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SCOURING ON BOULDER BED BEHIND A SEAWALL DUE TO TSUNAMI

Warniyati[1,3], Radianta Triatmadja[2*], Nur Yuwono[2]

[1]Doctoral Student at Department of Civil and Environmental Engineering Universitas Gadjah Mada, Yogyakarta, Indonesia
[2]Department of Civil and Environmental Engineering Universitas Gadjah Mada, Yogyakarta, Indonesia
[3]Department of Civil Engineering, Engineering Faculty, Universitas Pattimura, Ambon, Indonesia
*Corresponding author: radianta@ugm.ac.id

ABSTRACT

Based on post-tsunami surveys following the Japan Tsunami 2011, the most prominent seawall damage was due to scours that was formed behind the seawall. The downstream of a seawall is an essential part of the seawall stability which must be securely protected from the tsunami overflow in order to maintain seawall stability. The scouring process on boulder bed behind the seawall and the method to reduce the scour was investigated in a laboratory experiment. The scouring process and scour depth are assumed to be closely related with the tsunami hydrograph. Hence, the tsunami hydrograph was also modelled to imitate an existing reported tsunami hydrograph. The results showed that both the maximum scour depth and scour length are increased with the length of tsunami overflow or the hydrograph. The bed material behind the seawall was transported downstream. The transport of boulder can be blocked by a set of vertical screens installed in between the boulder bed. This method is found to be effective in reducing both the scour depth and scour length. The reduction of maximum scour depths are approximately 50%, 43%, and 34% for dimensionless screen distance of 5.33, 6.67, and 8.0, respectively, while the scours length for all various screen distance is reduced for about 25 %. Other than that, it is important to note that the scour depth exactly behind the seawall reduced significantly. This signify that, the screen also effective in keeping in place the bed material that directly support the seawall from sliding force and turning moment and thus secures the stability of the seawall.

Keywords: *tsunami, overflow, scour, screen, mitigation*

1 INTRODUCTION

Tsunami is one of the most unpredictable natural disasters that may destroy many structures in coastal area. When a tsunami reaches a beach, it slows down but increases in height due to the reduce water depth (Triatmadja 2010). The run-up of a tsunami in land with extreme energy may severely destroy the inundated land area. A seawall may be constructed to protect the land area from the tsunami attack, such as in the eastern Japan coastal area. The seawall was constructed to protect the essential coastal land and facilities from big waves including typhoons, storm surges, and tsunami that frequently occurred (Fraser et al. 2013).

A tsunami occured on 11 of March 2011 in east Japan that destroyed significant amount of coastal defense in the Japan eastern coast. The demolition of the seawall that was designed as tsunami protection lead to even greater destruction. Based on the many post-tsunami field surveys, there were many destroying patterns of the seawall (Ishikawa et al. 2011, Kato et al. 2012, Mikami, et al. 2012, Suppasri et al. 2013, Sato and Okuma 2014, Jayaratne et al. 2016). The most prominent seawall damage was due to scour that was formed behind the seawall (Kato et al. 2012, Yeh et al. 2013). The tsunami overflowed the seawalls and destroyed many parts of the seawalls. The overflow induced high-speed jet flow behind the seawall and scoured the seawall foundation. Such scour may endanger the seawall stability (Triatmadja et al. 2011, Kato et al. 2012, Suppasri et al. 2013, Jayaratne et al. 2016). When the seawall collapsed due to instability, tsunami could wash out the land and create disaster just like a dam break disaster.

Researches on the countermeasure of scour behind a seawall have been conducted using both physical modeling and numerical modeling. Some of the results are as follows. The tsunami energy can be broken by applying an artificial trench behind the seawall to reduce the scour depth (Tsujimoto et al. 2014). Toe protection can be applied behind the seawall to change the flow direction at the landing point to be horizontal and upward in order to horizontally expand the scour and reduce the scour depth (Mitobe et al. 2014). In the case of a breakwater, a concrete block namely Supleo Frame can be applied behind the seawall as environmentally friendly protection from the scour due to tsunami overflow (Matsushita 2012, Yoshizuka et al. 2018). A horizontal plate was proposed as a method to reduce scour depth due to tsunami overflow behind a breakwater (Sulianto et al. 2014).

