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The Use of Protective Filters to Address Cracking in Embankment Dams

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ABSTRACT

Granular filters are used in embankment dams to protect against internal erosion through both the embankment and foundation. Specifically, they can be used to protect against cracks that may develop after a seismic loading event. For proper performance, it is required that the filter itself not be able to sustain a crack. Historically, the mechanism used to limit cracking potential is a restriction of no more than five percent non-plastic fines, and this requirement is easily measured with the standard soil tests for grain size distribution (gradation) and plasticity (Atterberg Limits). Unfortunately, material meeting this requirement has been observed to be susceptible to cementation, and hence has cracking potential. Therefore a more robust test procedure is needed to better quantify the desired material properties (cementation potential), and to this end, modification of the Vaughan and Soares Sand Castle Test was undertaken. This paper describes a modified test procedure and the results from 16 source materials from around the United States. All materials meet ASTM C-33 sand gradation requirements (also known as 'concrete sand'). Additionally, unconfined compression tests were performed on each material to help quantify the strength gain from cementation. The Sand Equivalency Value (SEV) which further quantifies the amount and characteristics of the finer portion of a material was also determined for all sources to see how well it correlated with the Modified Sand Castle Test results. The Modified Sand Castle Test and unconfined compression are shown to be good indicators of cementation potential, and valuable additions to the original gradation and plasticity tests.

Introduction

Granular filters are used in embankment dams to protect against migration of fine grained core or foundation materials that could lead to internal erosion (piping) failures, and to provide drainage to relieve excess pore pressures that may build up in the embankment. Granular filters are particularly important in areas with seismic hazards and in cases where the embankment may desiccate, as core material may become cracked, creating the potential for concentrated flow and internal erosion. Early consideration of this issue led to a requirement that filter material not contain more than five percent fines and that the fines be non-plastic. While this requirement does limit the potential for cohesive behavior, it is thought that other binding agents such as soluble minerals can result in cementation of granular filter sands. Excavation into the filter zone of one particular embankment dam revealed material so strongly cemented (bound) it withstood blows by a hand shovel. The filter material also had sufficient strength to stand as an overhang. This cementing problem can be particularly bad in the Western U.S. where high daytime temperatures 'cure' the soil. Based on this apparent problem of filter cementation, test procedures beyond the original grain size and plasticity tests are needed to ensure that filter materials will perform as desired and not exhibit cementitious (i.e., crack sustaining) behavior.

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A test to measure cementation potential of granular materials, known as the Sand Castle Test, was developed by researchers at the University of London in the 1970's and 80's by Vaughan and Soares (1982). The test involved hand tamping a moist sand sample into a plastic cup, extracting the specimen and submerging it in water. After the material collapses under water, the submerged Angle of Repose (AOR) of the material was measured and compared to the AOR of the same dry material in air. If the submerged AOR was greater than the AOR in air, the material was deemed to have cementing capability and unsuitable for use as a filter material. However, the test is only loosely described in the literature, compaction parameters are unclear, and precise criteria for evaluating materials were not established.

Additional work by Yamaguchi (2001), Park (2003), and Bolton et al. (2005) has been performed to improve on the original Sand Castle Test. However, these revisions are still deficient regarding adequately specifying specimen preparation techniques to mimic field behavior and are not sensitive enough to distinguish subtle changes in cementation potential. Of particular concern is the recognition that cementation has not been given the opportunity to develop. During construction, filter sand is typically compacted with vibratory rollers in a wet state and then allowed to dry out at temperatures in excess of 50^{o}C (122^{o}F) during summer construction. Such conditions have lead to the observation of “crispy” filters, that is, material that appears cemented to the touch.

The research presented herein, undertaken jointly by the Bureau of Reclamation and the U.S. Army Corps of Engineers, is aimed at further examining the Sand Castle Test and developing a new index test to determine cementation potential. Such a test would serve as a tool for screening candidate filter materials as well as provide quality control criteria for construction specifications. The work was executed in three phases, with the testing procedures being refined between each phase. Additional materials were also added to the study as the research progressed. The next sections describe the specimen preparation methods, test procedures, test results, and relationships between modified sand castle test results and other soil properties.

