# EXPERIMENTS ON LOCAL SCOUR BEHIND COASTAL DIKES INDUCED BY TSUNAMI OVERFLOW

Yuta Mitobe[1], Mohammad Bagus Adityawan[1], Hitoshi Tanaka[1], Toshiya Kawahara[2], Tatsuaki Kurosawa[3] and Kazutaka Otsushi[4]

A lot of coastal dikes located along the Pacific Coast of Tohoku Region were severely damaged by the Great East Japan Earthquake Tsunami. In this study, hydraulic model experiments were conducted to understand characteristics of local scour at a landward toe of a coastal dike, which has been considered as a main cause of the failures of coastal dikes by the 2011 tsunami. A coastal dike model is fixed in a horizontal open channel with 4.5m length. Scouring of sandy bed behind the dike model under constant discharge is recorded by a video camera and temporal variations of sizes of the scour hole are extracted from the video images. In the experiments, two types of flow patterns, flow with hydraulic jump and submerged flow, were observed around the toe and it is found that the different flow types induce completely different processes of the local scouring, resulting in significant differences of scouring depths. Embedment of the landward toe induced the submerged-type flow to form deeper scour holes than those with a basic model of the toe without embedment. On the other hand, sheet-pile structure is found to be an effective measure against local scouring to delay start of suction of sand under the landward slope through the scour hole.

*Keywords: Tsunami overflow; coastal dikes; local scour; hydraulic jump*

## INTRODUCTION

Many coastal dikes were severely damaged by the 2011 Great East Japan Earthquake Tsunami. Fig.1 shows photos of one of a damaged coastal dike, which were taken about one month after the tsunami. The landward slope of the dike was completely destroyed, and a large scour hole was observed at the landward toe of the coastal dike. From the field surveys by Kato et al. (2012) and Tokida and Tanimoto (2012), the scours at the landward toes and the failures of landward slopes were found in many places along the Pacific Coast in Tohoku region, and width of the scours reached more than 20 m. The scours behind coastal dikes were induced by overflow of the tsunami, and sediments below the landward slopes were sucked out through the large scours at the toes resulting in collapse of the landward slopes. This pattern is considered as the most dominant pattern of failures of coastal dikes by the 2011 tsunami.

**Figure 1. Coastal dikes broken by the 2011 tsunami on Yamamoto Coast, Miyagi, Japan.**

Kato et al. (2012) showed also results of hydraulic model experiments on local scouring at landward toes of coastal dikes by tsunami overflow. However, detailed processes of local scouring at the landward toes have not been well understood yet. In order to understand characteristics of local scour at landward toes, further experiments are required to be done in various conditions. In addition, new countermeasures against tsunami overflow are required to be developed for the design of new coastal dikes. In this study, processes and characteristics of the local scouring at a landward toe of a coastal

[1] Department of Civil Engineering, Tohoku University, Aoba 6-6-06, Aoba-ku, Sendai, Miyagi, 980-8579, Japan
[2] Hokkaido Marketing Branch, Nippon Steel & Sumitomo Metal Corporation, North-2 West-4, Chuo-ku, Sapporo, Hokkaido, 060-0002, Japan
[3] Tohoku Marketing Branch, Nippon Steel & Sumitomo Metal Corporation, 6-1, Ichibancho 3-chome, Aoba-ku, Sendai, Miyagi, 980-0811, Japan
[4] Nippon Steel & Sumitomo Metal Corporation, 6-1 Marunouchi, 2-chome, Chiyoda-ku, Tokyo, 100-8071, Japan

dike were discussed through hydraulic experiments and effects of embedment and sheet-pile structure were tested as measures against the local scouring.

**EXPERIMENTAL SETUP**

A model of a coastal dike was put in a horizontal channel with 4.5m length, 15cm width and 61cm height (Fig. 2). Discharge of the channel was set in advance to be constant to keep constant overflow depths. 0.3mm sand was filled behind the coastal dike model and the deformation of the sand bed under the constant overflow depth was recorded by a video camera. Duration of the overflow is assumed to be 10min in real scale. The height and slope of the model were decided from the dimensional data of coastal dikes on Sendai Coast in Miyagi Prefecture; height $H$ = 5.2m from the ground level and slope = 1/2. The scale of the model was 1/26 (Fig. 2a) for the cases with smaller overflow depths, and 1/52 (Fig. 2b) for experiments with higher overflow depths. Range of overflow depths $h$ was 3.8~11.2cm (1~2.9m in real scale) for middle scale (1/26) model and 3.8~15.6cm (2~8m in real scale) for small scale (1/52) model (Table 1). Recorded images were rectified by projective transformation to get images referenced to the real $x$-$z$ coordinate system (Fig. 3). Bed shapes were extracted from the rectified images.