Based on the above researches, it is apparent that the downstream of a seawall is an essential part of seawall which must be protected from the tsunami overflow in order to maintain its stability. A heavy material configuration may be used as a protective material of seawall downstream due to the tsunami overflow, although in an extreme condition, scour may still occur. The effort to reduce the scour at the toe protection of seawall should be considered. Warniyati et al. 2019 studied the effectiveness of vertical screen installation within the boulder bed behind a seawall. The results indicates that such screen was capable of reducing the scour depth. This paper explains the mechanism and characteristics of scouring behind the seawall related to tsunami hydrograph. The effects of various screen installations in reducing the scour are also explained.

2 THEORETICAL BACKGROUND

When a water jet impinging on granular bed in a certain jet velocity, the jet energy starts to scour the bed to form a hole. Under a continuous action of the jet, the scour is getting deeper until it reaches a dynamic equilibrium (Gioia and Bombardelli 2005). The equilibrium scour is reached when the rate of scouring comes to zero (Bormann and Julien 1991). On the scour below a vertical drop, the equilibrium scour depth increase with increasing densimetric Froude number, while the increase of diameter and tailwater reduce the scour depth (Dey and Raikar 2007). In the scouring process due to tsunami overflow, the initial density of granular material has a significant effect. The higher is the initial density, the deeper is the maximum scour (Wang et al. 2016). Wang et al. 2016 also found that the overflow height also gives a significant effect on the maximum scour depth and that the scour depth is proportional to the overflow height.

The downstream scour of a seawall due to tsunami overflow are related to the following essential parameters where the boulder material was modelled using gravel material:

1. Overflow jet parameter (water densisty ρ, overflow height h_o, overflow time T_i)
2. Building parameter (seawall height h_b)
3. Gravel material parameter (diameter D_m, spesific gravity ρ_m, distance between screen L_c)

According to the above parameters, general expression representing the scour depth and scour length may be formulated as in Equation 1.

$$\emptyset = f(\rho, h_o, T_i, h_b, D_m, \rho_m, L_c) \tag{1}$$

Using dimensional analysis, the nondimensional parameters of scour depth and scour length are given in Equation 2.

$$\frac{d_s}{h_b}, \frac{L_s}{h_b} = f\left(\frac{L_c}{\Delta\, D_m}, T_i\sqrt{g h_d}\right) \tag{2}$$

where d_s is the maximum scour depth, L_s is the maximum scour length, $\Delta = (\rho_m - \rho)/\rho$ is the relative submerged particle, and $h_d = h_b + h_o$ is the initial head of the jet. With the above parameters, an empirical formula can be found through experimental works in the laboratory.

3 EXPERIMENTAL METHODS

3.1 Experimental Facilities

The experiment was conducted at the Hydraulics Laboratory of Civil and Environmental Engineering, Gadjah Mada University. The experimental facility consists of three parts. The first part is an overhead tank to store water that is equipped with a pipe network. The second part is a short flume to conduct the model test. The dimension of the flume is 9.2 m long, 0.8 m wide and 2 m high. The last part is a collecting tank to store the tsunami run-up water. In the pipe network, a gate with an electronic controller was installed to adjust the discharge of water from the overhead tank into the flume. The electronic controller can be programmed and operated at a certain speed and time delay to open or close the gate valve that makes the water discharge from the reservoir highly repeatable. In the short flume, a glass panel was provided at one side of the flume to observe the tsunami flow, its interaction with the seawall model, and the scouring process. In the collecting tank, a centrifugal pump was installed to return the water to the overhead tank before the model test is started. The photograph of tsunami generation facilities is shown in Figure 1. The design process of the facilities is available in Warniyati et al. (2019)

Figure 1. Photograph of tsunami generation facilities.

3.2 Bed Material Setup

A seawall model was placed in the middle of the flume. Gravel was placed behind the seawall model to simulate the boulder bed. The seawall model height at the upstream (h_s) was 0.16 m, the movable bed was 0.31 m below the seawall crest. In this case, the seawall height (h_b) is 0.31 m. The gravel material of (D_m) 0.025 m in diameter with density (ρ_m) of 2,500 kg/m^3 and was randomly placed at the downstream of the seawall. The schematic symbol of the flow and scour dimension in this research is shown in Figure 2.

