The erosion behavior of revetments using geotextiles under tangential flow condition

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ABSTRACT: To have a thorough understanding of the soil erosion behavior of tangential flows in revetments, this erosion testing was conducted using tangential flow erosion equipment and two types of geotextiles in different apparent opening sizes and included a series of indoor tests in different phases of the velocity of flow in line with the combinations of gravels in different sizes and soil. During the testing, changes in turbidity and flow were recorded in a synchronous manner and those in the testing tank in each phase of the velocity of flow were observed to learn the erosion behavior in each test combination. After the testing, soil worn away by the erosion was collected for particle size testing and analysis to understand the mechanisms of soil erosion. Testing results show that both critical and failure flow velocities tended to increase as parameters such apparent opening size, gravel porosity and size decreased; in addition to soil retention by the woven textiles, the gravels also retained the soil flushed out of the woven textiles by the water flows and acted as the second protection; and the soil carried by the flows into the water tank was mostly in a size of less than #200 mesh while that retained by the gravels was mostly in a size of #100 mesh.

Keywords: erosion behavior, tangential flows, grotextiles, critical flow velocity, failure flow velocity

1 INTRODUCTION

Unfavorable erosion on revetments may affect the slope stability of riverbanks and jeopardize the safety of adjacent buildings, and debris can be triggered by the soils and rocks eroded from the riverbanks and accumulate on the riverbed. Improvement works are needed to increase the stability of revetments as well as to reduce the possibility of failure. Current practices usually involve building tall concrete revetments, causing negative environmental impacts and instability of riverbanks under long-term erosion. Therefore, it is crucial to find materials suitable for building revetments which are safe and environmentally friendly as well.

Geotextiles used as a riverbank protection material is not only more environmentally-friendly but also more stable in long-term compared to concrete. However, improper design of geotextile revetments can cause considerable loss of riverbank soil, which might result in failure. Figure 1 is the typical cross-section of revetment using geotextile. According to the water flow direction, it can be divided into three zones. Above the high water level is zone 1, where the groundwater always flows into the river and result in the uni-directional flow condition. Between high water level and low water level is zone 2, where the soil-geotextile interface is subject to bi-directional flow. When the groundwater table within the revetment is higher than the river water level, water will flow out from the revetment. On the contrary, water may flow into the revetment when the river water level is higher. As mentioned, no matter in zone 1 or zone 2, the influence of water flow on the soil-geotextile interface only locates in X-Z plane. Zone 3 is under the low water level, and the percolation rate of water through a soil-geotextile system is insignificant due to the small hydraulic gradient between water side and bank side. The soil erosion behavior in X-Z plane is unobvious. However, the water flow along the revetment (Y-Z plane) may cause parallel erosion. Consequently, the main erosion problem in zone 3 is caused by the uni-directional tangential flow in Y-Z plane. Today numerous studies on erosion behavior of geotextile revetments have

been completed, but most of them focused on only uni-directional and bi-directional flow behavior. The actual flow behavior in geotextile revetments is rather complicated and can be categorized into uni-directional flow zone, cyclic flow zone, and tangential flow zone. In this study, a series of laboratory experiments were performed with parallel erosion test equipment that are able to simulate the erosion behavior of revetment using geotextiles under tangential flow directions.