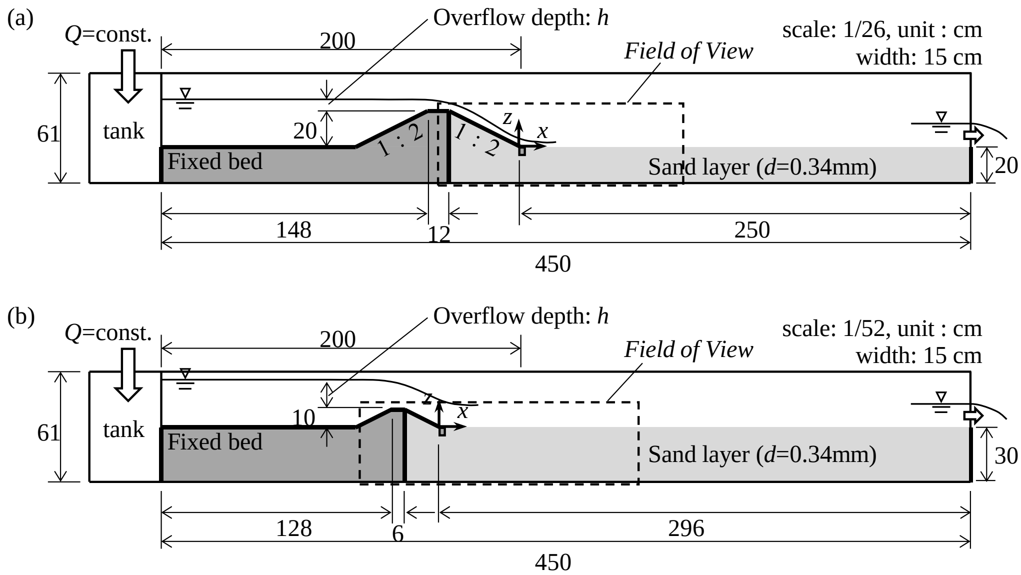


**Figure 2. Experimental setup. (a) middle scale (1/26) model, (b) small scale (1/52) model.**

**Table 1. Experimental condition. Values in parentheses are real scale values based on the model scale.**

| case | scale | Overflow depth $h$ (cm) | | Critical depth $h_c$ (cm) | Structure of landward toe |
|---|---|---|---|---|---|
| 1-1 | 1/26 | 3.8 | (1 m) | 3.3 | 1 |
| 1-2 | 1/26 | 7.7 | (2 m) | 6.8 | 1 |
| 2-1 | 1/26 | 3.8 | (1 m) | 3.3 | 2 |
| 2-2 | 1/26 | 7.7 | (2 m) | 6.8 | 2 |
| 2-3 | 1/26 | 11.2 | (2.9 m) | 10.1 | 2 |
| 2-4 | 1/52 | 3.8 | (2 m) | 3.4 | 2 |
| 2-5 | 1/52 | 9.6 | (5 m) | 8.9 | 2 |
| 2-6 | 1/52 | 15.4 | (8 m) | 14.5 | 2 |
| 3-1 | 1/26 | 3.8 | (1 m) | 3.3 | 3 |
| 3-2 | 1/26 | 7.7 | (2 m) | 6.8 | 3 |
| 3-3 | 1/26 | 11.2 | (2.9 m) | 10.1 | 3 |
| 4-1 | 1/26 | 7.7 | (2 m) | 6.8 | 4A |
| 4-2 | 1/26 | 7.7 | (2 m) | 6.8 | 4B |


