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Influence of Rate of Hydraulic Gradient on Washed-out Soil Mass Due to Perpendicular Contact Erosion or Poor Filter Design

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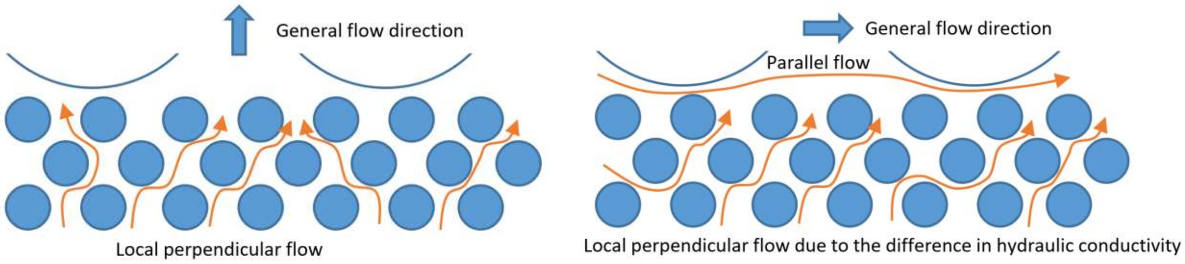
ABSTRACT

Contact erosion is a major type of internal erosion. It occurs at the interaction of a soil layer and filter. Based on the direction of seepage flow, traditional contact erosion comprises of perpendicular and parallel contact erosion. When soil particles are smaller than pore constrictions formed by the filter, they can be washed out sequentially if the flow at this interaction surface is strong enough. However, if the pore sizes are not too far from the particle sizes, a high hydraulic gradient may cause a jamming effect, which reduces the washed-out amount. This paper studies the washed-out amount in perpendicular contact erosion of the same soil under two hydraulic conditions: (1) an immediate jump and (2) a gradual, multi-step change. Soil is compacted to a predefined degree by Multi Testing System (MTS) and tested in a transparent erosion unit. The hydraulic head difference is varied from 2 to 5 m. The change is measured with pressure sensors and recorded continuously with a data logger. The laboratory results show a significant difference in the washed-out amount.

Keywords: *Contact erosion, hydraulic gradient; rate; eroded mass, filter*

INTRODUCTION

Contact erosion is a frequent hazard for hydraulic structures. Unlike the other three types of internal erosion, contact erosion is the only type that occurs between two soils, which may not abut before (Goldin and Rasskazov 2001, Bonelli 2012). In a traditional perspective, contact erosion can be either perpendicular or parallel to the interface between the two soils (Goldin and Rasskazov 2001, Cyril, Yves-Henri et al. 2009). The parallel seepage, in fact, can have both parallel and perpendicular impact (Figure 10).



a) Perpendicular contact erosion b) Parallel contact erosion

Figure 1. Local flow in contact erosion.

In the perpendicular contact erosion, the finer soil is often referred as base soil, while the coarser soil plays the role of a filter. If a fine particle is smaller than the pore constrictions formed by coarse particles, it may be washed through as long as the seepage flow is strong enough to detach it from the base soil. Hence, the focus of assessment often is particle size distribution, not hydraulic gradient (Indraratna and Locke 1999, ICOLD 2015).

Conventionally, the hydraulic criterion for perpendicular contact erosion is often defined at a critical hydraulic gradient or critical force ratio, which are based on density (VODGEO 1982), particle sizes (de Graauw, van der Meulen et al. 1984), pore constriction (VNIIG 1976), and ratio of particle size over pore constriction size (Goldin and Rasskazov 2001). Besides, the hydraulic criteria for parallel contact erosion can also be applied at some level to the perpendicular contact erosion (de Graauw, van der Meulen et al. 1984). This approach is reasonable when the pore constriction sizes are significantly larger than fine particle sizes.

However, when the constriction size is close to the fine particle sizes, the particles can form an arch to block a constriction larger than them, especially when all particles rush to the constriction. Therefore, the history of the hydraulic gradient may play an important role in internal erosion (Marot, Rochim et al. 2014). If the hydraulic gradient increases gradually, particles may be lifted in sequence and have enough time to form a sequential granular flow. In contrast, if the rate of the hydraulic gradient is high, particles may clog themselves as they do not have enough time to reorient.

In this paper, a configuration of perpendicular contact erosion is set. The general flow direction is with gravity, and the filter is tested with an immediate jump and gradual changes of the applied hydraulic gradient. The tests with varied hydraulic gradient found that stable soils with the conventional critical hydraulic gradient can be erodible with a much higher hydraulic gradient because water pressure enlarges the constrictions formed by the filter. Further investigation confirms that this trend discontinues as even higher gradients will result in a lower washed-out amount of soil mass.

LABORATORY SETUP

The research employs a universal erosion unit with an inner diameter of 100 mm (Figure 11). A marble diffuser of 12 mm and a laminator of 10 by 10 mm squares are used to avoid any direct flow impact. The filter is made of 6mm glass beads. As there is no crack in soil, the tests are related to conventional type of contact erosion test (Foster and Fell 2001). Firstly, the soil sample is saturated gradually from the bottom to avoid any air trap. Air is released through a top valve. Later, the downward seepage flow is released from a constant head tank placed at varied elevations. Water is cycled with a centrifuge pump and drainage system.

The hydraulic head is measured by two Wika A10 pressure sensors (Figure 11). Due to the significant size difference, the head loss in the filter is assumed to be insignificant to the head loss in the soil. During the test, the pressure data is recorded every minute as the electric current loss with a DT85GM data logger. Meanwhile, the washed-out soil mass is collected and weighed manually at every predefined time step. The amount of soil mass retained in the granular filter is insignificant and can be neglected.

This research employs five different soil mixtures (Figure 12), which is close to the boundary of Sherard's filter design criterion (Sherard, Dunnigan et al. 1984).

$$\frac{d_{15,F}}{d_{85,b}} < 9$$

Where $d_{15,F}$ = size that 15% of filter mass are finer, $d_{15,F}$ = 6mm; $d_{85,b}$ = size that 85% of soil mass are finer, $d_{85,b} \approx 0.67$ mm to be stable.

