# Tailing Dams 2000

# PROCEEDINGS

Association of State Dam Safety Officials • U.S. Committee on Large Dams

March 28-30, 2000 • Las Vegas, Nevada

# PERIMETER EMBANKMENTS TO INCREASE CAPACITY, MITIGATE SUBSIDENCE IMPACTS, AND ABANDON COAL REFUSE DISPOSAL IMPOUNDMENTS

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## Introduction

Economic considerations and increased environmental scrutiny have encouraged coal companies to expand the life of existing coal refuse disposal impoundments rather than build new disposal facilities. One method being successfully used to increase disposal capacity is to build perimeter embankments using coarse coal refuse to raise the crest of the facility above the level of the natural ridges. The upstream portion of a perimeter embankment is built over fine coal refuse deposited during previous stages which aids in the final covering of the impoundment during abandonment. Perimeter embankments can also be used as a barrier to mitigate the impacts of subsidence from abandoned underground mine workings. Details are presented for the design and construction of perimeter embankments including recommended placement and compaction criteria.

## Perimeter Embankments For Increasing Disposal Capacity/Abandonment

### *Layout and Staging*

Figures 1 and 2(a) show details of a perimeter embankment being built in stages above the level of a natural ridge at a disposal site in Virginia. Stages 1 through 6 of the facility were built in the disposal hollow up to the level of the top of the ridge. Stages 7 through 10 enable the crest of the disposal facility to be raised about 100 feet in elevation above the level of the top of the ridge.

An important aspect of this method is to begin construction of the perimeter dikes over the deposited fine coal refuse prior to the time when the fine refuse reaches the level of the natural ridge. French drains can then be installed during the initial phase of the perimeter embankment construction to maintain a phreatic surface at the desired level as shown in Figure 2(a). This early construction provides for a coarse refuse zone at the downstream toe of the perimeter embankment with sufficient thickness to meet the requirements for slope stability.

Perimeter embankment construction provides the owner with the flexibility to abandon the facility at any time during the staged construction by providing a working surface around the perimeter of the impoundment. For example, if additional life is needed beyond Stage 10, more stages can be built as shown in Figure 2(b). Alternatively, if recoverable reserves are nearing depletion, coarse refuse can be used to cap the impoundment during abandonment as shown in Figure 2(a).

### *Selection of Engineering Design Parameters for Fine Refuse*

Due to the length of perimeter embankments around a disposal hollow, construction is generally sufficiently slow to enable dissipation of excess construction pore pressures in the fine refuse. Therefore, the critical condition for stability of perimeter embankments is typically a post-earthquake static analysis where the shear strength of the fine refuse has been reduced due to excess pore pressure build-up caused by the design earthquake. The required level of fine refuse testing for the design of a perimeter embankment will depend on the resistance required to maintain stability. If seepage and stability analyses indicate that the embankment would remain stable even if the fine refuse loses all its strength as a result of liquefaction during an earthquake, then only static parameters (i.e. strength, consolidation, and permeability) would be required for design.[1]

If a nominal strength is required for the fine refuse to resist a failure during the design earthquake, then a conservative "liquefied strength" can be measured using in-situ vane shear testing. The residual strength measured after several revolutions of the vane shear probe can be used to estimate the undrained steady-state shear strength of liquefied fine refuse.[2, 3] If a higher strength is required for the fine refuse to resist slope instability during the design earthquake, then cross-borehole shear wave velocity and/or cyclic triaxial testing may be required to provide a more accurate estimate of the pore pressure build-up and resulting strength of the fine refuse during the design earthquake.[4, 5, 6]

### *Engineering Design Properties of Coarse Refuse at Various Placement Criteria*

Figures 3 and 4 show the relationship between engineering characteristics and the percentage of the standard Proctor maximum dry density (i.e. percent compaction) at various placement moisture contents for coarse refuse from a facility in Virginia. The samples were prepared at moisture contents ranging from about 4% below optimum moisture content to about 6% above optimum moisture content as defined by the standard Proctor test. This coarse refuse classifies as a GW-GM material according to the Unified Soil Classification System with a maximum particle size of about 2 inches and 8% passing a U.S. No. 200 sieve.

Figure 3 shows similar coefficients of permeability (k) for samples compacted to 90% and 95% of the standard Proctor maximum dry density. The coefficient of permeability reduced by nearly an order of magnitude by increasing compaction to 100% of the standard Proctor maximum dry density. Figure 4 shows about a 2-degree linear increase in the effective angle of internal friction from samples compacted to 90% to samples compacted to 100% of the standard Proctor maximum dry density. The coefficient of permeability varied by less than half an order of magnitude and the effective angle of internal friction varied by less than 1 degree by varying the placement moisture content at a given degree of compaction.

Although an increase in compactive effort results in a slight increase in the effective angle of internal friction, stress-strain characteristics are also important in assessing how coarse refuse will perform in a perimeter embankment. Figure 5 shows that the coarse refuse compacted to 100% of the standard Proctor maximum dry density achieves a peak deviator stress in triaxial testing at about 13% strain with a reduction in deviator stress at increased strain levels. At 95% compaction, the sample achieved a peak deviator stress at 15% strain that remained constant at higher levels of strain. At 90% compaction, the deviator stress continued to increase over the entire stress range tested. The deviator stress at 15% strain was conservatively used as the peak value in the determination of the effective angle of internal friction for the 90% compaction sample in Figure 4.

Figure 6 presents statistical compaction data from sites with different minimum allowable compaction criteria and maximum allowable lift thicknesses. Typically, when a minimum 90% compaction criteria is specified for a given test with maximum allowable lift thicknesses of 18 inches, the statistical median of the data will be on the order of 95% compaction. When a minimum 95% compaction criteria is specified for a given test with maximum allowable lift thicknesses of 12 inches, the statistical median of the data will be on the order of 100% compaction.

