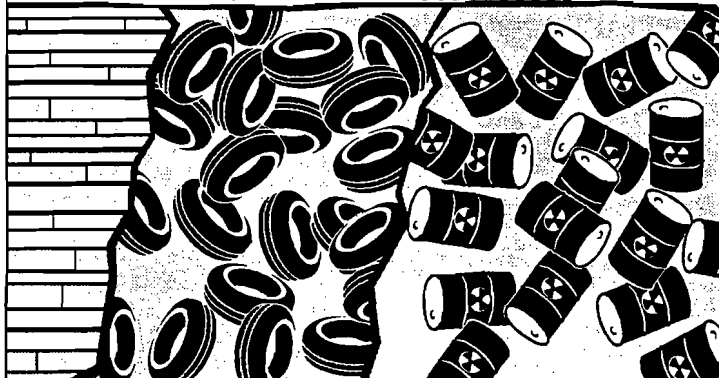
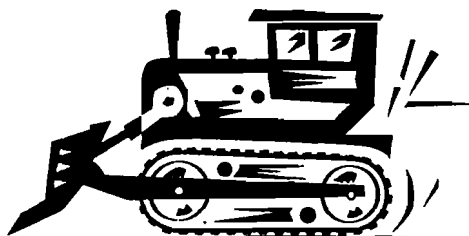




UNCONVENTIONAL FILLS: DESIGN, CONSTRUCTION AND PERFORMANCE



Friday, October 10, 1997
Holiday Inn North
Lexington, Kentucky

TENTATIVE PROGRAM

8:00 a.m. Registration

MORNING SESSION

- 9:00 a.m. **Keynote Speaker, Morning Session**
Timothy D. Stark, University of Illinois at Urbana-Champaign - *Seismic Design of a Failed Landfill Slope*
Timothy D. Stark and W. Douglas Evans
- 10:00 a.m. Technical Demonstration
- 10:30 a.m. Fred W. Erdmann, Dames & Moore, Cincinnati, Ohio - *Construction of a Highway Embankment with Gasoline-Contaminated Soil*
Fred W. Erdmann and Richard J. Hajer
- 11:05 a.m. G. D. Prasad, Canadian Highways International Corporation, Mississauga, Ontario - *Geotechnical Engineering Management of Unconventional Fill Materials in a Large Design Build Highway Project*
G. Durga Prasad and D. Guistini
- 11:40 a.m. Tommy C. Hopkins, Kentucky Transportation Center, Lexington, Kentucky - *Embankment Construction using Shale*
Tommy C. Hopkins and Tony Beckham
- 12:15 p.m. Lunch & Exhibitors Fair

AFTERNOON SESSION

- 1:25 p.m. Announcements
- 1:30 p.m. **Keynote Speaker, Afternoon Session**
Barry K. Thacker, Geo/Environmental Associates, Inc., Knoxville, Tennessee - *Liquefaction Mitigation Procedures for Coal Refuse Dams Built by the Modified Upstream Method*
Barry K. Thacker
- 2:30 p.m. Technical Demonstrations
- 3:00 p.m. Thomas O. Keller, GEI Consultants, Carlsbad, California - *Geotechnical Properties of a Lightweight Aggregate*
Thomas Keller and Frank Archambault
- 3:35 p.m. Jon H. Gould, Raytheon Engineers and Constructors, Inc. Birmingham, Alabama - *Crushed Glass Used as Structural Fill to Support Material Recovery Facility*
John H. Gould

LIQUEFACTION MITIGATION PROCEDURES FOR COAL REFUSE DAMS BUILT BY THE MODIFIED UPSTREAM METHOD

Barry K. Thacker, PE

Geo/Environmental Associates, Inc., Knoxville, Tennessee 37909

Abstract. The use of the upstream construction method offers cost savings and environmental advantages in building coal refuse disposal impoundments. Unfortunately, concerns over the potential loss of strength of hydraulically-placed fine coal refuse due to liquefaction during an earthquake have resulted in some designers refraining from the use of this method. A modified upstream construction (MUSC) method is presented which can mitigate the impacts of a loss of strength of the fine refuse during the design earthquake. Results of field and laboratory testing and performance monitoring data from existing coal refuse disposal sites are presented to illustrate the suggested design procedures for a dam built by the MUSC method.

INTRODUCTION

The oil embargo of the 1970's revealed our vulnerability as a nation to being dependent on a foreign source of energy. In response to this crisis, the public demanded that reliable and cost-effective domestic energy sources be developed in an environmentally sound manner. The coal mining industry responded to the challenge by developing and investing in high production mining equipment and methods. Although these methods increase productivity and lower costs, they result in higher percentages of shale and clay impurities being mined along with the coal. At the same time, power and steel companies have demanded a lower percentage of impurities in the coal being delivered by the mining companies. Again, the coal mining industry has responded to the challenge by developing more efficient processing techniques to furnish their customers with a cleaner coal product. More impurities being mined with the coal coupled with more efficient cleaning techniques have resulted in the generation of large quantities of waste requiring disposal. For example, some of the larger coal preparation plants in the United States will each generate on the order of 200 million tons of coal refuse waste over a 30-year life.