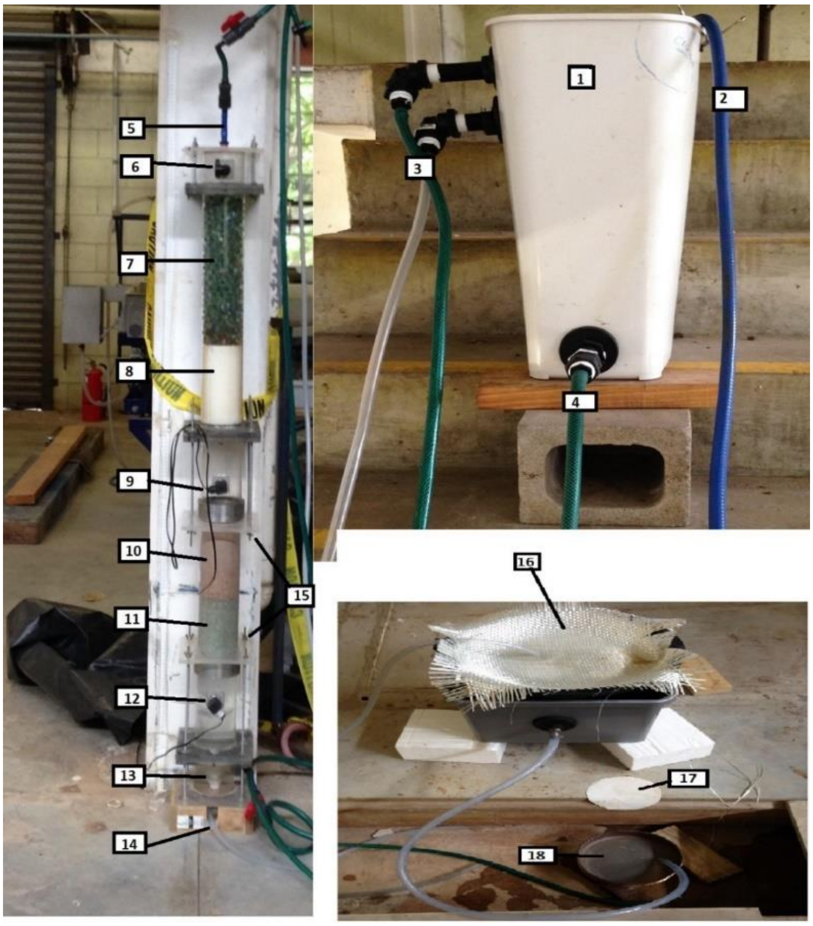


Figure 2. Laboratory setup

1 – Constant head tank; 2 – Tank inlet; 3 – Tank overflow outlet; 4 – Tank outlet; 5 – Inlet; 6 – Air release vale; 7 – Diffuser (12 mm marble); 8 – Laminator; 9 – Upstream pressure sensor; 10 – Soil sample; 11 – Filter (6 mm glass beads); 12 – Downstream pressure sensor; 13 – Funnel; 14 - Outlet; 15 – long bolts; 16 – Finer sieve A (geofabric); 17 – filter paper; 18 - Finer sieve B (metal net).

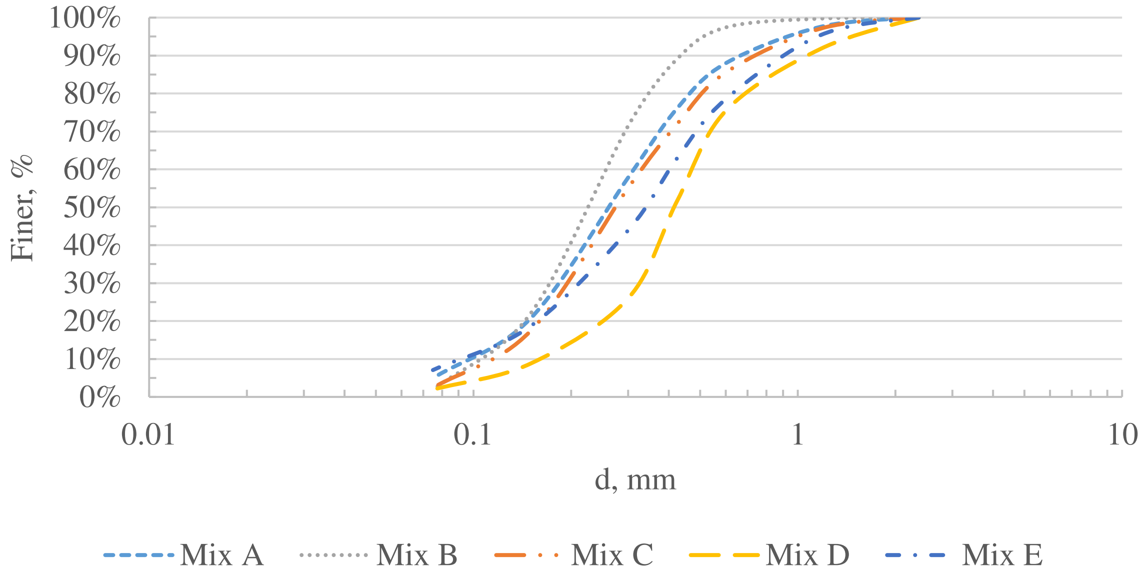


Figure 3. Particle size distribution of tested soils

Five mixtures have been made from available commercial soils. Mixtures A, B, and C are compacted by layers under a 3.5MPa load with MTS (Figure 13). Mixtures D and E are not compacted. More information about tested soils are given in Table 3.

