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I-SEEC 2012

Proceeding - Science and Engineering (2013) 599–606

Proceeding
Science and Engineering

www.iseec2012.com

Science and Engineering Symposium
4th International Science, Social Science, Engineering and Energy Conference 2012

Soil Retention Stability of Geotechnical Filter in Rip-rap Revetment

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Abstract

A novel framework for analyzing filtration stability under dynamic flow conditions is proposed, based on the idea derived from the findings of the research conducted on granular filters at Delft Hydraulic Laboratory reported in 1983. Stability of the filter for erosion control relies on retention capacity, which is dependent on four variables, namely indicative particle size of base soil, pore opening size of the filter, hydraulic gradient, and confining stress in the base soil. The framework is then extended to evaluate filtration stability of an alternative synthetic filter known as geotextile filter. Evaluation is made through comparison with (i) laboratory test data from selected independent studies and (ii) field performance data from bank and coastal protection sites. Evaluation results lead to the likelihood of the distinguishing between filter stability and conditions leading to an onset of an unfavorable action of soil loss passing through the filter, together with a companion analysis for comparison to design rules in engineering practice. The findings suggest that consideration of the loading conditions with reference to hydraulic gradient and confining stress can be used to better define a safety margin of the filter. However, the retention failure envelop is still tentative, not completely established, due to the very few systematic laboratory studies and field data. Further verification is recommended to validate the inherent safety margin in design practice that will gain confidence for long-term serviceability in drainage and soil retention of geotextile filter in rip-rap revetment.

Keywords: Filter, Rip-rap Revetment, Erosion, Coastal Protection

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1. Introduction

In filtration applications at river and marine protection works (i.e., rip-rap revetment), hydraulic loading is likely generated by reversing or pulsating the flow that yields a variety of cyclic flow regimes. A proper selection of geotechnical filter is one of the keys to effectively protect loss of the underlying geo-materials. The filter can be in a form of either packed granular material or synthetic fabrics. Granular filter is commonly used in the past, and its selection generally conforms to a well-known Terzaghi retention rule that $D_{f15}/D_{b85} < 4$, where D_{f15} is grain size of filter at which 15% is finer by weight, and D_{b85} is the grain size of base soil at which 85% is finer by

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weight. However, in the current practice, the synthetic fabric, namely geotextile, appears to replace the use of conventional granular filter due to its several advantages on quality control and cost effectiveness (see Fig.1). Selection of a candidate geotextile relies on many criteria based on hydraulic and mechanical properties to satisfy design and construction requirements. Among these requirements, retention capacity of the filter plays a very important role in serviceability of the rip-rap revetment structures. Rules for soil retention requirement are almost in a simple form that comprises at least two variables, namely a characteristic opening size of geotextile filter (O_F) and an indicative particle size of the base soil (D_i). For instance, a formula generally expressed as a filter ratio in relations with a constant value (B).

$$O_F/D_i < B \tag{1}$$

A characteristic opening size of geotextile is an index value given by the manufacturer. It can be quoted in many terms based on various standards of testing such as, AOS or O_{95} (US standard), O_{90} (ISO) and O_{98} (used by some European countries). An indicative particle size of the base soil that is commonly used is found to be either D_{90} or D_{85} or $D_{50.}$ Over 40 retention criteria from more than 20 authors, which are almost for the unidirectional steady flow, can be found in geosynthetic engineering textbooks (i.e., Sarsby [15]; and Geotechnical Engineering Office [3]). Note that the term “filter ratio” appears in further sections refers to a ratio using D_{85}.

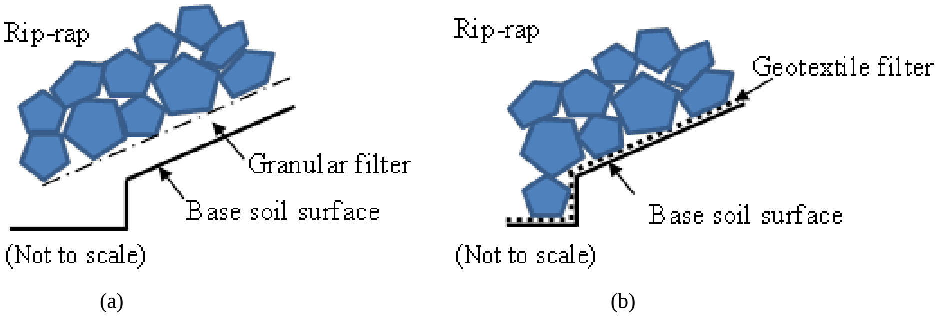

Fig. 1. Typical section of rip-rap revetment; (a) with granular filter layer and (b) with geotextile filter