Test Procedure

The Modified Sand Castle Test (MSCT) consists of two main components: (1) specimen preparation and (2) progressive soak testing. Each portion of the procedure is described in more detail below. The general approach taken is to compact the specimens in a saturated condition and then dry them to constant mass before wetting them and recording the amount of time it takes for the specimen to collapse.

Specimen Preparation

The sample preparation procedures are intended to mimic field conditions that favor development of cementation. The tested materials were washed and sieved to meet the gradation requirements of ASTM C33 fine aggregate (sand), with the additional requirement that the percent passing the 74-µm No. 200 sieve not exceed 2 percent. C33 concrete sand was selected because it has shown to be an effective general filter material in the United States and is suitable for a wide range of commonly encountered embankment and foundation base soils. Following washing, each sample was wetted to saturation and compacted to maximum index unit weight with a vibrating hammer according to ASTM D7382. Tap water is used for both washing and wetting. The compaction mold used was a modified Proctor cylindrical split mold, 2,124 cm^3 (0.075 ft^3) in volume, 15.25 cm (6 in) in diameter, and 11.64 cm (4.58 in) in height. This approach was chosen over impact (Proctor) compaction as it subjects the soil to less particle breakage and more closely mimics the way granular materials are compacted in the field (e.g., vibratory smooth drum rollers). Samples were compacted in three equal lifts with 60 seconds of vibratory compaction effort at each lift. Once compacted, the specimens were dried to constant mass in a 50°C (122°F) oven. This temperature was chosen based on observed ground temperatures of summertime fill placement in the western U.S. Three identical test specimens (replicates) of each material were prepared. Additional specimens were prepared as necessary to ensure that the dry density of three tested specimens agreed within 2%.

Progressive Soaking Test Procedure

The apparatus used for the progressive soaking portion of the test consisted of a cylindrical acrylic chamber partially filled with gravel, with plumbing at the bottom to allow the introduction of water (see Figure 2a). The gravel served to evenly distribute the flow of water into the chamber and acted as a base for the specimens. Each specimen was placed atop the gravel on a perforated acrylic disk and carefully leveled (Figure 2b).

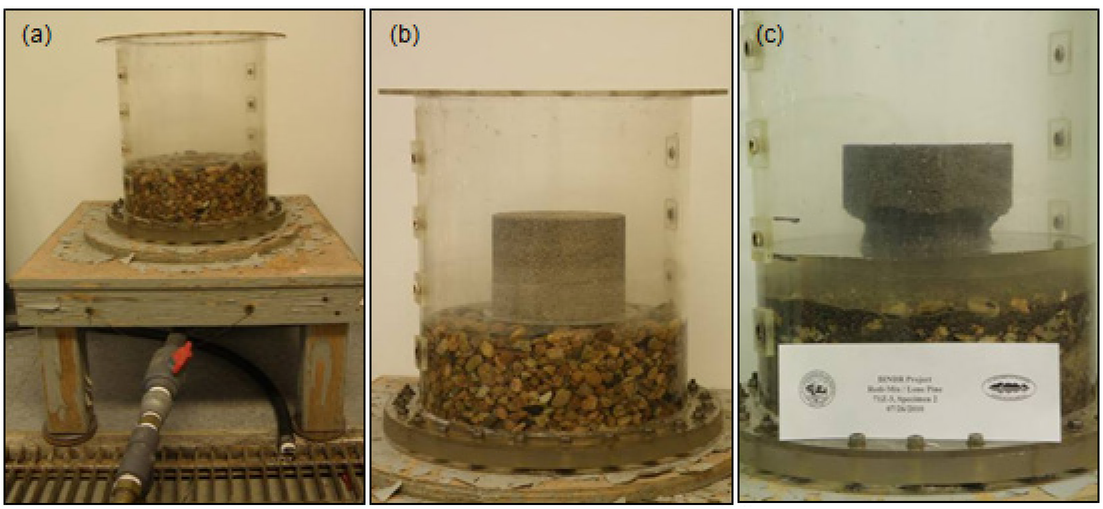

Figure 2.(a) Incremental soaking apparatus, (b) specimen on acrylic disk before introduction of water, and (c) test in progress with 2.54-cm (1-in.) deep water.

