Cut-Off Performance of a Soil-Cement-Bentonite Wall

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ABSTRACT
Results of a comprehensive evaluation of cut-off performance of an in-situ mixed soil-cement-bentonite (SCB) wall constructed at a Florida dike are presented and discussed. Cracks were observed during drilling of verification drill holes. Subsequently, additional transverse cracking within the top portion of the SCB wall away from those drill holes were also observed. The effects of the observed transverse cracks on the overall wall cut-off performance were studied. Permeability of cracked SCB samples and erosion potential of the SCB material within the crack were measured in the laboratory. Based on the laboratory results and seepage analyses using finite element, it was concluded that the cracks do not affect the long term overall cut-off performance of the SCB wall constructed.

RÉSUMÉ
Les résultats d'une évaluation complète de la coupure de performance d'un sol in-situ-mixtes ciment-bentonite (SCB) mur construit une digue à la Floride sont présentés et discutés. Forage de vérification la cause le craquage et supplémentaires fissuration transversale dans la partie supérieure de la paroi SCB loin de ces forages ont été observés. Les effets de la fissures observées sur la paroi réduction globale des performances de décollage ont été analysés. La perméabilité des échantillons SCB craquage et le test de risque d'érosion de la matière au sein de la SCB crack ont été mesurés en laboratoire. Sur la base des résultats de laboratoire et analyses d 'infiltration numérique, il a été conclu que les fissures ne portent pas atteinte à long terme seuil global de performance du mur construit SCB.

1 INTRODUCTION

A rehabilitation program was developed by the United States Army Corps of Engineers (USACE) to improve the stability of the Herbert Hoover Dike (HHD) at Lake Okeechobee, Florida. An in-situ cut-off wall is one rehabilitation measure designed by USACE as part of a system that also includes a seepage berm, toe ditch and drainage swale, all on the downstream side of the dike (Figure 1).

Available documents prepared for the HHD rehabilitation project indicate that the primary purpose of the SCB wall is to cut off pre-existing piping pathways (mostly through the dike), with the reduction of risk of new piping channel developing and reduction of seepage pressures within and beneath the dike as additional benefits. The documents also specify the required wall permeability and depth.

2 SCB WALLS CONSTRUCTED AT HHD

Soil-cement-bentonite (SCB) cut-off walls are used on many projects where the design requires a low-permeability hydraulic barrier with higher strength (i.e., stiffer response) than soil-bentonite (SB) walls. The design of the SCB mixes requires careful consideration of the interaction of many components including Portland cement, ground granulated blast furnace slag, bentonite, water, and in-situ soil (Evans 2007).

The SCB walls at HHD were constructed using several different techniques, including the panel type and continuous soil mixing methods. While the evaluations presented herein were made specifically for the SCB wall constructed in 2009 continuously using a vertical mixing tool, the conclusions made are general and independent of the construction process.

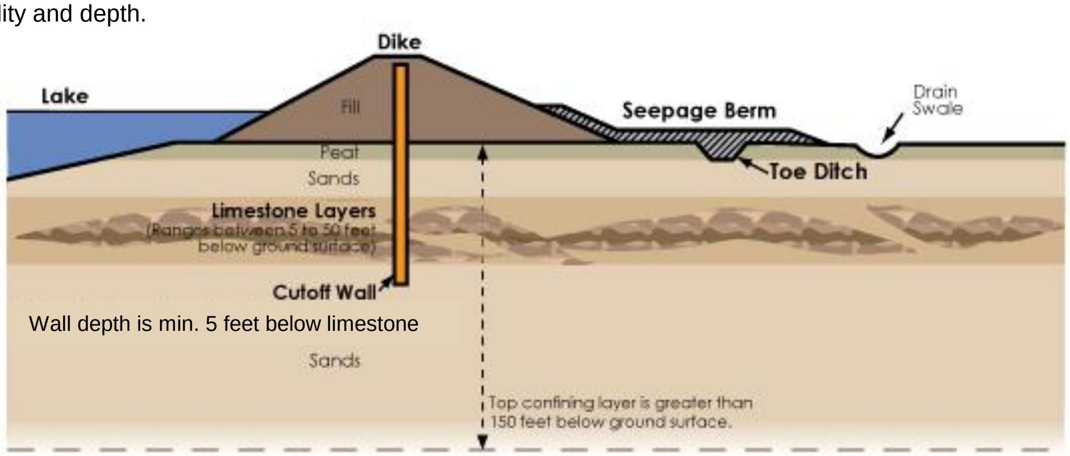

Figure 1. Schematic soil profile (source: USACE).