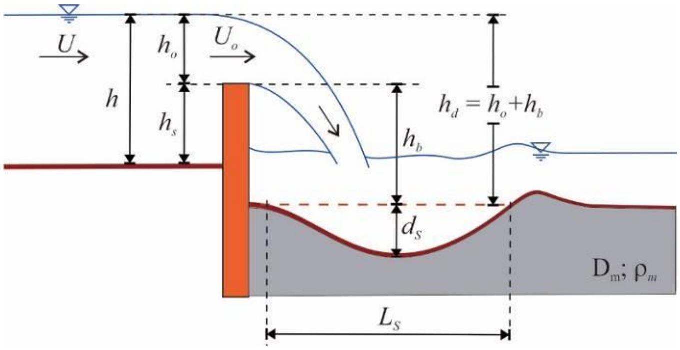
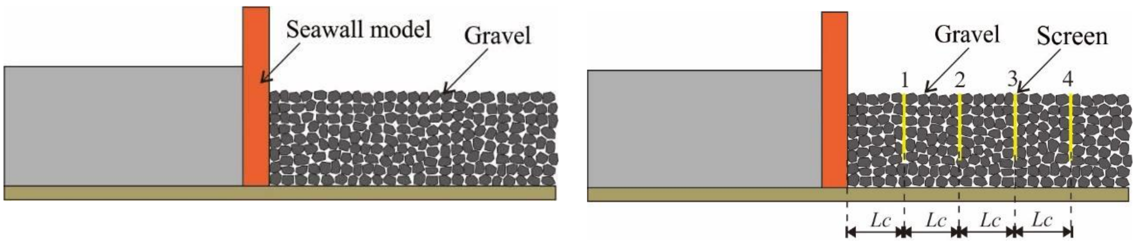


Figure 2. Schematic of symbol

The scouring tests were conducted in two scenarios. In the first scenario, the gravel was loose and was placed randomly behind the seawall. The second scenario was conducted to mitigate or reduce the scour. A set of wire meshes was installed vertically and parallel to the seawall along the movable bed part as screens. The wire meshes model were 0.3 m deep below the bed surface and were installed at a certain distance (L_c) along the movable bed starting exactly behind the seawall. The size of the screen was slightly less than the gravel to ensure that no gravel could pass through the screen. The schematic of the bed material and screen installation is shown in Figure 3.

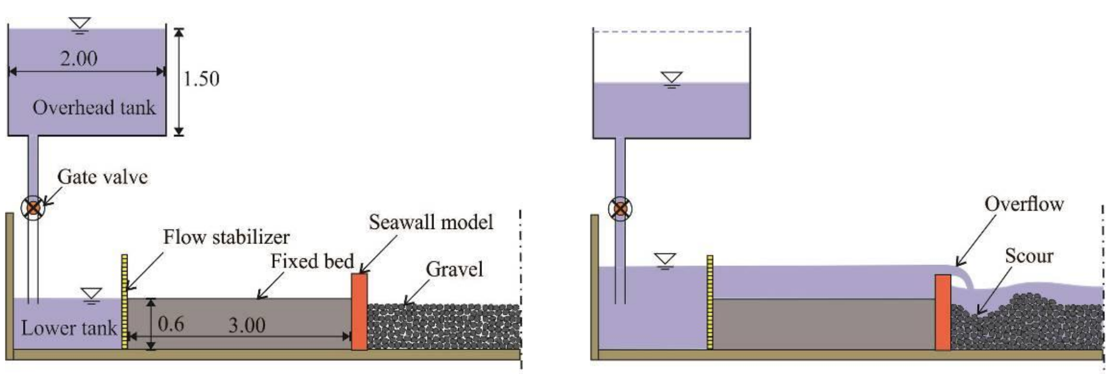


(a) Scenario 1 (without screen) (b) Scenario 2 (with screen)

Figure 3. Schematic of the bed material and screen installation

3.3 Tsunami Generation and Scouring Test

The simulation of tsunami and scour behind of a seawall is explained below referring to Figure 4. Before starting the simulation, the overhead tank was filled with water. By opening the gate valve at the pipe, volume of water was released from the reservoir into the flume. The lower tank's water elevation was maintained at the same level as the elevated fixed bed part before the simulation was started. The lower tank thus represented the sea while the fixed bed represented the land. The water level in the flume was increasing during the opening of the gate valve similar to the tsunami that arrived in land and was stopped by a seawall. After sometime water start overflowing the seawall when the water level is higher than the crest of the seawall model. The overflow continued depending on the tsunami hydrograph that was controlled by using the gate valve. Finally, the hydrograph decreased and then diminished representing the tsunami overflow hydrograph when the valve started closing. The generation of tsunami hydrograph is explained as follows.