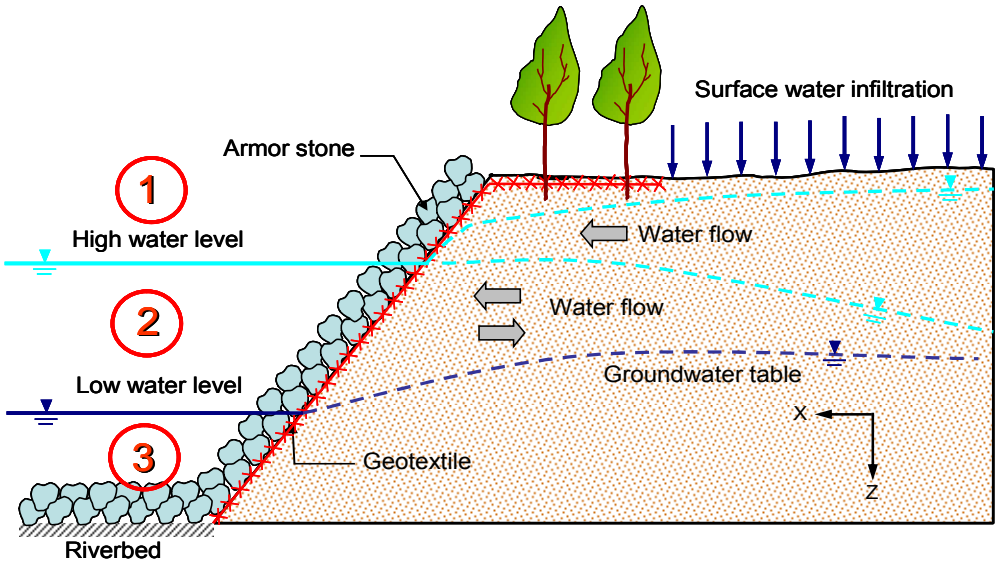


Figure 1. A typical cross-section of revetments using geotextiles.

2 PARALLEL EROSION TEST

In addition to the revetment works, among various phenomena implied in internal erosion like piping or suffusion, there is the contact erosion┐ that occurs at the interface between soil layers with different grain sizes. Indeed in numerous embankment dykes, it is usual to find a layered soil structure alternatively composed of fine sand or gravel. At the interface between a coarse layer and a fine one, if water is flowing through the coarse layer, contact erosion┐ in the form of fine grain removal may occur due to the shear stress of interface-parallel flow and can lead to backward erosion or settlements. This kind of erosion can also arise in core filled dykes, when the core is overtopped by water (Guidoux *et al.*, 2010).
For most of water retaining structures, such as the embankment dams or the riverbanks, groundwater seepage prevails under subsoil. If the subsoil is layered, the seepage might cause the parallel layer erosion between two layers. Scherzinger (1984) proposed that the critical erosion flow velocity ($v_{F,crit}$) of the gravel filter-subsoil interface is related to the critical Froude number (Fr_{crit}).

$$v_{F,crit} = Fr_{crit} \times n_F \times \sqrt{\frac{\gamma'_{sB} \times d_{50B}}{\rho_w}} \tag{1}$$

where n_F= porosity of gravel filter, γ'_{sB} = unit weight of subsoil, d_{50B} = subsoil's particle size corresponding to 50% passing, ρ_w = The density of water, respectively

In order to understand the effect of the subsoil particles size and the porosity of gravel filter on the interface erosion behavior, Brauns (1985) adopted a gravel filter-subsoil interface horizontal erosion equipment (Figure 2) and carried out a series test in laboratory. In this test, three different compositions of very uniform soil and four kinds of gravel filters are used but the porosity are almost the same ($n_F \approx 0.39$). There are fourteen of components with gravel filter and subsoil in his test. According to the test result, Brauns (1985) opined out that the critical Froude number (Fr_{crit}) is 0.65 to 0.70 and the variation is insignificant with gravel filter and subsoil particle size distribution. Hence, he suggested that Fr_{crit} = 0.65.

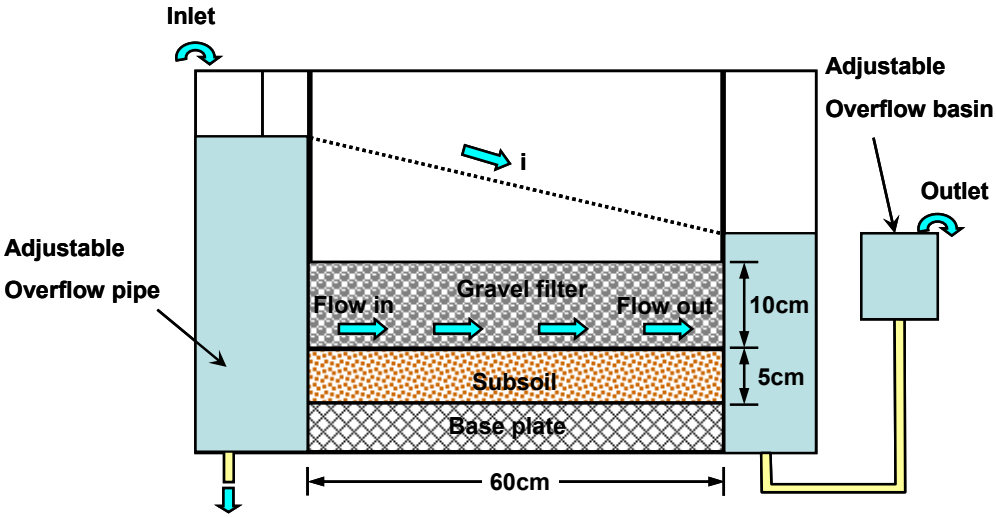


Figure 2. Illustration of the gravel filter-subsoil interface horizontal erosion test (Brauns, 1985).