Wall Verification Criteria In addition to traditional quality control measures that include laboratory testing on grab samples and field mixed samples, at the HHD rehabilitation project, USACE also required verification boreholes with recovery of core samples drilled at a maximum 61-meter (200-foot) spacing along the SCB wall.

Acceptance requirements of the SCB wall included:

- minimum 95-percent recovery of verification drill cores sampled in accordance with ASTM 2113 (2010),
- maximum permeability of 1×10^{-6} cm/sec measured by falling head testing of verification drill holes, and
- Unconfined Compressive Strength (UCS) within the range of 690 kPa (100 psi) to 3450 kPa (500 psi) on core samples aged 28 days (10-point moving average of breaks).

Both the verification drill holes and cores recovered were visually inspected for continuity and homogeneity of the SCB material profile.

Wall Verification Results During construction of the wall evaluated herein, some of the permeability values estimated from falling head permeability tests performed in the verification drill holes (drilled 28 days after the wall completion) were greater than the maximum specified of 10^{-6} cm/sec. All other performance requirements were satisfied. Through the use of borehole photography and video, vertical cracks were observed in the drill hole sidewalls at the locations of unsuccessful field permeability tests. Video inspection records indicated that the cracks were narrow and located perpendicular to the wall alignment (in the transverse direction). In general, cracks in the boreholes were more frequent with increasing depth. There were no cracks observed on the recovered cores.

All laboratory measured permeability values, including deep grab samples and shallow bulk samples, satisfied the acceptance requirements (e.g., see Figure 2 for permeability measured on grab samples). No cracking was observed on the tested samples.

Investigation of Cracking Causes Following the observation of wall cracking in verification drill holes, extensive field and laboratory test investigations and analyses were performed to evaluate the cause of the cracking and its effects on the SCB wall performance. During that investigation, which took place well after the wall was constructed, transverse cracks were also observed in the SCB wall away from the verification drill holes.

Test pits were excavated about 9 to 12 months after the wall construction to observe the wall at the core hole and transverse crack locations. Those test pits extended to a depth of about 2 meters (6 feet) below grade. It was found that all cracks were essentially vertical (see Figure 3). Crack widths were relatively constant within the 2-m depth observed in the test pits and ranged from approximately 0.5 mm to 1.4 mm. The crack surfaces were irregular and rough, and did not exhibit signs of shear distortion.

The comprehensive evaluation of the wall cracking concluded that the cracks inside the verification drill holes were caused by the significant drilling fluid pressure during coring and cracks away from those drill holes were mainly induced by drying and thermal shrinkage forces within the wall. It was also concluded that cracks away from drill holes do not extend below a zone with sufficient moisture to prevent drying shrinkage. The effects of shrinkage on the wall cracking will be discussed in more detail in Cermak et al. (2012).