**Figure 3. An example of recorded images and the image referenced to real x-z coordinate system.**

Figure 4 shows structures of the landward toe of the coastal dike model. A concrete foundation of 1m height and 1m width is usually located at a toe of a coastal dike in Japan. At first, the foundation of the landward slope was not considered and the model without foundation was applied as a most simple model (see Fig. 4: Structure 1). Next, a block with 1m height and 0.5m width was fixed at the landward toe as a model of the foundation (Structure 2). Finally, the landward toe with the foundation was embedded in the sand layer (Structure 3). This structure is considered as a method to interrupt suction of the sand under the landward slope through the scour hole at the landward toe. The three different structures of the model were set respectively with the middle scale (1/26) model to see effects of the local structures of the landward toe on the scouring processes, and the model with the foundation was used as a basic structure for the cases with smaller scale (1/52) model in order to see the difference of the scouring processes with higher overflow depths.

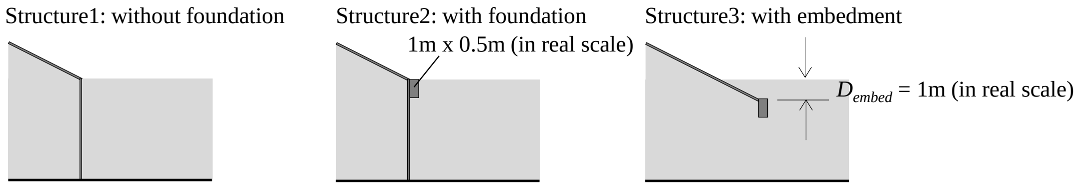


**Figure 4. Structures of the landward toe of the coastal dike model.**

In addition, sheet-pile structure is also considered as a countermeasure against the local scouring in this study and the effect of the structure was tested with 1/26 scale model (Figure5). A vertical wall was fixed under the landward toe and the length of the wall was set to be 3.8cm (1m in real scale, corresponding to the height of the foundation) and 7.7cm (2m in real scale) as a case with a sheet pile. In both cases, foundation was not put at the landward toe in order to see only the effect of the sheet pile on preventing sand suction through the scour hole at the toe. Duration of the overflow was set to be enough long to see the sand suction in both cases.

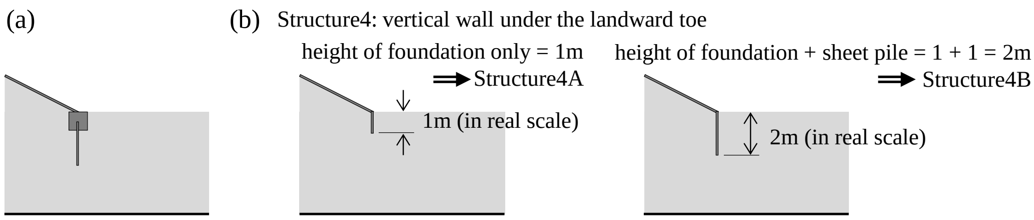


**Figure 5. Schematic image of sheet-pile structure (a) and the model of the sheet-pile structure in this experiment (b).**

## RESULTS

### Experiments with Coastal Dike Model without Foundation (Structure 1)

Figure 6 shows a rectified image and the extracted bed shapes with the 1/26 scale model without foundation (Structure 1 in Fig. 4). A bowl-shaped scour hole was formed and gradually developed by the flow into the scour hole directly from the landward slope. And deposition of the eroded sediment was observed just behind the scour hole. With higher overflow depth, *h*=7.7cm, larger scour hole was formed with the shape similar to that of the scour hole with smaller overflow depth, *h*=3.8cm. The depth of the scour hole with *h*=7.7cm (2m in real scale) became 20 cm, which is same as the height of the coastal dike model, in the middle of the experiment and reached the bottom of the channel.

