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SIMULATION OF SCOURING AROUND A VERTICAL CYLINDER DUE TO TSUNAMI

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ABSTRACT

Local scour due to tsunami is damaging especially on shallow foundation. Although relatively in a short duration, tsunami attack may scour material around buildings that led to destruction. A number of formulae on local scouring due to flood and tsunami have been available. The local scouring pattern and depth produced by tsunami may be affected by tsunami duration and tsunami surge Froude number and hence different to that resulted by flood which normally have much longer duration and lower Froude number. The research used a relatively short flume to create short duration tsunami surge that run-up on 1:20 beach slope and hit a vertical cylinder on land. Both the pattern and the depth of local scouring around the cylinder were observed and the results were compared with similar research but with different tsunami surge characteristic. It was shown that the maximum scour depth was significantly deeper than the final scour depth. When compared with other experimental study of local scour due to tsunami, the present local scour maximum depth seemed to be slightly less. This could have been caused by the relatively short duration of the present experiment. It was also found that the sidewall effect was insignificant when the ratio of cylinder diameter to the flume width was less then approximately 0.15.

Keywords: *Tsunami, scouring, maximum depth, numerical model, physical model, dam break*

1. INTRODUCTION

Scouring due to tsunami or floods may undermined structure stability and cause further structure failure. Triatmadja, et al (2011), FEMA (2007), Tonkin et al. (2003) and Jain et al, (1979), have showed many examples of scouring around structures. The scouring around cylinder especially bridge piers have been studied and relatively simple formulas for predicting such scouring have been established. These are for example as provided in Table 1. It can be seen from Table 1 that in general, the maximum scouring depends on a number of parameters these are Froude number (water depth and flow velocity), cylinder diameter, and sediment material. The duration is missing in many of the formula since most of the study was conducted for river flow where the duration may be long enough to create the maximum scouring depth irrespective of the duration. Naturally the maximum scouring depth dependent on the natural slope of repose of the material, since whenever the scour depth around the cylinder created a slope that larger than the angle of repose, the bed material slide down to create a stable slope and buried the scour hole.

Table 1. Maximum scouring around a vertical cylinder

Author(s)	Formula	Parameters used	Caused	Equation
Triatmadja, et al (2011)	$d_s/d_0 = 0.25\ to\ 0.3$	d_0	Tsunami	(1)
Dames and Moore(1980)	$d_s/h_0 = 0.4$	h_0	Tsunami	(2)
Tonkin (2003)	$d_s = \frac{\Delta P}{\gamma_b \Lambda}\left(1-4i^2 erf\,c\left[\frac{d_s}{2\sqrt{c_\upsilon \Delta T}}\right]\right)$	Λ, P, c_v	Tsunami	(3)
Jain et al (1979)	$d_s/b = 2.0(F_r - F_c)^{0.25}(d/b)^{0.8}$	F_r	Floods	(4)
CSU (1992)	$d_s = 2.0K_i d F_r^{0.43}\left(\frac{b}{d}\right)^{0.65}$	F_r , b, d	Floods	(5)