### *Recommended Coarse Refuse Placement Criteria*

The Mine Safety and Health Administration[7] (MSHA) recommends that coarse refuse placed in the structural portion of a coal refuse impounding structure meet the following criteria:

1) Material should be compacted to at least 95% of the maximum dry density as defined by the standard Proctor test, with the placement water content not exceeding the range of -2% to +3% of optimum.

2) In compacting coarse coal refuse, the lift thickness should not exceed 12 inches.

MSHA allows less stringent compaction specifications only when justified by extensive testing and analyses or in areas which can be shown to be "non-structural" portions of the dam.

In the design of water-retention dams, high strength and low permeability of the embankment materials are often a necessity. High strength allows for steeper outslopes resulting in less borrow material required for construction. Low permeability provides for less loss of water from the impoundment. High strength and low permeability are achieved in conventional earthen embankments by placing materials in thin lifts compacted to a high density near optimum moisture content.

Coal refuse dams that impound fine coal refuse have different design considerations than conventional water-retention dams. Building steeper slopes to reduce the volume of borrow material is not required. Coarse refuse is a waste product which would have to be disposed elsewhere if not used as borrow material in the dam construction. With regard to permeability, seepage through a coal refuse dam is impeded by discharging fine refuse immediately upstream of the coarse refuse embankment. The coarse refuse controls the rate of seepage only for a shallow depth of water that is impounded above the settled fine refuse, which is typically less than about 5 feet deep. As a result, the permeability requirements for the coarse refuse in a coal refuse dam are comparable to the permeability requirements of the downstream shell in a conventional water-retention dam (i.e. low permeability is not necessarily a desirable characteristic).

The paradigm that embankment materials must be placed in thin lifts and compacted to a high density near optimum moisture content is not applicable for coal refuse perimeter embankments. The selection of placement criteria should be based on site specific design considerations and engineering characteristics of the actual embankment materials. For the facility shown in Figures 1 and 2 with coarse refuse characteristics representative of the data shown in Figures 3 through 6, less stringent specifications than those recommended by MSHA can be justified. The data suggest that coarse refuse can be placed in maximum 18-inch thick lifts and compacted to a minimum 90% of the standard Proctor maximum dry density at moisture contents within the limits of -3% to +4% of optimum as justified in the following sections.

### *Seepage Analyses*

Figure 7(b) shows the results of a finite element seepage analysis presuming that the coarse refuse is placed in accordance with MSHA recommendations (i.e. minimum 95% compaction which results in a median compaction of about 100% of the standard Proctor maximum dry density). Figure 7(a) shows the results of a finite element seepage analysis with compaction criteria as recommended previously (i.e. minimum 90% compaction which results in a median compaction of about 95% of the standard Proctor maximum dry density). Comparison of Figures 7(a) and 7(b) shows that a lower phreatic level is predicted using a 90% minimum compaction criteria because the fine refuse in the impoundment serves as the primary seepage barrier for the perimeter embankment. As a result, increasing the degree of compaction to lower the coefficient of permeability of the coarse refuse can have the detrimental effect of elevating the phreatic level in the dam. Cedergren[8] reported a similar observation for sloping core dams with different permeabilities between the upstream core and the downstream shell.

An added benefit from the higher coefficient of permeability of the coarse refuse compacted at a minimum 90% level is the increased rate of seepage from the drains. As shown in Figure 7(a), a seepage rate of 451 gallons per minute (gpm) is predicted for the 4000-foot long perimeter embankment compacted to a minimum 90% compaction level. As shown in Figure 7(b), a seepage rate of 126 gpm is predicted for the perimeter embankment compacted to a minimum 95% compaction level. A sustained seepage rate of 126 gpm is less than the average rate of slurry pumping into the impoundment and accumulated runoff, thus requiring that a floating pump station be installed to keep the impoundment dewatered. At a sustained seepage rate of 451 gpm, the drains alone will keep the impoundment dewatered.

### *Stability Analyses*

As stated previously, the critical condition for stability of perimeter embankments is a post-earthquake static analysis. As shown in Figure 2(a), a minimum factor of safety of 1.21 is predicted presuming a complete loss of strength for the fine refuse foundation. This analysis was conservatively performed using the strength parameters for coarse refuse placed at a minimum compaction criteria of 90% (i.e. effective angle of internal friction of 33° with no effective cohesion). An effective angle of internal friction of 33° is in the lower range of the strength envelope shown in Figure 4, even considering a broader range of allowable placement moisture contents than is currently recommended by MSHA. Due to the conservative nature of this analysis in ignoring the strength of the fine refuse, a factor of safety in excess of 1.0 is considered acceptable.

If additional stages of construction are needed, in-situ vane shear testing of the fine refuse can be performed. The undrained steady-state shear strength of the fine refuse can be estimated using the results of residual shear strength from the vane shear testing as shown in Figure 8. Figure 2(b) shows that the required minimum factor of safety in excess of 1.0 can be achieved using the residual shear strength of the fine refuse in a post-earthquake static slope stability analysis.

Because a perimeter embankment uses previously deposited fine refuse as a part of its foundation, settlement of the embankment is expected due to consolidation of the underlying foundation during both static and earthquake loading conditions. As a result, coarse refuse placed at a minimum 90% compaction criteria is preferred because of its stress-strain response. As shown in Figure 5, the deviator stress of coarse refuse placed at a 90% compaction criteria continues to increase at higher levels of strain. The deviator stress at a 100% compaction criteria reduces at higher levels of strain. These analyses show that MSHA criteria for stability can be met by compacting coarse refuse to a minimum 90% compaction level for a given test which will result in a median compaction of the perimeter embankment on the order of 95% of the standard Proctor maximum dry density.