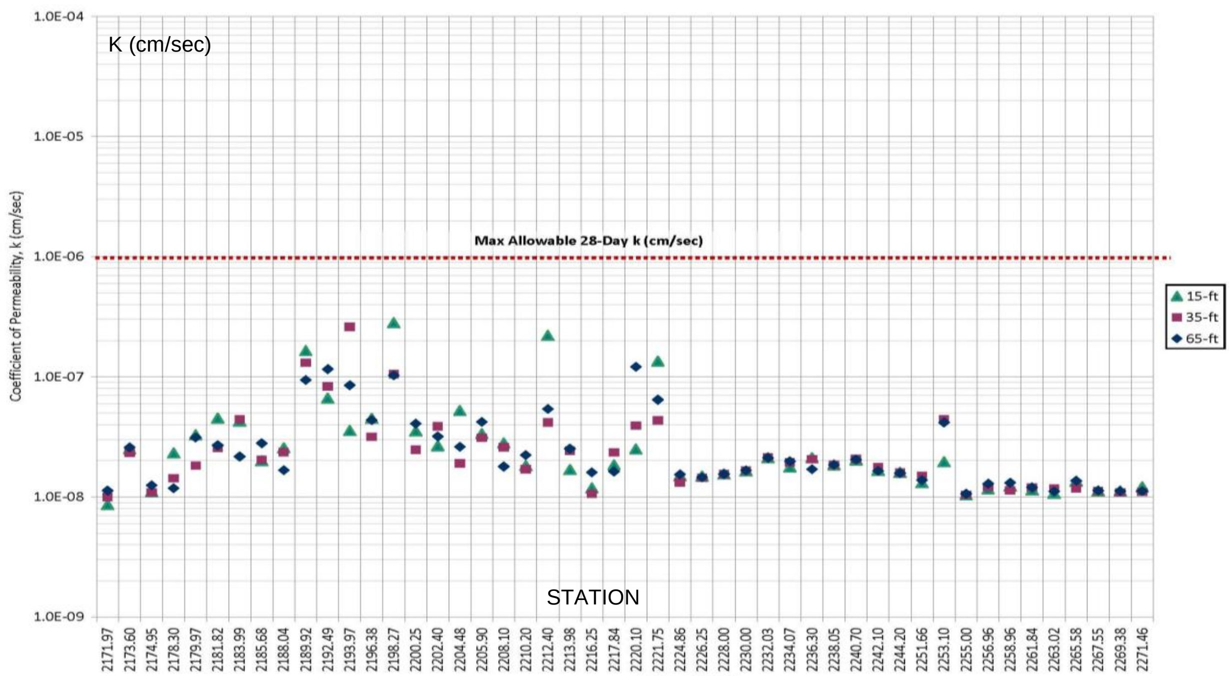

Figure 2. Results of laboratory permeability tests on grab samples.

Table 1. Summary of Hydraulic Conductivities

Stratum	Unit Weight kN/m^3 (pcf)	Elevations m (ft)	Vertical Hydraulic Conductivity (cm/sec)	Horizontal Hydraulic Conductivity (cm/sec)
Fill	19 (120)	+11.0 (+36) to +1.2 (+4)	1 x 10^{-3}	2 x 10^{-3}
Peat/Clay	17 (108)	+1.2 (+4) to -1.7 (-5.5)	1 x 10^{-5}	1 x 10^{-5}
Limestone	19 (120)	-1.7 (-5.5) to -9.0 (-29.5)	1 x 10^{-2}	1 x 10^{-2}
Sand	19 (120)	Below -9.0 (-29.5)	1 x 10^{-3}	1 x 10^{-3}

Figure 3. Wall cracking observed in a test pit.

3 LOCAL SEEPAGE ANALYSIS

Even though the evaluation of the crack causes concluded that the depth of transverse wall cracks (away from drill holes) is limited to the top portion of the wall, both our local and global seepage analyses assume that the cracks propagate the entire depth of the wall, to be conservative. Only the effect of the cracks away from the verification drill holes was considered as the drill holes will be grouted and the sidewall cracks sealed.

To establish the soil profile and hydraulic conductivities of the HHD soils for seepage analyses of the SCB wall, a geotechnical report prepared for the project by USACE was reviewed for gradation test results. In addition, laboratory test results from other locations around the dike and a technical paper by Davis et al. (2009) were also used.

The generalized soil profile based on USACE boring data report and representative average hydraulic conductivities adopted in our seepage analysis are summarized in Table 1.

3.1 Hydraulic Conductivity of Wall Cracks

When the cracks first develop in the SCB wall, the crack void is mostly empty. Therefore, the hydraulic conductivity of the crack, K_{crack}, can be calculated using an equation developed for the parallel plate crack model (Romm, 1966):

$$K_{crack} = (\gamma_w b^2) / 12 \mu , \qquad [1]$$

where γ_w is unit weight of water, b is the crack aperture, and μ is the viscosity of water.

For the average crack aperture, b, of about 1 mm as observed in the field, and assuming water temperature as 17.5^{o}C, the hydraulic conductivity of the crack calculated using Equation 1 is on the order of 80 cm/sec. It is generally accepted that the hydraulic conductivity calculated using Equation 1 provides an upper bound solution. In the field and in the laboratory, the measured hydraulic conductivity for cracks in concrete, for example, is typically one third to two thirds of that obtained from Equation 1 (Walton and Seitz, 1992).

Figure 4. Cracked SCB core for laboratory permeability testing.