The nature of the dynamic flow, especially the cyclic flow reversal, is believed to reduce the inherent margin of safety that is provided by filter criteria. Some criteria, therefore, adopt a concept of tight filter (Ogink [12], Luettich et al. [10], and Holtz et al. [6]). In applying this concept of tight filter, the belief is that O_F retains D_i and, if D_i retains the remainder of particles in the gradation curve, then retention stability is achieved. Undoubtedly, the concept works for a certain range of soil gradations with relatively coarse grains. However, when the base soil to be protected has a relatively small D_i, for example a fine sand or silt, then the tight filter approach may not be valid (Klein Breteler and Verhey [10] and Klein Breteler et al. [9]); otherwise using a double or multiple layers of geotextile would seem to raise an undue cost of the project. In contrast, the Dutch experience with geotextiles in filtration applications for coastal defense structures using an open filter (i.e. $O_F/D_i > 1$), yields a different approach for conditions of the cyclic flow, wherein $(O_F = O_{98})/(D_i = D_{85}) < 1$ to 2, for uniformly-graded cohesionless soils (Pilarczyk [14]). The criterion is also recommended in the Dutch revetment design manual, provided by Expertise Network for Flood Protection (Expertise Netwerk Waterveiligheid, ENW). It appears that most retention criteria do not take account any hydromechanical constraint namely, hydraulic gradient (i) and confining stress in the base soil (σ_c). This constraint is believed to be very significant to serviceable, which involves a stress change at the soil-geotextile filter interface in association with various hydraulic loads. Few systematic experimental studies for influences of these variables are reported for the conditions triggering excessive mass of soil erosion through the geotextile filter (Cazzuffi et al. [1] and Hawley [4]). Yet, no framework is available for comparison between test data and the field conditions. Accordingly, this work aims to propose the framework to illustrate inherent margin of safety in reference to the relation between filter ratio and hydromechanical constraint, based on selected laboratory data, and two field performance evaluation works (Heerten [5]; Mannsbart and Christopher[12]).

2. Hydromechanics-based Concept in Filter Stability

At Delft Hydraulic Laboratory in the Netherlands, the pioneer systematic experimental study of the influences of the hydromechanical variables on the mass of soil erosion was reported for granular filters by de Graauw et al., 1983 [2]. The tests were performed in a large flow chamber that enables the production of the conditions of the cyclic flow under a variation of magnitudes of hydraulic gradient at a predetermined confining stress in the base soil. The findings suggested that the amount of soil erosion through the filter is governed by the hydraulic gradient in association with confining stress. The relation is that the erosion amount will increase with increasing hydraulic gradient for a given constant level of confining stress. Alternatively, reducing confining stress will increase the erosion amount for a particular value of hydraulic gradient. Stress and hydraulic gradient have been demonstrated to govern the movement of soil particles in a granular filter (Indraratna and Vafai [8] and Indraratna and Radampola [7]). This relation guides an idea that the stability of the filter does not rely only on the filter ratio, but also the forces within the filtration system. With this idea, a new framework is feasible to be developed to explain the stability for such type of filter with reference to filter ratio, hydraulic load, and confining stress. It is reasonable to simplify the two variables of hydraulic load and confining stress to a dimensionless parameter for furthering the purpose of analysis and illustration. A normalized hydromechanical parameter (λ) is then proposed as;

$$\lambda = \frac{\Delta P_{\max}}{\Delta P_{\max} + \sigma_c} \tag{2}$$

where $\Delta P_{max} = i\gamma_w L$; is a maximum increase in water pressure at the base soil-filter interface; γ_w is the unit weight of water, and L is the length of the base soil along the imposed hydraulic gradient. A general trend of filter stability against soil erosion can be ideally illustrated in Fig.2. The λ parameter represents the severity or aggressiveness of the loading conditions. Mass of soil erosion may be expected to increase with a greater value of λ for a certain value of filter ratio and, if the filter ratio is too large, then catastrophic erosion may occur.