## Perimeter Embankments to Mitigate Subsidence Impacts

Many coal refuse disposal sites are underlain by abandoned mine workings. Perimeter embankments can be used to create a barrier between the abandoned mine workings and the fine refuse disposal impoundment to reduce the potential for an uncontrolled release. Figure 9 shows the results of a finite element seepage analysis for a coarse refuse perimeter embankment used in conjunction with an earthen mine seal barrier and an internal French drain. This arrangement allows for low hydrostatic pressures to be maintained against a previously undermined abutment for a later stage of construction of the facility shown in Figure 1.

## Observations and Conclusions

Observations and conclusions from the data included in this paper are as follows:

1) Perimeter embankments allow disposal capacity to be increased at coal refuse disposal sites by raising the dam above the level of the ridge top.

2) Perimeter embankment construction results in a staged reduction in the surface area of the impoundment. Coarse refuse placement around the perimeter of a disposal site creates a working surface during each construction stage which aids in the eventual elimination of impounding capabilities during abandonment. This staged sequence creates flexibility between providing additional storage capacity and beginning the final reclamation stage of construction.

3) Perimeter embankments can be used as barriers to mitigate the impacts of potential subsidence from underlying underground mine workings. Drains installed within the coarse refuse barrier can reduce hydrostatic pressures against previously mined abutments and thereby reduce the potential for an uncontrolled release of water/fine refuse from the impoundment.

4) Due to the relatively slow rate of construction of perimeter embankments, complete pore pressure dissipation typically occurs in the underlying fine refuse foundation, which can be verified by monitoring using pneumatic piezometers.

5) Construction of perimeter embankments should begin before the fine refuse in the impoundment achieves the level of the top of the ridge. This early construction provides for a coarse refuse zone with sufficient thickness to resist instability during critical earthquake conditions.

6) The proposed design procedure presented for perimeter embankments allows the level of fine refuse strength testing for earthquake loading conditions to be determined based on the level of strength required to resist slope instability during the design earthquake.

7) Specifying minimum compaction criteria for coarse refuse will result in an embankment composed of material that is significantly denser than the specified minimum level.

8) A broader range in the allowable moisture content, thicker lifts, and a lower minimum compaction standard than those recommended by MSHA can often be justified for coarse refuse placement in perimeter embankment construction by incorporating engineering characteristics based on site-specific data as outlined in this paper.

## References

1. Thacker, B. K. (1985), *The Use of Wick Drains in Upstream Construction*. Proceedings of the MSHA Seminar on Planning, Design, and Construction of Coal Refuse Disposal Facilities, Beckley, WV, 15 pp.
2. Poulos, S. J. (1988), *Strength for Static and Dynamic Stability Analysis*. Proceeding of the ASCE Specialty Conference on Hydraulic Fill Structures, Fort Collins, CO, pp. 452-474.
3. Thacker, B. K. (1997), *Liquefaction Mitigation Procedures for Coal Refuse Dams Built by the Modified Upstream Construction Method.* Proceedings of the Twenty-Eighth Ohio River Valley Soils Seminar, Lexington, KY, 26 pp.
4. Nofal, M. M. and Holbrook, R. M. (1995), *Laboratory and Field Measurements of Coal Refuse Properties*. Proceedings of the Twenty-Sixth Ohio River Valley Soils Seminar, Clarksville, IN, 11 pp.
5. Thacker, B. K., Ullrich, C. R., Smith, G., and Athanasakes, G. (1988), *Evaluation of a Coal Refuse Impoundment Built by the Upstream Method*. Proceeding of the ASCE Specialty Conference on Hydraulic Fill Structures, Fort Collins, CO, pp. 730-749.
6. Ullrich, C. R., Thacker, B. K., and Roberts, N. R. (1991), *Dynamic Properties of Fine-Grained Coal Refuse*. Proceedings of the Second International Conference on Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, MO, pp. 393-397.
7. Mine Safety and Health Administration (1990), Impounding Structures Safety Design Procedures: Compaction Specifications. U.S. Department of Labor, Procedure Instruction Letter I90-II-1, 4 pp.
8. Cedergren, H. R. (1973), *Seepage Control in Earth Dams*. Embankment-Dam Engineering, Casagrande Volume, John Wiley and Sons, New York, NY, pp 21-45.