2.1 *Test equipment*

Based on this observation, a parallel erosion test (PET) equipment was developed to study the behavior of tangential erosion. In addition, this equipment can also be used for probing into the internal erosion behavior of the soil under the uni-directional flow.

Figure 3 presents the layout of parallel erosion test system and Figure 4 shows the general view of this equipment. The equipment of parallel erosion test comprises two water tanks. Clean water is poured into the bottom water tank and meanwhile pumped into the upper water tank by a lift pump. After opening the valve, water flows into the steel cell room through the water pipe. Inside the steel cell room, sub-soil, geotextile, gravel, and rubber water bag are filled in sequence. The top of the rubber water bag is connected to a pressurization system in order to apply the vertical pressure. The elevation of the sub-soil that filled in the cell room equals to the bottom level of the water inlet and outlet, so that water will only flow through the gravel layer. Consequently, the water flow direction is parallel to the sub-soil surface, and hence this experiment is called parallel erosion test (PET). In order to measure the hydraulic gradient, the connector tube that connects to a water pressure head loss meter in the water inlet and outlet was set up separately. Water flows out and carries the eroded soil particles out of the water outlet. Hence, a turbiditymeter in the outlet was installed to survey the variation of water turbidity, and a flowmeter was installed to measure the water flow rate.

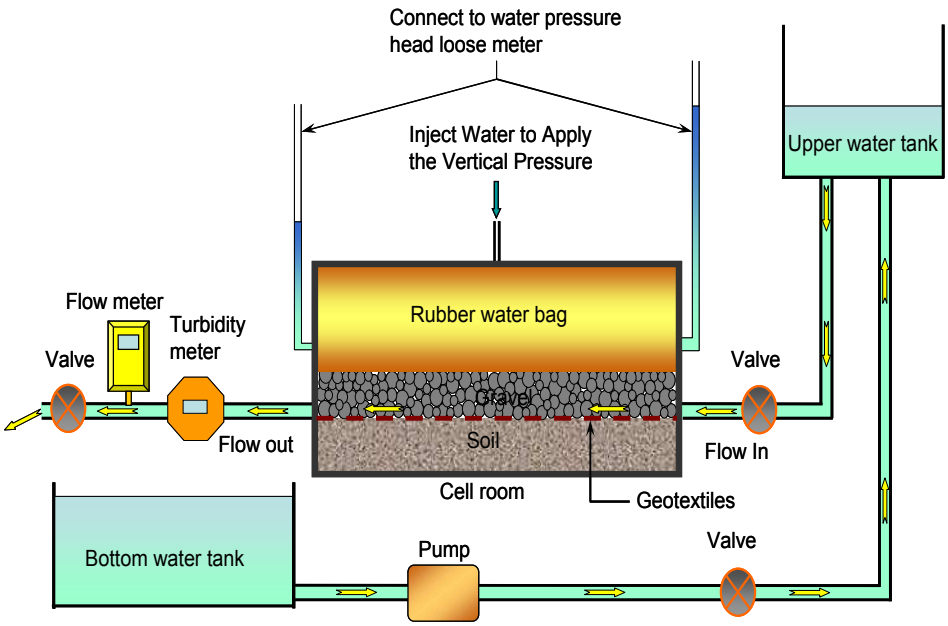


Figure 3. Illustration of the parallel erosion test equipments. (Ho, 2007)

Figure 4. General view of the parallel erosion test equipment.

2.2 *Test materials characteristics*

The main test materials for this study are the sub-soil, the gravel and the geotextiles. Their physical characteristics are described as follows.

2.2.1 *Sub-soil*

The soil used in this experiment comes from non-cohesive fine silty sand, a sedimentary deposit of the river. It contains some rounded gravel and pebbles but 90% of its grain size is lower than 400 microns. According to the USCS, it is a loamy sand (SM) and its average dry unit weight after compaction in the flume is γ_d = 16.2 kN/m^3 with 1.0×10^{-5}cm/s of the Darcy's permeability (k_s).

2.2.2 *Gravel*

In order to simulate the coverage of the revetment surface, three different sizes of marbles were used as the amour stone in this experiment. The average grain diameter of marble A, B and C is 25mm, 16mm and 20.5mm respectively. The parameters of those three marbles see Table 1.