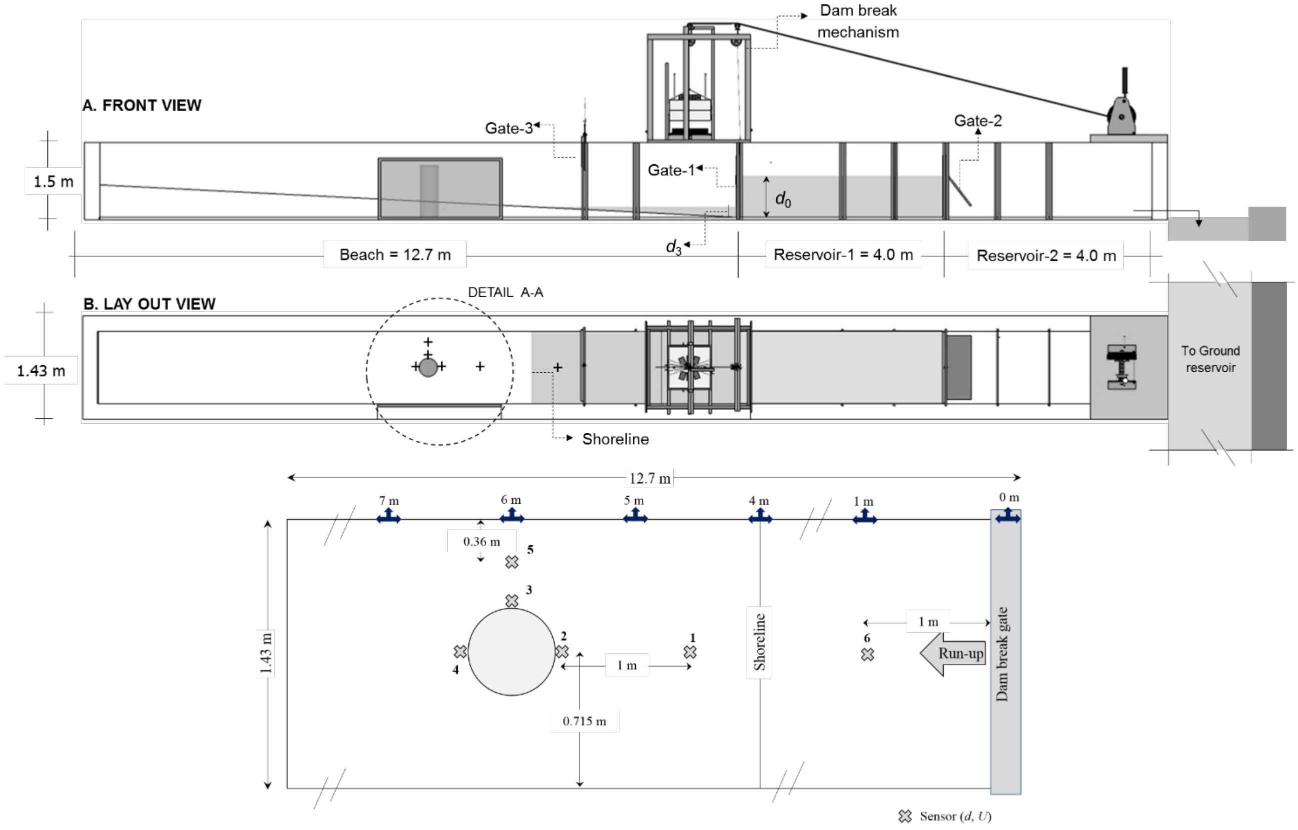
d_s: maximum scouring, d_0 : water depth of the reservoir, h_0: tsunami height, b : width or diameter of cylinder, d : water depth at the location of the building, *Fr :* Froude number, Fc: critical Froude number, *P :* pore pressure, Λ: a scour enhancement parameter, ΔT: time scale, Cυ: Terzaghi's coefficient of consolidation , Ki: correction factor

The local scour process may be slightly different during tsunami attack. Tsunami may last (starting from run-up up to the end of run-down) only a few hours hour or even only a few minutes. The run-up duration is more or less the same as the run-down duration. In between the run-up and run-down processes there is time when the velocity is nearly zero normally at maximum inundation. Another difference between tsunami scour and river flood scour is the speed and the Froude number of the flow. Tsunami surge flow is significantly faster than the river flood. Other than that, the Froude number of the surge is normally higher especially near the coastline. The difference of speed and Froude number may create different pattern of scouring and maximum scouring depth. The run-down has different flow pattern than the run-up. Such different flow pattern is expected to yield different scouring pattern created by tsunami during run-up.

The study is aimed at finding the local scour depth around a vertical cylinder due to tsunami attack based on physical simulations using dam break surge to represent tsunami.

2. Materials and Method

A model of coastal zone was prepared in a flume of 20.7 m long (*L*), 1.45 m wide (*B*), and 1.5 high (*h*) (Figure 1). From downstream end of the flume to 12.7 m upstream, the flume bed was sloping with a ratio of 1:20 (vertical: horizontal). About 11.7 m of it was made of fine sand, which represented erodible sandy beach. Two quick opening gates were installed. The first was at 12.7 m from downstream end of the flume, the other was 4 m upstream of the first. In between the gates water were initially stored to generate tsunami like surge by opening the two gates at the same time quickly. Kuswandi et al (2017) have employed this method. The resulting surge was a tsunami like surge that run-up on land (downstream) and another surge that went directly to the ground tank to reduce the effect of secondary run-up. The surge height was varied by varying the water depth in the reservoir (d_0) and the water depth at downstream of the first gate (d_3). The depth of the water downstream of the first gate varied due to the bed slope. The difference between initial upstream water depth or the initial reservoir water depth (d_0) and the downstream water depth d_3 is d'. The maximum height of the surge is $d'' = 4/9\,(d_0 - d_3)$ which occurred at the location of the first gate.