(a) before the simulation started (b) during the simulation

Figure 4. Schematic of tsunami generation and simulation of scouring (unit in meter)

Many scenarios of flow discharges to generate tsunamis were applied. The release of water was controlled by adjusting the speed of opening, the percentage of opening, the delay before the gate was closed, and the speed of closing. The overflow height (h_o) was recorded during the simulation. The tsunami overflow was represented by a tsunami hydrograph, which is the relation of time and tsunami overflow. The tsunami hydrograph was similar to the historical tsunami hydrograph observed during the Japan tsunami in 2011 by Fritz et al. (2012). The tsunami hydrograph in Figure 5 was applied in the simulation of the scouring process. In the tsunami hydrograph, *Ti* is the time duration from the start of the overflow to the inflection point. After that point, the overflow became small and reduced slowly with time. During the tsunami overflow, the inflection point was the most significant part of the tsunami attack on the seawall. Therefore, it is used to specify the tsunami hydrograph. The method to define the inflection point is described in Warniyati et al. (2019).

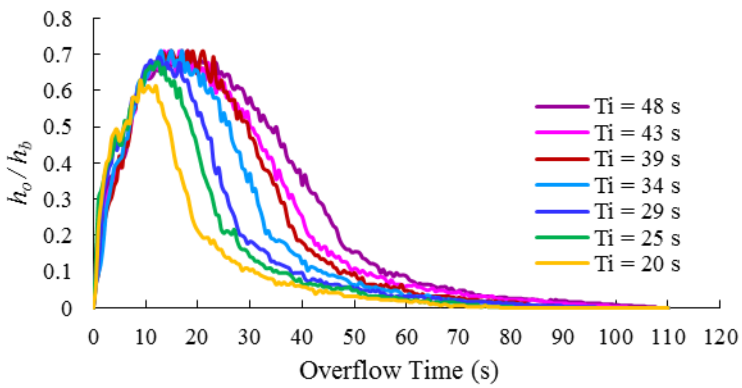


Figure 5. Overflow tsunami hydrograph

4 RESULTS AND DISCUSSION

4.1 Scour at Downstream of a Seawall

Scour behind a seawall started when the overflow jet started to remove the gravel material from the original position and dragged them downstream. When the overflow increased, the scour depth and width increased until a certain condition where the overflow could not scour the gravel bed any further. When the overflow significantly reduced, the overflow jet position shifted upstream and become closer to the seawall. Hence the gravel near the rear wall of the seawall were dragged into the scour that has been previously created (Warniyati et al. 2019). This mechanism resulted in deeper scour near the seawall which was not good in term of seawall stability.

The scouring process during the simulation can be explained based on the relation between tsunami hydrograph and the scour depth in Figure 6. At small overflow discharge (approximately after 2 second of overflow where h_o/h_b =0.2, the jet force could not move the gravel. As can be seen the value of d_s/h_b =0.0. At a certain overflow discharge h_o/h_b = 0.4, the jet force started to move the gravel and scoured the bed. The scour depth increased with the increasing overflow until the condition where the overflow hydrograph reached its maximum where the jet force and the scour depth reached its balance condition. Such condition was also affected by the increasing tail-water and water cushion above the scour hole. It can be seen in Figure 6, that the longer was the peak of the hydrograph, the longer was the constant (slightly fluctuating) scour depth. When the overflow decreased, the scour depth was reduced because the overflow jet dragged the gravel that were closer to the seawall into the scour hole. Hence the scour depth near the seawall increased in a relatively short time while the maximum scour depth was slightly reduced due to the incoming gravel material from the area next to the sea wall. The final scour depth was reached after the overflow hydrographs almost reached the inflection point. After the point of inflection, the jet force was unable to scour the bed and the scouring process stop. It can be inferred that the scouring process depends on the tsunami hydrograph.

