Scouring Around Coastal Structures Due to Tsunami Surge

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Abstract: Shallow foundation is normally utilized for simple buildings or housings in sandy beach areas. Parangtritis beach at south coast of Yogyakarta is an example where a lot of houses are built based on shallow foundation. Other similar beach may be found in Indonesia. Parangtritis area is certainly prone to tsunami attack. Tsunami disaster in 2006 which directly hit Pangandaran beach has minimal impact on Parangtritis beach. However, more significant and damaging result may happen if larger tsunami were generated directly to the south of Parangtritis beach. When tsunami surge hit a structure, the surge is deflected to both sides of the building and creates turbulence at the rear of the building. The speed of the surge and the highly non parallel flow around the building easily lift up the sand particle resulted in scouring around the structure. Such scouring may endanger the structure stability. Once the structure is toppled or lifted up by tsunami, it may be brought further downstream, hit other buildings and create more damages. Therefore it is important to study the impact of tsunami surge on scouring around structures erected on shallow foundation in sandy beach. Physical model was conducted at Center for Engineering Science Universitas Gadjah Mada to study the scouring around coastal buildings which was represented by cylinder and square columns and vertical wall due to tsunami surge. The lay out was designed to enabled the study of the tsunami surge on sandy beach based on dam break model. Various tsunami heights, position of columns and vertical wall were simulated. Some existing formulae were compared with the present results to examine their used for approximating the scouring around structure under tsunami attack.

Keywords: tsunami, scour, simulation, model, sea wall

1. INTRODUCTION

Tsunami’s power, depending on its scale, is unquestionably capable of bringing down almost everything near the coast line that is on its course. Beside its powerful impact force, tsunami also scour surrounding area of the building which may endanger the stability of the buildings. People with insufficient knowledge on the characteristics of tsunami surge and how it destroys buildings may have no idea whether their houses are safe or unsafe from tsunami attack. Without enough knowledge people would assume that their building would be safe under tsunami attack even if they were built on sand dunes.

An example of residential complex built in coastal sand dunes is Parangtritis beach. The beach is located approximately 20 km to the south of Yogyakarta city the capital of Yogyakarta Special Province, Indonesia. The dune stretches from Parangtritis to the west end of the Province. At present only Parangtritis that is populated with residential houses. In the future, as the population increases, it is possible that most of the sand dunes area will also be used as residential area.

One possible cause of building collapse is the instability of its foundations. Reference [1] listed 5 mechanisms that caused structural damagein which scouring is one of the list. When tsunami surge hit a building, it is deflected sideways at high speed. There may also a clear separation between the surge and the building depending on the angle of approach and the shape of the building or foundation. Such high velocity and turbulence may easily pick up sand particles and creates scouring around structures. Reference [2] observed that during the Banda Aceh tsunami in 2004 scouring on some sea wall reached up to 4 m. Reference [1] quoted Dame and Moor, suggested that the scour depth for loose sand under tsunami attack is approximately 80% of the water depth when measured at location less than 100 m from the beach. However [1] also indicated that scour could even occur significantly further than 100m from the shore line based on the Indian Ocean Tsunami observation. The ratio of scour depth to water depth is given in Table 1 from [1] which was adapted from Dames and Moor. When compared with Yeh and Tonkin method, [3] concluded that FEMA’s over estimated scouring depth.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Expected Depth (D/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loose sand</td>
<td>0.80</td>
</tr>
<tr>
<td>Dense sand</td>
<td>0.50</td>
</tr>
<tr>
<td>Soft silt</td>
<td>0.50</td>
</tr>
<tr>
<td>Stiff silt</td>
<td>0.25</td>
</tr>
<tr>
<td>Soft clay</td>
<td>0.25</td>
</tr>
<tr>
<td>Stiff clay</td>
<td>0.10</td>
</tr>
</tbody>
</table>
2. PRECEEDINGS STUDIES

2.1. Tsunami surge speed

Scouring is significantly related with flow speed. Many formulae of scour around civil engineering structures such as bridge piers are related to Froude number. Reference [4] indicated that tsunami flow depth is in general shallower than that of normal river flow depth for the same flow velocity (Figure 1). The tsunami surge velocity may be written as in Equation 1.

\[ V = k \sqrt{g d} \]  

(1)

Where \( V \) is velocity, \( g \) is gravitational acceleration, and \( d \) is the surge depth. The coefficient \( k \) may be regarded as surge Froude number which can be regarded as the ratio between the speeds of the surge to the speed of shallow water wave propagation. As indicated by Figure 1, the surge Froude number, suggested by [4], is approximately equals 2.0. This is similar to that of [5].

