

Many field surveys were carried out after the 2011 Tohoku Tsunami to clarify the actual damage to these coastal dykes, and possible causes of the failures have been discussed based on the survey results (e.g. Mano et al., 2013; Mase et al., 2013). The authors also carried out field surveys after the tsunami, inspecting coastal dyke failures along the affected coast (see Figure 1 showing one example of the typical damaged section of a coastal dyke). As shown in the figure, the damage on the landward side of the coastal dyke was more severe than that on the seaward side. Scouring took place at the back of the dykes and this led to subsequent collapse of the inner core and the concrete panels covering the landward side of the dyke. This type of failure was mainly caused by an overflowing tsunami, and hence the overflowing tsunami is now paid much more attention to. However, the effects of the overflowing tsunami on coastal dykes have not yet been fully understood.

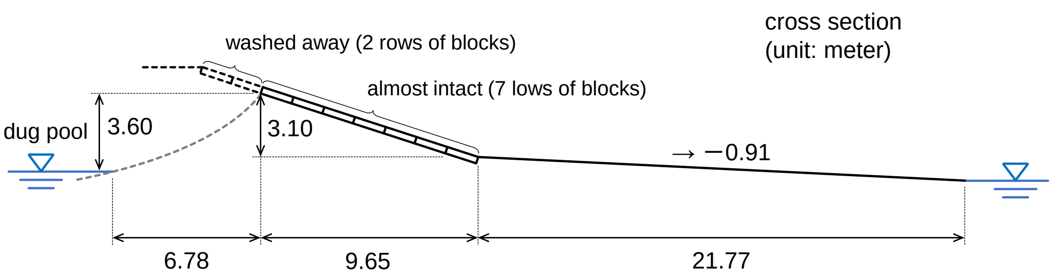

Figure 1. Damaged section of a coastal dyke in Soma City, Fukushima Prefecture. The Landward side of the dyke was washed away due to overflowing tsunami.

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The present paper aims to analyze the basic hydraulic characteristics of overflowing tsunamis on coastal dykes. First, by using field data, including measured tsunami heights and recorded video during the event, possible fluid motion of overflowing tsunamis are analyzed. Then, the classification of flow geometry around a coastal dyke is discussed. Finally, based on this classification, the possible relationships between fluid motion and failure mode are analyzed by the means of both laboratory investigations and numerical experiments.

PREVIOUS STUDIES

In Japan, normal three-surface armoring coastal dykes were constructed after the frequent typhoon attacks around 1950 and the 1960 Chile Tsunami. After constructing the coastal dykes, there were only a few tsunami events in Japan, and hence extensive coastal dyke failure, which was observed during the 2011 Tohoku Tsunami, was not seen. Thus, during this period, researches on coastal dyke failure due to tsunamis mainly focused on how to evaluate the tsunami impact on a dyke front and the scouring induced by return flow.

Hamzah et al. (2000) carried out direct numerical simulations to investigate tsunami run-up and pressure acting on a vertical onshore wall. Kato et al. (2006) carried out a series of large-scale experiments to measure the distribution of wave pressure acting on a coastal dyke. In these investigations, solitary waves with breaking on slopes were generally used and less attention was paid to the effects of prolonged overflowing tsunamis.

Nishimura et al. (1978) carried out a series of two-dimensional experiments with solitary waves to clarify the scoring at the seaward toe of coastal dykes. As a result of this study, two parameters, the rate of return flow and water layer thickness, were found to be important for the quantitative prediction of the total amount of scouring and the scouring patterns. Noguchi et al. (1997) also carried out large-scale experiments on scouring due to return flow.

FIELD DATA

To understand coastal dyke failure mechanism during the 2011 Tohoku Tsunami, it is necessary to understand how the tsunami overtopped coastal dykes. In this sense, two different types of field data can be helpful materials: the distribution of the tsunami height measured by the Joint Survey Group (2012) and some videos recorded during the 2011 event. Here two examples of field data at different locations are explained.