The most common method for disposal of coal refuse is to build a dam in stages using the coarse refuse (shale) as borrow material and to pump the fine refuse (silt, sand, and clay) to the impoundment created by the dam, as shown in Figure 1. In the past, many coal companies built these dams by the upstream construction method, whereby subsequent stages were partially founded on fine refuse deposited from previous stages of construction. The upstream method provides several cost and environmental advantages because the downstream face of the dam can be covered with soil and vegetated concurrently as construction progresses. Also, permanent

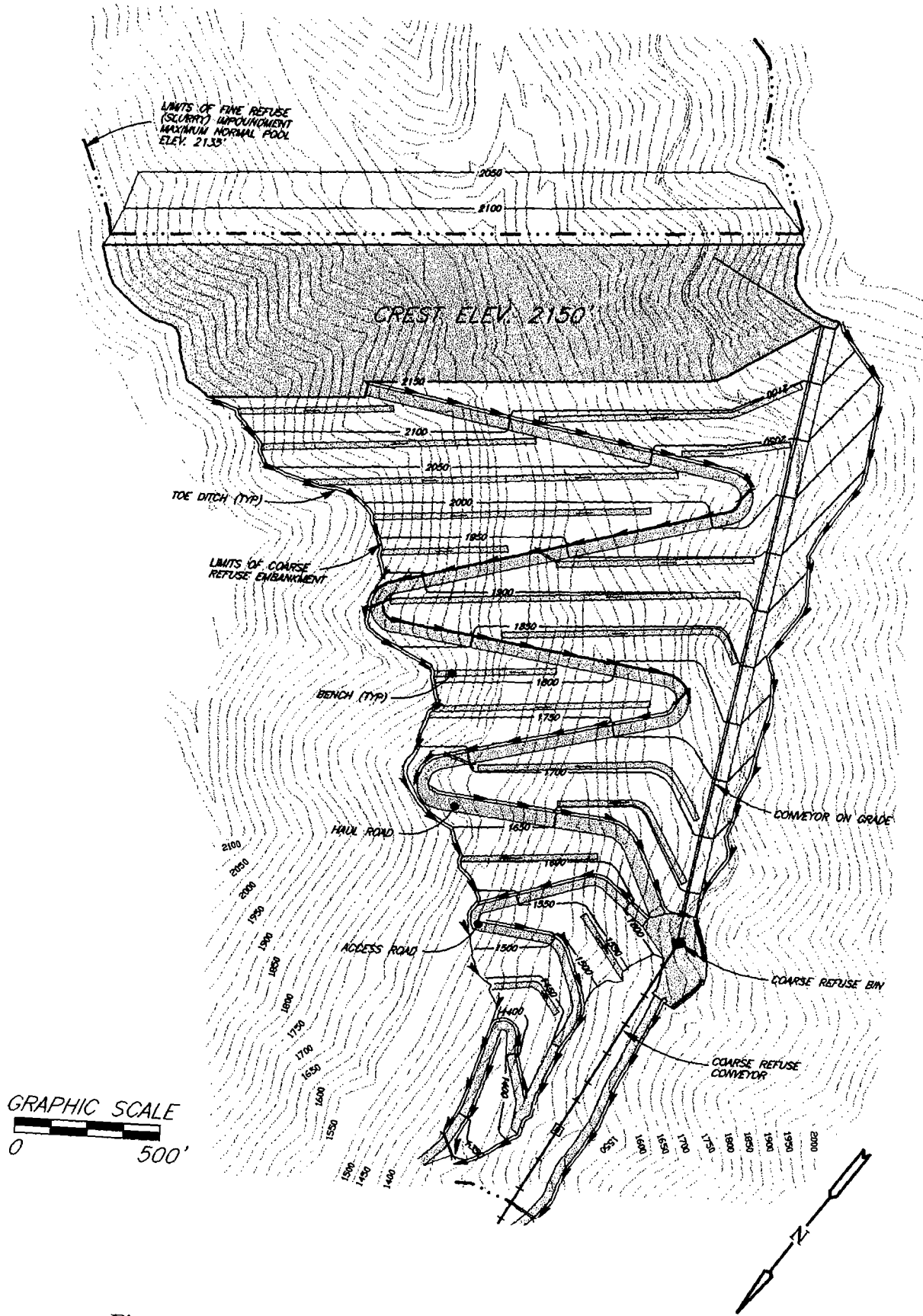


Figure 1. Plan View of a Coal Refuse Disposal Impoundment

conveying structures and/or hauling roads used for transportation of the coarse refuse can be installed initially and then extended during subsequent stages.

Concerns over the potential susceptibility of the hydraulically-placed fine refuse to liquefy during an earthquake have forced some designers to abandon the upstream construction method for the use of the downstream construction method. In downstream construction, subsequent stages of the dam are built downstream of the previous stage with a foundation on natural ground. A larger quantity of coarse refuse is required to raise a dam to a given height by the downstream method than by the upstream method which typically means that more stages of construction are required. Vegetation of the final downstream face of the dam must be postponed until the last stage of construction. Furthermore, new conveying structures and/or hauling roads are required for each stage of downstream construction which significantly increase the cost of coarse refuse placement. Current state and federal regulations require placing a cap over the fine refuse to eliminate impounding capabilities upon final abandonment. As shown in Figure 2, upstream construction is therefore required during abandonment even in those cases where the main dam is being built by the downstream method.