A complete analytical surge speed has been developed by [6] and [7]. The solution for surge speed resulted from a dam break over nearly horizontal dry bed is given in Equation (2).

\[ \left( \frac{1}{\sqrt{d}} \left( \frac{U}{g d} \right)^2 \right)^{1/3} = \left( \frac{U}{g} \right) t \]  

(2)

where \( f \) is the friction coefficient, \( S_0 \) is the slope, \( V_0 \) is the initial velocity, \( U \) is the front celerity and \( t \) is time and \( h_0 \) is the depth of the reservoir which represent the maximum tsunami height. Equation 2 suggests that \( U \) decrease with time. Interestingly, the free surface profile and hence \( U \) was shown to agree quite satisfactorily with experimental data and also with tsunami Indian Ocean wave front data [7]. Equation 2 indicates that the larger is \( f \) (higher friction factor) and \( t \) (larger traveling distance) the smaller is the velocity as expected.

Chanson analytical solutions also provide the surge profile which shows that the surge Froude number decreases further inland. The surge Froude number close to the shore line was estimated to be close to 2.0 for example by [4] as presented in Figure 1. Such value is considered as extremely high if occur in a river and may create large local scouring around obstacles. However, as indicated in Table 1, tsunami design criterion for scouring is 80% of the water depth. One of the reasons for such small scour depth could have been due to shorter duration of tsunami attack when compared to natural scour in rivers. Even so, with scour to water depth ratio of 80%, when combined with the impact force, tsunami can endanger simple building with shallow foundations.

2.2. Scour depth

Many researches have been devoted for studying scour depth yielding a lot of formulae. Formulae relevant to scouring around structure such as bridge piers involved parameters for example width of structure (\( b \)), flow depth (\( d \)), Froude number (\( Fr \)) and coefficients to accommodate shape of structures and irregularities. Followings are a number of simple formulae on scour around bridge pier [8]. Breusers’formula for computing scour around bridge pier is presented in Equation (3).

\[ d_s = 1.35 K_i b^{0.7} d^{0.3} \]  

(3)

Where \( d_s \) is scour depth, \( d \) is water depth, \( b \) is pier width (diameter). The coefficient \( K_i \) is a shape coefficient which equals 1 for cylinder and 1 to 1.2 for square columns. Colorado State University method (CSU) included Froude number (\( Fr \)) in predicting local scour. The equation read

\[ d_s = 2.0 K_i d Fr^{0.43} \left( \frac{b}{d} \right)^{0.65} \]  

(4)

The CSU method has been proven to be more suitable in certain cases [9] and [10]. Two other simple methods of Breusers listed by [8] are given in Equation (5) and (6).

\[ d_s = 1.4b \]  

(5)

\[ d_s = 1.5 K_i b \tanh \left( \frac{d}{b} \right) \]  

(6)

Equation (5) is very simple and lack of other parameters such as water depth, velocity, and grain size of bed material. Equation (6) takes into account the water depth. However, the hyperbolic tangent (\( \tanh \)) is asymptotic to 1.0 as \( d/b > 3 \). It may be said that for \( d/b > 3 \) which is likely to occur, Equation (6) become

\[ d_s = 1.5 K_i b \]  

(7)

which is almost the same as Equation (5).

The time scale of tsunami surge however is different to river flow. Tsunami surge last only in the order of minutes whilst river flow may last for hours or even days during flood event giving enough time for the scouring process. However, as depicted in Figure 1, tsunami surge velocity is normally much faster than river flow for the same flow depth. Furthermore, the local scour is a relatively rapid process [8], hence it may be expected that Equation (3) and (4) may still be valid for the case of tsunami surge.

