Local Scouring of Gravel Mound due to Tsunami Overflow and Its Countermeasure

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Many cases of structural damage have been reported after Tohoku tsunami earthquake. Among those cases, the failure of breakwater caused by the local scouring on gravel mound due to tsunami overflow can be selected as one of the typical structural damages. This study is intended to clear the characteristics of local scouring on gravel mound under several tsunami overflow conditions. Four cases of discharge and three kinds of gravel diameter were employed to investigate the characteristics of local scouring under tsunami overflow condition. Furthermore, this study proposed a horizontal plate which was introduced to reduce the local scouring. Numerical simulation was also conducted to investigate the flow pattern above the gravel mound and pressure distribution on proposed horizontal plate. This study revealed that the scales of local scouring, its depth and length, depend largely on both overflow discharge and gravel size. Based on the experimental data, this study proposed an equation that can estimate maximum scoured depth under different gravel diameter as well as several overflow conditions. The horizontal plate showed good performance in reducing the scale of local scouring. The length of horizontal plate affects the magnitude of vortices and the maximum scoured depth.

Key Words: Tsunami overflow, local scouring, gravel mound, horizontal plate

1. INTRODUCTION

After the investigation of structural damages due to tsunami inundation by Tohoku earthquake, coastal engineers recognized the importance of persistent coastal structure to reduce the tsunami damages. In order to realize the persistent structure, it is important to understand the mechanism of structural damage under tsunami inundation1).

Many cases of structural damage have been reported after Tohoku tsunami earthquake2). Among those cases, the failure of breakwater caused by the local scouring on gravel mound due to tsunami overflow can be selected as one of the typical structural damages.

The local scouring problem can be seen in the hydraulic engineering field, and many previous studies have indicated a lots of important findings3,4). For example, Bormann et al. (1991) noted that the equilibrium scoured depth was written as a function of velocity, flow depth, and particle size. Among those previous studies, the most of their purposes were the problem of local scouring due to storm wave and currents, and their focuses were on the local scouring of gravel mound, which supports coastal structures, to secure stability of them5,6).

Based on above background, this study is intended to clear the characteristics of local scouring on gravel mound under tsunami overflow conditions. Furthermore, based on understanding of local scouring properties, this study also proposes a countermeasure, which is a simple horizontal plate installed behind the structure, to reduce the local scouring of gravel mound.
2. MODEL SETUP

(1) Hydraulic experiment

The hydraulic experiments were conducted in a two-dimensional open channel flume, 0.4m in width and 0.4m in height. The open channel was used to generate a certain discharge flow. The flow was dropped into the sub-tank as shown in Fig.1(a) to reproduce the overflowed condition seen behind the breakwater. The sub-tank has 1.2m in length, 0.4m in width and 0.7m in height, and it was filled with water and gravel.

The local scouring is governed by the overflow discharge. In this study, four cases of discharge \( Q = 0.015 \text{m}^3/\text{sec}, 0.025 \text{m}^3/\text{sec}, 0.035 \text{m}^3/\text{sec}, \) and \( 0.045 \text{m}^3/\text{sec}, \) were employed in order to generate several tsunami overflow conditions. The local scouring is also governed by the size of gravel diameter of the mound. Three kinds of gravel diameter, crushed stone with \( d_{50} = 10 \text{mm}, 20 \text{mm}, \) and \( 40 \text{mm}, \) were employed in this study.

The crushed stone was placed in the bottom of sub-tank, and its layer was 0.25m in thickness as shown in Fig.1(a). This stone layer imitates the gravel mound below a breakwater. The water depth above the stone layer is 0.23m. The discharged flow into the sub-tank scour the gravel mound. The deformation of gravel mound proceeds after a time, and it finally converges to a certain scale in steady state. The scoured shape of gravel mound in steady state was measured with using point gauges. Scouring process was recorded in video to understand the relationship between flow pattern and scouring process.