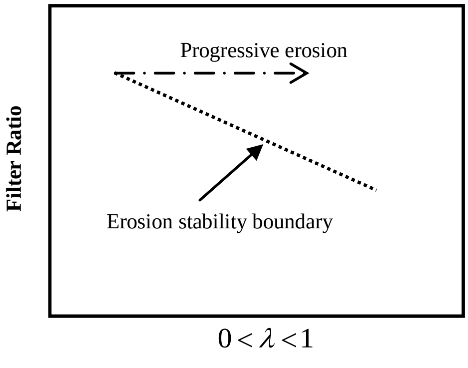

Fig. 2. Conceptual erosion stability of geotechnical filter

However, the framework is yet very conceptual, developed form the idea initiated from the findings of research conducted for the purpose of selecting appropriate granular filters in dynamic flow conditions. The challenge is that to import the laboratory test data and the field performance evaluation data on geotextile filters into the framework in order to verify the concept, the safety margin of the mentioned design criteria may be examined.

3. Selected Laboratory Database

2.1 Permeameter test data of Hawley (2001)

The study was undertaken in the cyclic flow device to examine the filtration compatibility of three sands and seven geotextile filters. The soil specimen is 10 cm. in diameter and approximately 10 cm. long. The filter is located beneath the soil specimen, and the vertical stress is applied on the top of the soil specimen. The resulting database comprises twenty one test combinations examining a filter ratio in the range of 0.6 to 2.8, for two needle-punched nonwoven and five woven geotextiles. Tests were conducted at only one average hydraulic gradient (i_{av}) of approximately 4. Test variables examined comprise vertical effective stress of 25 and 0 kPa, namely unload (or σ_c = 26.5 kPa and 1.5 kPa at the geotextile filter surface), and the wave period of cyclic flow reversal (T = 50 or 10 s). The test sequence involved a relatively long stage of cyclic flow at T = 50 s (1080 cycles) that was followed by a shorter stage at T = 10 s (260 cycles), whereupon the normal stress was reduced from 25 kPa to zero, and the shorter stage at T = 10 s then repeated (260 cycles). Each cyclic stage was preceded and followed by a stage of unidirectional flow.

The combination of river sand and seven geotextiles yields a filter ratio in the range of 0.6 to 1.8 was reported as retention compatible with essentially no soil loss through the geotextile. Mine tailing sand is also reported compatible with no loss in the range of filter ratio smaller than 1.5, but evidence of some mass loss was reported in the range between 1.5 and 2.1. In the latter case, the losses were deemed necessary for the development of filter stability and are not believed to represent retention incompatibility of the soil-geotextile combination; it was concluded that all of these test combinations were also stable. Port Coquitlam river sand was reported stable for a filter ratio of smaller than 1.4. However, results of tests on a woven geotextile at a filter ratio of 2.0 were also reported as stable at σ_c = 26.5 kPa. Very interestingly, piping failure that involved excessive amounts of mass loss occurred when σ_c reduced to 1.5 kPa. The piping phenomenon was repeatable by the other test at the same filter ratio. Additionally, one planned test involving a woven geotextile at a filter ratio of 2.8 exhibited an excessive soil loss through the geotextile during reconstitution of the soil specimen by water pluviation against the geotextile, which it is clearly a case of retention incompatible.

2.2 Permeameter test data of Cazzuffi et al. (1999)

The study described results from cyclic flow tests on one soil, a uniform fine sand (D_{85} = 0.2 mm. with no presence of fines), in combination with two types of geotextile, a nonwoven (O_{95} = 0.16 mm.) or a woven (O_{95} = 0.44 mm) geotextile. The laboratory tests were performed in a bi-directional flow apparatus, with a permeameter that accommodates a cylindrical specimen of 300 mm. in diameter and 400 mm. long. In testing, the influence of the vertical effective stress at the soil-geotextile interface was examined, including the range of 4 to 154 kPa, for a hydraulic gradient in the range of 3 to 16, and an unspecified wave period in the range of 2 to 20s, for the test duration of the typical 1500 cycles.

At a filter ratio 0.8, for the nonwoven geotextile, a negligible washout less than 10 $g/m^2/100$ cycles was reported, and the combination was deemed retention compatible. At a filter ratio of 2.2, for the woven geotextile, the response was more subtle; mass loss for this test was negligible at confining stress ≈ 50 kPa, but was reported to increase dramatically when the top stress was reduced to zero (only self-weight of 4 kPa applies to the geotextile). The result suggests the onset of retention incompatibility was triggered at i_{av} = 5 and σ_c = 4 kPa (see Table 1.).