A problem with physical modeling is as always, the scaling of the sediment material. It is a very rare case that one would be able to scale down the bed material for sediment modeling purpose. Parameters such as average diameter, fall velocity, and \( \rho \) are difficult to scale in order to fulfill the similarity requirement for small scale model.
In case of scouring, the critical angle of repose, which is the maximum slope angle of scour, is another limiting condition. Even if the turbulence flow has the capacity to create deeper scour yet if the slope of the sand (scour) is already beyond the angle of repose, the slope will collapse and forms a critical angle of repose which finally establishes the maximum scouring depth. The ability to produce wider area of scour depends on the width of obstacle. Wider obstacles such as piers increase the possibility of wider scour depending on the Froude number. Therefore Equation (3) and (4) that accommodate the angle of repose were expected to be suitable for predicting tsunami scour around structures.

Reference [11] used both sand and gravel as bed material for simulation of scouring around a cylinder. The maximum scour depth of sand material with average diameter of 0.35 mm was approximately 7 cm at the front of the cylinder. The maximum scour with gravel material was approximately 13 cm which was almost twice than that of the sand counterpart. This indicated that the maximum scour was not merely dictated by the size of the bed material. When scale up to possible prototype of tsunami, Tonkin’s model may not completely follow similarity law.

Reference [12] studied scouring around square structure using both physical and numerical model. In the physical model the diameter of the bed sediment were 0.2 mm and 0.45 mm whilst the width of the structure was 14 cm. With relatively small incident wave, when scaled up, the size of sand prototype will be as large as gravel.

When modeling scouring due to tsunami, it has to be noted that there will normally be a return flow due to draw down. Such return flow may modify the scouring pattern as well as the scouring depth due to incoming tsunami surge. Therefore, [11] set up equipment to enable them to record the scouring time history. This provided valuable understanding on the generation of scour around cylinder. It can be inferred from their experiment that the scour around the cylinder was developed very quickly before reaching the maximum possible scour. The total time before reversal flow was approximately 6 s from the impact. However, the maximum scour was established approximately at 2 s after the impact time.

Reference [13] simulated scouring around cylinder using sand and gravel material. They concluded that in most cases gravel material was not necessarily reduce scour. The gravel even increased the scour when located inshore, and hence they underlined that the used of gravel for armoring was not supported by the research.

3. PHYSICAL MODEL SET UP

Physical model was prepared in Hydraulic and Hydrology laboratory, Universitas Gadjah Mada. A flume of 20.4 m long and 0.60 m wide was divided in to two segments. The upstream segment was used to store water and act as a reservoir. The downstream part was used for testing the scouring model. The two segments were divided by a sluice gate that can be open quickly. The time required to completely open the gate was less than 0.4 s. With such method a repeatable dam break model can be generated where the surge may represent tsunami surge inland. Such method of simulating tsunami surge has been used for example by [14]. The model lay out is given in Figure 2.

The arrangement of tsunami surge suggests that the length of the tsunami was relatively short. If the scale was considered as 1:100 ($\alpha_{ml} = 100$), the length of the tsunami was merely 760m. This is of course a tsunami size that is much smaller than the Indian Ocean Tsunami in 2004, but close to tsunami in Pangandaran in 2006. The inundation time was approximately 6 to 12 s in laboratory scale. Reference [11] simulated tsunami scour around cylinder using similar character of tsunami where the tsunami run up time was approximately 13 s.

The sediment material used in the model may be considered as loose sand. The mean diameter of sand particle was 0.3 mm which was slightly smaller than that used by [11]. Such diameter was certainly too large when scaled up to prototype. The prototype sand diameter such as found in Parangtritis was approximately 0.25 mm to 0.5mm. Although the sediment model did not strictly follow the similarity laws the model may still represents the prototype based on the following arguments. First, the critical angle of repose may limit the scour around structure of certain size. Secondly, many empirical formulae such as Equation (3) to (6) even exclude the bed material characteristics which indicate that their effect on maximum scour may be neglected.