This study proposes a horizontal plate to reduce the local scouring due to tsunami overflow. The flow over the breakwater hits the water surface at a falling point as shown in Fig.1(b). The location of local scouring is affected by this falling point. In this study, two kinds of horizontal plate, 0.3m and 0.5m in length, were installed behind the breakwater as shown in Fig.1(b) to reduce the local scouring. Each plate was submerged 0.09m below the water surface, where this submerged depth nearly a half of water depth above the gravel mound. The deformation of gravel mound was also measured with using point gauges.

The flow over the breakwater hits the water surface directly at falling point, and the intensity of this impact may influence the hydraulic forces on the horizontal plate. The hydrodynamic pressure acting on the horizontal plate was measured under different flow discharge condition. Some pressure gauges were attached on the horizontal plate as shown in Fig.1(b).

(2) Numerical modeling

CADMAS-SURF/2D was used to investigate the flow pattern inside the sub-tank. The numerical model was also used to investigate the characteristics of pressure distribution acting on the horizontal plate. CADMAS-SURF model solves the Navier-Stokes equation and continuity one, and also employs volume of fluid (VOF) method to solve the temporal elevation of free surface.

The tsunami flow was generated in the open channel which was set as a numerical flume. The generated flow was discharged into the sub-tank in the same manner as the hydraulic experiments. The anisotropic mesh was used. The grid size was taken from 0.5cm to 0.2cm along \( x \) axes, and fixed 0.2cm along \( z \) axes.

In this numerical simulation, the tsunami flow in the open channel was generated by applying a time history of both water surface elevation and flow velocity on the input boundary. The input data of these water surface elevation and flow velocity were tuned to adjust the discharges of experimental condition. In this process, the flow velocity was estimated from the water surface elevation by applying the analytical formula proposed by Fukui et al.8,9.
3. RESULT AND DISCUSSION

(1) Local scouring of gravel mound

a) Characteristics of topographical changes

The local scour is governed by the overflow discharge and the size of gravel diameter. The characteristics of local scouring of gravel mound were investigated under the combination of those parameters.

Fig.2 shows the scoured topography in the case of different gravel diameters, $d_{50}=10$ mm, 20 mm and 40 mm. The flow discharge is $Q=0.025$ m$^3$/sec. It is clear that the scale of local scouring, its depth and width, decrease with increase of gravel diameter. The maximum scoured depth is approximately 0.15 m in the case of the smallest gravel diameter, $d_{50}=10$ mm. On the other hand, the maximum scoured depth is less than 0.05 m in the case of the largest gravel diameter, $d_{50}=40$ mm. Similar characters can be seen in the case of other discharges.

The flow dropped into the sub-tank hits the water surface directly at the falling point, where this falling point changes depending on the flow discharge. The large vortex is formed beneath this falling point, and this large vortex scours the gravel mound structure.

Fig.3 also shows the scoured topography in the case of different flow discharges, $Q=0.025$ m$^3$/sec, 0.035 m$^3$/sec, and 0.045 m$^3$/sec. The gravel diameter is $d_{50}=20$ mm. This figure shows that the scale of local scouring becomes larger with increase of flow discharge. In addition to this, the maximum scoured location changes, because the falling point of discharged flow in the sub-tank changes depending on the flow discharge. With increase of flow discharge, the location of the falling point keeps off from the breakwater and the scale of local scouring, its width and maximum depth, becomes large. Similar characters can be seen in the case of other gravel diameters.

b) Flow pattern formed in sub-tank

The flow fallen from the open channel into the sub-tank hits the water surface, and it produces some large vortexes. The scale of local scouring is related to the formation of these vortexes which interact with the mound layer. In order to clear the flow pattern in the sub-tank, this study conducted a numerical simulation with CADMAS-SURF/2D.