Oirase Town, Aomori Prefecure

The recorded video in Oirase Town, Aomori Prefecture shows that the sea level gradually rose and finally overtopped the coastal dyke with high speed flow, as shown in Figure 2. Though the inundation heights in the hinterland were decreased due to the coastal dyke, the flow speed became high. The distribution of the measured tsunami heights in this area corresponds with this flow pattern (see Figure 3). The inundation heights behind the coastal dyke were T.P. + 1-5 m, and these were smaller than the height of the coastal dyke (T.P. + 6.0-7.5 m). Tohoku Regional Development Bureau (2011) reported that this coastal dyke had damage on the landward slope. This means that high speed flow (supercritical flow) generated behind the coastal dyke could cause damage on the landward slope.

Kuji City, Iwate Prefecure

The recorded video in Kuji City, Iwate Prefecture shows that after the tsunami overtopped the coastal dyke, the sea water was accumulated behind the coastal dyke because of the adjacent hill, as shown in Figure 4. The inundation heights behind the coastal dyke relatively quickly increased, and even after the tsunami went back to offshore, the inundation heights remained high. The distribution of the measured tsunami heights in this area corresponds with this flow pattern (see Figure 5). The inundation heights behind the coastal dyke were T.P. + 11-16 m, and these were almost equal or higher than the height of the coastal dyke (T.P. + 12.2 m). Iwate Prefecture Tsunami Prevention Technical Committee (2011) reported that this coastal dyke remained almost intact and there was no clear damage on the landward slope. It was also reported that the fact that the landward slope and toe of the coastal dyke were covered by concrete could be one of the reasons why this coastal dyke survived the tsunami. However, it can be said that the accumulated sea water between the coastal dyke and the hill prevented the overflowing tsunami from becoming supercritical flow, which has a potential to cause damage to the landward slope, as explained in the case of Oirase Town.

Figure 2. Snapshots of the video recorded in Oirase Town during the 2011 Tohoku Tsunami. Left one shows the approaching tsunami, and right one shows the overflowing tsunami.

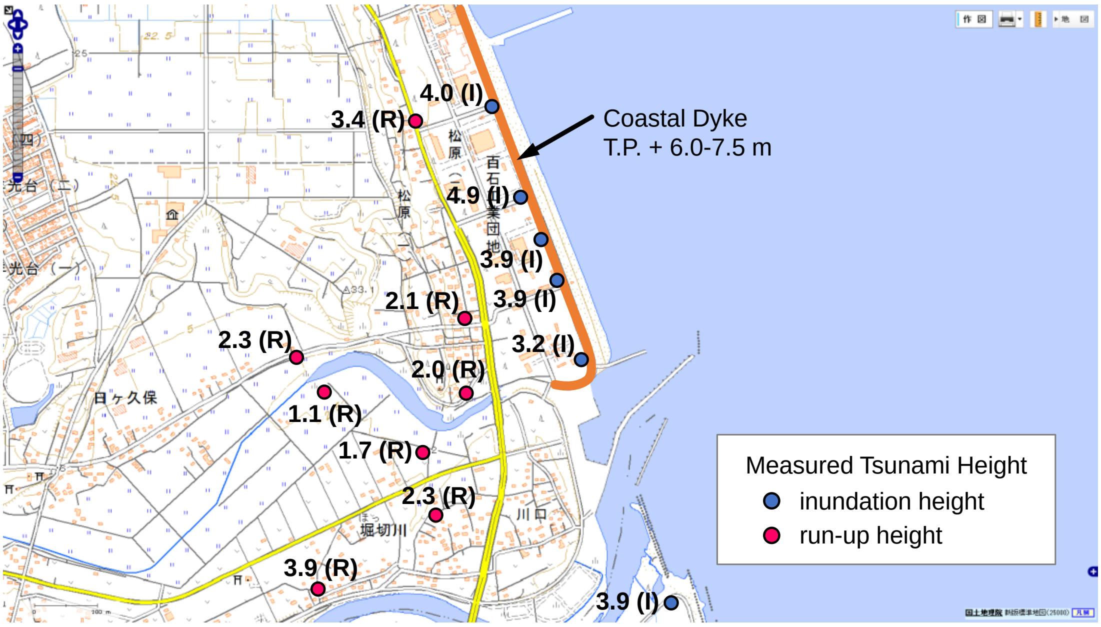

Figure 3. Topographic map (Geospatial Information Authority of Japan) with the measured tsunami heights (Joint Survey Group, 2012) around the coastal dyke in Oirase Town.