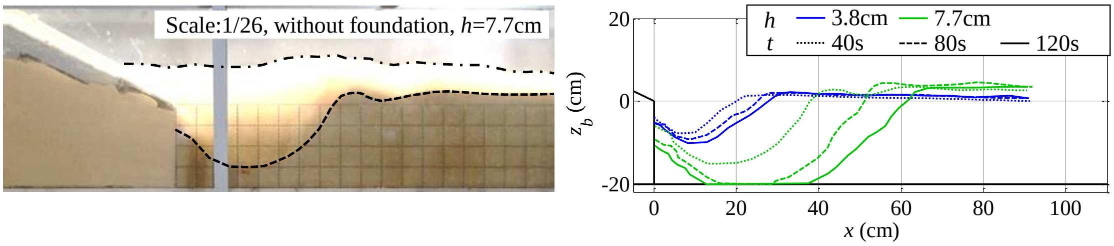


**Figure 6. Results of the cases without foundation at the toe (case1-1~1-2).**

**Experiments with Coastal Dike Model with Foundation (Structure 2)**

In the case with the model with the foundation (Structure 2 in Fig. 4), a hydraulic jump occurred on the toe during almost whole period of the experiment and the direction of the flow was changed to be horizontal or upward (Fig. 7). The reduction of vertical downward velocity at the toe resulted in formation of a shallow scour hole compared with the scour holes in the cases without foundation. The sand bed was eroded around the landing point of the jumping water and the shape of the scour hole was horizontally expanded. But even in the case with *h*=11.2 cm, the scour hole did not reach the bottom of the channel. The existence of the foundation itself has a significant role to reduce the depth of the scour hole.

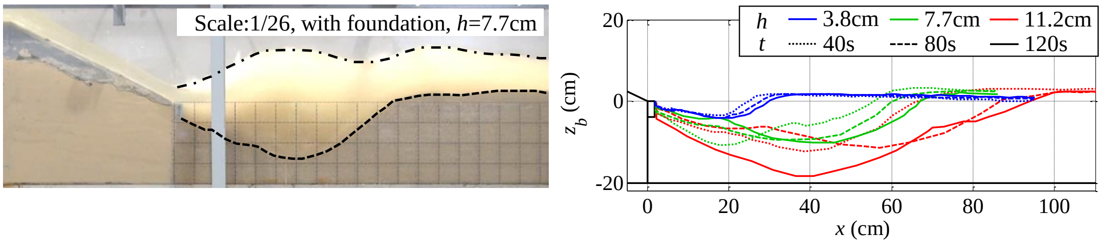


**Figure 7. Results of the cases with foundation at the toe (case2-1~2-3).**

Figure 8 shows the results of the cases with small scale (1/52) model with the foundation. With *h*=3.8cm, which is corresponding to 2m in real scale condition, shallow scour hole was formed and the shape of the scour hole was similar to the shape in the case with 1/26 scale model with *h*=7.7cm (Fig. 7), which is also corresponding to 2m in real scale. However, with higher overflow depths, *h*=9.6cm and 15.4cm, the shape of the scour hole was similar to the shapes without foundation in the experiments with 1/26 scale model (Fig. 6). Downstream water level in these cases was almost same or higher than the top of the coastal dike model and flow over the top of the dike plunged into the downstream water pool soon after the overflow. That induces the flow pattern similar to the cases without foundation and also causes the formation of the bowl-shaped scour holes like those of the scour holes without foundation.

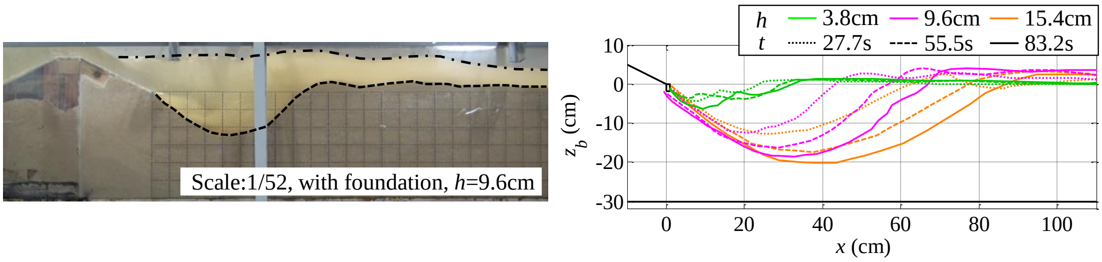


**Figure 8. Results of the cases with higher overflow depth (case2-4~2-6).**

**Experiments with Coastal Dike Model with Embedment (Structure 3)**

Figure 9 shows the results of the cases with embedment of the landward toe (Structure 3 in Fig. 4). In these cases, a hydraulic jump was not observed, and bowl-shaped scour holes similar to the scour holes in the cases without foundation (Fig. 6) were formed. In these cases with embedment, position of the foundation at the landward toe was lower than the cases without embedment. In addition, deposition behind the scour hole occurred also in the cases with embedment. Because of relatively higher downstream water level to the foundation, flow on the landward slope plunging into the downstream water pool before reaching the foundation at the toe. That caused the formation of the flow pattern without a hydraulic jump at the toe and also the formation of the scour hole similar to the scour hole in the cases without foundation. Compared with the cases with the basic structure (with foundation and without embedment: Fig. 7), larger scour holes were formed and the scour hole with *h*=11.2cm reached the area under the foundation.