Table 1. The parameters of marbles.

Marble Type	Average grain diameter, D_{50}(mm)	Porosity, n (%)	Darcy's permeability k_r (cm/s)
A	25	9.43	10.07
B	16	8.43	9.57
C	20.5	5.42	7.53

2.2.3 *Geotextiles*

Two different geotextiles were used to cover the sub-soil in this study. The apparent opening size (AOS) of Geotextile α is 1.249mm and its thickness is 0.304mm, the weight per unit area is 93.23g/m^2. Geotextile β with 0.568mm of AOS, 0.264mm of thickness and 132.68 of weight per unit area. The AOS of Geotextile α is larger and thicker than Geotextile.

2.3 *Erosion criteria*

Moreover, Figure 5 shows the variation of water turbidity and flow velocity with time. As shown, there is a peak value at the initial stage of testing. That is probably due to the sudden increase of flow velocity which washed away the soil particles that adhered to gravel surface or deposited in the water pipe, and

caused transient increase of water turbidity. According to the variation of water turbidity by time, the following three soil erosion states can be summarized:

1. Non erosion:

After the peak water turbidity of the initial stage, if no soil particles continued to be washed out by water, the water turbidity will decrease with time. As Figure 5(a) shows, water turbidity decreased to zero after the peak point, meaning that the water outflow is clean and without any soil particles and consequently no soil erosion occurred. Hence, under this condition, the soil is in the non erosion state.

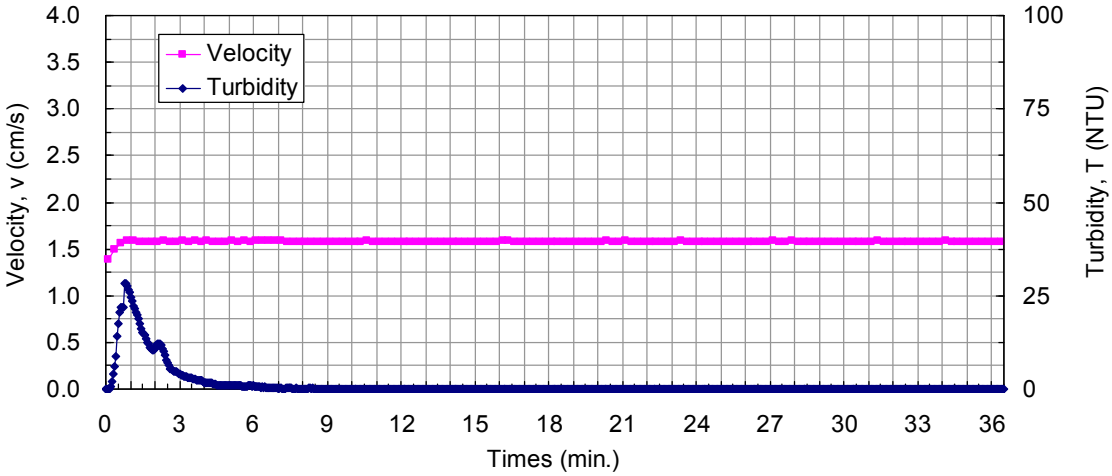
2. Steady erosion:

As shown in Figure 5(b), the water turbidity also decreased but could not decay to zero after the peak turbidity. The residual turbidity keeps constant with time. In addition, by observing the state of the soil through the observation window of cell room it can also be found that particles are migrated by flow. It presents that the follow-up water outflow included a fixed quantity of soil particles. In other words, the sub-soil was eroded and the erosion rate remains unchanged under the fixed flow velocity. It can say that the soil is in the state of steady erosion.