B. Detail A-A Figure 1. Experiment setup (Kuswandi, et al., 2017)

A number of tests to observe the scouring pattern around a vertical cylinder were conducted as listed in Table 2. The diameter of the vertical cylinder (*b*) was also varied to observe its effect on the surge flow pattern and the resulted local scour. As can be expected a large relative cylinder diameter (*b/B*) may obstruct the flow and even create backwater. This change of pattern may subsequently change the scouring pattern around the vertical cylinder. Four cylinder diameters were to be tested. These were *b/B* = 0.07, *b/B* = 0.14, *b/B* = 0.25 and *b/B* = 0.35. After each test, the scour and erosion was filled with bed sediment (sand) to obtain a smooth slope.

Table 2. List of the simulations

Test	d_0	d_3	d' (m)	b/B	Test	d_0	d_3	d' (m)	b/B
1	0.45	0.18	0.27	0.07	7	0.45	0.18	0.27	0.25
2	0.50	0.20	0.30		8	0.50	0.20	0.30	
3	0.55	0.22	0.33		9	0.55	0.22	0.33	
4	0.45	0.18	0.27	0.14	10	0.45	0.18	0.27	0.35
5	0.50	0.20	0.30		11	0.50	0.20	0.30	
6	0.55	0.22	0.33		12	0.55	0.22	0.33	

d_0 is the reservoir water depth, d_3 is downstream depth, $d' = d_0 - d_3$

The measurement of the scour was conducted using a laser distance meter after the run down was completed and no water was inside the scour hole. The area that has been scoured may also be filled by sediment during the process of run-up and run-down, when the velocity of the flow reduced significantly. In order to observe the maximum scour depth, a simple tool was installed at certain locations. The tool was a wire mesh of 1 cm square opening, which was shaped like a cylinder and was installed vertical at the location of the study (Figure 2). Most part of the wire mesh was under the sediment surface and only a few portions was above the sediment bed and above the glass ball to make sure that the glass ball stayed inside the wire mesh during the simulation. Other than that, before implemented, the method was tested a number of time to assure that there was insignificant local scouring due to the wire mesh itself.

It was expected that when the maximum scour depth occurred, the ball fell at the lowest elevation. Whenever re-deposition occurred later, the ball would still be at the lowest position but was covered by sediment. In this way, the maximum scour depth can be observed.

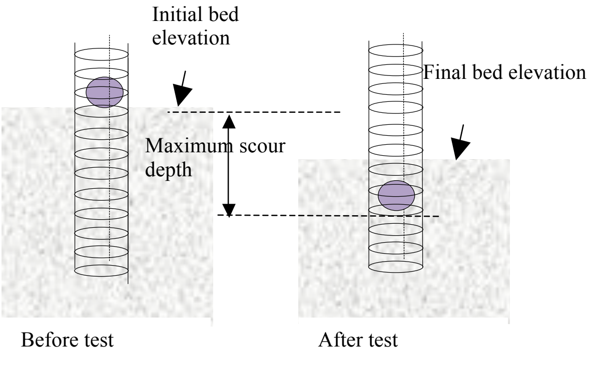


Figure 2. Example of glass ball positions within the cylinder mesh before and after the experiment.

The bed material was of very fine sand where the particle size distribution is provided in Figure 3. As can be seen that most of the sand diameters were between 0.1 mm and 0.4 mm with mean diameter equals 0.19 mm. Hence, the material may be classified as fine sand. Other characteristics values of the bed material are given in Table 3. The sediment porosity was quite high whilst the density was less than 2.0 ton/m^3.