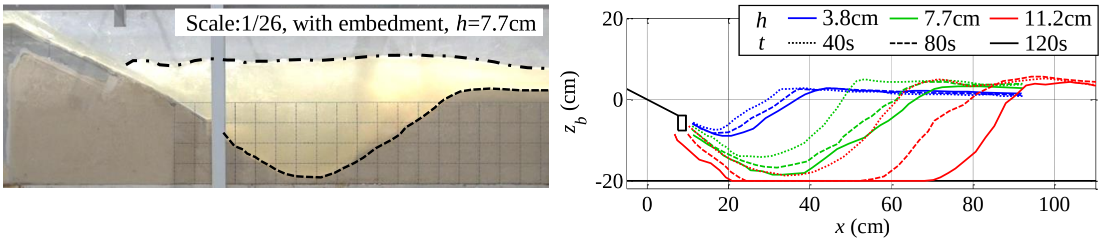


**Figure 9. Results of the cases with embedment at the toe (case3-1~3-3).**

**Relationship between Overflow Depth and Sizes of Scour Holes**

Figure 10 shows the relationship between overflow depth and sizes of the scour holes at the end of the experiments, the time corresponding to 10min from start of overflow in real scale condition. The scour depth in cases without a foundation (Structure 1) and cases with embedment (Structure 3) was more than twice of the depth in cases with a foundation at the end of experiments. Concrete foundations of coastal dikes have a significant effect on reduction of scour depth. On the other hand, there was almost no difference on width of the scour holes in the cases with different structures of the landward toe.

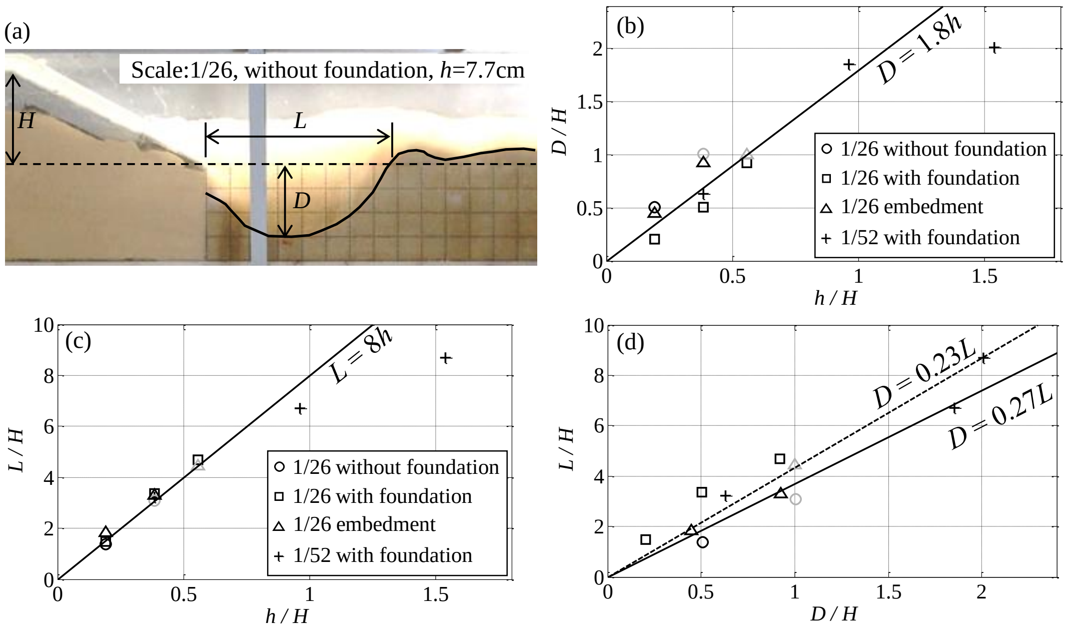


**Figure 10. Relationship between overflow depths and sizes of scour holes. Definitions of depth *D* and width *L* of the scour hole are shown in (a). Dot line and Solid line in (d) show the empirical relationship based on the sizes of the scour holes observed after the 2011 tsunami by Tokida and Tanimoto (2012). Gray markers: results of the cases in which the scour holes reached the bottom of the channel.**