The scouring process behind a seawall due to tsunami overflow is different from the scouring process behind or downstream of a river structure caused by a continuous flow such as weir (Dargahi 2003, Adduce and La Rocca 2006, Dey and Raikar 2007, Guan et al. 2019). The tsunami overflow occurred in a relatively short time and hence, the tsunami hydrograph affected the scouring process. The scouring process in this research is different from the previous researches on tsunami overflow that was conducted by Kato et al. (2012), Tsujimoto (2014), and Wang et al. (2016). The tsunami generation in those researches were using a pump system with continuous and constant flow discharge. Therefore, the application of the tsunami hydrograph in tsunami overflow and the scour process is more realistic when dealing with tsunami event.

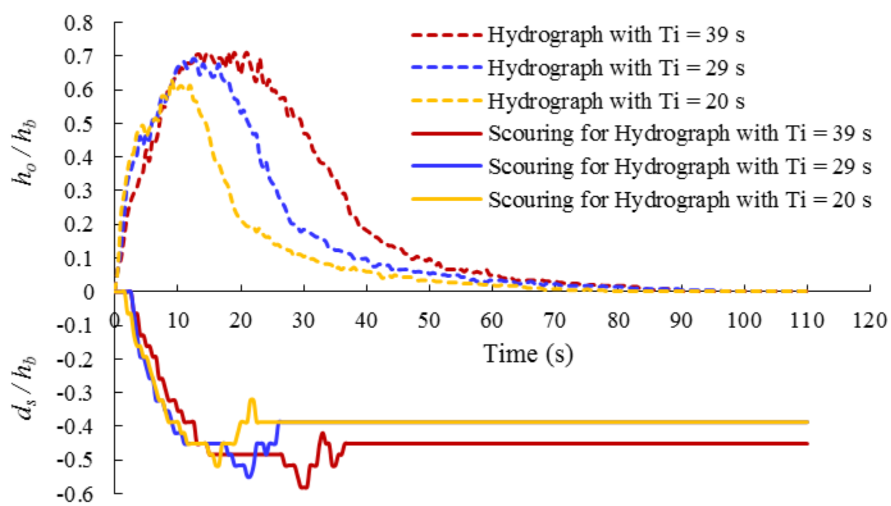


Figure 6. Relation of tsunami overflow and scour depth

4.2 Reduction of Scour Depth by Vertical Screens

It was observed during the experiment that, the jet flow initially created small scour hole in the movable gravel bed. The flow trasported the granular material downstream away from the scour hole and subsequently the jet force created deeper and large scour hole.

As the hole become larger and deeper, the turbulent flow in the scour hole should be able to lift the bed material from a deeper location in order to deepen the scour and move the bed material away. This was possible when the width of the scour was relatively large thus, creating milder slope of the scour where lifting the bed material was easier for the jet flow. Installing the screen limited the possibility of widening the scour hole and hence limited the possibility of the jet to create milder slope and deeper scour hole. The scouring process in both loose material (Case 1) and with screen installation (Case 2) are presented in Figure 7.

In Case 1, the gravel was transported downstream without restriction and were easily washed out downstream. Therefore, the scour increased as long as the jet force was able to lift the bed material. When the scour reached the maximum depth, the jet turbulence continued to drag the bed material downstream hence, the scour area was enlarged to reach the maximum scour length. In Case 2, the transport of the bed material was blocked by the screen. The gravel could only be dragged away by the flow when they were lifted above the top of the screen. This condition limited the scour depth since it was more difficult to lift the bed material within significantly less space (in between two screens) as the scour getting deeper. It was observed during the simulation that screen positions number 2, number 3 and number 4 effectively blocked the transport of the bed material.

As mentioned previously, when the overflow was finally reduced at the end of tsunami hydrograph, the overflow jet scoured the bed close to the seawall and the bed material were deposited in the scour hole that was previously created. In Case 1, the deeper scour adjacent to the seawall may endanger the stability of the seawall as can be seen in Figure 7 (left) at time 25 s. It may create a critical condition for the seawall stability. In the Case 2, the bed material were blocked by the screen at position number 1. The final scour nearby the seawall in Case 2 was almost negligible. Therefore, the seawall stability was maintained (see Figure 7 right).