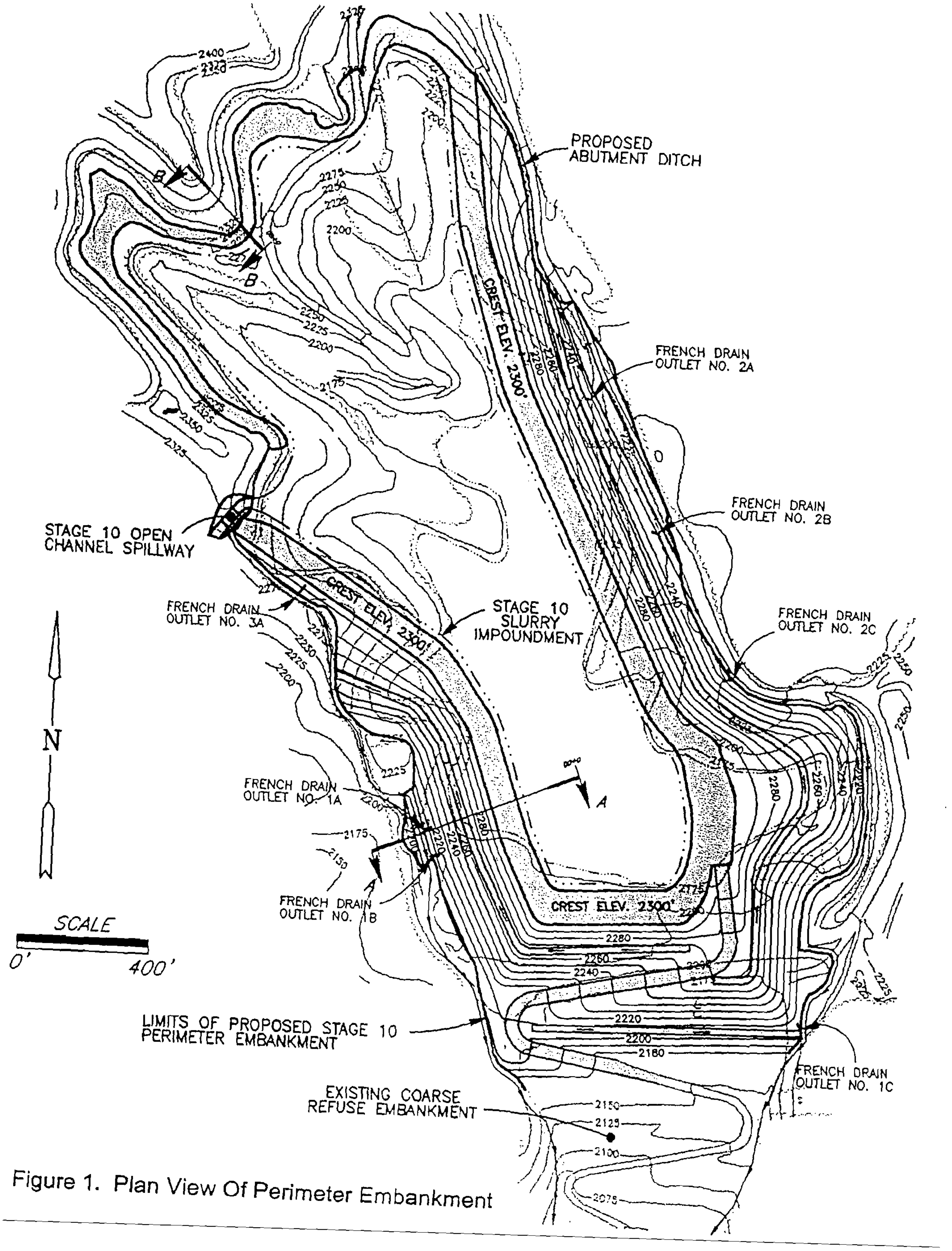
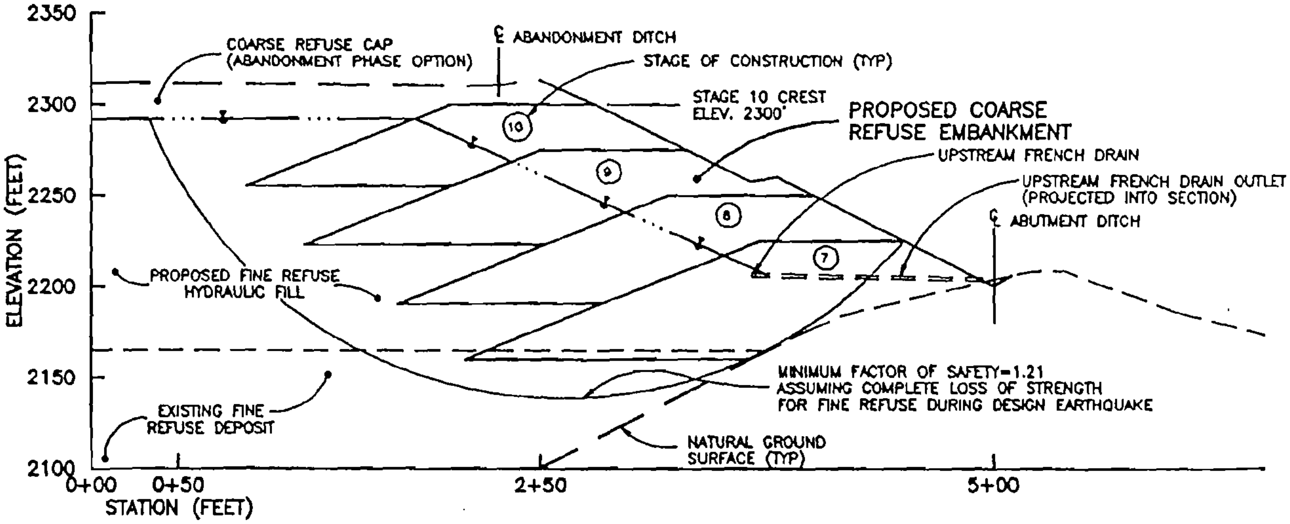
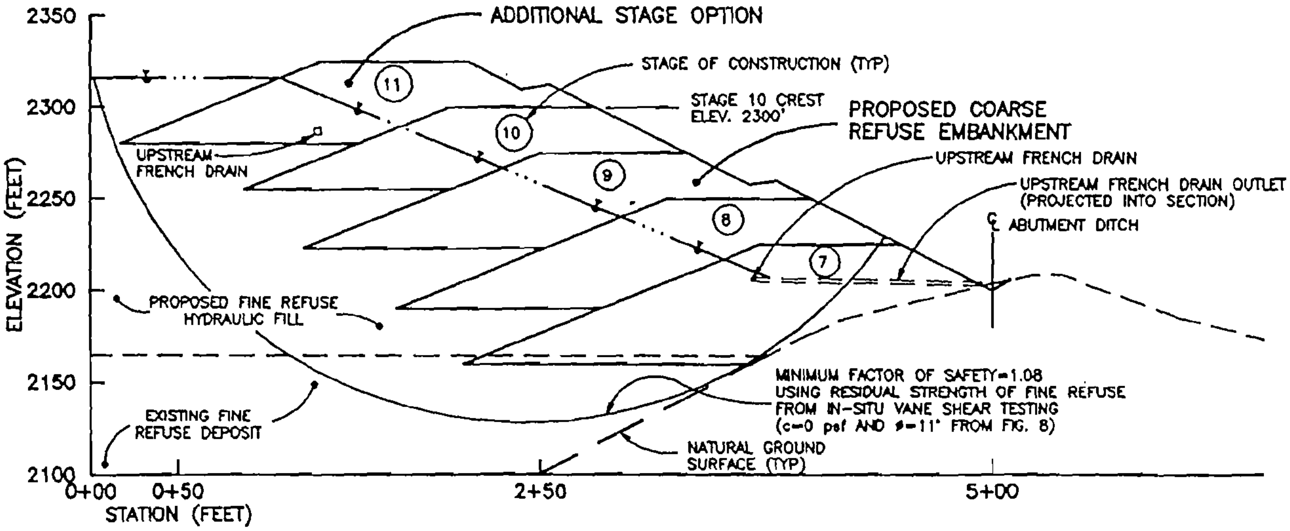