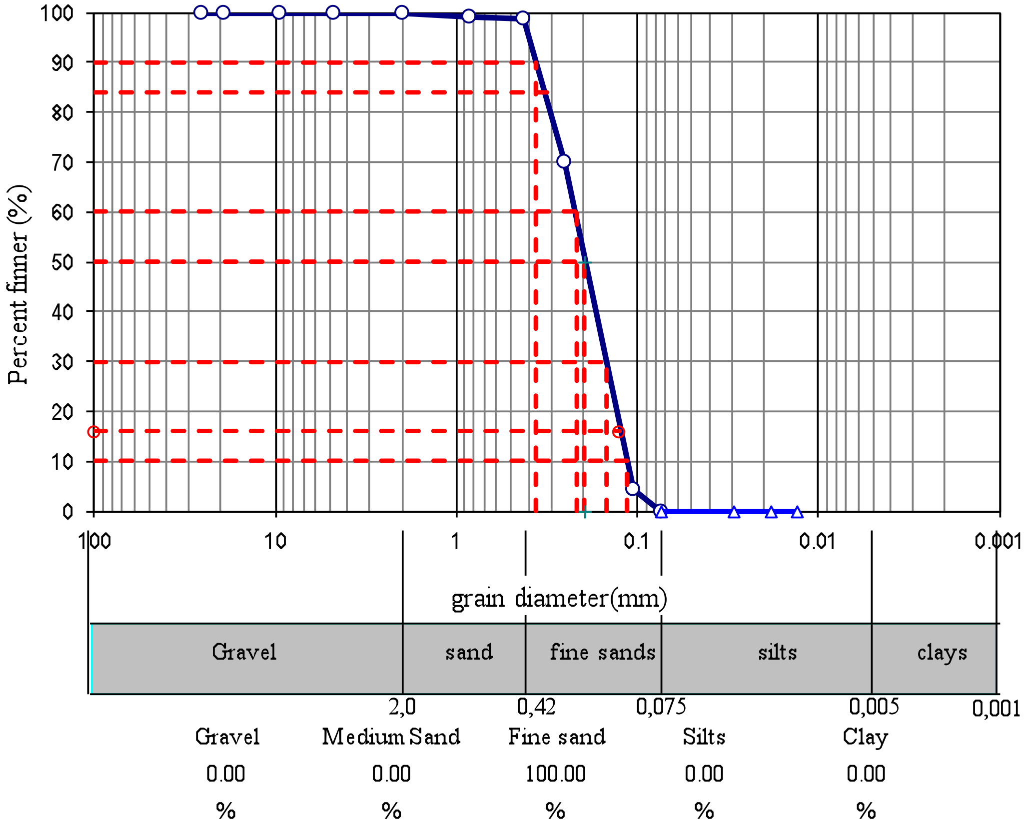


Figure 3. Grain sizes distribution of the sediment bed

Table 3. Characteristics of bed material, Kuswandi et al, (2017)

Properties	Value
diameter (d_{50})	0.19 mm
ρs	1.76 ton/m^3
porosity	0.45
average fall velocity	4.9 cm/s

3. **Experimental results**

1. Effect of relative cylinder diameter

As has been discussed above that the sidewalls may significantly affect the flow pattern when *b/B* was significantly large. Figure 4 provides a clear indication of the effect of the sidewalls during run-up at different value of *b/B*.

At time t =0.53 seconds where the surge front just hit the cylinder (see Figure 4, top), all pictures show that there was no sidewall effect. As can be seen the water levels at the wall were almost the same for all model. There was no effect of sidewalls on the simulation (Figure 4, center) even after the surge hit the cylinder for 0.12 seconds. However, the reflected wave from the cylinder start to move toward the walls. Triatmadja and Nurhasanah (2012) used the same dam break system and flume and found that the reflected wave from the center of the flume required less than 0.5 seconds to reach the walls.