Fig.4 shows the example of flow pattern in the case of $Q=0.045$ m$^3$/sec obtained from the numerical simulation. The numerical simulation was conducted under the fixed gravel mound condition with 0.5 porosity. A large counterclockwise vortex was formed on the right hand side of the falling point where the water vein directly hits the water surface. This counterclockwise vortex is the largest among the vortexes formed in the sub-tank, and this mainly contributes to the local scouring on gravel mound. A clockwise vortex was also formed on the left hand side of the falling point as a countercurrent of above main vortex.

c) Estimation of maximum scoured depth

The estimation of maximum scour depth on gravel mound is very important to design persistent structure. The local scouring phenomenon include complex interaction between bed materials and flow, and many researches have proposed the equation to
predict the maximum scour ed depth\textsuperscript{10,11}. Among those studies, this study employs the equation proposed by Noguchi \textit{et al.}\textsuperscript{(1997)}, as expressed in eq. (1).

\[ D = 2.1R \] (1)

where, \( D \) is the maximum scour ed depth and \( R \) is the diameter of steady vortex formed by water vein thrust into the water surface. \( R \) is obtained by following eq. (2).

\[ R = g^{-1/4}q^{1/2}Z_f^{1/4} \] (2)

Eq. (1) is basically derived for the estimation of local scour ed depth in the case of sand material, and it says that the maximum scour ed depth, \( D \), is 2.1 times of steady vortex diameter, \( R \). This proportionality constant, \( P.C. \), is considered as the function of the size of bed material.

\textbf{Fig.5} shows the relationship between \( D \) and \( R \) in the case of gravel mound. Each solid line means the result of linier regression, and their gradient have the different values depending on the gravel diameter. From the regression analysis between the gravel diameter and the gradient of each line in \textbf{Fig.5}, the relationship between \( P.C. \) and gravel diameter is obtained as follow.

\[ (P.C.) = 0.65d_{50}^{-0.13} \] (3)

From eq. (1), (2) and (3), this study obtains eq. (4) to estimate the maximum scour ed depth with considering the gravel diameter.

\[ D = 0.65d_{50}^{-0.13}R \] (4)

\textbf{Fig.6} shows the agreement between measured maximum scour ed depths and estimated one. The agreement seems fairly good, though estimated depth is slightly less than measured depth in the range of larger gravel diameter, and also larger than the measured depth in the range of smaller gravel diameter.

\textbf{(2) Effectiveness of horizontal plate}

\textbf{a) Reduction of local scouring depth}

This study purposes a countermeasure, which is a simple horizontal plate, to reduce the local scouring of gravel mound. \textbf{Fig.7} shows the effect of horizontal plate on reducing the maximum scour ed depth. The plate length is 0.3m and gravel diameter is \( d_{50}=20\text{mm} \). The result in the case of \( Q=0.015\text{m}^3/\text{sec} \) and \( Q=0.025\text{m}^3/\text{sec} \) are shown in \textbf{Fig.7(a)} and the result of \( Q=0.035\text{m}^3/\text{sec} \), and \( Q=0.045\text{m}^3/\text{sec} \) are shown in \textbf{Fig.7(b)}.

As shown in \textbf{Fig.7(b)}, the horizontal plate only changes the location of the scour ed area, and the maximum scour ed depth in each discharged takes nearly the same value in the case without horizontal plate. This is because the location of the falling point on each discharge flow exceeded the tip of the horizontal plate, and the large vortex is consistently formed on the downstream side of the plate.
Fig. 8 The effect of horizontal plate, 0.5m in length, on local scouring: (a) $Q=0.015 \text{m}^3/\text{sec}$ and $0.025 \text{ m}^3/\text{sec}$, (b) $Q=0.035 \text{ m}^3/\text{sec}$ and $0.045 \text{ m}^3/\text{sec}$

Fig. 8 also shows the effect of horizontal plate in the case of 0.5m in the plate length. The result in the case of $Q=0.015 \text{m}^3/\text{sec}$ and $Q=0.025 \text{ m}^3/\text{sec}$ are shown in Fig. 8(a) and the result in the case of $Q=0.035 \text{m}^3/\text{sec}$, and $0.045 \text{ m}^3/\text{sec}$ are shown in Fig. 8(b). It is clear that the horizontal plate reduces the local scouring effectively. This is because the length of the horizontal plate is sufficiently longer and it covers the location of the falling point in all cases. In this condition, the shallow water depth on the plate limits the generation of large vortex above the plate as well as on downstream of it.