Figure 4 shows a cracked core sample that was tested in our in-house laboratory. The testing and its results will be discussed in a separate paper. The crack permeability values obtained in the laboratory are about one tenth of the values calculated using Equation 1. It is very likely that the crack surfaces on our test samples are rougher than those used by Walton and Seitz (1992), causing more friction and disturbance, and therefore, reducing the conductivity. For this analysis, we have conservatively assumed K_{crack} = 40 cm/sec, which is a half of the hydraulic conductivity of the empty crack calculated using Equation 1, yet about five times higher than that measured during our laboratory testing. Such a conservative assumption was used to represent the worst case long term scenario.

3.2 Groundwater Entrance and Exit Gradients Through Cracks

To study the hydraulic gradients of groundwater flow through a wall crack (should a crack extend deeper than the groundwater table), a two-dimensional finite element model was developed using Seep/W (2004). Figure 5 shows one of the analyses performed in our study (in a plan view). This case assumed a 1-mm crack in the 0.7-m (27.5-inch) wall which represents a typical condition.

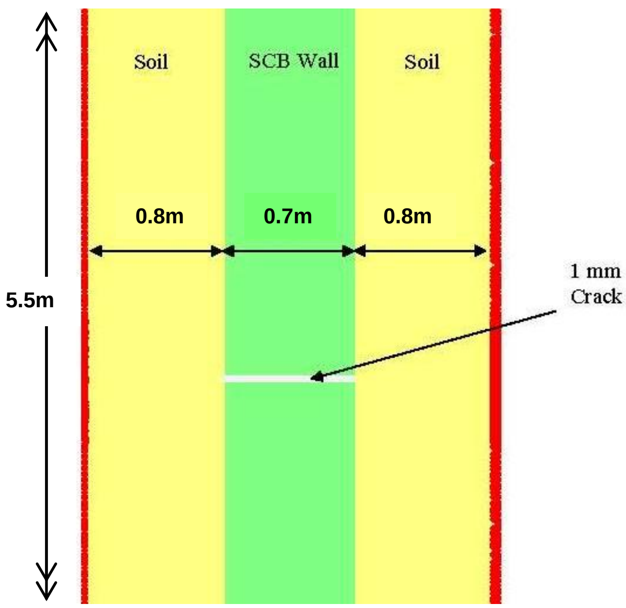

Figure 5. Local seepage finite element model.

Six-node triangles were used and finer elements were specified for the crack and its vicinity to capture the local gradient concentrations. The length of the wall was modeled as 5.5 m (18 ft), as this represented the lower end of the distance between cracks observed in the field. The hydraulic conductivity of the SCB wall material (intact wall) was taken to be 1 x 10^{-7} cm/sec based on laboratory testing data on both grab and bulk samples from the construction of the wall (Figure 2). As discussed earlier, the conservative value of 40 cm/sec was used for the hydraulic conductivity for the opened empty crack. Soils on both sides of the wall were modeled with K = 1 x 10^{-3} cm/sec (representative average value of the dike fill and shallow sand). Hydraulic head boundary conditions were used with a head difference of 3m (10 feet) across the model. This 3m head difference is an approximate maximum which will be experienced by the wall during a design flood event that was based on the global seepage analysis.

Under the long term steady state conditions, the calculated entrance and exit gradients are high, on the order of 80 as shown on Figure 6. It is possible that these high gradients may induce some local disturbance of the soils in the vicinity of the crack and cause migration of fine particles into the crack, as discussed later. As a comparison, the local entrance and exit hydraulic gradients for the case where the crack is filled with fines, assuming K_{crack} of 1 x 10^{-3} cm/sec (same as for the soils in the crack vicinity), is about 5. The 1 x 10^{-3} cm/sec for the crack is conservative as the actual value should be lower than the surrounding soils, since only finer soil particles will fill the crack.

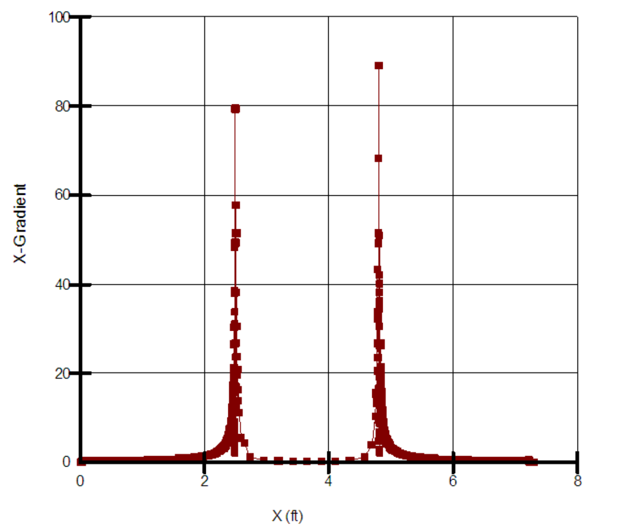

Figure 6 Local gradients across the 1 mm crack from the local seepage model (3.28 ft = 1m).