Once the specimen was placed inside the chamber, water was introduced from the bottom of the chamber to a depth of 2.5 cm (1 in) up the specimen. The timer was started once the water reached the 2.5 cm mark. The water was maintained at this depth for the first 20 minutes of testing. In general, specimens absorbed water due to capillary action and crumbed or eroded from the base of the specimen towards the top (Figure 2c). Some materials were observed to completely collapse or disintegrate during this first 20 minutes. However, if the specimen was still intact after 20 minutes, the water level was increased to 5 cm (2 in). The water level was further increased to completely submerge the specimen if the specimen was still intact after a total of 100 minutes since the start of the test. The test was continued for 24 hours of elapsed time (i.e., the specimen fully submerged for 22 hours and 20 minutes), at which time it was terminated and the condition of the specimen noted.

Results

The MSCT was performed on 16 sand materials, as summarized in Table 1. The recycled (crushed) concrete (71Z-1) and Colorado Silica Sand (36F-1136) were chosen to serve as the controls (good and poor performance bounds based on previous studies). The remaining 14 materials (three from Florida, five from California, and six from Oregon) were from a variety of commercially available pits as well as undeveloped sources.

Table 1. Summary of Materials Tested

Lab Index Number	Origin and Location[1]	$\gamma_{d,max}$ (pcf)	MSCT Failure Time (min)	MSCT Class	SEV[4] (%)	UCS[4] (kPa)	C_u[4]	FM[4]
36F-1136	Natural Silica Sand, CO	111.9	4.3	I	95	13	2.34	2.41
36F-1137	Manufactured Basalt Sand, CA	120.3	24.3	III	95	112	7.50	3.05
36F-1138	Hope Creek Alluvium[2], CA	122.5	37.0	IV	80	260	7.26	2.98
36F-1139	Orestimba Creek Alluvium, CA	113.7	7.9	II	78	67	6.28	3.01
36F-1140	Los Banos Creek Alluvium, CA	113.6	26.7	IV	76	74	4.38	3.00
36F-1141	Manufactured Granite Sand, CA	117.0	22.4	III	96	57	6.80	2.86
71Z-1	Crushed roadway concrete, CO	96.2	1440.0[3]	VI	92	31	4.67	2.80
71Z-2	Manufactured Sand of Alluvial Origin, OR	109.7	7.5	II	81	48	3.48	2.53
71Z-3	Crooked River Alluvium, OR	112.2	9.3	II	88	30	4.45	2.50
71Z-4	Deschutes River Alluvium, OR	113.1	28.3	IV	92	173	5.70	2.88
71Z-5	Crooked River Alluvium (Upper Terr.), OR	109.3	17.7	II	89	30	3.48	2.54
71Z-6	Crooked River Alluvium (Floodplain), OR	105.5	20.4	III	90	50	4.20	2.58
71Z-7	Natural Silica Sand, FL	112.5	1.3	I	100	3	3.53	2.58
71Z-8	Manufactured Limestone Sand, FL	110.5	100.5	V	95	240	6.67	2.81
71Z-9	Natural Silica Sand, FL	119.2	1.9	I	96	13	3.29	2.51
71Z-10	Glacial outwash (Ochoco Drainage)[2], OR	117.1	21.8	III	92	65	5.87	2.72

[1]CO = Colorado, CA = California, OR = Oregon, FL = Florida

[2] Material is partially manufactured, containing about 20-30% crushed material

[3] Specimens did not collapse, test terminated at 24-hours elapsed time

[4] SEV = Sand Equivalency Value, UCS = Unconfined Compressive Strength, Cu = Coeff. of Uniformity, FM = Fines Modulus

Modified Sand Castle Test Results

Based on the results of the 16 materials tested, and along with insight gained from previous studies, the following six classes were proposed:

- Class I: collapse within 5 minutes of the introduction of 2.5 cm (1 in) of water
- Class II: collapse within 20 minutes of the introduction of 2.5 cm (1 in) of water