FLOW GEOMETRY OF OVERFLOWING TSUNAMIS

The field data explained in the previous section indicates that there were different types of overflowing tsunamis during the 2011 event and these types could be related to coastal dyke failure. For example, shallow flow with high velocity took place behind the dyke and caused damage to the landward slope in one place, while the water gradually accumulated behind the dyke because of an adjacent hill and the flow did not cause severe damage to the dyke in other place. These findings show that it is necessary to take flow geometry (types of overflowing tsunamis) into account when considering coastal dyke failure induced by overflowing tsunamis.

Flow geometry of overflowing tsunamis can be classified into three types based on the classical classification of flow over a dyke presented by Hom-ma (1940), as shown in Figure 6. In type (a), the subcritical flow passes to the supercritical flow near the crown of a dyke and the supercritical flow runs down into the hinterland. In type (b), the hydraulic jump is generated near the landward slope of a dyke. In type (c), the main stream flows near the water surface and the vortex with lower velocity is generated below. Among these different types, type (a) and (b) can be considered to have a higher potential to cause damage to the landward slope and the hinterland (as explained later).

Figure 4. Snapshots of the video recorded in Kuji City during the 2011 Tohoku Tsunami. Left one shows the approaching tsunami, and right one shows the overflowing tsunami.

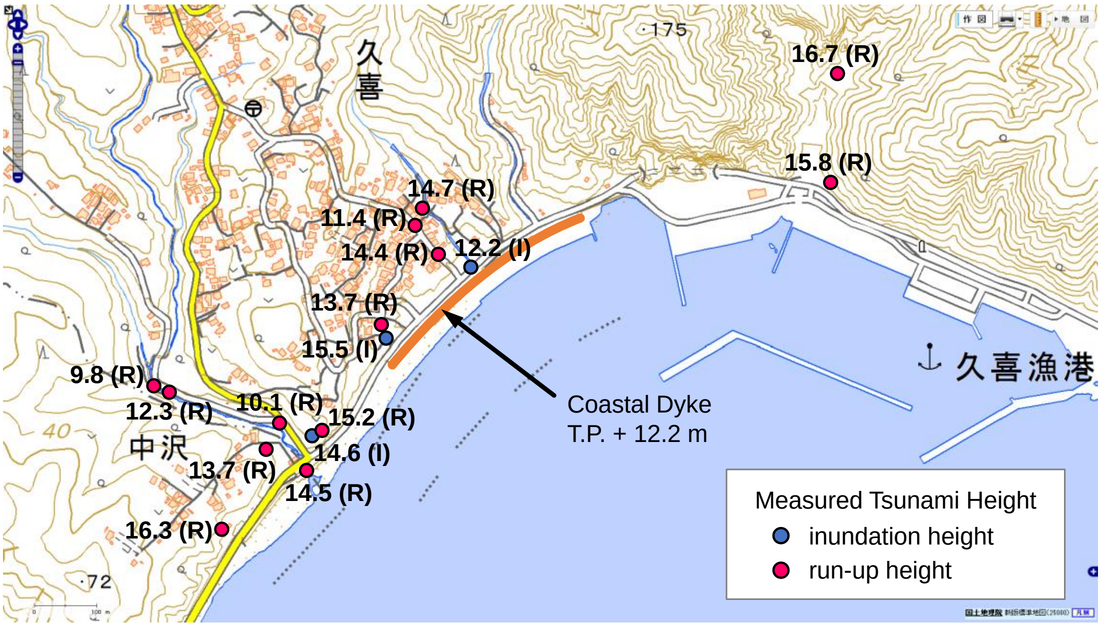

Figure 5. Topographic map (Geospatial Information Authority of Japan) with the measured tsunami heights (Joint Survey Group, 2012) around the coastal dyke in Kuji City.