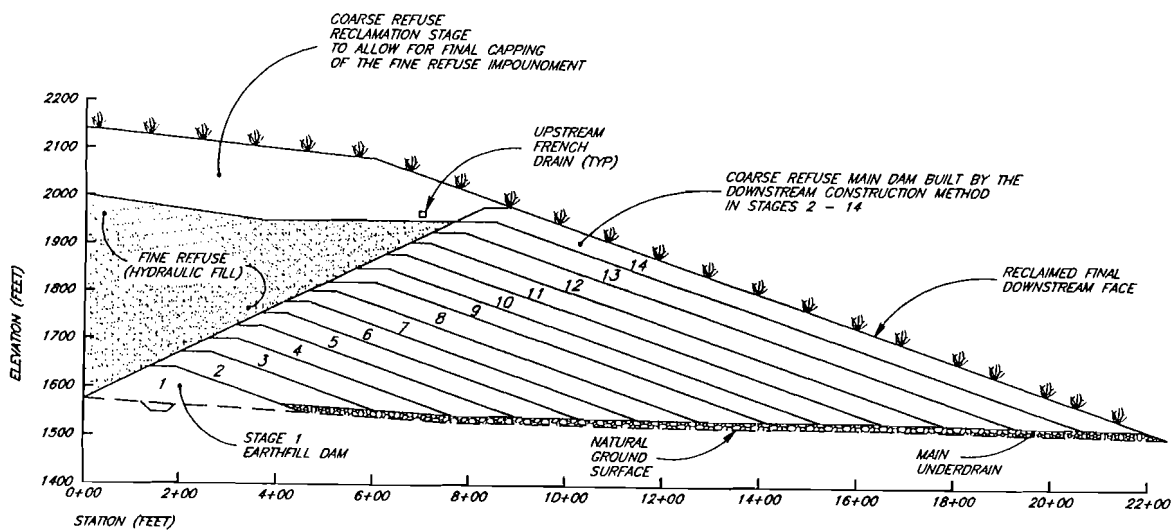


Figure 2. Down-Valley Profile of a Coal Refuse Dam Built by the Downstream Construction Method with Additional Stages Built by the Upstream Construction Method for Abandonment

A procedure is presented for the design and construction of a coal refuse dam using a modified upstream construction (MUSC) method that can be resistant to a loss of strength of the fine refuse during an earthquake. Results of triaxial compression, triaxial consolidation, and permeability testing performed on coarse refuse compacted to various ranges in density and moisture content are presented to illustrate the impact of placement criteria on engineering characteristics. Also, results of performance monitoring data (i.e. settlement measurements, seepage rates, phreatic levels, and statistical analysis of field density and moisture content measurements) from existing coal refuse dams are documented for comparison with the engineering data. Placement criteria are proposed for the coarse refuse in a dam built by the MUSC method based on the results of this testing and performance monitoring data along with supporting engineering analyses. Finally, a potential method of pumping both coarse refuse and fine refuse to the later stages of a facility built by the MUSC method is presented to aid in the final capping during abandonment.

MODIFIED UPSTREAM CONSTRUCTION METHOD DESIGN PROCEDURES

Design Requirements and Considerations

Typical design requirements and considerations for a coal refuse disposal impoundment built by the MUSC method are summarized as follows:

1. year-round disposal capabilities for coarse refuse and fine refuse;
2. economic transportation capability for coarse refuse to the active level of disposal at all times during construction;
3. capacity for fine refuse disposal at all times during staged construction after an initial starter dam is built;
4. staging calculations based on estimated annual production rates for coarse refuse and fine refuse as specified by the owner;
5. ability to cap the impoundment during the final active phase of disposal to meet regulatory abandonment requirements;
6. spillways to enable the design storm, typically the probable maximum flood, to be stored and/or passed;
7. suitable factors of safety against slope instability for both static and earthquake conditions; and

8. runoff and erosion control for the downstream face of the dam throughout construction and for the final capped surface during and after abandonment.

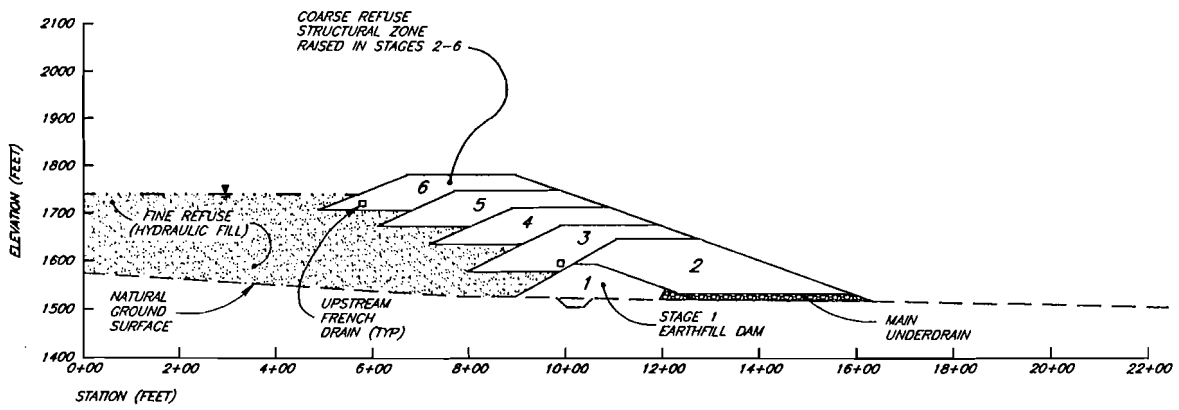
Layout and Staging

Several stages of construction are required in the MUSC method to meet the previous design requirements and considerations. After construction of an initial starter dam and a downstream stage, additional stages of the dam are built using the conventional upstream construction method as shown in Figure 3 a) (i.e. structural zone Stages 3 through 6). After the dam achieves a given height, the available capacity in the impoundment for disposal of fine refuse will typically increase at a faster rate than the capacity of coarse refuse required to build the structural zone of the dam. Excess coarse refuse not required to build the structural portion of the dam can then be placed downstream of the dam in a buttress zone that is raised intermittently in a single stage as shown in Figure 3 b). The required level of the buttress stage at any time is that level that provides adequate resistance to the potential loss of strength of the fine refuse during an earthquake. The downstream slope of the buttress stage can be covered with soil and vegetated as each phase of the buttress is completed.