4 LOCAL SOIL EROSION POTENTIAL AND FILTER CRITERIA

Representative gradation curves of granular dike material encountered in borings and considered in our study are shown on Figures 7 and 8.

The dike embankment materials are generally very heterogeneous as most of the dike was hydraulically placed. Typically, they comprise of loose to compact, fine to coarse sands with various amounts of silt, clay, shells and organic soils. However, portions of the dike fill may also contain pockets of gravel and cobbles with occasional boulders.

The dike fill is typically overlying a complex system of natural deposits. The upper most layer consists of layered deposits of peat and organic silts and sands followed by carbonate deposits and quartz sands. The carbonates include a segmented limestone unit (with decomposed limestone and sand layers). The top portion of the quartz sands typically comprises fine sand that may be partially cemented.

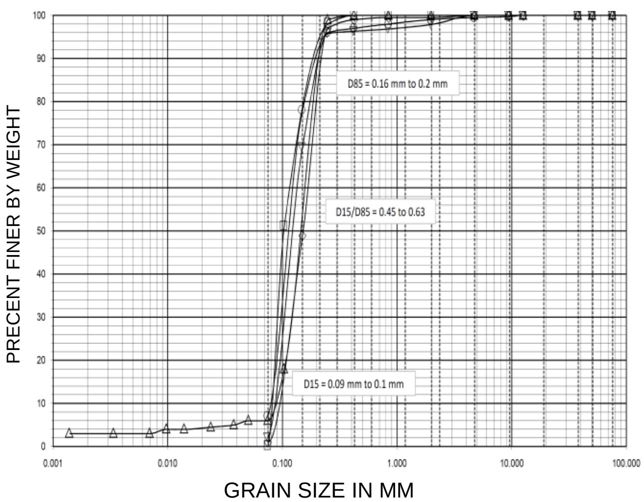

Figure 7. Gradation curves for poorly graded dike sand.

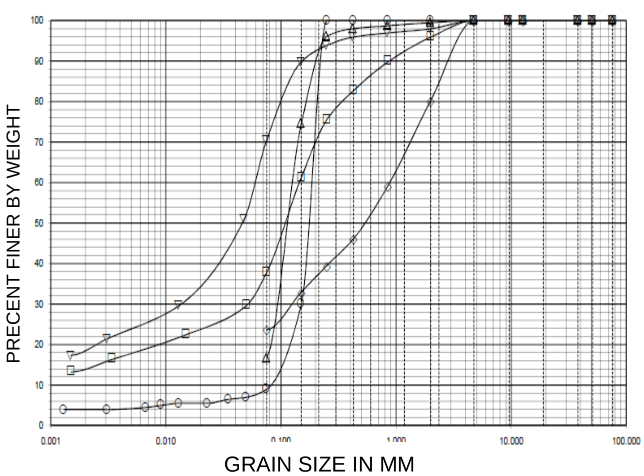

Figure 8. Gradation curves for dike silts and sands with significant fines.

4.1 Internal Stability Criteria

In the evaluation of erosion potential of soils around a wall crack, internal stability of the material upstream from a crack was first considered. Internal stability refers to the movement of fine particles in granular soil through a network of its coarser particles and it is largely governed by the grain size distribution (Fell et al., 2005). USACE in the 1950's used the term "inherent stability" or "internal stability" to define the resistance of the filter to segregation and piping within itself (Li, 2008). Kenney and Lau (1985) defined the term "internal stability" as the ability of granular material to prevent loss of its own small particles due to disturbing agents such as seepage. They also used the word "suffosion" (often spelled "suffusion") to describe the transport of fine particles of a granular soil within its pore space.