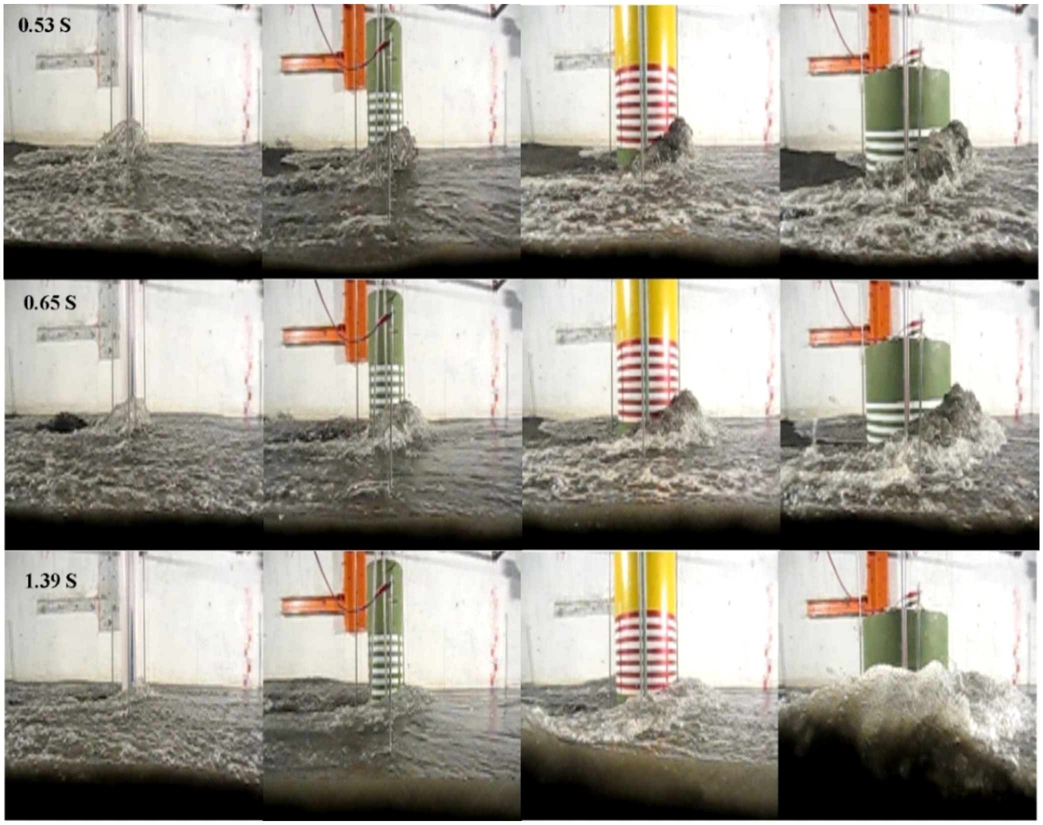


Figure 4. Sidewalls effect

At 1.39 seconds or about 0.86 seconds after the surge hit the cylinder, the effect of the cylinder on the flow pattern become obvious. The largest value of b/B=0.35 resulted in a significant backwater as can be seen at the wall (Figure 4 bottom right). The difference of water level at the same observation time with b/B = 0.25 clearly indicated that the diameter of cylinder was too large to be free of sidewalls effect. The relative cylinder diameter of b/B = 0.14 and b/B = 0.07 showed no effect on the sidewall at the same observation time. This concludes that the relative cylinder diameter that can be used without any sidewalls effect is less than 0.15. Kato et al. (2000), mentioned that their simulation using relative cylinder diameter of b/B = 0.25 did not significantly affect the run-up height and hence they concluded that such relative cylinder diameter may be used to study local scouring around cylinder. Tonkin et al. (2003) who used the same relative cylinder diameter, made similar claim because the local scour extended less than half way between the sidewall and the cylinder. In their cases however, the tsunami were represented by solitary wave that has not broken prior to hitting the cylinder. It may be expected that the flow velocity at the cylinder location be significantly smaller compared to the present study. Hence, the effect of the relative cylinder diameter could have been more tolerated.

2. Scouring around a vertical cylinder

The simulation of scouring around a vertical cylinder was conducted only for *b*/*B* =0.14 and 0.07 as these cylinders were relatively small and no sidewalls effect was observed. The results of the scouring patterns were given in Figure 5 up to Figure 8. When the relative cylinder diameter was large (0.14), the scouring pattern was not symmetrical around the cylinder (Figure 5 and 7). These results were different compare to that of Tonkin, et al (2003). As mentioned previously, the different of flow speed and Froude number could have some contribution to the difference. The present experiment produced significantly less scouring depth at both the upstream and the downstream of the cylinder. However for *b/B* = 0.07 the scour pattern was almost symmetrical (Figure 6 and 8). As can be seen more clearly in Figure 8 that the cross section along the shore (from left to right) and the cross section across the shore (front to back) were similar. This result was closer to that of Tonkin, et al (2003). As mentioned in the previous chapter that the wall effect was relatively small or negligible during the experiment with *b/B* = 0.07. Secondly, as the cylinder was small, the effect of separation flow only last for relatively short duration.