Table 1. Soil parameters

Parameters	Mix A	Mix B	Mix C	Mix D	Mix E
C_u	2.04	1.05	1.86	2.94	4.22
Classification (USCS)	SP	SP	SP	SP	SP
Porosity	0.40	0.39	0.40	0.45	0.44
d_{85}	0.502	0.391	0.593	0.825	0.731

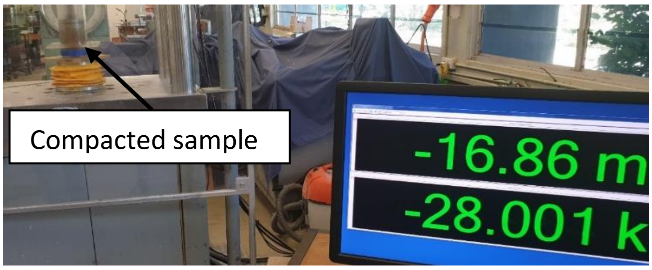


Figure 4. Soil compaction.

All soils are tested with two hydraulic conditions. In the first condition, the hydraulic gradient increases abruptly. The constant head tank is placed directly on the top stair of the staircase before the inlet valve is opened. In the second condition, the hydraulic gradient increases gradually. The tank is placed right above the erosion unit before the inlet is opened. Later, the tank is moved up by two stair steps (392mm) after every consistent period of time. This research employs intervals of 30, 40, and 60 minutes to evaluate the impact of the rate.

RESULTS

The tests show that continuous piping can be seen only in Mix B. All other mixtures have only discontinuous voids (Figure 14). Piping voids and surface subsidence of few millimetres are also observed.

a) b) c) d)

Figure 5. Soil samples: a) Mix B before the test (top view); b) Piping in Mix B after the test (top view); c) Height reduction in Mix B after the test (side view); d) Voids in Mix C after the test (side view)

The total washed-out amounts of soils are summarised in Table 4. Although Mix A and Mix C are not influenced much by the rate of the hydraulic gradient, tests on Mix D and Mix E show that a lower rate may result in a higher washed-out amount. The influence may change the susceptibility to contact erosion from stable (less than 3% mass washed-out) to unstable (more than 5% mass washed-out)(Goldin and Rasskazov 2001). Mix B is unstable with any rate as the filter may not work well with this fine soil. Typical results with 30-minute steps are shown in Figure 15. The graph of Mix B is an exaggerated image of most other tests.

Table 2. Total washed-out amount of soil.

Mix	d_{85}, mm	Washed-out amount (%) with different time steps (minutes)			
		0	**30**	**40**	**60**
A	0.502	1.61	0.88	1.65	1.61
B	0.391	19.30	13.54	16.57	24.37
C	0.593	2.65	2.39	2.58	2.60
D	0.825	2.07	2.78	3.48	4.47
E	0.731	2.83	3.92	4.50	5.28

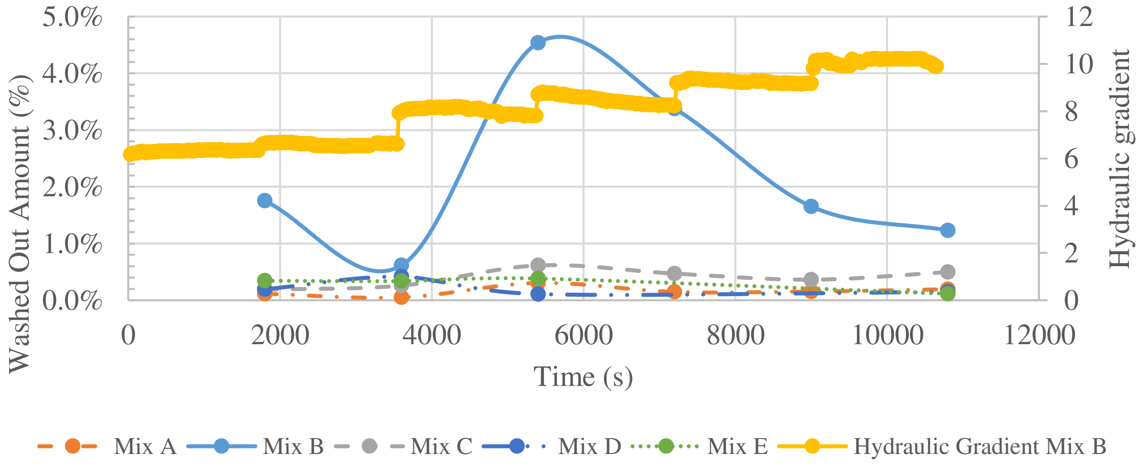


Figure 6. Washed-out amount of soils in the tests with 30-minute steps.

The graph of the washed-out amount by time shows an increase in the third step (Figure 15) at the hydraulic gradient of roughly 8 (Figure 16, Figure 17). Note that the filter is a uniform artificial soil, which may work better than a graded filter in some general criterion. The critical hydraulic gradient for filters with perpendicular seepage flow can be estimated approximately from the Particle Size Distribution (de Graauw, van der Meulen et al. 1984):

$$i_c = \left(\frac{0.06}{n_F^3 d_{15,F}^{4/3}} + \frac{n_F^{5/3} d_{15,F}^{1/3}}{1000 d_{50,b}^{5/3}} \right) \left(1.3 d_{50,b}^{0.57} + 8.3 * 10^{-8} d_{50,b}^{-1.2} \right)$$

Where n_F = porosity of the uniform filter, $n_F \approx 0.28$; $d_{50,b}$= size that 50% of soil mass are finer. The results spread from 0.39 to 0.65 for the given soils. However, except Mix B, all tested soils are stable for the hydraulic gradient of 6 or lower.

After that, most soils show a deduction in the washed-out amount when the hydraulic gradients are high. However, the tests with 40 and 60-minute steps show clearly that the erosion process seems to be continued after the tests at a lower rate. The confusion of a wider result variation might be caused by soil heterogeneity and longer collection time. In contrast, tests with 30-minute steps of all soils, except Mix C (Figure 16), show that the erosion process may stop if the hydraulic gradient increases rapidly (Figure 17). The exception of Mix C may be caused by a developing pipe.