- Class III: collapse within 5 minutes of increasing the water level to 5 cm (2 in), 25 minutes total elapsed time
- Class IV: collapse within 80 minutes of increasing the water level to 5 cm (2 in), 100 minutes total elapsed time
- Class V: collapse within 5 minutes of submerging the sample
- Class VI: collapse after 5 minutes of submerging the specimen, or no collapse within 24 hours

Essentially, the more rapidly a material collapses, the lower the class and higher the quality of the material for use as a filter. Preference was given to materials that collapsed within five minutes of introduction of water or increase of water depth. Figure 3 graphically depicts the failure times for the materials tested. Error bars are shown to represent the range of failure times for each material (i.e., variation between specimens used to compute the average). Note that the plot is in log scale, causing the errors for the Class I and II materials to appear exaggerated compared to the higher classes.

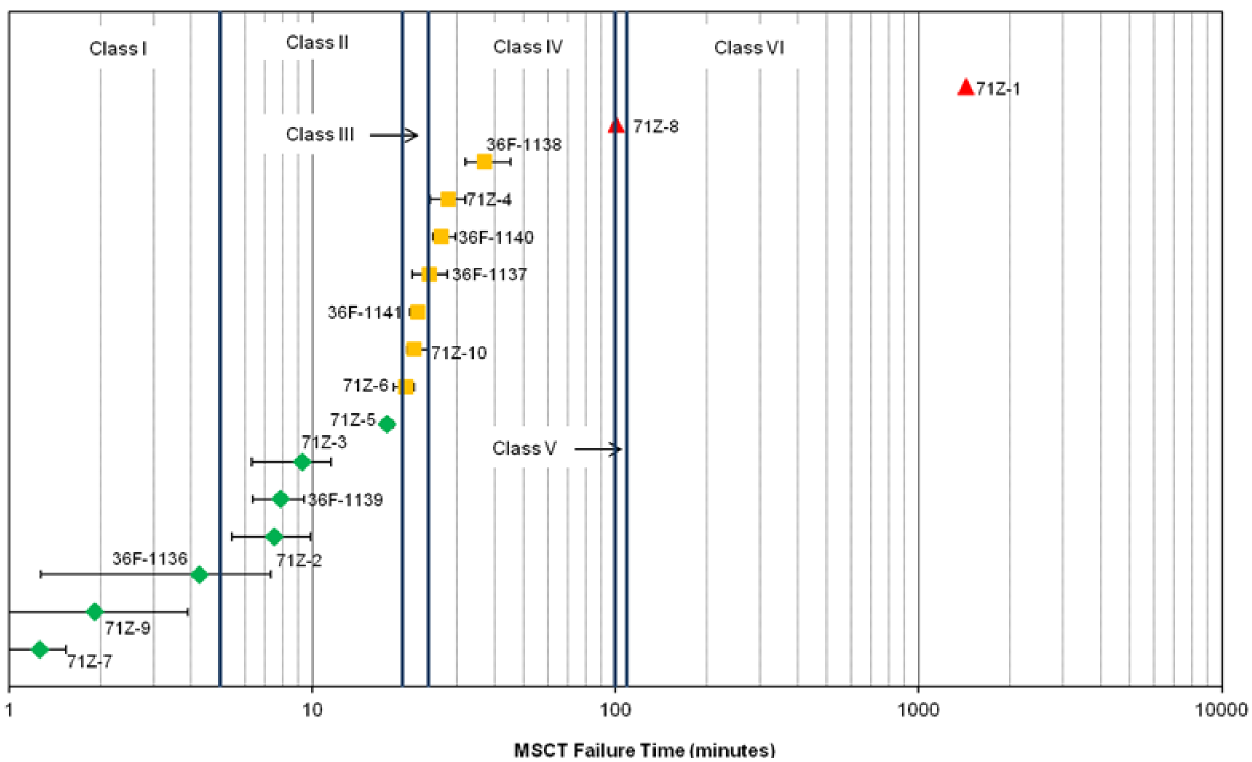

Figure 3. Summary of MSCT failure times for materials tested with depiction of class designations. Green diamonds represent Class I and II materials, yellow squares represent Class III and IV materials, and red triangles represent Class V and VI materials.