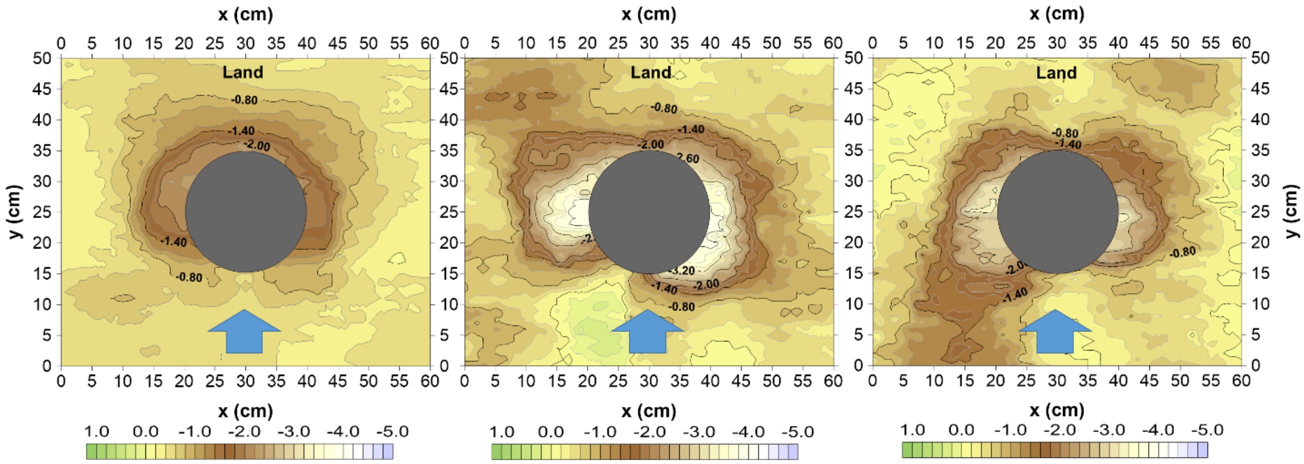


Figure 5. Scouring pattern around cylinder (b/B = 0.14) with *d′* = 0.33, *d′* = 0.30, *d′* = 0,27 respectively

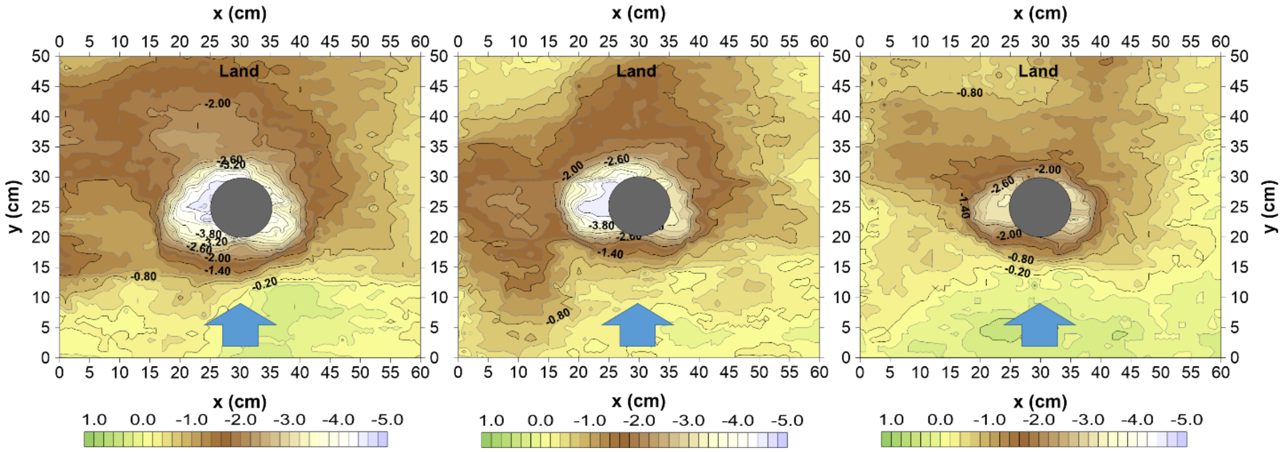


Figure 6. Scouring pattern around cylinder (b/B = 0.07) with $d' = 0.33$, $d' = 0.30$, $d' = 0{,}27$ respectively