LABORATORY INVESTIGATIONS

Generation Method of Overflowing Tsunami

When conducting laboratory investigations on tsunamis, one of the most important thing is to decide an appropriate method of tsunami generation. Generally speaking, to generate a tsunami-like flow in a wave flume or a wave basin, three types of methods exist, namely using a solitary wave, a dam break flow, or a pump flow (Figure 7). A solitary wave and a dam break flow have been used for many tsunami laboratory investigations. On the other hand, a pump flow was not widely used to simulate a tsunami. However, after the 2011 Tohoku Tsunami, this type of flow came into use (e.g. Kato et al. 2012) as it is easy to create a prolonged overflowing tsunami. In a pump flow system, the downstream and upstream sides of a flume are connected and a circulated flow can be generated. Though this method is not an appropriate method for investigating impact force or run-up process of tsunamis, this method can be used for investigating overflowing tsunami behavior.

In the present study, to understand the basic characteristics of an overflowing tsunami on a coastal dyke, a pump flow system was used for the laboratory investigation. The hydraulic characteristics of each flow geometry explained in the previous section were analyzed.

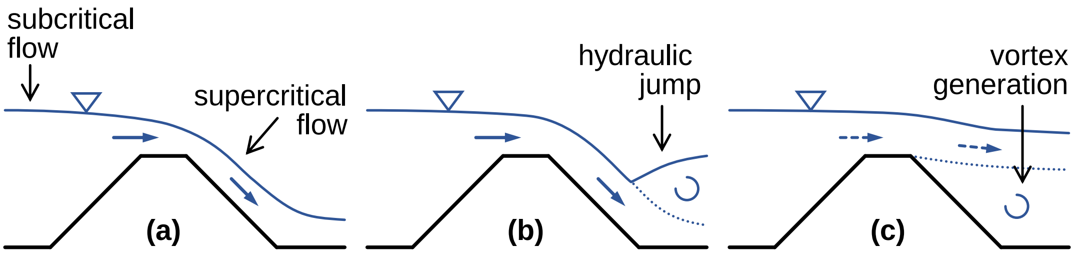

Figure 6. Flow geometry of overflowing tsunamis based on the classification presented by Hom-ma (1940).