A geometric criterion based on the grain size distribution can address the comparative sizes of finer and coarser soil particles. If constrictions in the pore network of the coarse particles are larger than the finer particles, then the finer particles can be transported by seepage flow. The Burenkova (1993) criterion is one of the most commonly used internal stability criteria (Li, 2008 and Fell et al., 2005). It is based on the three representative particle sizes, D_{15}, D_{60}, and D_{90}, and the heterogeneity of the soils is described by two ratios, h' and h'', called conditional factors of uniformity, where

$$h' = D_{90} / D_{60} \quad \text{, and} \qquad [2]$$
$$h'' = D_{90} / D_{15} \qquad [3]$$

Based on these two ratios, Burenkova (1993) presented the boundaries separating the internally unstable soils from the internally stable soils. A soil sample is considered stable if it satisfies

$$(0.76 \log h'' + 1) < h' < (1.86 \log h'' + 1) \qquad [4]$$

This criterion was applied to the gradation curves, except those classified as Stratum "Peat/Clay" or where D_{15} was not available as the materials are cohesive. Results of this screening are summarized in Table 2 which indicates that over 60 percent of the granular samples were classified as internally unstable, indicating that the fine particles could migrate within and out of the material matrix. It should be noted that if the crack width is larger than majority of particles in soil matrix, even internally stable soils will migrate into the crack.

4.2 Slot Opening (Crack Width) Criteria

Following the internal stability evaluation, the potential for clogging at the upstream end of a crack in granular soils was evaluated. As discussed earlier, the local entrance and exit gradients at a crack are relatively high when the crack is first formed and empty. Under those high gradients, fine particles in internally unstable soils are likely to migrate towards the crack.

In general, if the crack width is smaller than the diameter of the migrated fines, the fine particles will accumulate at the upstream face of the crack. This zone of fines with a lower hydraulic conductivity will block the crack and stop further particle migration and decrease the average hydraulic conductivity of the cracked wall. Thus, progressive soil migration of the fines through the crack is likely prevented in such a case. If the crack width is larger than the diameter of the migrating fines, the fines will migrate out of the soil matrix and into the crack.

NAVFAC DM-7.1 (1982) recommends a criterion for grain size of materials in relation to slot openings in drain pipes:

D_{85} of materials in the vicinity of the pipe / maximum slot width ≥ 1.2 to 1.4.

Table 2. Internal Stability Evaluation – Summary

Stratum*	Total Number of Samples**	Samples Analyzed**	Internally Stable Samples	Internally Unstable Samples
F	11	11	7	4
S1	17	14	2	12
S2	9	8	3	5
Total	37	33	12 (36%)	21 (64%)

Notes: * F – Fill (dike embankment); S1 - Upper Sand (between limestone and peat); S2 – Lower sand (below limestone)
** Only samples in granular strata were analyzed. Four did not have sufficient information for the screening.

To evaluate the tendency of fine particles migrating into the cracks, one could modify the NAVFAC criterion to:

D_{85} of materials in the vicinity of the pipe / maximum slot width < 1.2,

by assuming that the inherent factor of safety is close to unity. Applying this criterion to all HHD gradation curves evaluated, about 40 percent of the samples will have tendency to migrate into a 1-mm crack. For the maximum crack width of 2.8 mm (representing twice the maximum width observed in the field), over 70 percent of samples show tendency to migrate into the crack.

4.3 Filter Criteria

To further evaluate potential local granular soil erosion downstream of a crack, empirical design criteria for embankment dam filters have been considered. The criteria use the basic filtering concept that a filter should have a particle size distribution which prevents loss of the adjacent base soil into the filter. There has been fairly extensive research in filtering concepts for hydraulic structures. An early filter criterion concept presented by Terzaghi in the 1920's (Fannin, 2008) was the basis for many subsequent studies (primarily by the US Department of Agriculture Soil Conservation Services, USDA SCS; e.g., Sherard and Dunnigan, 1989).

The filter criteria used in our study were those based on the most recent U.S. Bureau of Reclamation design standards (USBR, 2007) which were developed by Sherard and Dunnigan (1989) and are shown in Table 3. Those standards are based on the original Terzaghi filter concept. Some of the more recent filter concept studies published in literature have not been incorporated as their performance record has not been established by the government agencies (Fell et al., 2005 and USBR, 2007 provide an overview of the existing filter studies).

The USBR filter concepts and criteria used in our evaluation are the same as those in most recent USACE engineering manuals (USACE, 2004; USACE, 2000; and USACE, 1986).