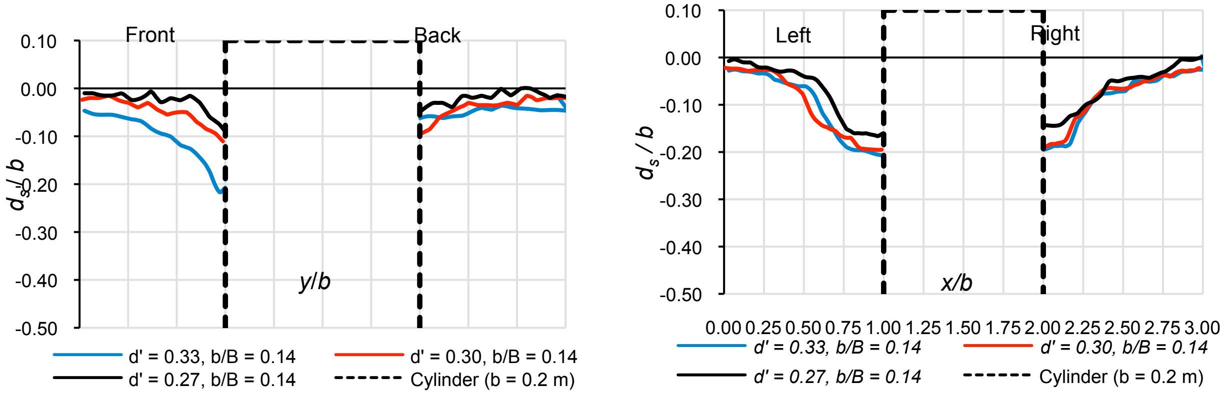


Figure 7. Cross and long sections of scouring at $b/B = 0.14$

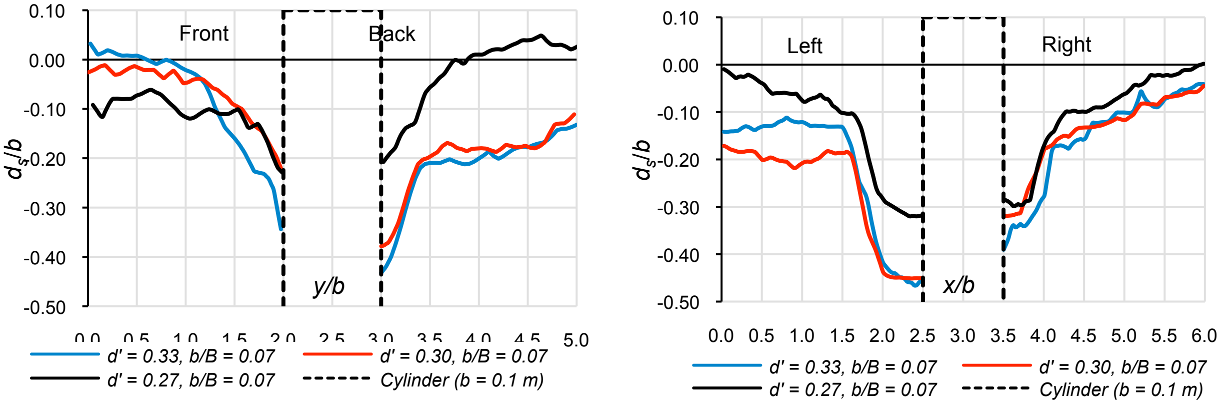


Figure 8. Cross and long sections of scouring at $b/B = 0.07$

3. Maximum scouring depth

The maximum scouring depth for each experiment was plot in Figure 9. The figure indicates clearly that the maximum scour depth were deeper than the final scour depth d_s. In average, the maximum scour was 1.5 times of the final scour depth.