The length of horizontal plate is very important in reducing the local scouring. In the design of horizontal plate, its length must be taken to cover the falling point of discharged flow. Shorter horizontal plate has no impact on reducing the depth of local scouring even in the case of small discharge such as $Q=0.015 \text{m}^3/\text{sec}$.

b) Pressure distribution on the horizontal plate

The flow fallen from the open channel into the sub-tank hits the water surface, and the horizontal plate interacts with complex flows formed above it.

Fig. 9 shows the distribution of pressure acting on the upper face of horizontal plate with 0.3m in length. The pressure was normalized by the hydrostatic pressure, $pgh$, above the plate. The symbols with line mean the results obtained from numerical simulation, and the symbols filled with the different colors mean the measured data. This figure shows that numerical results agree well with measured pressure in each discharge, though only the measured pressure at 0.3m in the case of $Q=0.015 \text{m}^3/\text{sec}$ shows the twice of computed one.

Fig. 10 also shows the distribution of normalized pressure acting on the upper face of horizontal plate with 0.5m in length. In the case of longer plate, good agreements can also be seen between numerical results and measured data, though only the measured pressure at 0.3m in the case of $Q=0.015 \text{m}^3/\text{sec}$ shows larger value. The discrepancy at 0.3m may be caused by unique complex flow formed just blow the falling point in experiment under $Q=0.015 \text{m}^3/\text{sec}$, and this must be examined more.

From Fig. 9 and Fig. 10, the maximum pressure on the horizontal plate tends to appear near the falling point of discharged flow. The maximum pressure on the plate submerged nearly a half of water depth takes a few times of hydrostatic pressure above the plate, and the magnitude of maximum pressure become larger with increase of overflow discharge.
both overflow discharge and gravel diameter. Fairly scoured depth with considering the parameter of proposed an equation that estimates the maximum increase of gravel diameter. 

The maximum scoured depth becomes larger with the increase of overflow discharge and gravel size. The performance of this plate depends largely on its maximum depth and length, depend largely on the overflow discharges. On the other hand, the normalized pressures in the case of \( h = 0.15 \text{m} \) and \( h = 0.23 \text{m} \) are less than two times of hydrostatic pressure above the plate. The actual maximum pressures take the similar value on each submerged depth, though the normalized maximum pressures take different values in the case of \( Q_s = 0.045 \text{m}^3/\text{sec} \). This is because the overflowed water vein hits the water surface hardly, and its effect approaches to the plate in both cases \( h = 0.05 \text{m} \) and \( h = 0.23 \text{m} \) as presented in Fig.12.

4. CONCLUSIONS

This study cleared that the scales of local scouring, its maximum depth and length, depend largely on both overflow discharge and gravel size. The maximum scoured depth becomes larger with the increase of overflow discharge and it decreases with increase of gravel diameter.

Based on those experimental data, this study proposed an equation that estimates the maximum scoured depth with considering the parameters of both overflow discharge and gravel diameter. Fairly good agreement were confirmed between estimated scoured depth and measured one, though the estimated depth is slightly less than measured depth in the range of larger gravel diameter, and also larger than measured depth in the range of smaller gravel diameter.

This study also proposed the horizontal plate as the countermeasure to reduce the local scouring of gravel mound. The performance of this plate depends on the relationship between the length of plate and the falling point of water vein overflowed into the water. The length of horizontal plate should be taken to cover the falling point of discharged flow.

The maximum pressure on the horizontal plate tends to appear near the falling point of discharged flow. The plate submerged under the water takes a few times of hydrostatic pressure above the plate, and the magnitude of maximum pressure become larger with increase of overflow discharge.

ACKNOWLEDGMENT: This work was supported by JSPS KAKENHI Grant Number 25420529.

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