Both of depth and width of scour holes increase almost in proportion to overflow depth until *h/H*=1, and ratios of the depth and width of scour holes to overflow depth are about 1.8 and 8 respectively. On the other hand, their rate to overflow depth were relatively smaller in the case with highest overflow depth (*h/H*=1.5). In this case, water level near the toe was higher than the height of the dike and water cushion was formed to reduce fluid force acting on the sand bed.

Figure 10(d) shows the relationship between the depth and the width of the scour holes. According to the field observation after the 2011 tsunami by Tokida and Tanimoto (2012), ratio of the depth to the width behind coastal dikes induced by the 2011 tsunami was about 0.23 on average and about 0.27 for the deepest cases. The ratio of our experimental data shows the good agreement with the ratio based on the field observations. It is impossible to directly convert results of model scale experiments with movable bed to real scale values because of the limitation of the material to be used as the bed sediment, but the agreement suggests that scouring processes measured in this study is to some extent similar to real scale phenomena.

### Temporal Variations of Depth and Width of Scour Holes

Figure 11 and 12 show the temporal variations of the width and the depth of the scour holes with 1/26 scale model and 1/52 scale model respectively. In all cases, the width of the scour holes almost monotonically increased with time, while the increase rate of the width was getting smaller with time. In the cases without foundation or with embedment, the depth of the scour holes also increased monotonically. However, in the cases with foundation, the depth of the scour holes decreased several times in each experiment.