Relationship to other Index Properties

Various researchers have suggested the use of other index properties, such as the Sand Equivalency Value (SEV) per ASTM D2419 and Unconfined Compressive Strength (UCS) per

ASTM D1633 and D2166, as potential tests to screen candidate filter materials for cementing potential as described in McCook (2005) and FEMA (2011). Several other properties of the materials were investigated to determine if any relationships existed between those properties and cementation potential.

The first trend noted was that an increase in the Coefficient of Uniformity (C_u) and Fineness Modulus (FM) corresponds to an increase in cementation potential (see Figure 4). This is explained as materials with higher values of C_u or FM are more well-graded, which leads to more grain to grain contacts. This trend is more pronounced for Classes I though IV. Classes V and VI are only represented by a single material and the physical properties do not necessarily reflect what would be typical for the Class. For this reason, the best fit lines shown in Figure 4 do not take Class V and VI materials into account.

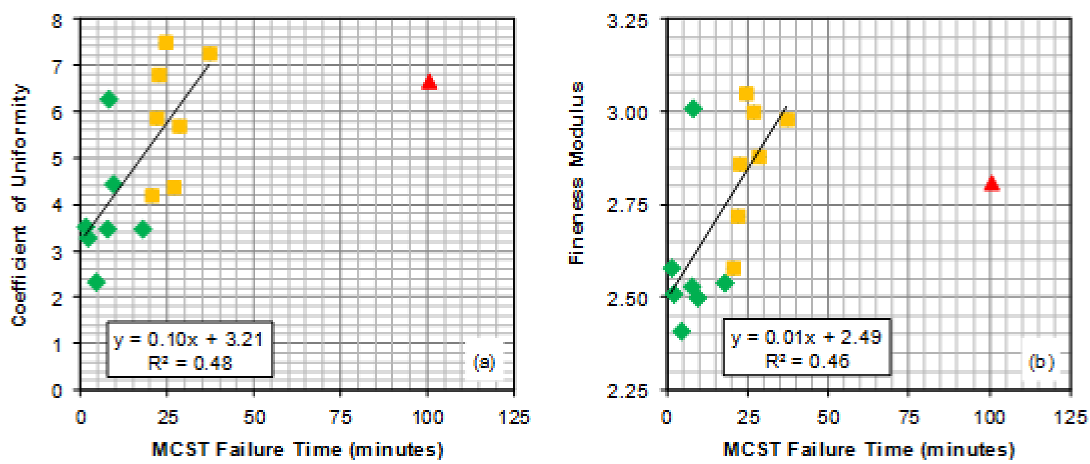

Figure 4. Relationship between MSCT failure times and (a) Coefficient of Uniformity, and (b) Fineness Modulus. Green diamonds represent Class I and II materials, yellow squares represent Class III and IV materials, and red triangles represent Class V and VI materials. Note the 'best fit line' does not include the Class V and VI materials.

Also examined was the relationship between SEV, UCS and the materials MSCT Class. As shown in Figure 5a, decreasing SEV generally leads to increased failure time for Classes I through IV, although this correlation is relatively weak. The premise that granular filter materials can be evaluated based on SEV is not supported by the results presented here. Specifying a minimum value of SEV alone is likely not sufficient to screen out potentially cementitious materials.

As far as UCS, a clear correlation exists between strength gain due to cementation and MSCT failure time (Figure 5b). The specimens used for UCS testing were prepared in the same manner as those for MSCT testing. A special split mold, 7.6 cm (3 in) in diameter by 17.1 cm (6.75 in) high (length:diameter ratio = 2.25) was used. The specimens were compacted in three lifts using the vibratory hammer and an appropriately sized tamping foot. The vibration time per lift was varied from that specified in ASTM D7382 in order achieve a similar level of compaction (density) as achieved by running ASTM D7382. A vibration time of 15 seconds per lift was found to produce the best results. After compaction, specimens were dried to constant mass in a 50° C oven.