If fine particles migrate into a wall crack, they may either clog the crack (through arching mechanisms) or migrate through the crack. If they migrate through the crack, the ability of downstream soils to act as a protective filter and prevent progressive migration of the fines out of the cracks can be evaluated based on the filter criteria.

The particle size of the protective filter (in our case, soil downstream of the cracks) for which 15% by weight is finer (DF_{15}) and the particle size of the material, for which 85% by weight is finer (DB_{85}), that is being protected (material migrating through the crack) were used to evaluate the potential for progressive migration of soil particles. The Retention Ratio is defined as DF_{15} divided by DB_{85}.

Table 3. Empirical Filter Design Criteria.

Type of Base Soil	Fine Content	Retention Ratio Criteria (DF15/DB85)
Fine Silts and Clays	> 85%	≤ 9 [a]
Sandy Silts and Clays	40 – 85%	≤ 5 [b]
Silty and Clayey Sands	< 15%	≤ 4 [c]

Notes:
a. With minimum DF15 = 0.2 mm
b. An alternate criteria is DF15 ≤ 0.7 mm
c. For soils with fine content 15-40%, it is conservative to adopt DF15/DB85 ≤ 4 and DF15 ≤ 0.7 mm.

To evaluate DB_{85} (for particles migrating through the crack), gradation curves were adjusted since the crack width limits the particles size that can migrate through the crack. A review of the gradation curves of HHD soils concluded that Retention Ratios defined in Table 3 for all samples satisfied the filter criteria.

Therefore, the filter analysis indicated there is no risk of progressive soil migration through the cracks as the downstream soils provide a natural filter.

4.4 Potential for Erosion of SCB Material

As part of the laboratory testing of the cracked cores, the potential for erosion of the SCB material within the crack was evaluated. The testing indicated that even for velocities of flow through a crack two times greater than those estimated to represent flood conditions, there is no measurable erosion of the SCB material.

5 GLOBAL SEEPAGE ANALYSES

The results of the local seepage analyses were used in a global seepage model to evaluate the overall performance of the SCB wall constructed. A two-dimensional finite element model similar to that used in the original design performed for the HHD rehabilitation project by USACE was developed. A similar study of effects of cracking on performance of dam cut-off walls was recently performed by Rice and Duncan (2010).

A concept of equivalent conductivity was used to model the SCB wall with transverse cracks in the two-dimensional model. Following the evaluation discussed earlier, the hydraulic conductivity of 1×10^{-3} cm/sec for the crack filled was used in the analyses. This represents a crack filled with soil particles or reduced hydraulic conductivity of soil upstream of the crack. The equivalent hydraulic conductivity of the SCB wall was calculated using the conventional width-weighted arithmetic mean method. Using hydraulic conductivity of 1×10^{-7} cm/sec for the intact SCB wall (based on HHD laboratory data), the equivalent long term hydraulic conductivity of the wall (K_{wall}) having a 1 mm crack every 5.5m (18 feet) is estimated to be on the order of 3×10^{-7} cm/sec which is below the specified limit of 1×10^{-6} cm/sec. Since the range of the crack spacing is measured between 3.0m to 18.3m (10 and 60 feet) with more data points in the range of 4.6m to 9.1m (15 to 30 feet), this estimated equivalent hydraulic conductivity is reasonable is reasonable.

Figure 9 shows the finite element model developed to study the global seepage condition. The upstream lake level of Elev. +7.6m (+25 ft) was used (i.e. the Standard Project Flood Elevation, Davis et al., 2009). The downstream groundwater level in the model is at Elev. +3.0m (+10 ft) based on Davis et al. (2009).

Figure 10 show the calculated total heads obtained from the analysis under the steady state condition. We also analyzed two additional limit cases to investigate the sensitivity of the hydraulic conductivity of the SCB wall: one with $K_{wall} = 1 \times 10^{-7}$ cm/sec (represents an intact wall without cracks) and the other with $K_{wall} = 1 \times 10^{-6}$ cm/sec (represents the maximum specified wall permeability). The calculated total heads and seepage quantities for all cases had insignificant differences.

6 CONCLUSIONS

The comprehensive evaluation of the SCB wall cut-off performance indicate that the long term global seepage performance of the wall constructed at the site will not be affected by the presence of the transverse cracks even if they extend the entire depth of the wall (which is contrary to the conclusions of the evaluations). Cracks in verification drill holes will be sealed during grouting of the holes.