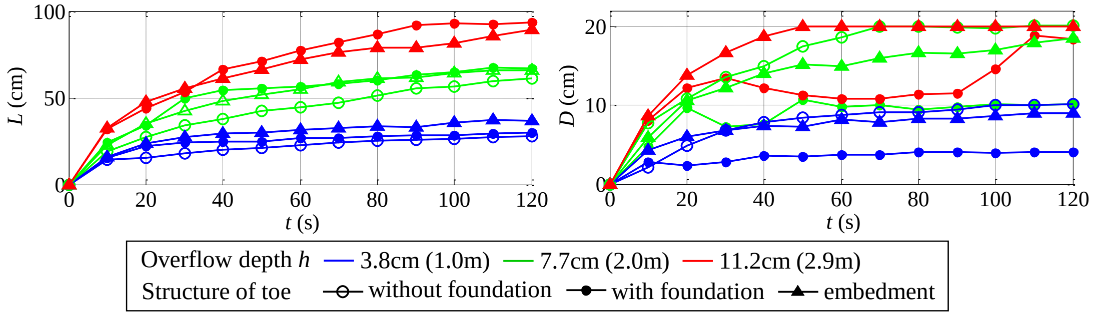


**Figure 11. Temporal variations of the width and the depth of the scour holes with 1/26 scale model.**

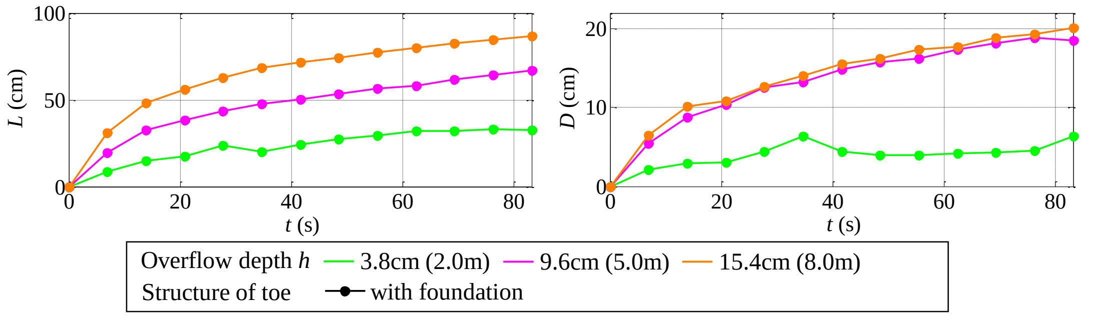


**Figure 12. Temporal variations of the width and the depth of the scour holes with 1/52 scale model.**

As explained in the previous sections, two different types of the flow structures, hydraulic jump (see Figure 13: Type1) and submerged flow (Type2), were observed through the experiments and they induced different sizes of the scour holes. To see the relationship between the flow types and scouring process, water level distributions are also extracted from the video images.

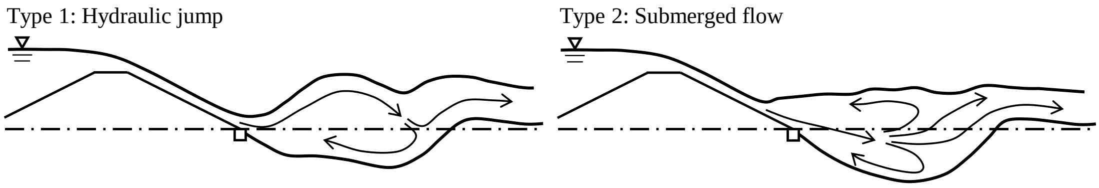


**Figure 13. Two typical flow structures observed in the experiments.**

Figure 14 shows spatial and temporal distributions of the extracted water level $\eta(x,t)$ and bed elevations $z_b(x,t)$. In the case without foundation, in which monotonic increase of the size of the scour hole was observed, trend of the spatial distribution of the water level was stable in one state and getting larger gradually. And the size of the scour hole is also gradually and monotonically increasing with keeping the trend of the spatial distribution. On the other hand, pattern of the spatial distribution of the water level in the case with foundation was not stable with time. Usually with a hydraulic jump on the toe, $x$=0cm, water level on the toe itself must be enough smaller than maximum downstream water level, which appears just behind the landward toe. Almost all time during the experiment in this case, the water level at the toe was lower than 5cm, while the maximum water level was more than 10cm, showing that the hydraulic jump occurred in this period. However, sudden increase of the water level on the toe can be seen in Figure 14(b) at $t$ = about 40s. This sudden increase of the water level at the toe indicates the transition of the flow types from the flow with hydraulic jump (Type1) to submerged flow (Type2), and sudden decrease after that indicates the transition of the flow type back to the flow with hydraulic jump. At the time same as the transition of the flow to Type2, position of the deepest area of the scour hole suddenly became closer to the toe and the scour depth became deeper. And after the transition back to Type1 flow, the deepest area was getting further and the scour depth became slightly shallower. This result shows that the two different flow types cause completely different processes of the scouring around the landward toe and the transition of the flow type results in the fluctuation of the temporal variation of the scour depth.