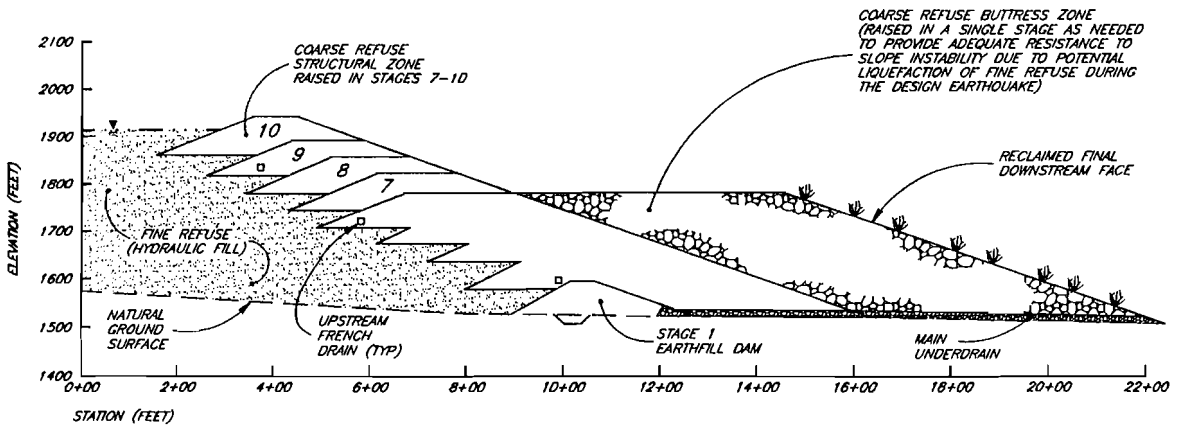
After the buttress zone achieves the level of the structural zone as shown in Figure 4 a), the embankment is raised in a single zone as shown by Stages 13 and 14 in Figure 4 b). As the final stage in the construction of the facility, coarse refuse is placed upstream of the dam over the settled fine refuse in the final capping of the impoundment. The coarse refuse in this "reclamation stage" can be capped with soil and vegetated in increments as areas are completed to achieve final abandonment status.

Selection of Engineering Design Properties for Fine Refuse

The required level of testing of the fine refuse in a dam built by the MUSC method 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. 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 estimated and confirmed during construction 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 (Poulos 1988). If a higher strength is required for the fine refuse during the design earthquake to resist slope instability, 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 (Thacker et al. 1988, Ullrich et al. 1991, Nofal and Holbrook 1995).

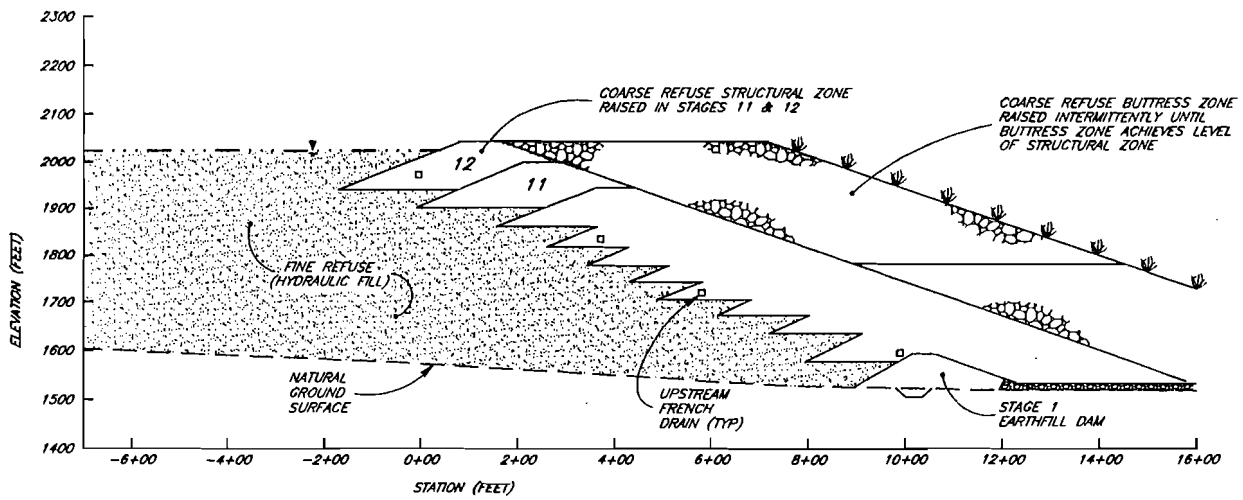


a) Phase I Construction - No Buttress Zone

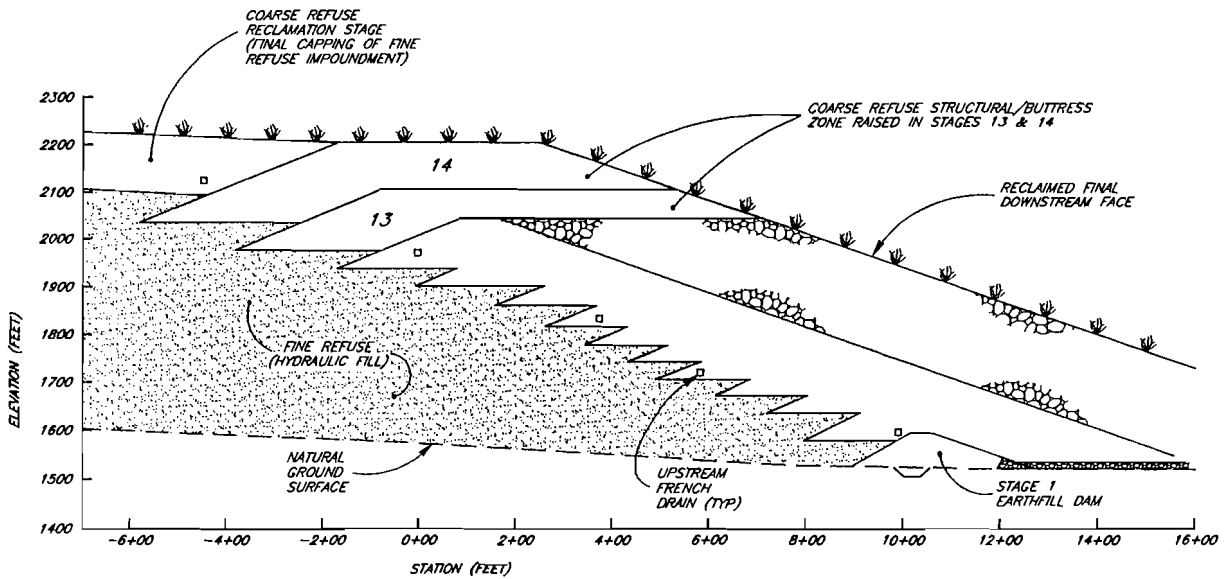


b) Phase II Construction - Partial Buttress Zone

Figure 3. Down-Valley Profile of Phases I and II of a Coal Refuse Dam Built by the Modified Upstream Construction (MUSC) Method



a) Phase III Construction - Buttress Zone Achieves Level of Structural Zone



b) Phase IV Construction - Combined Structural/Buttress Zone
 Phase V Construction - Reclamation Stage
 Phase VI Construction - Abandonment