Figure 1. Plan View Of Perimeter Embankment



(a) option to abandon facility after stage 10



(b) option to raise the dam after stage 10

Figure 2. Cross Section A-A Illustrating The Flexibility Of Perimeter Embankment Construction For Beginning Abandonment At Any Time

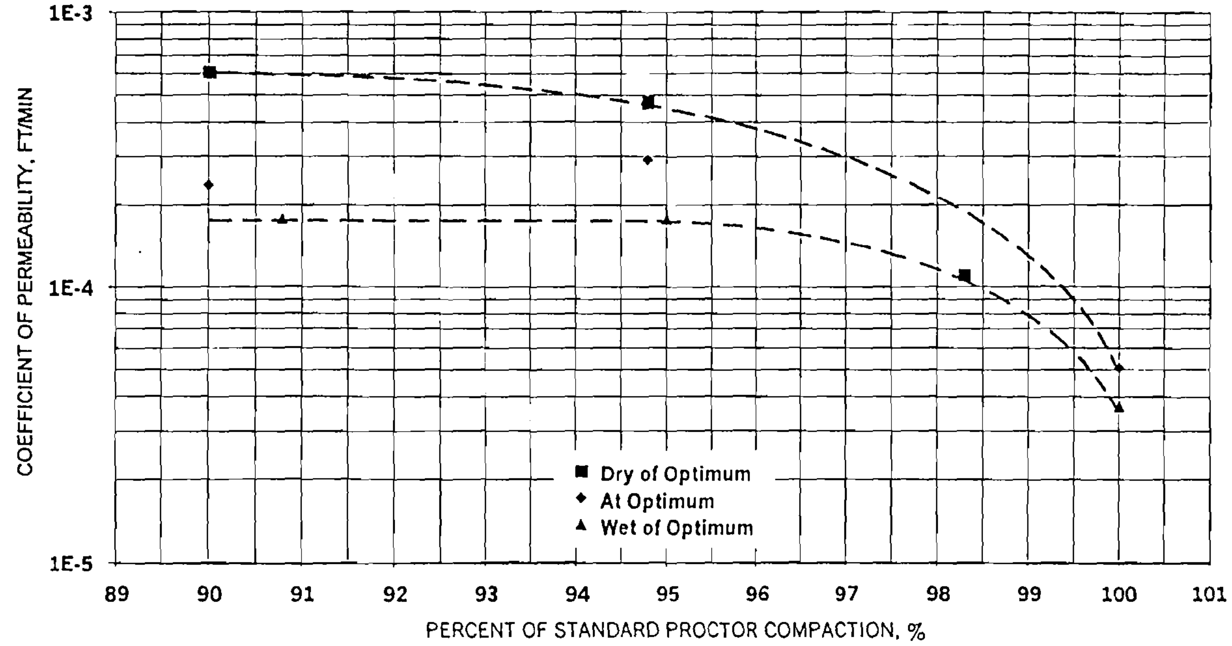


Figure 3. Results of Permeability Testing on Remolded Samples of Coarse Refuse

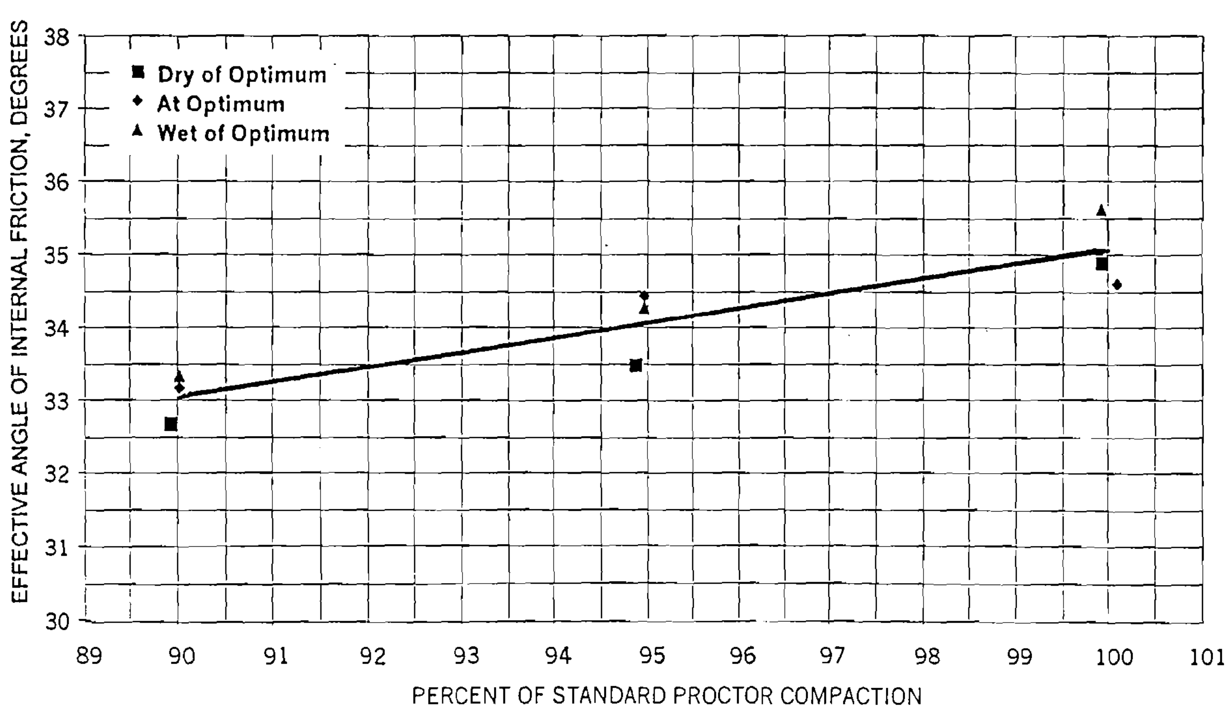


Figure 4. Results of Consolidated-Drained Triaxial Compression Testing of Coarse Refuse at Confining Pressures = 60 psi