Table 1. Data deduced from Cazzuffi et al. 1999

i_{av}	Mass loss for different confining stress (filter ratio = 2.2)			
	154 (kPa)	113 (kPa)	54 (kPa)	4 (kPa)
3	3	-	4	21.9
5	5	-	8	323
16	7	-	10	426

4. Selected Field Database

4.1 Data of Heerten (1982)

Heerten [5] reported the forensic study on the filtration properties of geotextile filters, considering the long-term conditions. Sixteen geotextile samples were cut and removed from rip-rap revetments of the sea dikes and banks of the inland waterways at different locations in North Germany. None of the sites reported any problematic conditions at that time; filtration performance of those geotextile filters was deemed satisfied. The work mainly focused on the investigations of several properties of the exhumed geotextile samples, which include the condition of geotextile, tensile strength, elongation, filtration, fabric weight and contaminated soil content. The grain size analysis and permeability tests were also performed on the base soil samples. Based on the results and analysis, he proposed the retention criterion $O_{90}/D_{50} < 1$ for non-cohesive soils under the dynamic flow conditions.

An approximate 10 kPa of contact stress caused by rip-rap load is reported as the typical value for all sites. Even though the magnitudes of wave height and other related information were not given, wave loads are needed to estimate λ value. It is conservative to assume the wave height for the range of 1 – 3 m. accordingly, yields λ value in a range from 0.5 to 0.75. Note that some base soils in the database are uniformly graded. Therefore, O_{90}/D_{50} in the criterion is fairly close to the referred filter ratio (O_{95}/D_{85}), and it is set equal to 1 for plotting in the framework.

4.2 Data of Mannsbart and Christopher (1997)

Mannsbart and Christopher [12] reported on the long-term field performance of geotextiles used as a filter in coastal and bank protection applications. They provided schematic drawings of cross-section of the rip-rap revetments for all sites, together with information on the grain size distribution curve of each base soil, material properties of each geotextile, and descriptive severity of the hydraulic action at each site location. Filtration compatibility was considered satisfied at all sites, based on the fact that no evidence was found to indicate concerns either for clogging or piping activity over the service life of the installation at that time. Taken collectively, it yields a sufficiently comprehensive record to allow for a comparison with the proposed framework. All of the geotextiles were needle-punched nonwoven fabrics, samples of which were exhumed for forensic analysis, enabling the determination of the corresponding filter ratio.

From the drawings provided for each site an approximate value of confining stress (σ_c) the soil-geotextile interface was calculated based on the thickness of the overlying armor layer (assuming a submerged unit weight of 13 kN/m^3). An approximate value of ΔP_{max} at the soil-geotextile interface was feasible to be established indirectly. Wave-generated pressure on the armor layer is a function of wave characteristic and geometry of the slope. This value may be assumed equal to ΔP_{max} in order to define a λ value at particular field location. Pilarczyk [14] proposed a simplified relation between the maximum value (P_{max}) of wave-generated pressure and a significant wave height (H_s):

$$\Delta P_{\max} = A_0 \gamma_w H_s \tag{3}$$

where A_0 is an empirical factor which may be obtained by experiments, γ_w is the unit weight of water, and H_s is the significant wave height or design value of wave height.

The value of A_0 is a function of wave characteristic that accounts for the influence of both hydrostatic and hydrodynamic components of wave energy. Suggested for calculation purposes, the value of A_0 can be assumed equal to 2 as an approximation for a value of ΔP_{max} within the armor stone; in a filter layer (the soil-geotextile interface), a value of $A_0/2$ is suggested where the wave impact will be partly damped by the armor stone. Hence, an average value of 1.5 is used in the calculation.

A value of H_s is not reported for each site in the work of Mannsbart and Christopher. However, it is possible to obtain an approximate value of H_s by indirect means, knowing the characteristic size (or mass) of the armor stone. The Hudson formula (USACoE, 1984 [16]) relates H_s to mass of the median rock size (W_{50}):

$$W_{50} = \frac{w_r\, H_s^{\;3}}{K_D\ (G_r - 1)\cot\theta} \qquad (4)$$

where K_D is the stability coefficient, w_r is the density of rock mass, G_r is the specific gravity of rock, and θ is the slope of the rip-rap.

The value of K_D varies significantly with type and shape of armor materials, whether the wave is a non-breaking or breaking method of armor placement. Breaking waves may result in a large pressure variation. At all sites reported herein, inspection of the drawings indicates the stones are angular in shape, and randomly placed. Assuming a condition of the breaking wave leads to K_D of approximately 2.2 (USACoE, 1984). Values of w_r = 2650 kg/m^3 and G_r = 2.65 were assumed for all four sites. Establishing W_{50}, again from the inspection of the drawings allows for a back-calculation of H_s (Eq. 4). Knowing H_s, a value of P_{max} is then back-calculated (Eq. 3). The general information and back analysis results are summarized in Table 2.