Figure 4. Down-Valley Profile of Phases III, IV, V, and VI of a Coal Refuse Dam Built by the Modified Upstream Construction (MUSC) Method

Engineering Design Properties of Coarse Refuse at Various Placement Criteria

The MUSC design procedure conservatively presumes a loss of strength of the fine refuse during the design earthquake. Therefore, the stability of the dam is determined in large part by the engineering characteristics of the coarse refuse zones. Laboratory data are presented from two existing coal refuse disposal facilities to illustrate the impact of placement criteria (i.e. moisture content and degree of compaction) on the engineering characteristics of coarse coal refuse.

Figures 5, 6, and 7 show the relationship between engineering characteristics and dry density as a percentage of the standard Proctor maximum dry density (i.e. percent compaction) for coarse refuse from a facility located in Ohio. This coarse refuse classifies as a GW-GM type material according to the Unified Soil Classification System with a maximum particle size of about 3 inches and 6% passing a U.S. No. 200 sieve. The laboratory testing was performed on the remolded portion of the sample finer than 3/8-inch size, unless otherwise specified, to account for particle break-down during placement and after long-term weathering. Moisture contents during sample preparation were on the order of 2% over optimum as defined by the standard Proctor test. Results from the laboratory testing indicate that increasing the dry density of the Ohio coarse refuse results in a modest increase in its shear strength and a reduction in its permeability and compressibility.

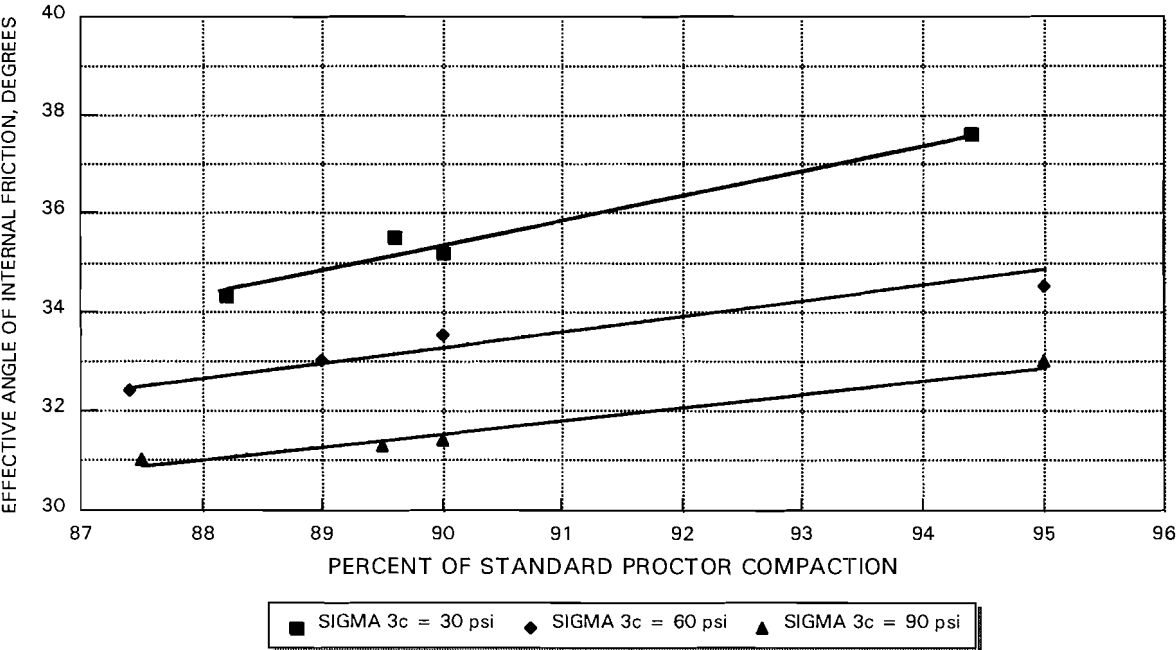


Figure 5. Consolidated-Drained Triaxial Compression Test Data for Ohio Coarse Refuse