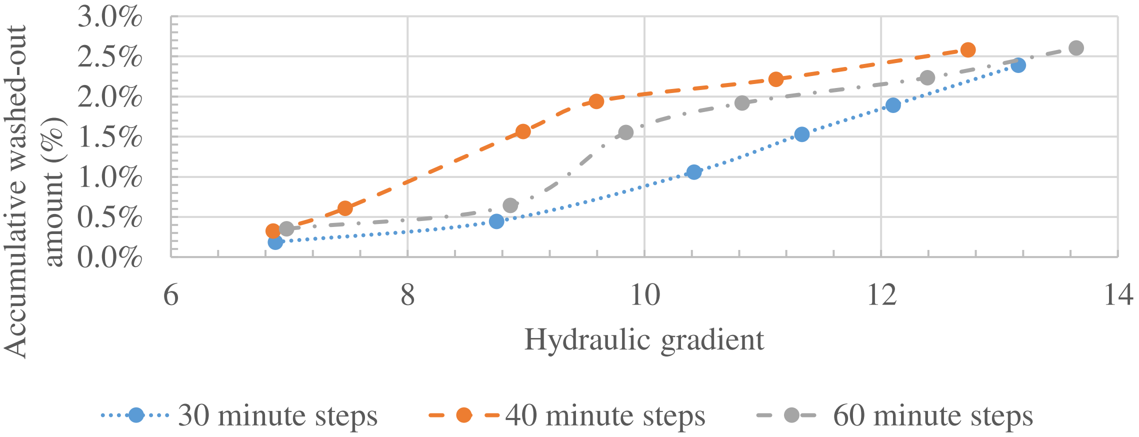


Figure 7. Accumulative washed-out amount of Mix C

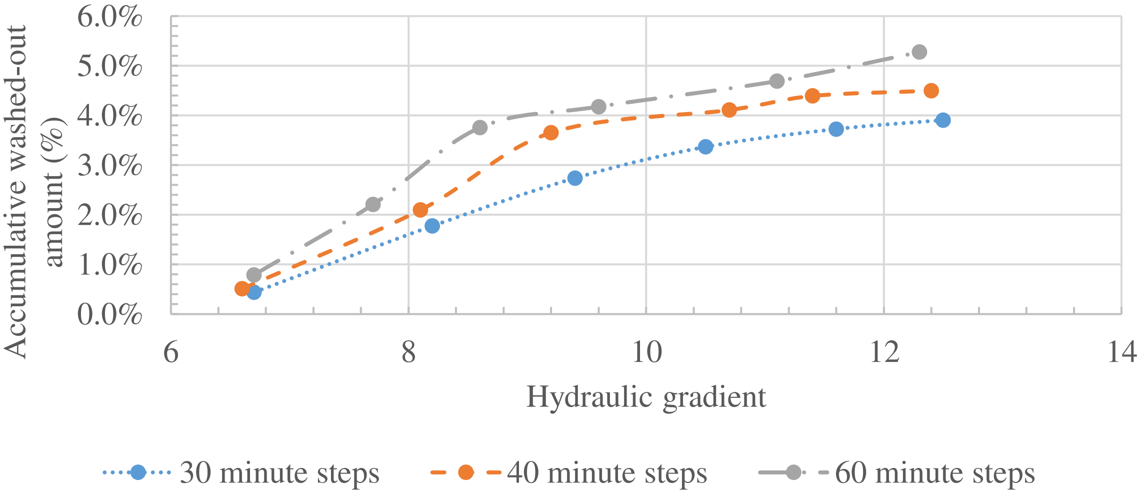
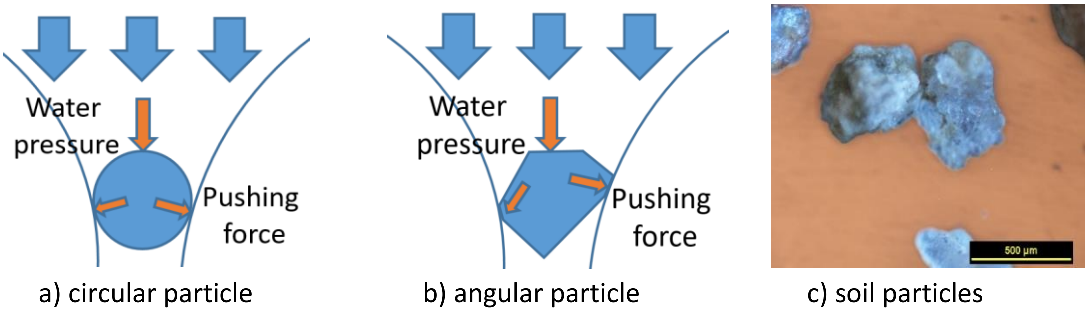


Figure 8. Accumulative washed-out amount of Mix E

DISCUSSION

The results show several interesting phenomena, which may need some hypotheses to comprehend.

Firstly, soils are not eroded at the critical hydraulic gradients, but a much higher gradient. A reasonable explanation for this phenomenon is the high water pressure acting on soils has been transferred onto the filter (Figure 18). It may enlarge the constrictions and/or push soil particles through them. Note that the specimen and filter could not be scanned because the constriction sizes would change due to the unstable piping voids if the specimen was removed and brought to another lab for CT-scan. Hence, the evidence for this hypothesis is not clear. However, the hypothesis may be reasonable. As the water flow is downward, particles are initially stable with support from the coarse filter. This way, the hydraulic force needs to overcome geometrical resistant rather than gravity. When a particle is pushed through the first constriction jammed with many fine particles, it may be transported easily. This requirement of high water pressure may lead to another critical hydraulic gradient for geometrical resistance, not gravity, nor soil effective stress.



a) circular particle b) angular particle c) soil particles

Figure 9. Transfer of water pressure to pushing force.

Secondly, most tested soils seem to be more susceptible to erosion when the hydraulic gradient is just over the “new” critical hydraulic gradient (Figure 15). However, when the hydraulic gradient continues to increase, the washed-out amount decreases at various levels. Mix E seems to stop erosion at a high hydraulic gradient (Figure 17). This trend may occur since all erodible particles have already been washed out. Nevertheless, from a metaphorical perspective, when people evacuate from a building, they may get jammed at the door if the pressure is too big, and the door cannot be widened any more. Therefore, an appropriate gradient may wash out more particles.