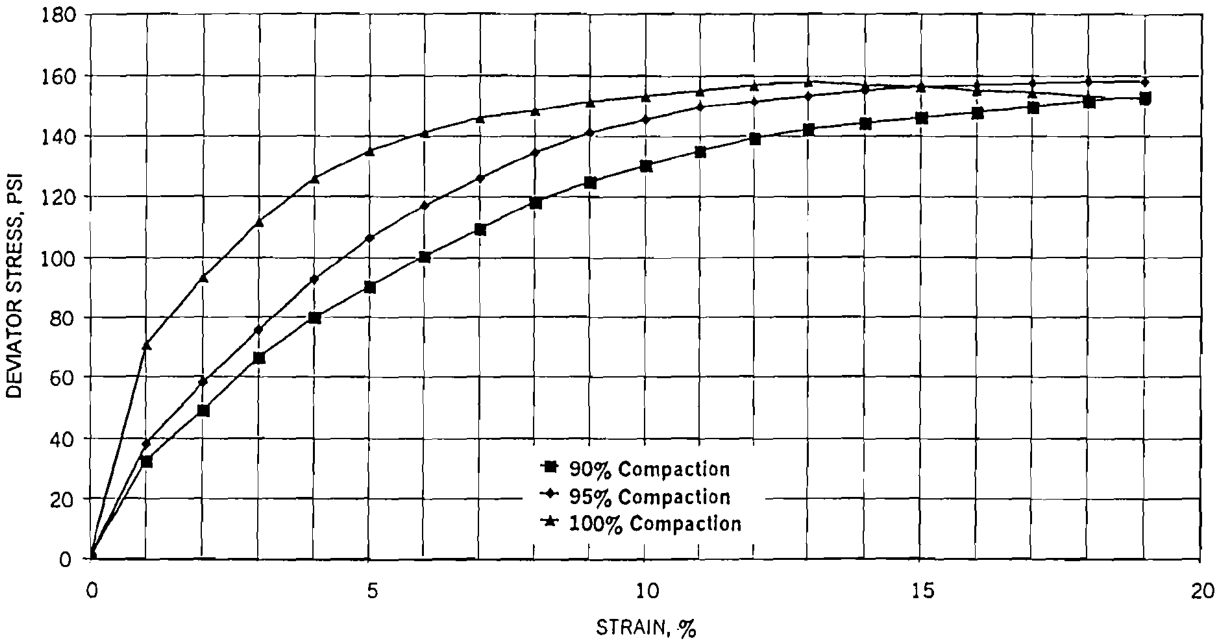


Figure 5. Stress-Strain Curves from Consolidated-Drained Triaxial Compression Testing of Coarse Refuse at Confining Pressures = 60 psi (Samples Remolded Near Optimum Moisture Content)