Both maximum scour and final scour for various scenarios of the bed material arrangement are presented in Figure 8. In the Case 2, the screen installation was applied in three different distances with nondimensional distances ($L_c / \Delta D_m$) were 5.33, 6.67, and 8.0. The screens were installed along the movable bed in the area where the maximum scour length was formed during the experiment with no screen installed. It was clearly seen that the installation of the screens reduced both the scour depth and the scour length.

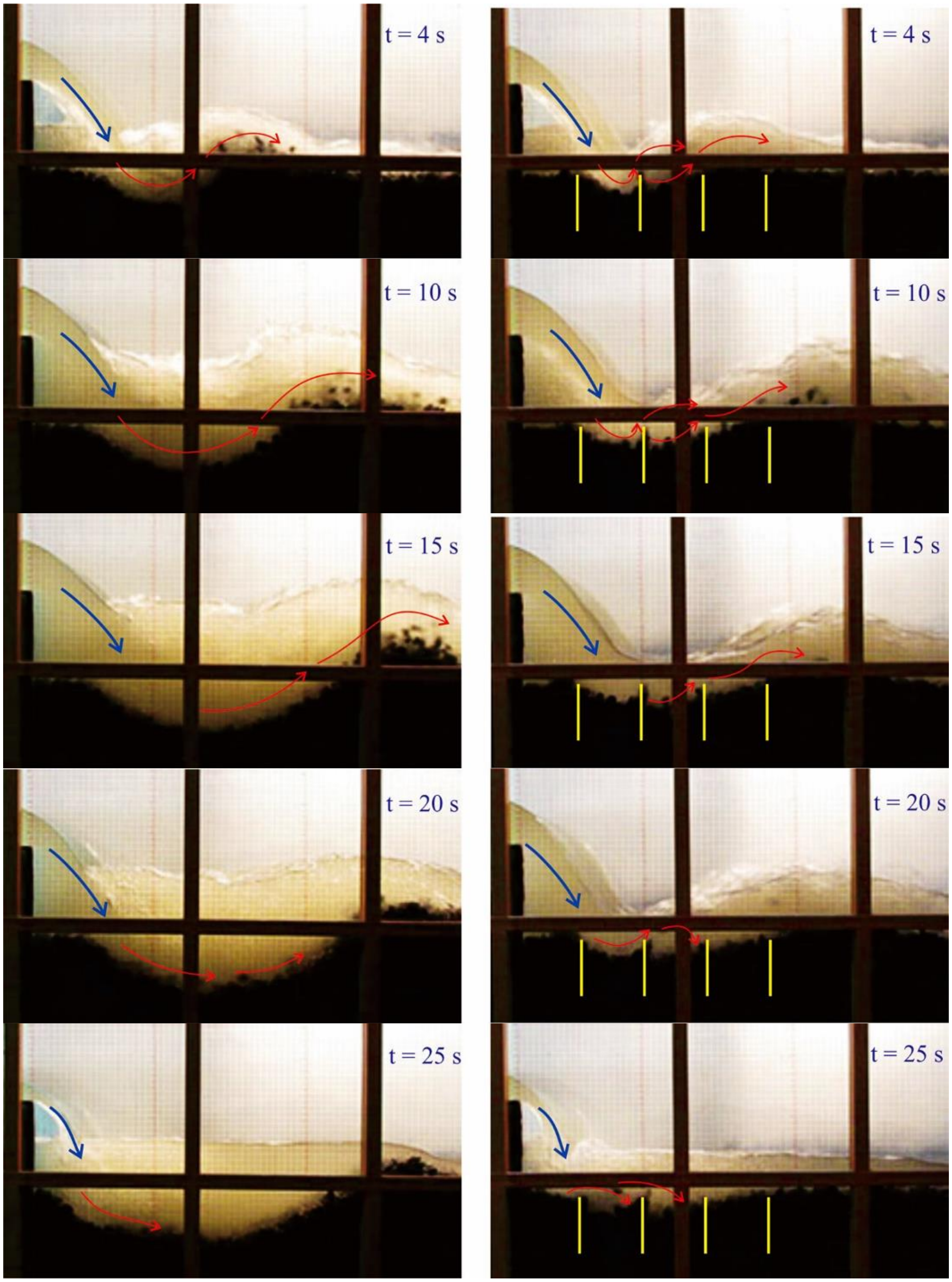


Figure 7. Scouring process of loose material without screen (left) and with a set of the screens for $L_c/(\Delta D_m) = 5.33$ (right). Blue arrows are the overflow jet, the red arrows are the directions of material transport.