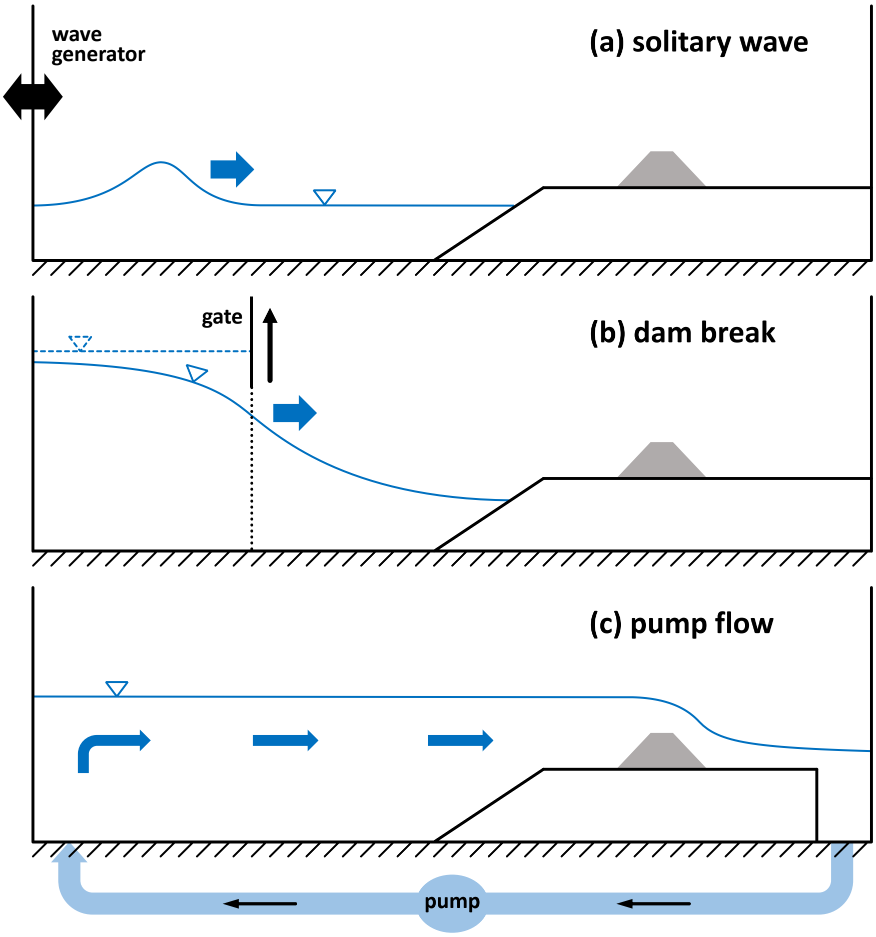

Figure 7. Three types of tsunami generation methods: (a) solitary wave, (b) dam break flow, (c) pump flow.

Settings of Laboratory Investigations

The laboratory investigations were carried out in a wave flume (about 12 m long ×0.4 m wide × 0.6 m wide) at Waseda University, Japan. In the flume, 1:10 slope and horizontal sections were installed as a fixed bed condition, as shown in Figure 8 (a). A 10 cm high stainless coastal dyke model was attached on the horizontal section, as shown in Figure 8 (b). The investigations were scaled with Froude similitude at a length scale of 1:50. After filling the flume with water, circulated flow was generated using a pump. By controlling the initial depth of the water in the flume and flow rate, different types of overflowing tsunamis shown in Figure 6 could be generated. For example, in the case of an initial depth of 15 cm, type (a) flow was generated with flow rate per unit width of 0.054 m^2/s, type (b) flow was generated with flow rate per unit width of 0.040 m^2/s, and type (a) flow was generated with flow rate per unit width of 0.011 m^2/s (the results of these cases were explained below).

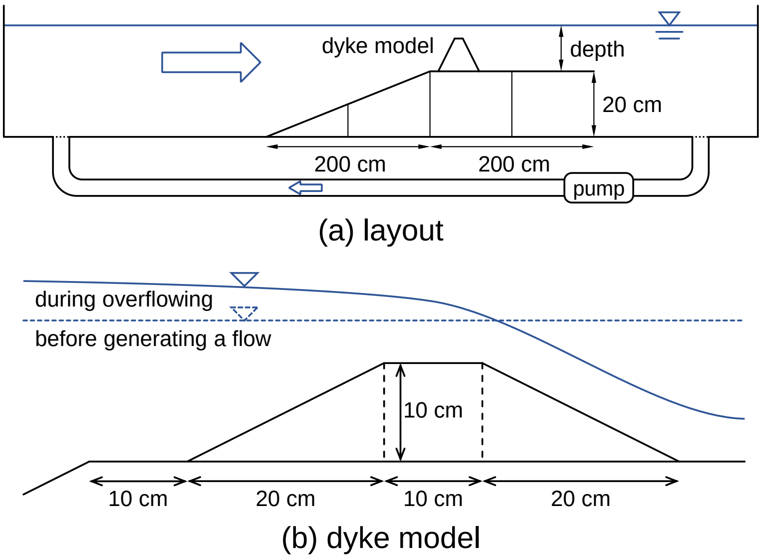

Figure 8. Settings of laboratory investigations. The upper panel shows the cross-sectional view of the flume and the lower panel shows the cross-sectional view of the dyke model.

To understand the hydraulic characteristics of each flow geometry, the velocity field around the dyke model were visualized using a sheet of laser light with particles in the water and the pressure acting on the dyke model surface was measured using pressure transducers.