Thirdly, the washed-out mass of the soils seems to be larger if the hydraulic gradient rate is low (Table 4). The erosion process seems to continue after the tests with a lower rate. Meanwhile, no significant amount has been observed in the last step of the tests with the high rate of hydraulic gradients. Perhaps, a low rate may give more time for particles to reorient and pass through narrow constrictions (Figure 18b). Thus, more particles can be washed out. As the difference is large enough to change soil from stable to unstable, this phenomenon deserves more attention in future studies.

Finally, although the observed influence of the rate may be applicable to mix B at some level (Table 4), the washed-out amount with immediate hydraulic gradient jump is large.

Maybe, the washed-out amount of very fine soils may depend on the test time and particle arrangement rather than the rate.

However, there are also two remarkable arguments needing to be considered.

The first argument is about the presence of the “new” critical hydraulic gradient in real structures, such as a dam core with high hydraulic gradient. As the effective stress among soil skeleton in real structure may be very high, it may be hard to enlarge the constrictions of filters. However, nearly stable soils may not need to push the coarse filter much due to soil heterogeneity. Authorial experience shows that, even uniform filter may have several loose particles, which may be enough to start piping. Besides, a numerical model stated that if the filter is well graded, only a small number of coarse particles carry the most effective stress (To, Torres et al. 2015, To, Galindo-Torres et al. 2016). Meanwhile, other particles transfer less stress and, therefore, may be easy to be adjusted. The final answer for this argument may be verified experimentally, using stress-controlled erosion apparatus (Chang and Zhang 2011), or numerically, using DEM-LBM models (Cheng, Galindo-Torres et al. 2018).

The second argument is about the impact of the hydraulic gradient rate in real structures. The results for compacted soil is less significant than for uncompacted soils (Table 4). In fact, soils in hydraulic structures are often well compacted to increase the shear strength. If the particles are compacted, they do not have room to reorient themselves. Therefore, the low gradient rate may not have significant impact. Nevertheless, the compaction layers are often at their maximum allowable thickness of 0.15m (ACT Government 2002, State of Tasmania 2008), which is thicker than the 0.05m compacted layers in the tests. It is an authorial experience that soils dumped at dam constructions often form layers of 0.45m or more if there is no control. Hence, soils at hydraulic constructions may have more flexibility than the tested soils. An in-situ evaluation of the impact may be done using a large-scale setup for erosion tests.

CONCLUSION

This paper has presented an experimental study on the influence of the hydraulic gradient rate on the washed-out amount in contact erosion test. The tests found that soil may be stable with the critical hydraulic gradients, but unstable with a much higher gradient. Also, a low rate may have a significant impact on uncompacted soils that soil may change from the stable state to unstable.

Nevertheless, the tests are undertaken without surcharge, which may differ from the real situation at hydraulic structures. Further studies with complex stress states are required to confirm the discovery.

ACKNOWLEDGMENT

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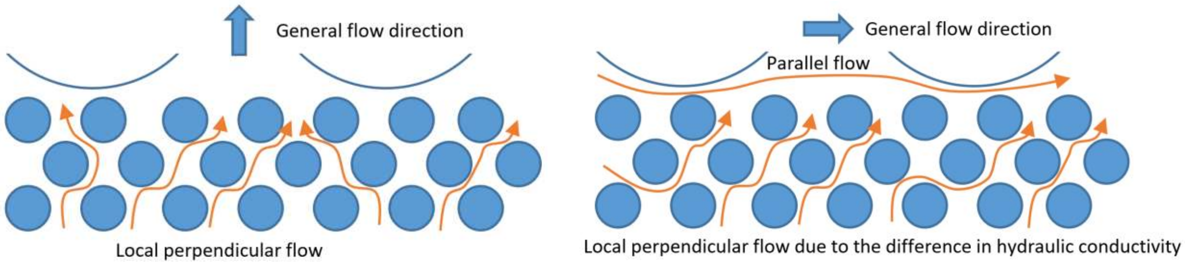

b) Perpendicular contact erosion

b) Parallel contact erosion

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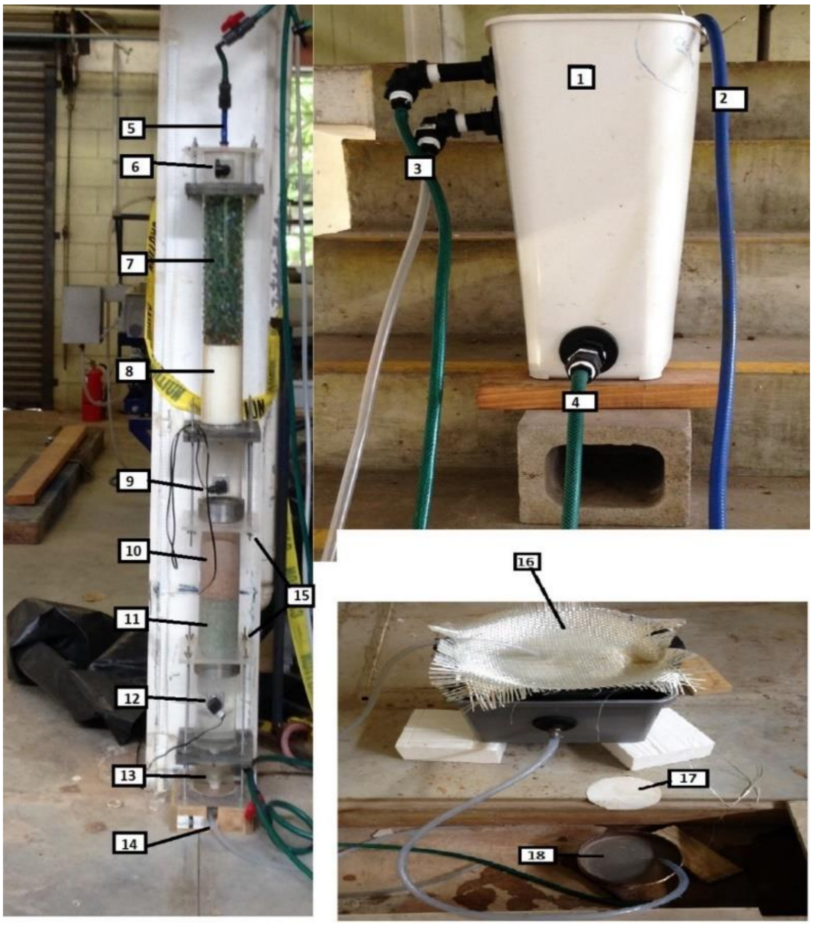