The sand material bed was located from the gate to approximately 7.0 m downstream. The first 2.0 m from the gate was horizontal sand bed while the slope further downstream was 1:100 for all simulations. Such beach slope may represent parts of Parangtritis beach. Reference [15] also used similar beach slope (1:100) when simulating tsunami run up in Banda Aceh. At the gate the thickness of the sand bed material was 0.05m. With such arrangement, the storage depth ($h_0$) was measured above the sand material at the gate to the water surface. The model structures (cylinder and square column) were placed at three different positions i.e. at $X = 4.5$ m, $X = 5.5$ m and $X = 6.5$ m downstream of the gate where $X = 0$. The cylinder column diameter was 0.033 cm whilst the square column was 0.045 x 0.045m. The selection of such small model size was based on the size of the flume. Reference [16] realized that their box model used for simulating tsunami force was slightly too large even when the ratio between the box model width to flume width was 0.15. During their simulation, the wall effect was observed by recording the water level across the flume. In this simulation therefore a smaller model size (column width to flume width ratio was 0.08) was utilized. It was expected that the effect of the side walls would be much smaller and can be neglected. The simulations were conducted separately for each type of columns and positions. For each structure and location the simulation was carried out using three different storage (reservoir) depth above the bed material at the gate($h_0$ equals0.15 m, 0.25 m and 0.35m. Since the thickness of the bed material...
at the gate was 0.05m, the total reservoir depth was actually 0.05 m more than $h_0$.

In addition to the columns, to represent structures a sea wall model was installed at 5.50 m downstream of the gate. The height of the wall ($H$) was 0.05 m. At the back of the wall was sand material of 0.05 m thick of approximately 1.90 m long. No sand materials were provided in front of the wall.

Due to tsunami run up and run down which create dynamic scour around structures, [11] recorded the dynamic process and time history of the scouring and showed that the final scour depth and pattern may be significantly different to that at maximum scour. However such instrumentation to record the dynamic scouring process was not yet available in the Hydraulic and Hydrology laboratory in Universitas Gadjah Mada. In order to minimize reversal flow, tsunami surges were let to flow downstream. This was made possible by limiting the land height to a certain elevation. When tsunami run up higher than the limiting elevation at the downstream end of the sand material, the surge will overflow out of the flume as depicted in Figure 2. By doing so, only small part of tsunami surge that run up inland return to the sea which may modify the new scouring. At 0.15 m total depth, the total volume of the storage was almost equal to the volume of water to fill up the flume from upstream to the downstream end of sand material. As the tsunami surge was expected to be small for such small $h_0$, hence only small part of the water is expected to overflow the sand material. At total storage water depth of 0.35m, some amount of water will be discharged through the downstream end during run up. The rest would be discharged slowly because the amount water has been reduced significantly during run up.

4. TSUNAMI SURGE SPEED

The tsunami front speed was recorded using digital video and wave height meter. The speed of the surge was determined by their arrival time after travelling a certain distance. Figure 3 shows the typical tsunami surge during simulation. The front speeds were determined using these type images in digital video.

![Figure 2. Physical model layout](image)

![Figure 3. Tsunami surge taken from digital video image](image)

Figure 4. Surge speeds at different basin depths

The surge speeds are given in Figure 4. From the figure, the surge speed seems to be almost constant with distance. However at smaller tsunami surge the speed reduction with distance was more apparent. Figure 5 shows the observed surge speed as compared with [6] solution using $f = 0.02$. The agreement between the analytical solution and the observation suggests that the friction coefficient for such material was approximately 0.02. Such friction factor is relatively smaller than the real tsunami. In reality for example, [6] used $f = 0.5$ to simulate the Indian Ocean tsunami which run up in Banda Aceh. The surge speed however varied and become slower at maximum wave height. Since the speed was obtained based on the surge front location and the time of arrivals, the resulted surge speed may be regarded as the maximum front speed. At the front however, the water surface change rapidly to a maximum. Reference [17] indicated that the maximum tsunami surge height corresponded to approximately 2/3 of the maximum front speed. For convenience, [17] expressed the maximum surge speed based on tsunami maximum height.