Table 2. Summary field data and back-calculated wave height

Project Site Location	Armor layer thickness (m)	slope	σ_c (kPa)	W_{50} (kg)	$H_{s(cal)}$ (m)	Filter ratio
Lacanau (France)	3	1:2.0	39	1500	2.24	0.19
Pantai Murni (Malaysia)	1.6	1:3.0	20.8	430	1.69	0.24
Greifenstein (Austria)	1	1:1.5	13	125	0.89	1.1
Sungai Buntu (Malaysia)	1.6	1:3.0	20.8	200	1.31	1.8

5. Unified Database

Total eleven data points, comprising six data points of the two laboratory studies and five data points of field studies, are plotted in the proposed conceptual framework (see Fig.3). Be reminded that one point at filter ratio 2.8 and two points at filter ratio 2.0 are derived from Hawley database, and the three points plotted at the filter ratio of 2.2 are of Cazzuffi’s study. Error bars of the field data points are to illustrate the variation of λ value calculated from a value A_0 (in Eq. 3) ranging from 1 to 2. Generally good agreement is found between the concept (see Fig.1) and the database of independent laboratory and field experience. The framework is found to distinguish between filter stability and instability in the form of soil erosion action through the geotextile. Inspection of the data suggests that filter ratio should not exceed 2 for λ values lower than 0.5 and not exceed 1 for λ values greater than 0.5. More specifically, the suggestion is consistent with the Dutch experience that recommends the filter ratio be less than 1 to 2 (1 and 2 is lower and upper limit, respectively), for narrowly-graded cohesionless soil. A threshold value of λ at 0.5 may be useful to define whether the lower limit or upper limit is appropriate for certain loading conditions associated with an appreciative safety margin. However, the retention failure envelop is tentative. More laboratory test and field data are needed to verify the boundary. Further analysis to establish science-based criteria of design practice is recommended in order to improve confidence for the long-term serviceability in drainage and retention of geotextile filter in rip-rap revetment.

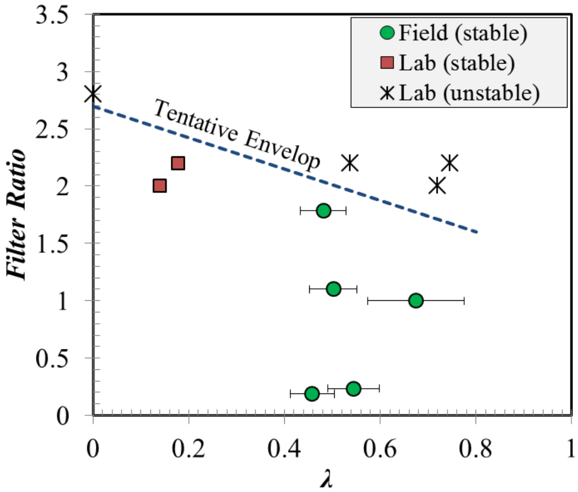

Fig. 3. Tentative retention failure envelop for geotextile filter in rip-rap revetment

6. Conclusion

A framework is proposed for analyzing filtration stability of a filter layer in rip-rap revetment, based on the work at Delft Hydraulic Laboratory reported by de Graauw et al. (1983). The framework is initiated from the mechanical response of the granular filters and then adopted for retention stability analysis of geotextile filter. Laboratory test data from two studies, and selected field data from two studies, were analyzed in reference to the attributes of the base soil (D_{85}), the pore size opening of the geotextile (AOS or O_{95}), an estimate of likely wave-generated pressure (ΔP_{max}) from the cyclic and dynamic flow, and the confining stress (σ_c) in the base soil. Influences of the first two variables are represented by a filter ratio, and for the latter, two variables are indicated by a normalized hydromechanical parameter (λ). Accordingly, the unified database provides opportunity to illustrate the unspecified margin of safety associated with criteria for soil retention. The relation between filter ratio and λ may distinguish the use of the lower and upper limits suggested by Pilarczyk [14], which was developed with reference to practical experience but not supported by any systematic laboratory study. However, the retention failure envelop is not yet completely established due to a lack of laboratory tests and field data from systematic studies. Further studies are recommended to validate the inherent safety margin in the traditional design rules, and thereby improve the confidence of their application to engineering practice.

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