Velocity Field around Dyke Model

The velocity field around the dyke model for each flow geometry was analyzed qualitatively by using visualization technic (see Figure 9). In type (a) and (b), the supercritical flow was generated along the dyke model surface. On the other hand, in type (c), the supercritical flow was not generated and the velocity near the dyke model surface was lower than the upper flow. These results indicate that from the point of view of the velocity field, the high velocity flow along the dyke surface observed in type (a) and (b) can cause scouring failure.

Pressure Acting on Dyke Model

The pressure acting on the dyke model surface was measured at 6 points with a sampling frequency of 200 Hz. Figure 10 shows that the water surface and the acting pressure for each flow geometry. The pressure plotted in the figure is the mean pressure between 20 to 30 seconds after starting the pump attached to the wave flume (during this period, the flow was stable). In type (a) and (b), the centrifugal force due to the curved flow caused the different pressure profile on the landward slope, compared to type (c). On the top of the landward slope, the pressure was lower, and on the toe of the landward slope, the pressure was higher. These results indicate that the non-uniform pressure profile on the landward slope in type (a) and (b) can cause the instability of concrete panels covering the core of the dyke.

NUMERICAL EXPERIMENTS

Governing Equations and Numerical Scheme

In the numerical experiments, the flow field is solved by a one-phase (liquid-phase) Large Eddy Simulation (LES) model which is applied to a laboratory scale. The governing equations are the spatial filtered Navier-Stokes equations along with the continuity equation,

$$\frac{\partial \overline{u_i}}{\partial t} + \overline{u_j}\frac{\partial \overline{u_i}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \nu \frac{\partial^2 \overline{u_i}}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j}\left(\tau_{ij}\right) + g_i \tag{1}$$

$$\frac{\partial \overline{u_j}}{\partial x_j} = 0 \tag{2}$$

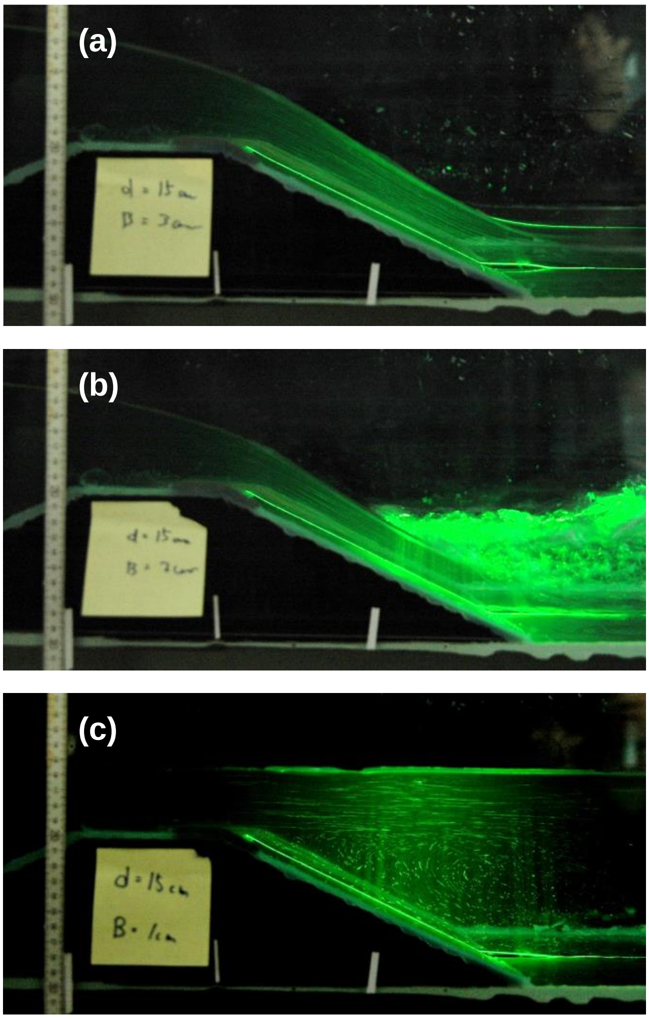

Figure 9. Velocity field visualized with a sheet of laser light. (a), (b), and (c) correspond to the classification explained in Figure 6.

where u_i is the velocity component, t is time, x_i is coordinate spacing, ρ is the density of fluid, p is the pressure, v is the kinematic viscosity, g_i is the gravitational acceleration, τ_{ij} is the sub-grid-scale (SGS) stress. The Smagorinsky model (Smagorinsky, 1963) is used to estimate the SGS stress.