It seems that the scour depths were independent of b or the cylinder diameter as also was found by Triatmadja et al. (2011). The final scour depth ranged from 0.27 d'' to 0.34 d'' whilst the maximum scour ranged from 0.35 d'' to 0.60 d''. It may be said that

$$dsd''=0.34 \tag{6}$$

$$dsmaxd''=0.60 \tag{7}$$

Where d_{smax} is the maximal scour depth. Equation 7 is comparable to Equation 1 of Triatmadja et al (2011). The value of d'' in this experiment was equal to 4/9(d_0) in Triatmadja's and hence based on Equation 1,

$$0{,}56 \leq dsd'' \leq 0.67 \tag{8}$$

Although they only observed the final scour depth but since their experiment employed horizontal slope, no run-down occurred and less re-deposition occurred in the scour hole was expected. The result of the present experiment is in between the range given by Triatmadja et al. (2011).

The maximum scour depth of the present experiment can also be presented in term of the maximum flow depth. Unfortunately, no observation was conducted to obtain the data across the shore. However the water depth at 1 m or 6.8 d'' in front of the cylinder was recorded. This location was approximately 1 m or 6.8 d'' downstream of the coastline. Hence the data at this location was used to represent the maximum flow depth (d_{max}) to yield $dsdmax$= 0.63. Dames and Moore (1980) as reported by FEMA suggested that the approximated maximum scour for loose sand was $dsdmax$ = 0.6 at a distance greater than 300 ft and $dsdmax$ = 0.8 at a distance less than 300 ft (approximately 91 m). Considering that the maximum d'' or tsunami height in the present experiment was 0.15 m, it may be said that the scale of the present model was more or less 1:100 depending on the real tsunami height. With a 1:100 scale model the distance of the cylinder from the coastlines was approximately 50 m in which $dsdmax$ = 0.80. The present maximum scour therefore was 0.80 of the approximated scour depth by Dames and Moore (1980). Similarly the maximum scour obtained by Tonkin et al (2003) was presented based on the maximum tsunami flow depth by the present authors to yield $dsdmax$ = 0.91 which was slightly larger than 0.80 as suggested by Dames and Moore (1980).

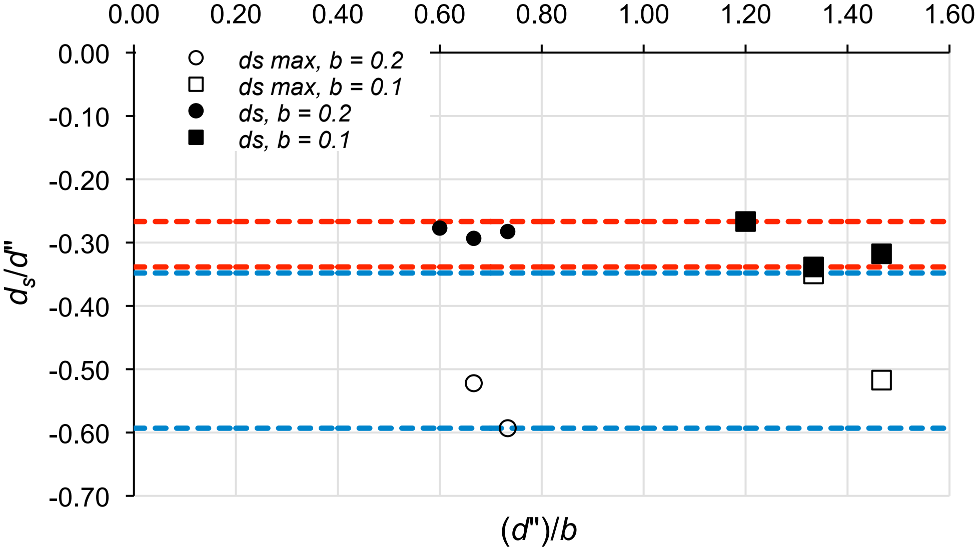


Figure 9. Final and maximum scour depth around cylinder due to relatively short tsunami

3. Conclusion

1. The maximum ratio of cylinder diameter to the channel width that may not produce sidewalls effect of tsunami surge model is (b/B) < 0.15
2. The maximum local scour around a vertical cylinder during tsunami attack is higher than the final scour due to re-deposition of sediment.
3. The maximum local scour around a vertical cylinder during a tsunami attack may reach approximately 0.60 of the tsunami height. This finding was based on short tsunami. A longer tsunami may result in deeper local scour.

Acknowledgement

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