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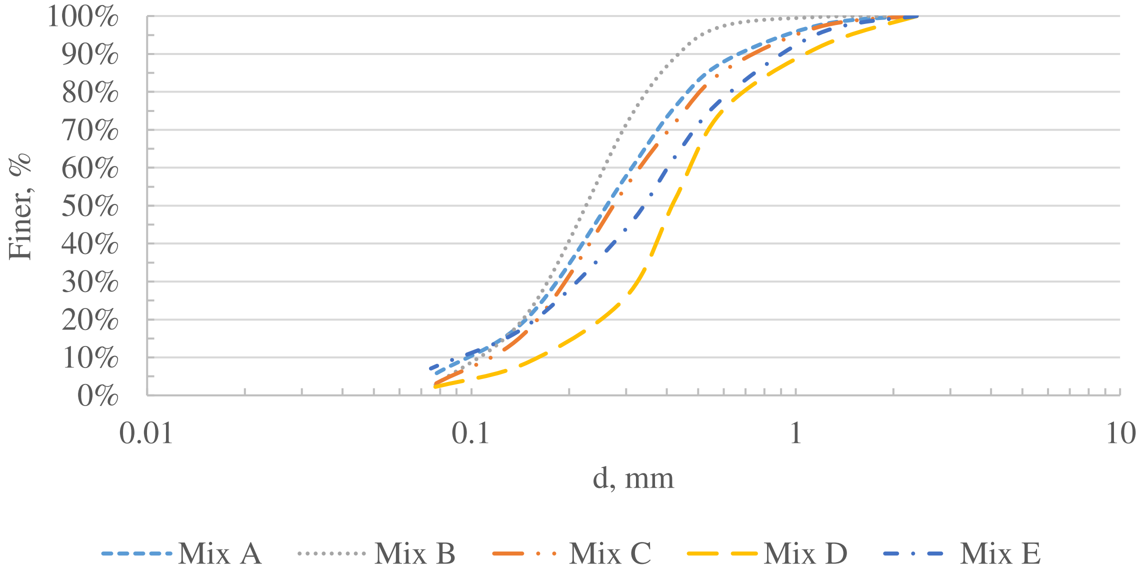

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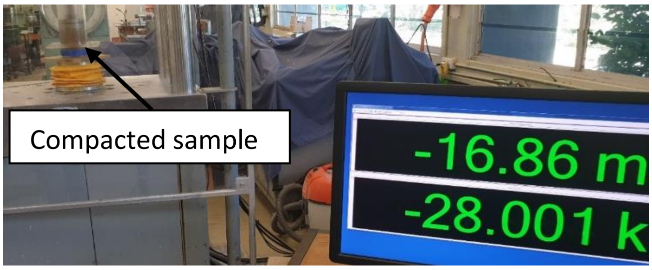

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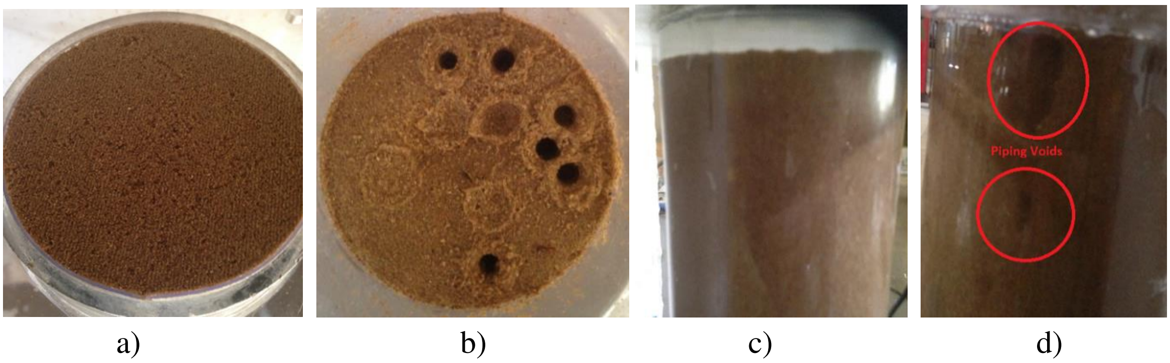


Figure 14. Soil samples: a) Mix B before the test (top view); b) Piping in Mix B after the test (top view); c) Height reduction in Mix B after the test (side view); d) Voids in Mix C after the test (side view)

The total washed-out amounts of soils are summarised in Table 4. Although Mix A and Mix C are not influenced much by the rate of the hydraulic gradient, tests on Mix D and Mix E show that a lower rate may result in a higher washed-out amount. The influence may change the susceptibility to contact erosion from stable (less than 3% mass washed-out) to unstable (more than 5% mass washed-out)(Goldin and Rasskazov 2001). Mix B is unstable with any rate as the filter may not work well with this fine soil. Typical results with 30-minute steps are shown in Figure 15. The graph of Mix B is an exaggerated image of most other tests.

Table 4. Total washed-out amount of soil.