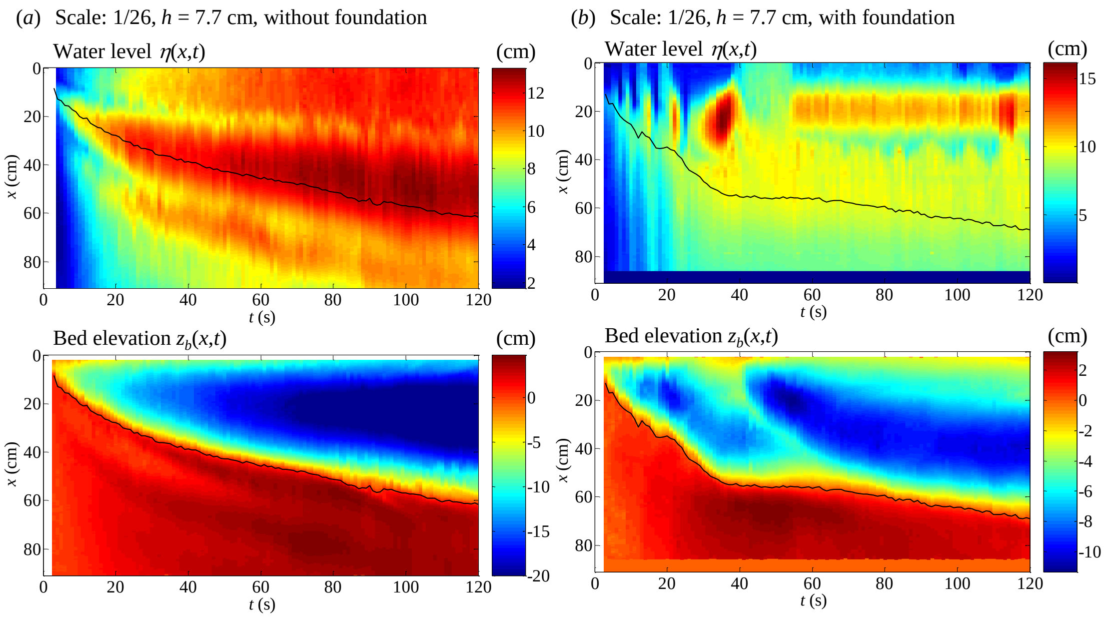


**Figure 14. Spatial and temporal distributions of water level and bed elevation.**

## Effect of Sheet-Pile Structure (Structure 4)

Finally, the effect of the sheet pile structure was tested with same setup of the experiment. Figure 15 shows the recorded images in the cases with different lengths of vertical walls under the landward toe. In both cases, erosion under the landward slope was developed from the landward toe after the scour hole reached the lower end of the vertical wall. However, the time when suction started in the case with the longer vertical wall was more than twice of the time in the case with the vertical wall with height of the foundation only. This result clearly shows that the sheet-pile under the landward toe can delay the start of the sand suction significantly and reduce the possibility of the collapse of the landward slope.

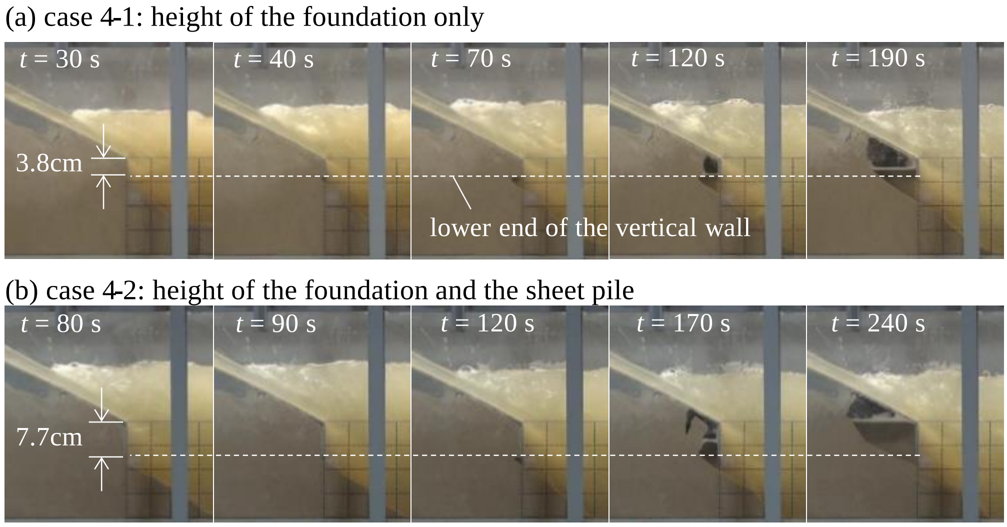


**Figure 15. Results of the cases with the vertical wall under the toe (case4-1~4-2).**

## CONCLUSIONS

In this study, two different types of flow patterns around the landward toe were observed; hydraulic jump and submerged-type flow. The different flow types induce completely different processes of scouring, resulting in different depth of the scour holes. Conditions which decide the flow patterns need to be discussed in detail with further researches to understand temporal characteristics of local scour induced by tsunami overflow.

A concrete foundation at a landward toe of a dike has significant effect to reduce scour depth through formation of hydraulic jump type of flow. On the other hand, with embedment of the landward toe, submerged type of flow is induced by high downstream water level compared with the foundation at the toe, and forms deeper scour holes. Local structures around a landward toe have significant effects on processes of local scouring behind coastal dikes, and they should be properly considered in physical or numerical experiments on local scouring behind coastal dikes.

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