The digital video camera for recording tsunami wave height was located at a distance of approximately 1.0 m to the structure models. Together with the front speed, the data was used to determine the Froude number at model locations.
5. SCOUR AROUND CYLINDER AND SQUARE COLUMN

The scour around cylinder and square columns were measured after the flume was drained. The results are presented in Figure 6. Figure 6(a) shows the relative maximum scour depth against distance from the shore line. The data are relatively scattered with approximate average of $d/h_0 = 0.2$, where $d$ is the scour depth while $h_0$ represents the maximum tsunami height. The scour depths of square columns were slightly larger than the cylindrical columns. Reference [11] using a much larger scale model (the diameter of the cylinder was 50 cm or 10 times larger than the present model) found that the maximum scour depth was approximately 7 cm for incident wave height of 22 cm which become approximately 29 cm at run up point. This gives $d/h_0 = 0.24$. Although not directly comparable, it is interesting to note that [11] result was within the range of the present study that is $0.14 < d/h_0 < 0.26$.

During the draining process of the flume to prepare for next simulation, a conventional method to determine the contour of the scour was conducted by delineating certain level of contour within the scour area with white string. Some typical results are provided in Figure 7. These figures were taken after the water was drained slowly from the flume and the columns have been taken out from the sand. They show the effect of the shape of the structure on the scouring pattern and depths. All of the scouring patterns show that the upstream slope of scour was relatively steeper than the downstream slope. At higher surge Froude number, such pattern is more obvious. Similar results were obtained by [11] with larger model scale. During run up, the scour at upstream of the cylinder column was significantly larger than that at the downstream location. Both sides of the column were also scoured as deep as that at the upstream position. During run down, however, the scour pattern changed significantly where the scour at the front (sea side) of the cylinder was deeper than the scour at the rear side (land side) of the cylinder even when compared with the maximum scour during run up.

Figure 7 shows that the scouring patterns behind the columns were not exactly circular. The scour were extended further downstream at the right and left sides of the structures. This was due to the fact that the tsunami surges were deflected sideways by the structures and eroded more sand material behind the structure.

The scour pattern may be given in term of average scour width. This is provided in Figure 8. The figure has been prepared by averaging the scour widths at certain scour depth. In general it is indicated that the maximum scour depth of square columns were larger than that of the cylinder. From Figure 8 it may be said that the slope of the scour ranges from 1:3 (Vertical to Horizontal) to 1:2, at $19 < X/h_0 < 43$ from the gate. Reference [8] recommended that the width of scour protection of bridge pier should be $6B$, where $B$ is the bridge pier width. In this case, at $19 < X/h_0 < 43$ the width of the scoured area was found to be $6B$ which agree with that of [8]. Nearer to the gate where $15 < X/h_0 < 37$ the slope ranges from 1:2 to 1:1.5. At $13 < X/h_0 < 30$ the slope ranges from 1:1.5 to 1:1.2 yet most of the slope were steeper than those further away from the gate. It seems that the critical angle of repose significantly affect the maximum scour depths closer to the gate.
At the upstream of the columns, the slopes were steeper. The maximum scour slope (at $13 < \chi / h_0 < 30$) was approximately 1:1.

Figure 9 provides the cross section of local scour due to square columns at $19 < \chi / h_0 < 43$, $15 < \chi / h_0 < 37$, and $13 < \chi / h_0 < 30$. It is clear in the figure that the slope was steeper at the upstream. The average tangent of the upstream slope was approximately 1.5 of the downstream slope.

![Figure 9](image9.png)

Figure 9. Cross sections of local scour around square columns. (a) at $19 < \chi / h_0 < 43$, (b) at $15 < \chi / h_0 < 37$ and (c) at $13 < \chi / h_0 < 30$. Blue line: $h_0 = 0.15$ m, black line: $h_0 = 0.25$ m, red line: $h_0 = 0.35$ m.