Mix	d_{85}, mm	Washed-out amount (%) with different time steps (minutes)			
		0	**30**	**40**	**60**
A	0.502	1.61	0.88	1.65	1.61
B	0.391	19.30	13.54	16.57	24.37
C	0.593	2.65	2.39	2.58	2.60
D	0.825	2.07	2.78	3.48	4.47
E	0.731	2.83	3.92	4.50	5.28

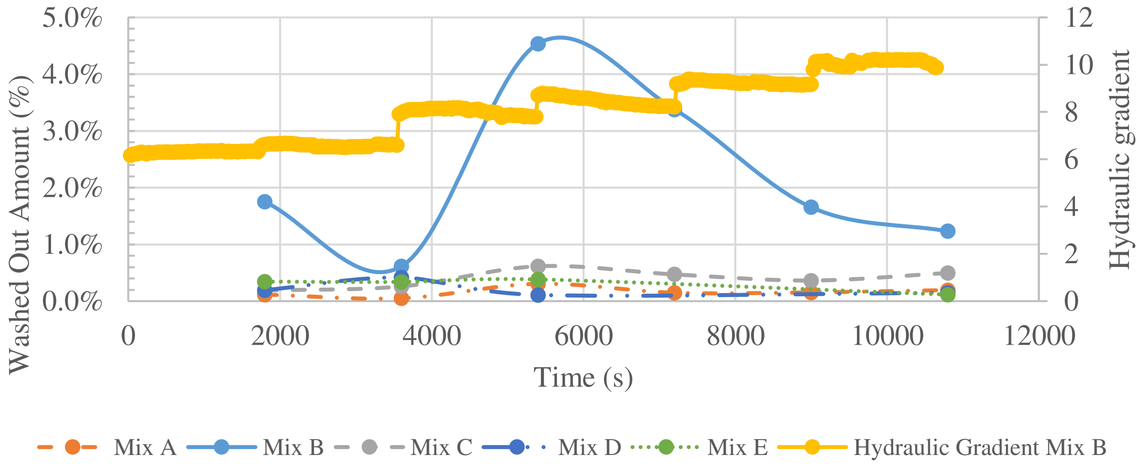


Figure 15. Washed-out amount of soils in the tests with 30-minute steps.

The graph of the washed-out amount by time shows an increase in the third step (Figure 15) at the hydraulic gradient of roughly 8 (Figure 16, Figure 17). Note that the filter is a uniform artificial soil, which may work better than a graded filter in some general criterion. The critical hydraulic gradient for filters with perpendicular seepage flow can be estimated approximately from the Particle Size Distribution (de Graauw, van der Meulen et al. 1984):

$$i_c = \left(\frac{0.06}{n_F^3 d_{15,F}^{4/3}} + \frac{n_F^{5/3} d_{15,F}^{1/3}}{1000 d_{50,b}^{5/3}} \right) \left(1.3 d_{50,b}^{0.57} + 8.3 * 10^{-8} d_{50,b}^{-1.2} \right)$$

Where n_F = porosity of the uniform filter, $n_F \approx 0.28$; $d_{50,b}$= size that 50% of soil mass are finer. The results spread from 0.39 to 0.65 for the given soils. However, except Mix B, all tested soils are stable for the hydraulic gradient of 6 or lower.

After that, most soils show a deduction in the washed-out amount when the hydraulic gradients are high. However, the tests with 40 and 60-minute steps show clearly that the erosion process seems to be continued after the tests at a lower rate. The confusion of a wider result variation might be caused by soil heterogeneity and longer collection time. In contrast, tests with 30-minute steps of all soils, except Mix C (Figure 16), show that the erosion process may stop if the hydraulic gradient increases rapidly (Figure 17). The exception of Mix C may be caused by a developing pipe.