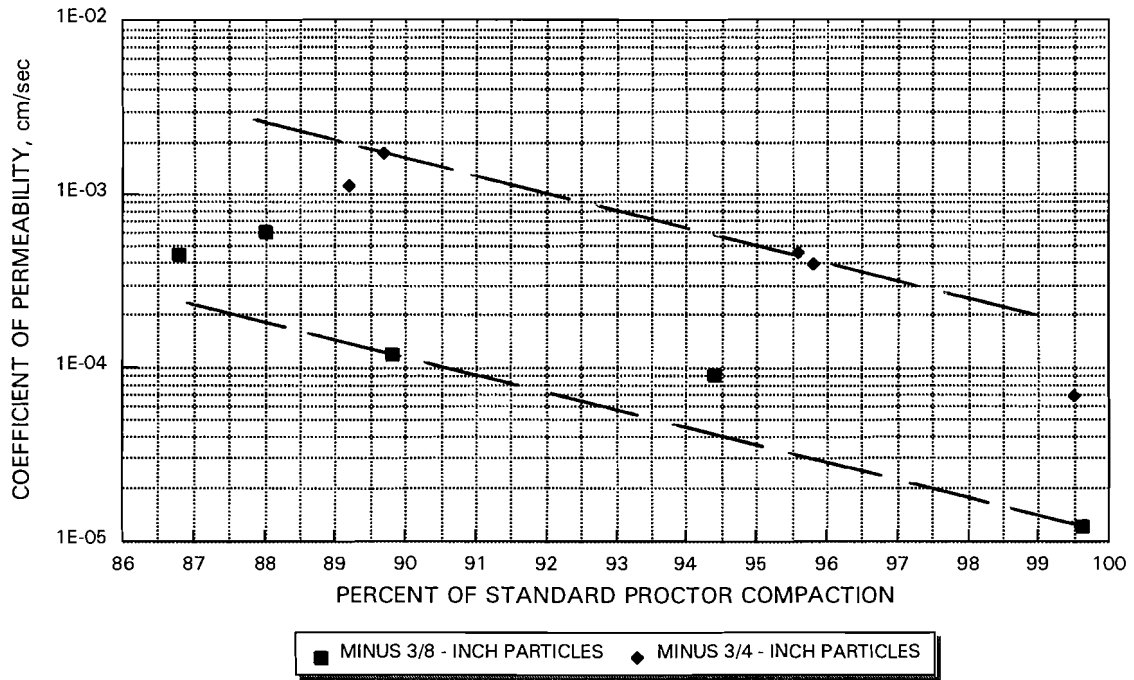


Figure 6. Permeability Data for Ohio Coarse Refuse

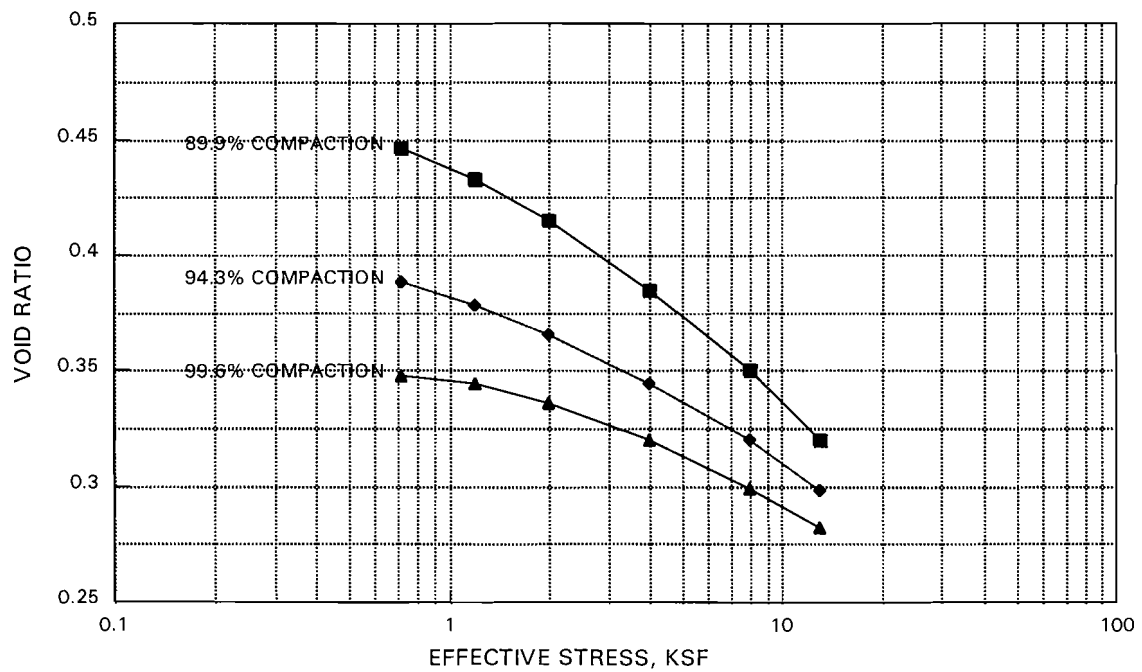


Figure 7. Triaxial Consolidation Data for Ohio Coarse Refuse

Figures 8, 9, 10, and 11 show the relationship between engineering characteristics and dry density as a percentage of the standard Proctor maximum dry density (i.e. percent compaction) at various placement moisture contents for coarse refuse from a facility located in West Virginia. The samples were prepared over a range in placement moisture contents 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 GP-GM type material according to the Unified Soil Classification System with a maximum particle size of about 2 inches and 10% passing a U.S. No. 200 sieve. The laboratory testing was performed on the remolded portion of the sample finer than 3/8-inch size to account for particle break-down during placement and after long-term weathering.

Results from the laboratory testing of the West Virginia coarse refuse indicate similar overall trends to that of the testing of Ohio coarse refuse with regard to the effect of increased dry density on the engineering characteristics of the material. However, for a given placement moisture content, the impact of increasing the dry density had different effects on the engineering characteristics. For example, a higher strength was measured for the West Virginia coarse refuse compacted wet of optimum to the 95% level than was measured for the samples compacted over the range of moisture contents to the 100% level. Also, a lower compression index (C_c), defined as the change in void ratio over one log cycle of change in effective stress, was measured for samples compacted wet of optimum moisture content than for samples compacted to a higher density at or dry of optimum moisture content.