The analysis of potential for local soil erosion concluded that there would be no progressive migration of particles through the narrow wall cracks. Particles in soil upstream of a crack may migrate into the crack due to high local gradients. If the particles do not clog the crack and migrate through the crack, the downstream soil will act as a protective filter preventing progressive migration of those particles. The crack will be then filled by the fines which will significantly reduce the conductivity of the crack itself and the average hydraulic conductivity of the crack and the wall. The width of the crack is unlikely to increase based on laboratory tests.

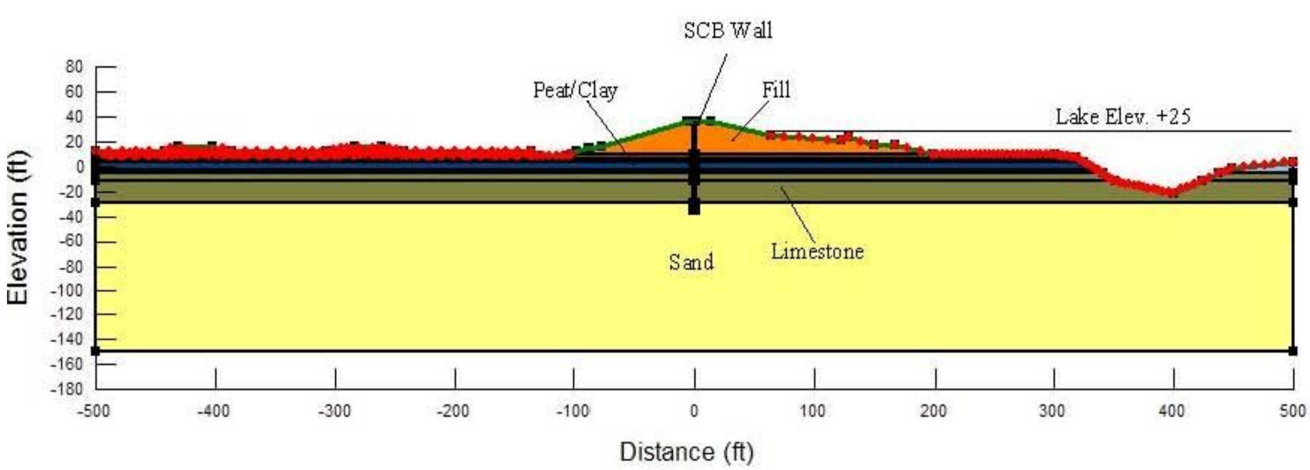

Figure 9. Global seepage finite element model. (3.28 ft = 1 m)

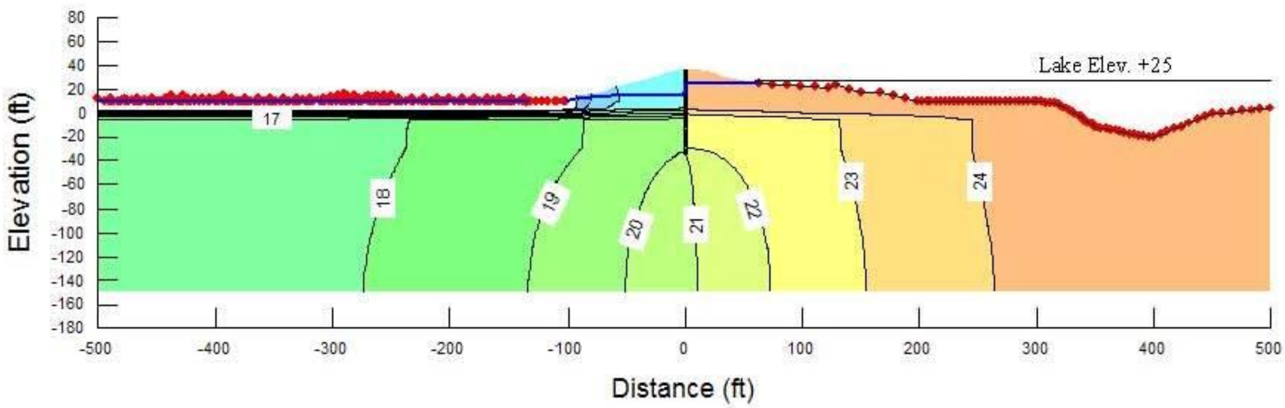

Figure 10. Total head contours from the global seepage model. (3.28 ft = 1 m)

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