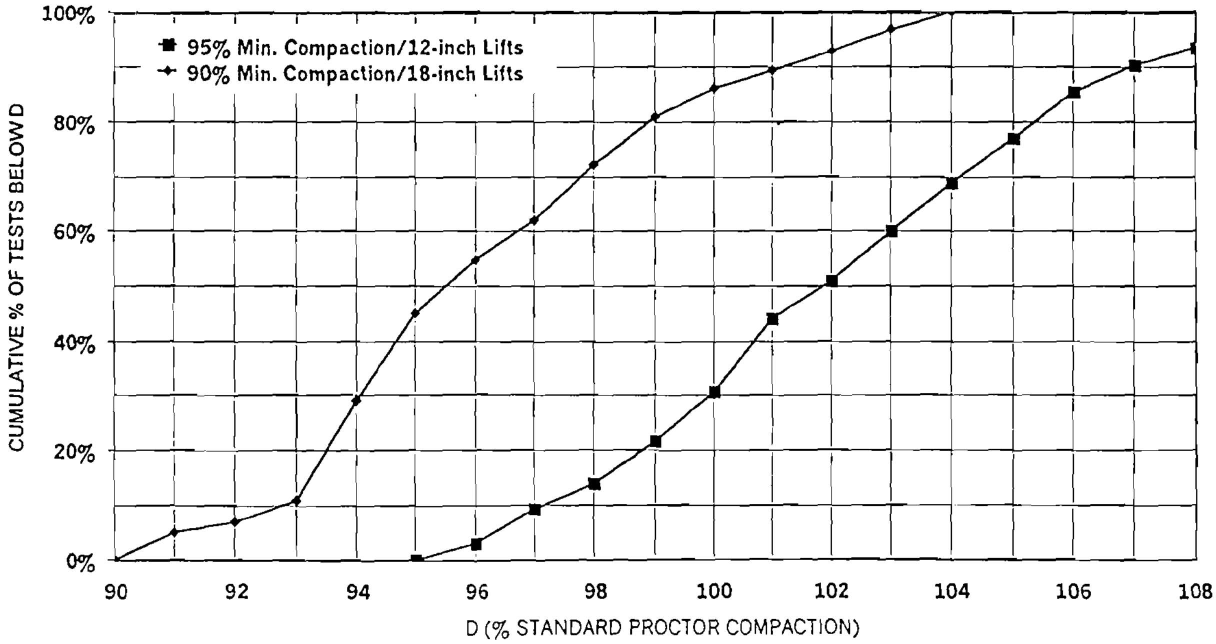
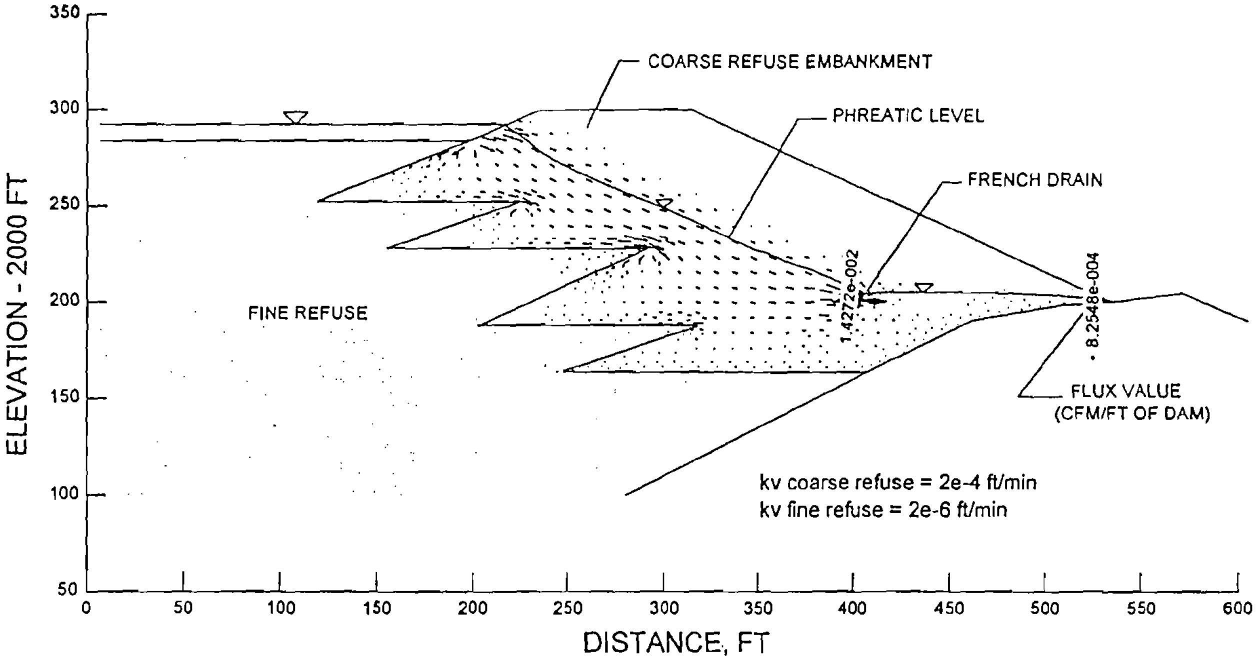
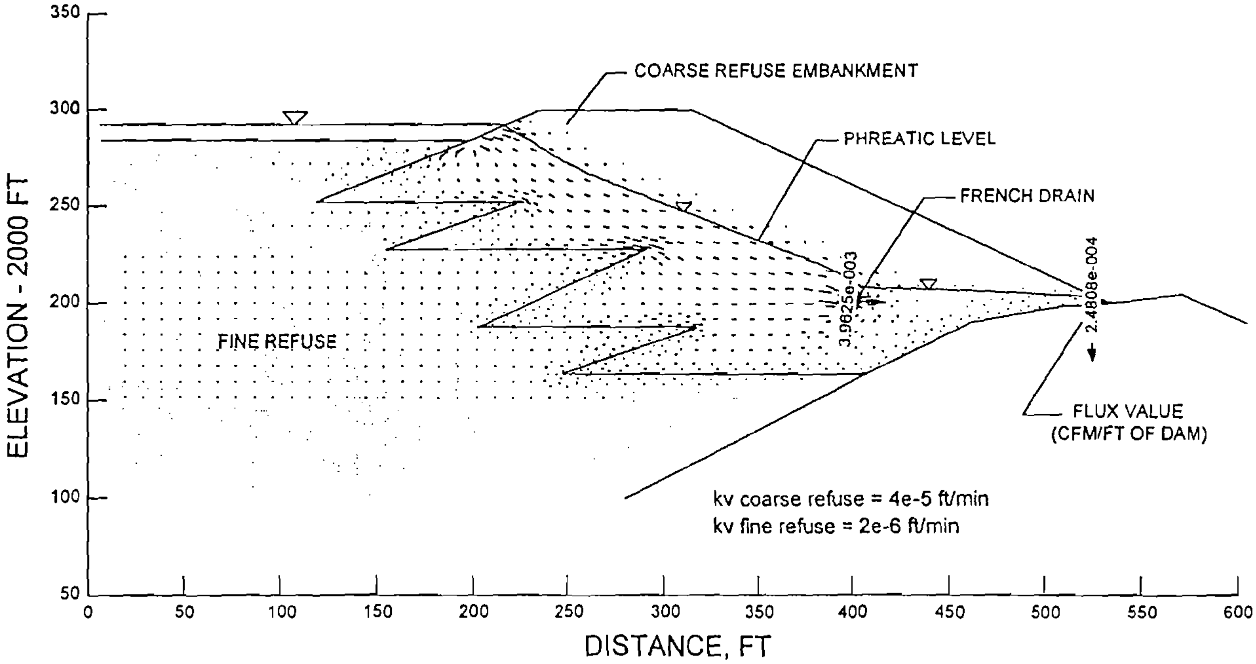


Figure 6. Statistical Analysis of Field Density Data for Coarse Refuse from Sites with Different Minimum Compaction Criteria and Maximum Allowable Lift Thicknesses



(a) coarse refuse compacted to a minimum of 90% of the standard Proctor maximum dry density ($k_{vertical}$ = 2e-4 ft/min)