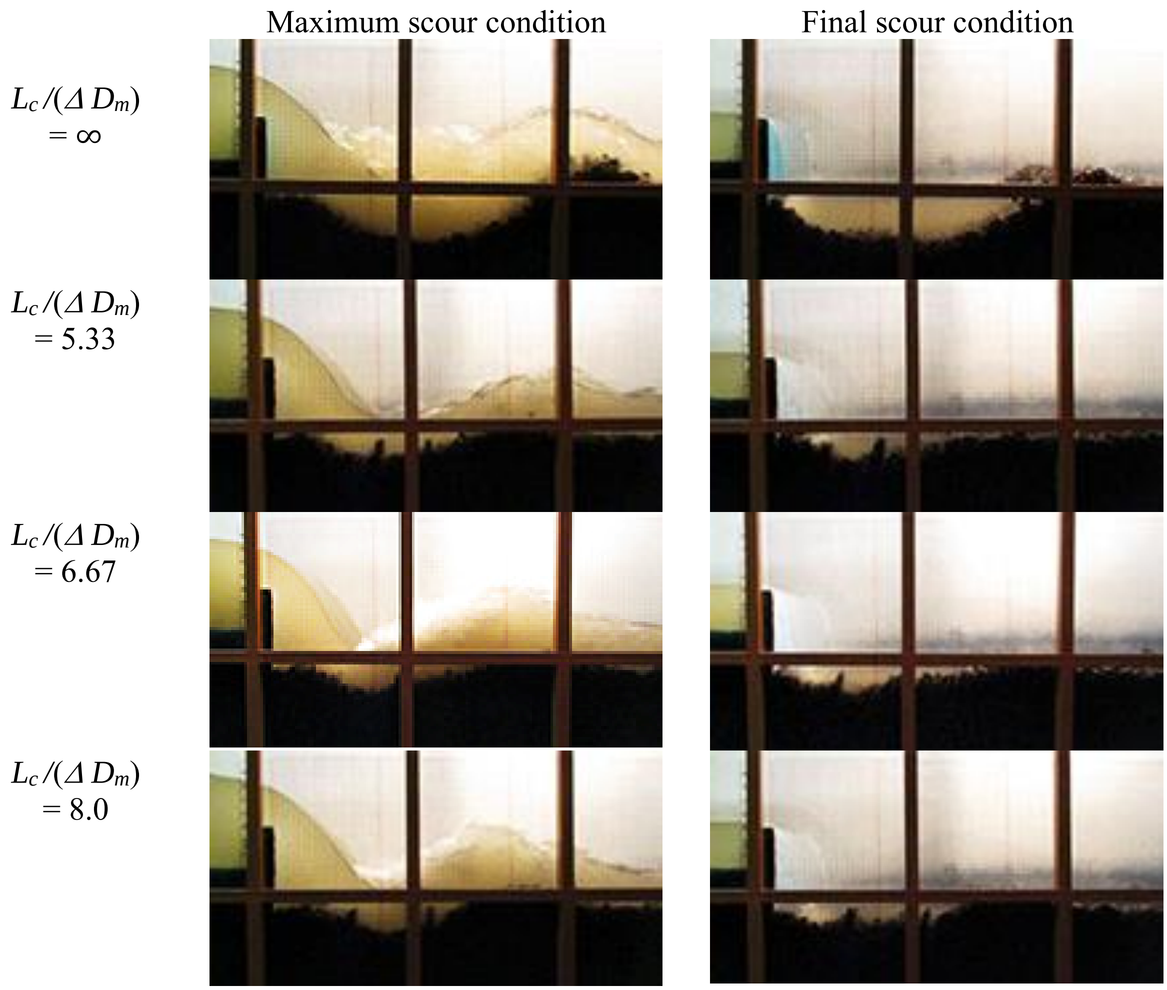


Figure 8. Maximum scour (left) and final scour(right) in various distances of the screens

The installation of the vertical screens within the bed material has been reported by (Warniyati et al. 2019) to significantly reduce the scour depths. In this research, it was found that the horizontal distance between the screen plays an important role to limit the vertical movement of the gravel and hence the scour depth. Referring to Equation (2), the effect of the screen on the scour depth and scour length are provided in Figure 9 and Figure 10. Figure 9 and 10 show that both the maximum scour depth and the scour length are gradually increased depending on the duration of the tsunami overflow.