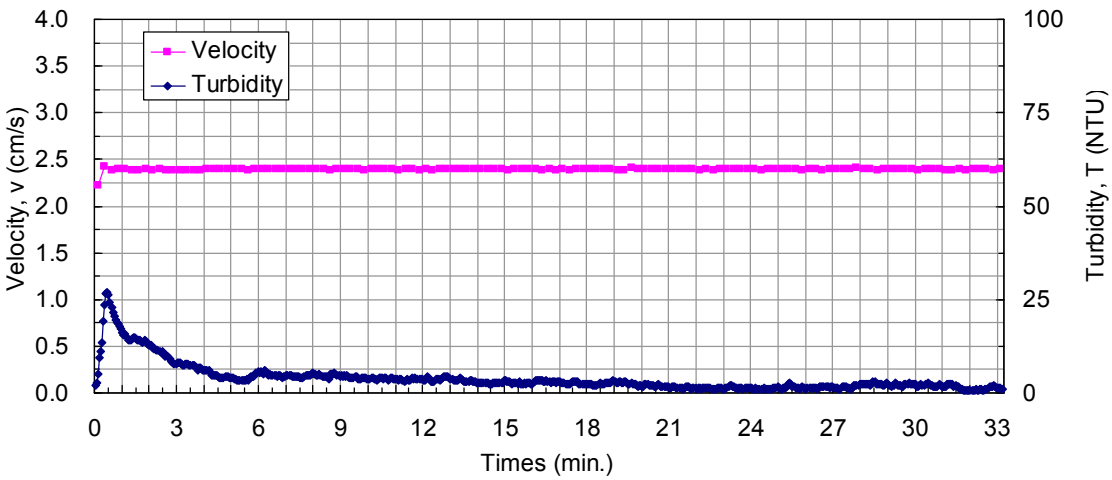
3. Failure erosion:

The water turbidity increases with increasing flow velocity. Figure 5(c) shows that the water turbidity is high and the variation is irregular with time when the flow velocity keeps constant. This shows that the water contains a large quantity of soil particles. On the other hand, the soil has undergone obvious erosion as observed through the transparent plexiglass while testing. Under this condition, the soil is in the failure erosion state and will produce failure quickly.

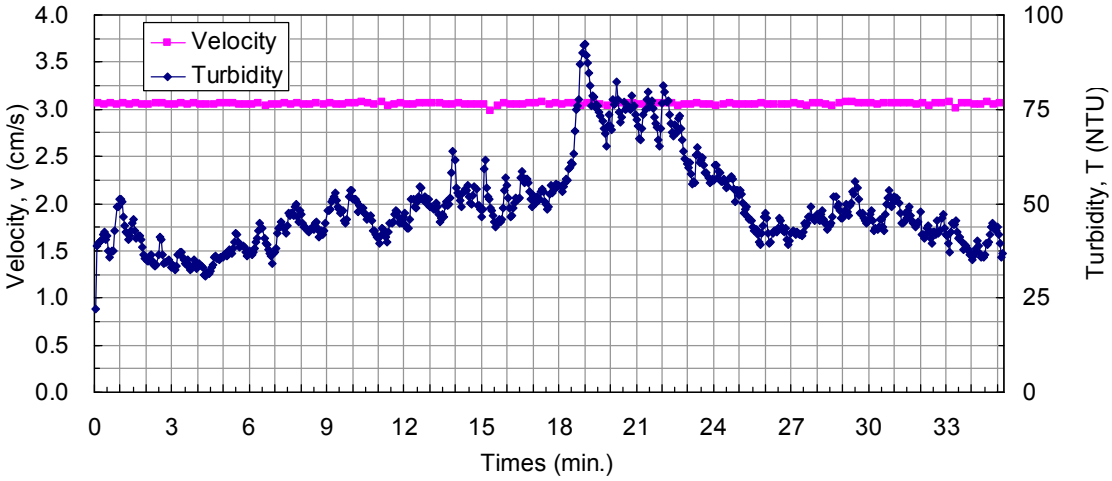
Under the smaller flow velocities, non soil erosion occurred. With the increase of the flow velocity, the soil begins to erode gradually. The critical flow velocity (V_c) was defined that the flow velocity when the soil begin to erode. In addition, the flow velocity when the soil situated between steady erosion and failure erosion is named the failure flow velocity (V_f).



(a) Non erosion state



(b) Steady erosion state



(c) Failure erosion state

Figure 5 Types of soil erosion states.

3 TEST RESULTS

3.1 *The performance on erosion control*

Nine experiments were carried out in this study. Test 1 to Test 3 used the Geotextile α with marble A, B and C respectively. Test 4 to Test 6 used the Geotextile β with marble A, B and C respectively. Moreover, Test 7 to Test 9 without geotextile and cover with marble A, B and C on sub-soil directly.

The test result shows the critical flow velocity (V_c) and failure flow velocity (V_f) of Test 7-8 are lower than Test 1-6 (see Table 2). It is obvious that the geotextile cover on the surface of sub-soil could protect the soil erosion. To compare with different geotextiles used in this test, V_c and V_f of Geotextile β are higher than Geotextile α used. It indicates that to use the smaller AOS of geotextile has better performance on erosion control. Moreover, The performance on erosion control of different marbles used, marble C is the best, followed by marble B and marble A is the worst. That is because the porosity of marble C is the smallest and marble A is the biggest. This shows that amour stone porosity is also one of the factors on erosion control.