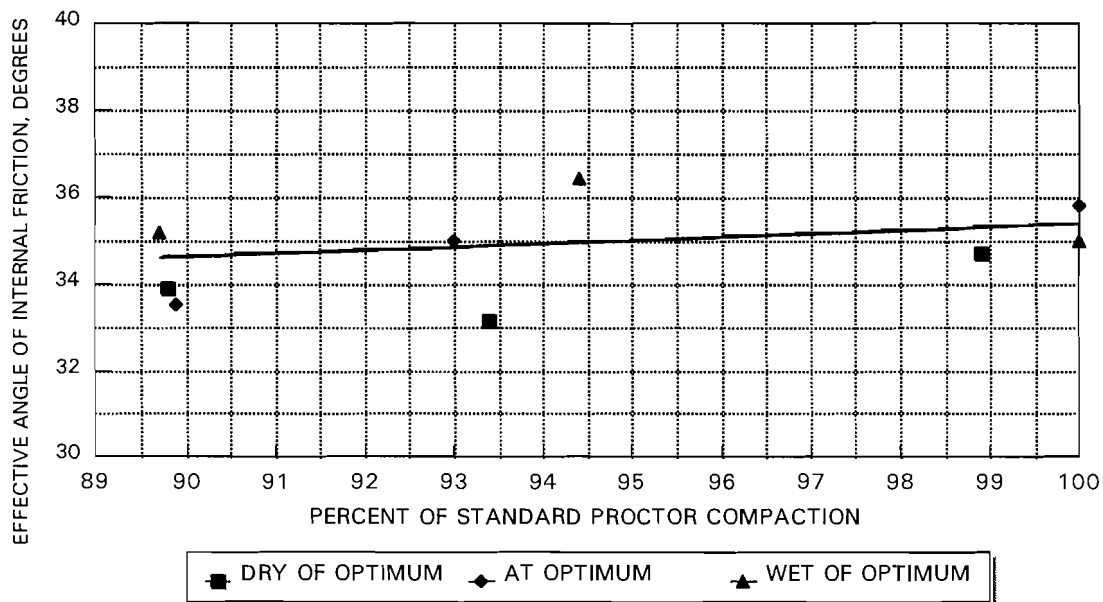


Figure 8. Consolidated-Drained Triaxial Compression Test Data for West Virginia Coarse Refuse at Confining Pressures = 60 psi

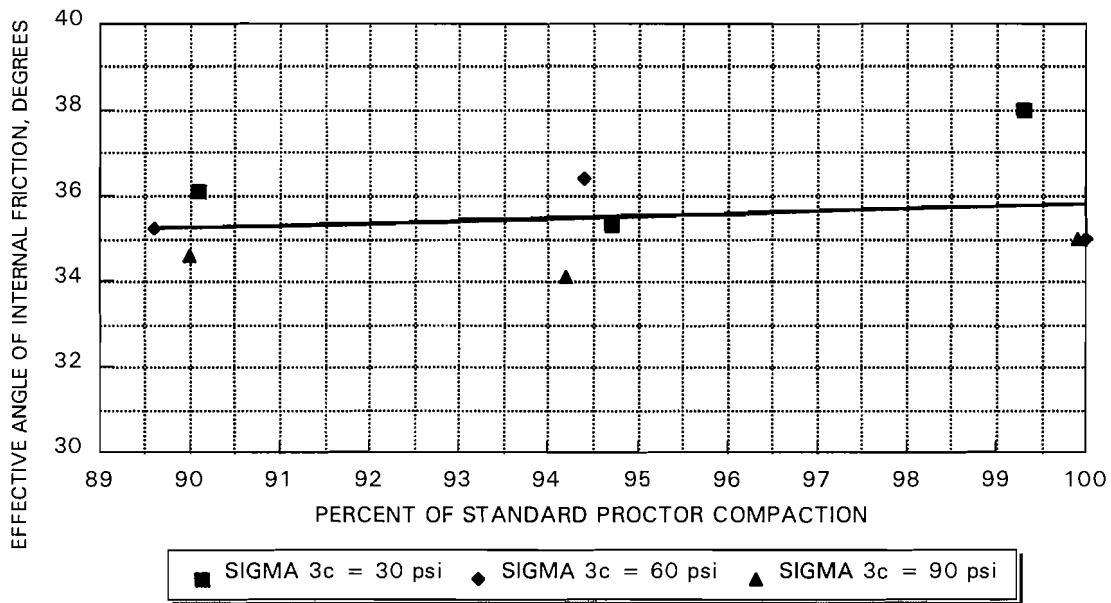


Figure 9. Consolidated-Drained Triaxial Compression Test Data for Samples of West Virginia Coarse Refuse Compacted Wet of Optimum Moisture Content