Figure 9 reveals that the installation of the screen within the loose bed material significantly reduced the scour depth. The jet easily dragged the gravel and flushed them downstream to create longer scour holes. In Case 1 ($L_c/(\Delta D_m) = \infty$), the scour depth reached a half of the seawall height. In Case 2 ($L_c/(\Delta D_m)$ = 5.33, 6.67, and 8.0), the screen blocked the transport of bed material and reduced the scour depth. The average reduction of scour depth were about 50%, 43%, and 34% for $L_c/(\Delta D_m)$ = 5.33, 6.67, and 8.0 respectively. Figure 10 reveals that the total scour lengths are almost the same despite of the distances between the screens. The scour length reduction was about 25% from that of Case 1.

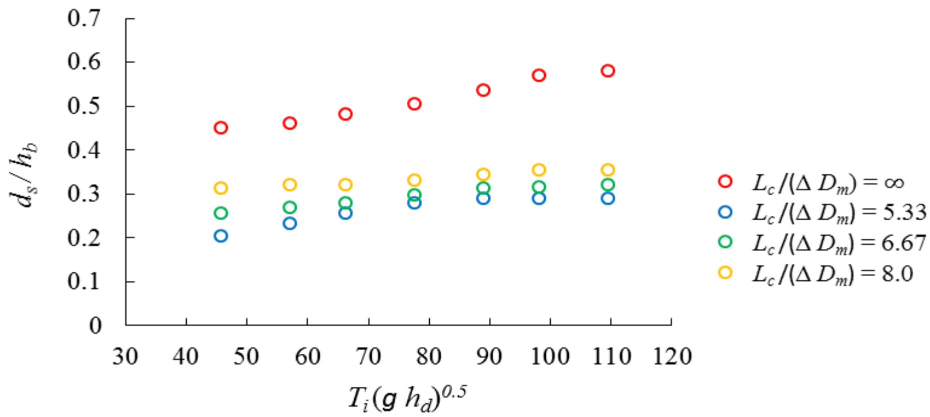


Figure 9. Nondimensional scour depth

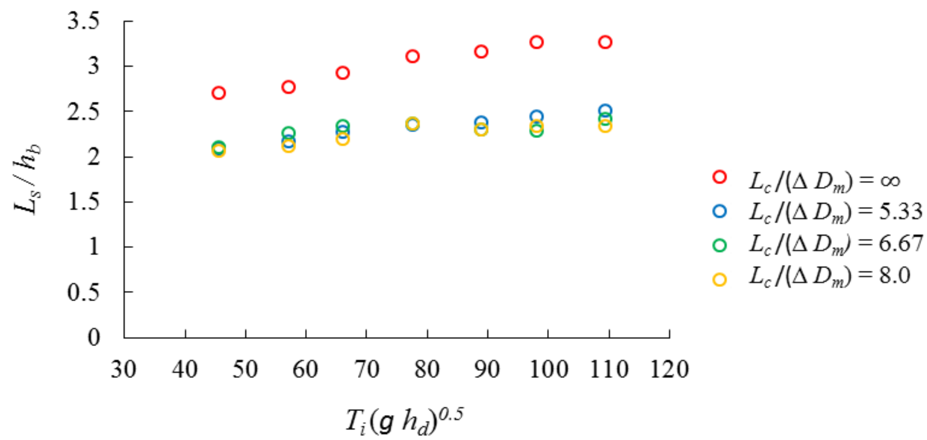


Figure 10. Nondimensional scour length

5 CONCLUSIONS

The research concluded the following:

1. The scouring process depends on the tsunami hydrograph that overflows the seawall.
2. Both the maximum scour depth and the scour length increase with the increasing tsunami overflow duration.
3. The installation of vertical screens within the loose boulder bed (modeled using gravel) effectively reduced both the scour depth and the scour length.
4. The reductions of the maximum scour depths due to the vertical screens were approximately 50%, 43%, and 34% for $L_c/(\Delta D_m)$ = 5.33, 6.67, and 8.0, respectively, while the scour lengths were reduced by 25 % for all scenarios.

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