Table 2. The list of erosion tests.

Test No.	Sub-soil	Geotextiles	Marble	V_c (cm/s)	V_f (cm/s)
1	SM soil	α	A	55	89
2			B	112	147
3			C	151	207
4		β	A	58	125
5			B	156	207
6			C	209	235
7		No	A	53	73
8			B	62	110
9			C	73	98

3.2 *The formula of flow velocity*

In order to realize the V_c and V_f in different cover condition, regression analysis was used in this study. There are totally 38 sets of test data were obtained for those nine experiments. The following is the regression formula of V_c and V_f.

$$\begin{cases} V_c = 126.88 \times U - 37.412 \\ V_f = 118.59 \times U + 17.988 \end{cases} \tag{1}$$

where V_c = critical flow velocity, V_f = failure flow velocity, U = cover condition coefficient, respectively

$$U(mm^{-1}) = \frac{1}{POA \times n \times D_{50}} \tag{2}$$

where $POA(\%)$ = pore opening area ration of geotextile, n = porosity of amour stone, D_{50} = average grain diameter of amour stone.

Moreover, the erode soil were collected in the bottom water tank. The particle size distribution of the erode soil shows that more 85% of particle size is small than 200 mesh (0.074mm). In order to evaluate the relationship between erosion and flow rate, the erosion rate was calculated under the different flow velocity(Figure 6). The erosion rate formula is:

$$m'(t/m^2/yr) = \kappa \times \left[\left(\frac{V - V_c}{V_c}\right) + \left(\frac{V - V_c}{V_f - V_c}\right)^{\alpha} \right] \tag{3}$$

where m' = soil erosion rate, κ = coefficient of geotextile properties, α = coefficient of amour stone properties.

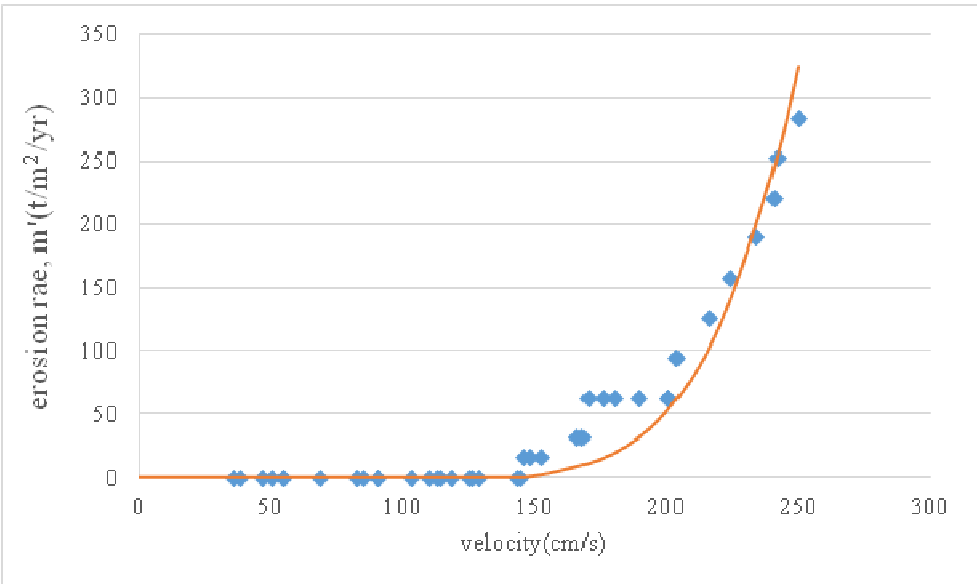


Figure 6 The erosion rate and flow velocity relationship .

4 CONCLUSIONS

(1) Both critical and failure flow velocities tended to increase as parameters such apparent opening size, gravel porosity and size decreased.
(2) Lower amour stone porosity, smaller geotextiles apparent opening size and greater geotextiles coverage contribute to the increase in erosion control.
(3) In addition to soil retention by the geotextiles, the gravels also retained the soil flushed out of the woven textiles by the water flows and acted as the second protection.
(4) The soil carried by the flows into the water tank was mostly in a size of less than 200 mesh while that retained by the gravels was mostly in a size of 100 mesh.

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