The Cubic Interpolated Pseudo-particle (CIP) method (Yabe et al. 1990) is employed to solve the governing equations and the Successive Over-Relaxation (SOR) method is employed to solve the pressure equation. The free surface position is calculated using the density function method. If a grid cell is filled with water, the density function f takes 1, and f takes 0 with no water in a grid cell. The free surface is located in a grid where the density function is 0.5. The density function is described by the equation below, which is calculated using the CIP method:

$$\frac{Df}{Dt} = 0 \tag{3}$$

The grid size applied in the calculation is 1 cm in all three directions, with non-slip conditions applied to the bed and lateral boundaries. The flow in the computational domain is generated on the offshore boundary by giving inflow.

In order to observe a change in flow characteristics, a slope is attached behind a dyke to represent a hill which allowed the water to accumulate, as shown in the case of the coastal dyke in Kuji City, Iwate Prefecture during the 2011 Tohoku Tsunami.

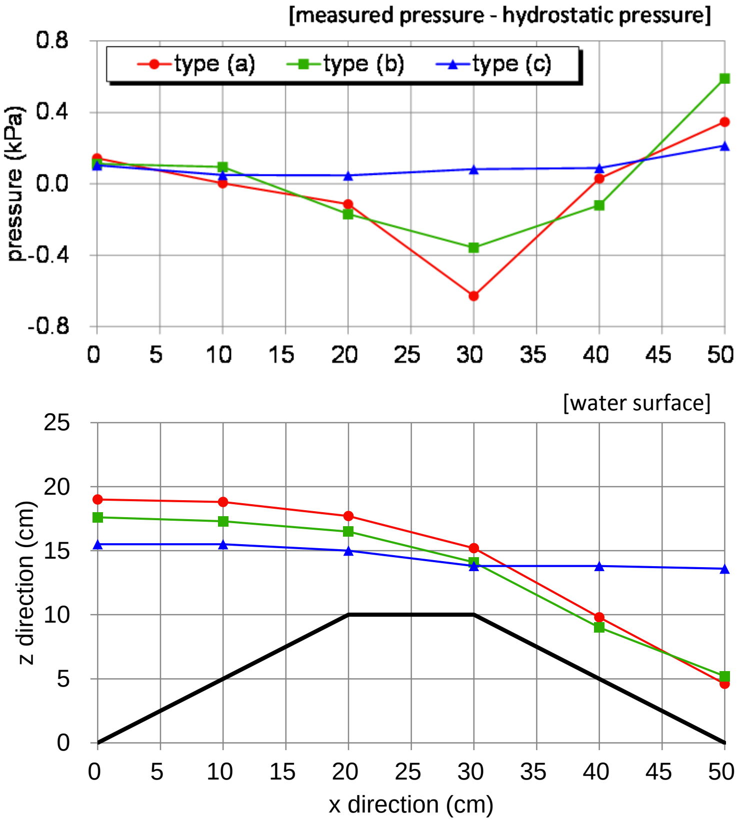

Figure 10. Water surface and pressure acting on the dyke model surface for each flow geometry.

Results and Discussion of Numerical Experiments

Figure 11 shows that flow geometry gradually changes, as the water accumulates behind the dyke. Thus, it is necessary to reproduce time-dependent flow around coastal dykes when considering overflowing tsunami effects on dykes. First, flow geometry is similar to type (a), in which the supercritical flow is generated on the landward slope. After the water depth behind the dyke becomes almost same as the dyke height, flow geometry is similar to type (c), in which the flow velocity along the dyke surface is lower than the upper flow. These results indicate that it is necessary to reproduce time-dependent flow around coastal dykes when considering overflowing tsunami effects on dykes.