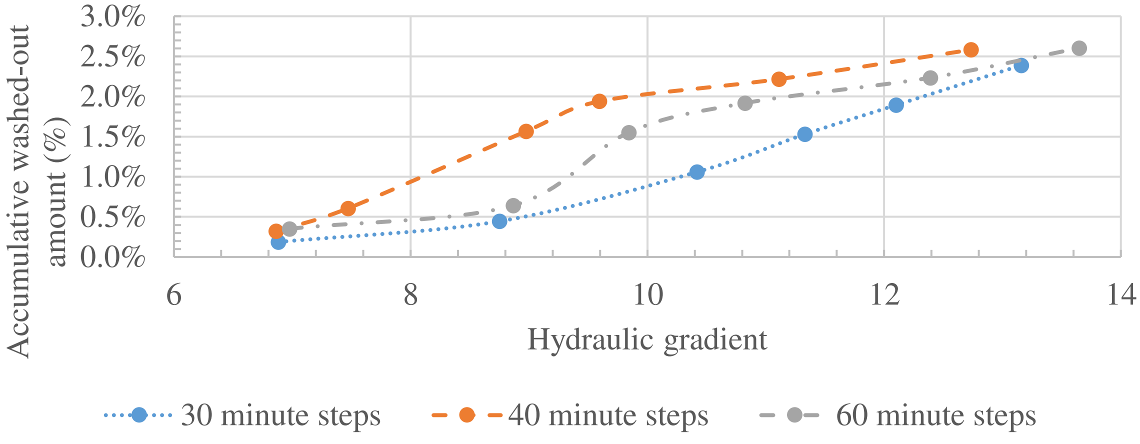


Figure 16. Accumulative washed-out amount of Mix C

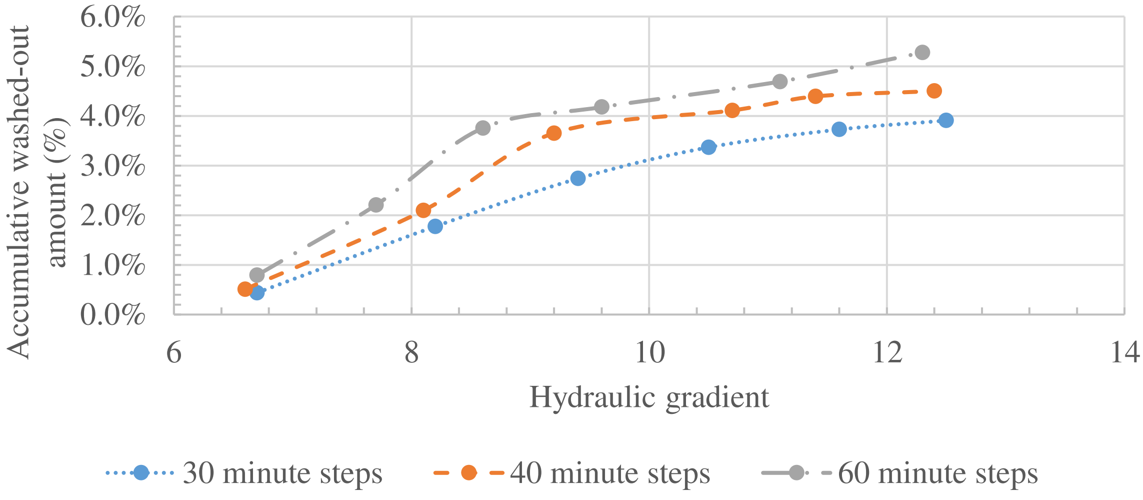
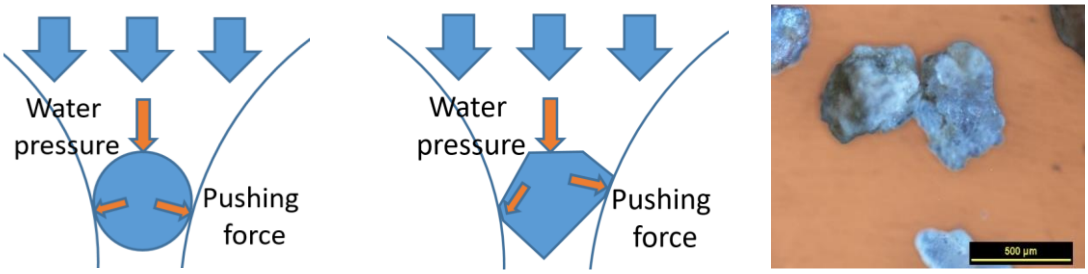


Figure 17. Accumulative washed-out amount of Mix E

DISCUSSION

The results show several interesting phenomena, which may need some hypotheses to comprehend.

Firstly, soils are not eroded at the critical hydraulic gradients, but a much higher gradient. A reasonable explanation for this phenomenon is the high water pressure acting on soils has been transferred onto the filter (Figure 18). It may enlarge the constrictions and/or push soil particles through them. Note that the specimen and filter could not be scanned because the constriction sizes would change due to the unstable piping voids if the specimen was removed and brought to another lab for CT-scan. Hence, the evidence for this hypothesis is not clear. However, the hypothesis may be reasonable. As the water flow is downward, particles are initially stable with support from the coarse filter. This way, the hydraulic force needs to overcome geometrical resistant rather than gravity. When a particle is pushed through the first constriction jammed with many fine particles, it may be transported easily. This requirement of high water pressure may lead to another critical hydraulic gradient for geometrical resistance, not gravity, nor soil effective stress.



a) circular particle b) angular particle c) soil particles

Figure 18. Transfer of water pressure to pushing force.

Secondly, most tested soils seem to be more susceptible to erosion when the hydraulic gradient is just over the "new" critical hydraulic gradient (Figure 15). However, when the hydraulic gradient continues to increase, the washed-out amount decreases at various levels. Mix E seems to stop erosion at a high hydraulic gradient (Figure 17). This trend may occur since all erodible particles have already been washed out. Nevertheless, from a metaphorical perspective, when people evacuate from a building, they may get jammed at the door if the pressure is too big, and the door cannot be widened any more. Therefore, an appropriate gradient may wash out more particles.

Thirdly, the washed-out mass of the soils seems to be larger if the hydraulic gradient rate is low (Table 4). The erosion process seems to continue after the tests with a lower rate. Meanwhile, no significant amount has been observed in the last step of the tests with the high rate of hydraulic gradients. Perhaps, a low rate may give more time for particles to reorient and pass through narrow constrictions (Figure 18b). Thus, more particles can be washed out. As the difference is large enough to change soil from stable to unstable, this phenomenon deserves more attention in future studies.

Finally, although the observed influence of the rate may be applicable to mix B at some level (Table 4), the washed-out amount with immediate hydraulic gradient jump is large. Maybe, the washed-out amount of very fine soils may depend on the test time and particle arrangement rather than the rate.

However, there are also two remarkable arguments needing to be considered.

The first argument is about the presence of the "new" critical hydraulic gradient in real structures, such as a dam core with high hydraulic gradient. As the effective stress among soil skeleton in real structure may be very high, it may be hard to enlarge the constrictions of filters. However, nearly stable soils may not need to push the coarse filter much due to soil heterogeneity. Authorial experience shows that, even uniform filter may have several loose particles, which may be enough to start piping. Besides, a numerical model stated that if the filter is well graded, only a small number of coarse particles carry the most effective stress (To, Torres et al. 2015, To, Galindo-Torres et al. 2016). Meanwhile, other particles transfer less stress and, therefore, may be easy to be adjusted. The final answer for this argument may be verified experimentally, using stress-controlled erosion apparatus (Chang and Zhang 2011), or numerically, using DEM-LBM models (Cheng, Galindo-Torres et al. 2018).

The second argument is about the impact of the hydraulic gradient rate in real structures. The results for compacted soil is less significant than for uncompacted soils (Table 4). In fact, soils in hydraulic structures are often well compacted to increase the shear strength. If the particles are compacted, they do not have room to reorient themselves. Therefore, the low gradient rate may not have significant impact. Nevertheless, the compaction layers are often at their maximum allowable thickness of 0.15m (ACT Government 2002, State of Tasmania 2008), which is thicker than the 0.05m compacted layers in the tests. It is an authorial experience that soils dumped at dam constructions often form layers of 0.45m or more if there is no control. Hence, soils at hydraulic constructions may have more flexibility than the tested soils. An in-situ evaluation of the impact may be done using a large-scale setup for erosion tests.

CONCLUSION

This paper has presented an experimental study on the influence of the hydraulic gradient rate on the washed-out amount in contact erosion test. The tests found that soil may be stable with the critical hydraulic gradients, but unstable with a much higher gradient. Also, a low rate may have a significant impact on uncompacted soils that soil may change from the stable state to unstable.

Nevertheless, the tests are undertaken without surcharge, which may differ from the real situation at hydraulic structures. Further studies with complex stress states are required to confirm the discovery.

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