(b) coarse refuse compacted to a minimum of 95% of the standard Proctor maximum dry density ($k_{vertical}$ = 4e-5 ft/min)

**Figure 7. Results of Finite Element Seepage Analyses for Varying Coefficients of Permeability for Coarse Refuse and a Constant Coefficient of Permeability of 2e-6 ft/min for Fine Refuse (Stage 10, Section A-A)**

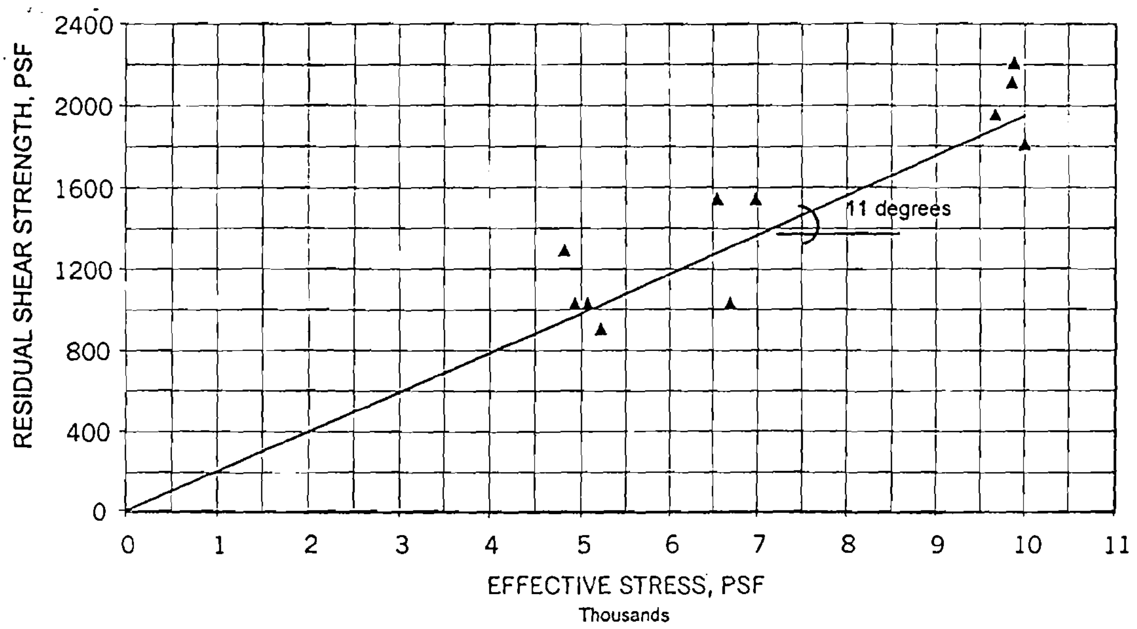


Figure 8. Results of In-situ Vane Shear Testing of Fine Coal Refuse (Undrained Steady-State Shear Strength Based on Residual Values)

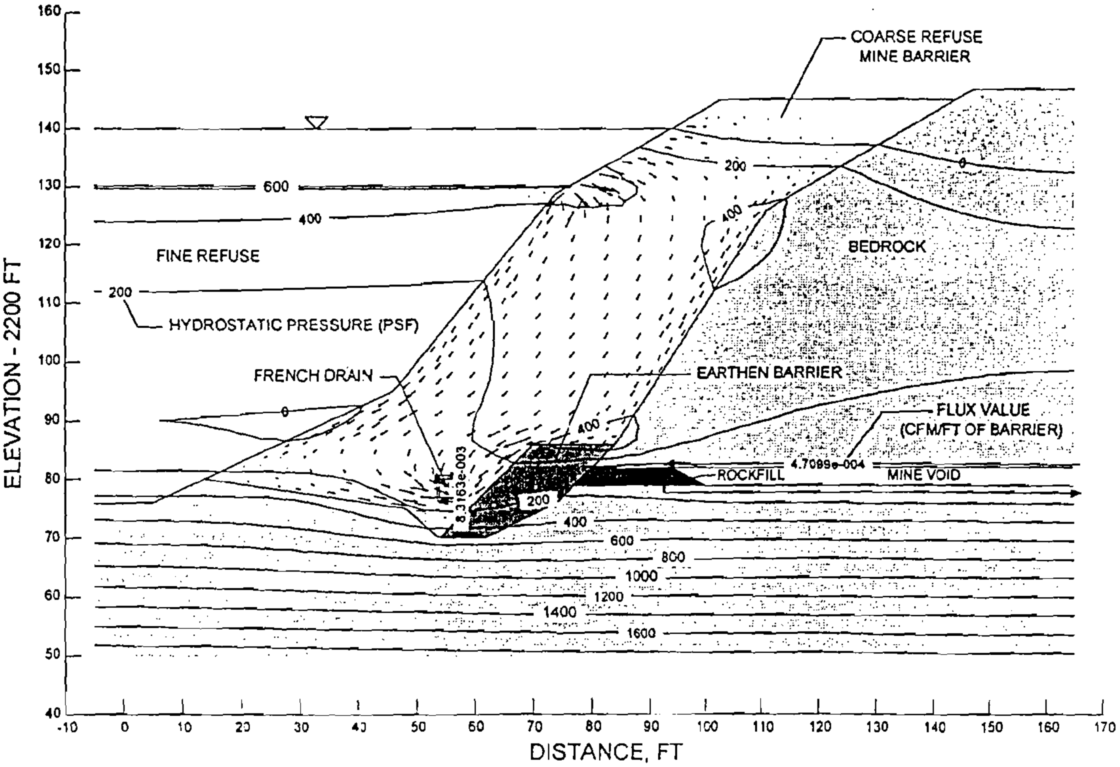


Figure 9. Results of Finite Element Seepage Analysis for a Coarse Refuse Perimeter Embankment Used as a Mine Seal Barrier (Stage 12, Section B-B)