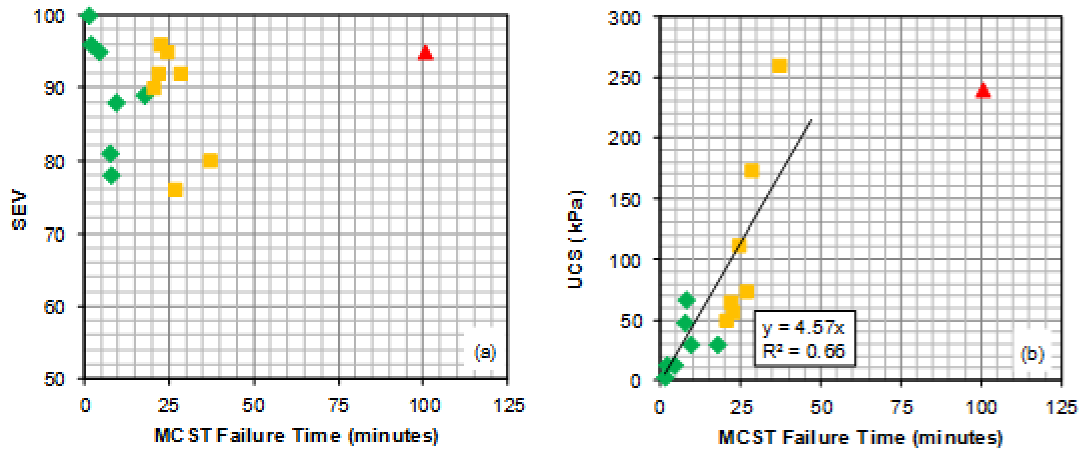

Figure 5. Relationship between MSCT failure times and (a) Sand Equivalency Value, and (b) unconfined compressive strength. Green diamonds represent Class I and II materials, yellow squares represent Class III and IV materials, and red triangles represent Class V and VI materials. Note the 'best fit line' does not include the Class V and VI materials.

It is particularly interesting that the recycled concrete does not follow the trend for UCS versus MSCT failure time. Even though the recycled concrete is classified as a Class VI and did not collapse after submerged for 24 hours, it exhibited very minimal strength gain. This provides good justification for using multiple test methods, rather than relying on a single test when screening potential materials for use in embankment filters. There are a variety of bonding mechanisms, and as demonstrated by the recycled concrete, they may not manifest themselves equally in each test.

Application

Since the role of the filter is to protect against cracks that may develop in the dam; due to seismic loading, differential settlement, and desiccation, similar cracking of the filter is not acceptable. The cracking potential of the filter medium should be evaluated during evaluation of existing dams, during the design phase for new dams, and/or modification of existing dams. Candidate filter materials could be tested using the tests described in this paper (modified sand castle test, C_u, FM, and unconfined compression) to assure that the cracking potential is within acceptable limits.

The test procedures described in this paper can then be used in two ways. The first would be to evaluate potential borrow areas during the design phase. Candidate materials that are capable of sustaining a crack, as indicated by these test procedures, would be eliminated from consideration and not listed in the specification (tender) documents provided to bidders. The other application of the procedures would be during execution of the work during submittal acceptance and quality control as the contract requirements are enforced during construction.

Conclusions

This research has demonstrated that the current specimen preparation and progressive soaking test procedures are sensitive to cementation potential. Further, the specimen preparation techniques, including drying in a 50°C oven, encourage cementation and simulate field conditions. Based on these findings, MSCT testing appears to be an acceptable test procedure to screen candidate embankment filter materials for cementation potential. A detailed description of the test procedures is provided in Rinehart and Pabst (2014).

A strong correlation between MSCT failure time and SEV was not found. A weak trend does exist such that a decreased value of SEV corresponds to increased cementation potential. A good relationship between UCS, C_u, FM, and MSCT failure time was found, with materials with higher cementation potential exhibiting higher strength. However, the recycled concrete material did not follow this trend. This provides a good illustration of why it is recommended to use the aggregated results of several tests (i.e., MSCT, Cu, FM, and UCS testing) when screening materials. Based on an understanding of the cementing mechanisms in granular filter materials, a single criterion (e.g., SEV > 80) should not be used to separate acceptable from unacceptable materials.

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