TABLE 2.
TSUNAMI HEIGHT (AVERAGE AT 1 s AND 2 s AFTER IMPACT) AND SURGE FROUDE NUMBER (BASED ON TSUNAMI HEIGHT AT THE STRUCTURES)

<table>
<thead>
<tr>
<th>$X$ (m)</th>
<th>$d$ (m)</th>
<th>Fr</th>
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<tbody>
<tr>
<td>$h_0 = 0.35$ m</td>
<td>$h_0 = 0.25$ m</td>
<td>$h_0 = 0.15$ m</td>
</tr>
<tr>
<td>4.5</td>
<td>0.110</td>
<td>0.075</td>
</tr>
<tr>
<td>5.5</td>
<td>0.112</td>
<td>0.085</td>
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<tr>
<td>6.5</td>
<td>0.103</td>
<td>0.079</td>
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</table>

TABLE 3.
COMPARISON OF OBSERVED SCOUR DEPTHS AROUND CYLINDER AGAINST COMPUTED SCOUR DEPTH USING EQUATION 3 TO EQUATION 6

<table>
<thead>
<tr>
<th>$X$ (m)</th>
<th>Average observed scour depth (mm)</th>
<th>Average calculated scour depth (mm)</th>
<th>Average calculated scour depth (mm)</th>
<th>Average calculated scour depth (mm)</th>
<th>Average calculated scour depth (mm)</th>
<th>Observed Fr</th>
</tr>
</thead>
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<tr>
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<td>0.117</td>
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<tr>
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<td>0.018</td>
<td>0.119</td>
<td>0.046</td>
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<td>0.119</td>
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<td>0.048</td>
<td>0.87</td>
</tr>
</tbody>
</table>

Surprisingly, Equation 5 and 6 resulted in scour depth that are closer to the observed whilst the CSU method produces significantly higher scour depths. There are a number of reasons for such large discrepancy. The large Froude number used in the simulation could be one of the reasons. Reference [9] recommended the use of CSU based on prototype scours of bridge piers where the range of Froude number was 0.175 to 0.208, whilst [10] used laboratory data where the Froude numbers were less than 0.6. The Froude number used in Table 3 was based on the surge front speed.

In reality, behind the front, the surge velocity decreased quite significantly as shown by [17]. Assuming surge speed of 66% of the maximum, the CSU method yield slightly better comparison. Equation 3 under predicts the scour depth yet in term of engineering view this equation is probably more suitable as it provides some safety factor.

6. SCOUR BEHIND A VERTICAL WALL

The experiment on scour depth and pattern behind a vertical wall was conducted using the same storage heights (0.15 m, 0.25 m, and 0.35 m and an additional 0.4 m). The sand material used for the simulation was the same as that used for modeling of scour around columns. The results are presented in Figure 10.

From the figure it may be concluded that the scour depth behind a vertical wall depends on the wave height. Higher tsunami resulted in a deeper scour. The deepest location shifted downstream as tsunami wave become...
higher. Higher tsunami wave resulted in higher Froude number and hence the upward deflection of the surge becomes stronger which resulted in further distance of maximum impact with the bed.

Figure 10. Scour behind vertical wall model

7. CONCLUSION

1. The ratio of maximum tsunami scour around cylinder and square columns to tsunami height \( \frac{d_s}{h_0} \) was approximately 0.25 to 0.3. FEMA recommends \( \frac{d_s}{h_0}=0.4 \) (where \( h_0 \) is tsunami height). Such recommendation is supported by this research.

2. Simple formulae of Bruisers were found in good agreement with the present research. However for design purposes Equation 3 is more appropriate to calculate scour around columns.

3. The used of CSU method resulted in approximately twice to three times larger score depth than the observed. However, in certain tsunami hazards where the structures were exposed to longer tsunami period attack with lower Froude number (maybe in case of long tsunami in densely populated area) the method is probably more suitable. In case of important structures that have to withstand tsunami hazard such as evacuation tower or buildings, CSU method is recommended.

4. The depth and location of maximum scour behind vertical wall depends on the wave height and hence the Froude number. Therefore structures built on sand material behind such vertical wall should be designed by considering the local scour around the structure and the scour due to the vertical wall.

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