Based on the results of the laboratory investigations and numerical experiments shown in the present study, if the water depth behind a coastal dyke relatively quickly becomes high, the coastal dyke can more likely survive the overflowing tsunami event from the both points of views of velocity field and pressure around the landward slope. The possible solutions to create this condition is, for example, to have some obstructions, such as coastal forests and secondary dykes, and to make the landward slope milder. Thus, now it is necessary to evaluate the effects of these solutions to overflowing tsunamis on coastal dykes, by conducting laboratory investigations and numerical experiments.

CONCLUSIONS

After the 2011 Tohoku Tsunami, many studies on coastal dyke failure due to overflowing tsunamis have been conducted. In the present study, first, the characteristics of overflowing tsunamis on coastal dykes observed during the 2011 tsunami were described using field data. Then, flow geometry were discussed based on the classification presented by Hom-ma (1940). Finally, the relationships between the hydraulic characteristics of overflowing tsunamis around coastal dykes (velocity field and pressure profile) and coastal dyke failure were discussed in detail by means of both laboratory investigations and numerical experiments.

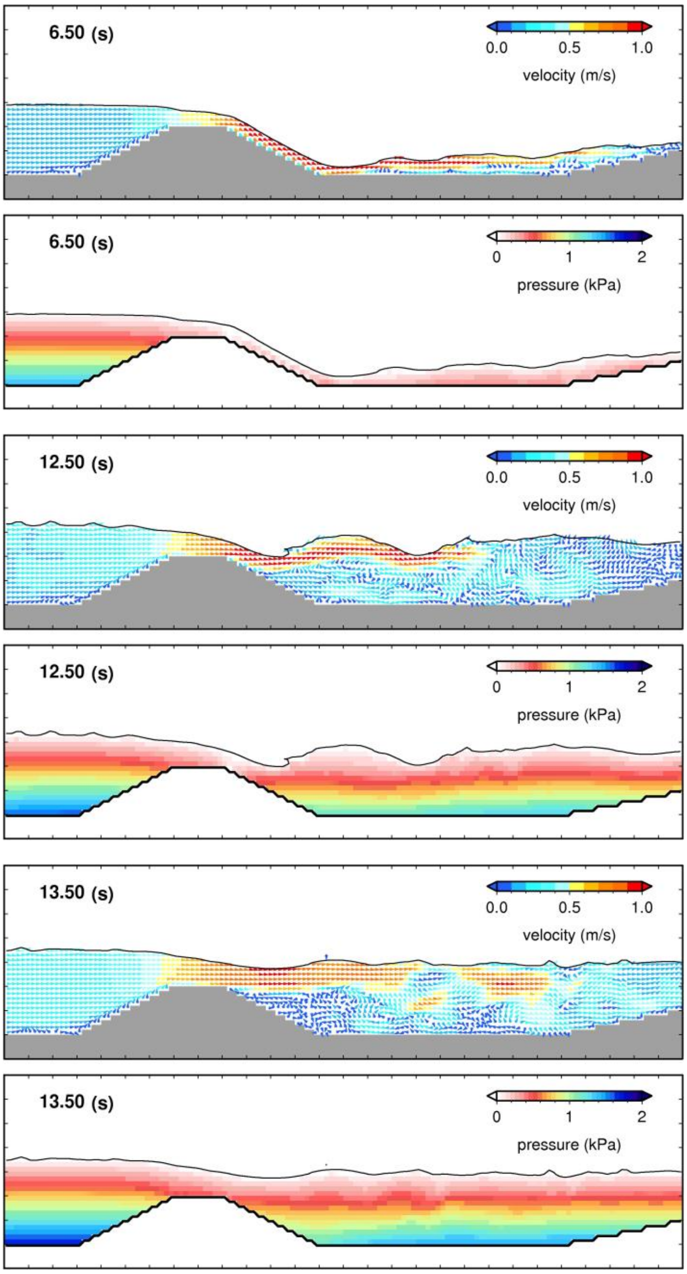

Figure 10. Results of the numerical experiments. The velocity and pressure fields around the coastal dyke are shown.

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