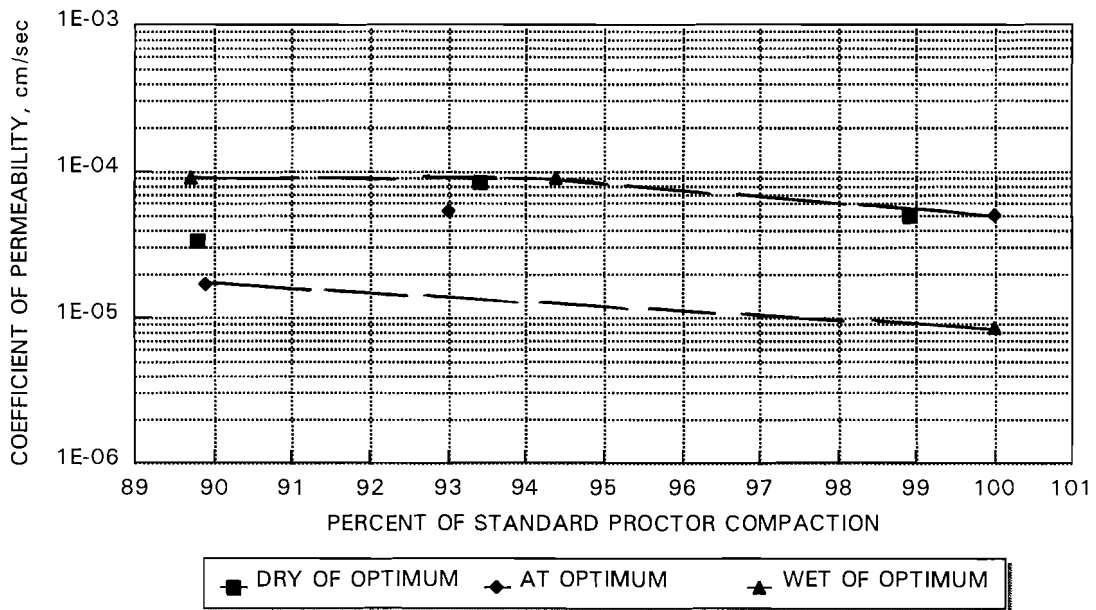


Figure 10. Permeability Data for West Virginia Coarse Refuse

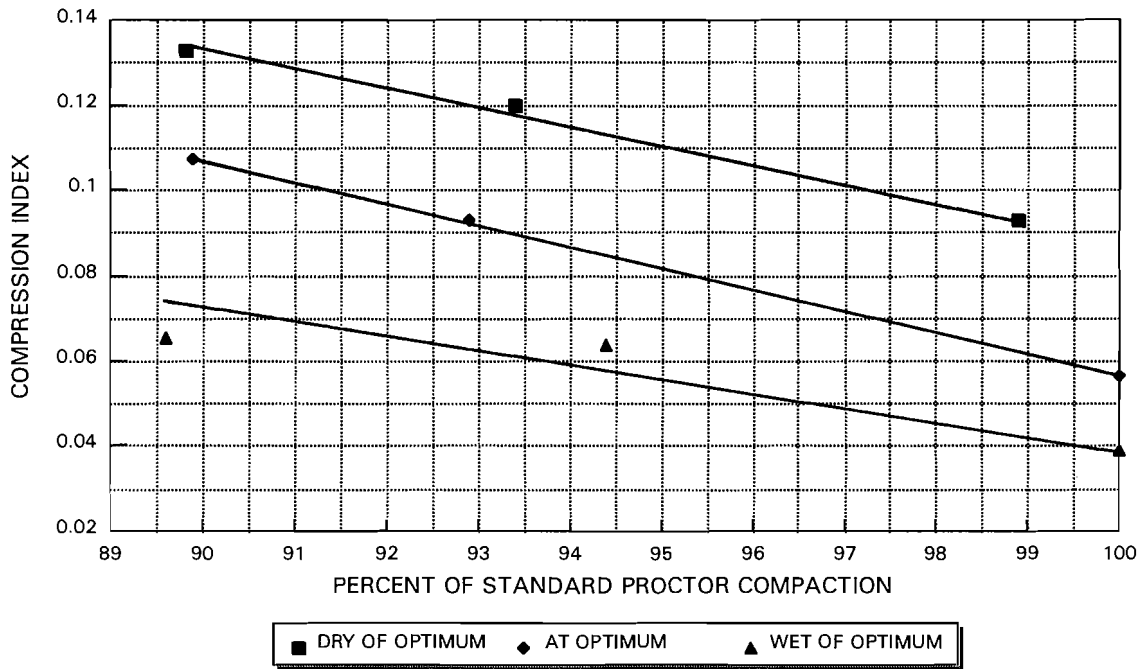


Figure 11. Triaxial Consolidation Data for West Virginia Coarse Refuse (Measured Between Effective Stresses of 30 psi and 60 psi)

Allowable Placement Criteria Options for Coarse Refuse

The Mine Safety and Health Administration (MSHA 1990) requires 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 (1990) 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 cases where a less stringent compaction criteria is specified, MSHA requires the designer to show that "all potential problems, including settlement, cracking, piping, instability, stratification, and seepage, have been taken into account in the design and that compensating design features have been incorporated."

MSHA references the Bureau of Reclamation (1987), Saxena et al. (1984), and other authorities in their development of these recommendations. The Bureau of Reclamation (1987) recommends that materials with greater than 50% passing a No. 4 sieve be compacted to at least 90% of the standard Proctor maximum dry density with a statistical median in excess of 93% of the standard Proctor maximum dry density. For a material with 26% to 50% passing a No. 4 sieve, a minimum 92.5% compaction with a statistical median of 95% compaction is recommended. The Bureau of Reclamation also recommends that the statistical median moisture content upon placement range from -2% to +2% of optimum.

Saxena et al. (1984) compared the strength and permeability of coarse refuse from a site in West Virginia to lift thicknesses and compaction using various placement equipment. They measured a general decrease in the coefficient of permeability with a decrease in lift thickness and an increase in compactive effort. Saxena et al. reported an effective cohesion (c') of 1.3 psi and an effective angle of internal friction (ϕ') of 35.4° for a sample of loosely compacted coarse refuse. They reported parameters of $c' = 6.6$ psi and $\phi' = 36.8^\circ$ for a sample of densely compacted coarse refuse. The strength testing was performed on undisturbed 5-inch diameter Shelby tube samples of coarse refuse. Data presented by Saxena et al. showed that the shear strength of coarse refuse placed in 2-foot thick lifts and compacted with a D-8H bull dozer was comparable to the shear strength of the coarse refuse placed in 1-foot thick lifts and compacted using a smooth drum vibratory compactor. Even though their study did not examine the effects of placement moisture content and their results showed little or no increase in strength and only a general decrease in permeability by reducing the lift thicknesses and increasing the compactive effort, Saxena et al. reported as follows:

"Based on the findings of this study, it is recommended that coarse coal refuse, typical of eastern United States coal regions, be compacted near optimum moisture content to a density greater than 95% of the maximum standard Proctor dry density. Compacted lifts should not be greater than 1-foot in thickness. Suitable types of equipment are smooth drum and sheepsfoot rollers having a total applied force of not less than 46,000 pounds."

Proposed Placement Criteria for Coarse Refuse in MUSC Dams

In the design of water-retention dams, high strength and low permeability of the embankment materials are often a necessity. High strength allows the slopes to be built on a relatively steep inclination resulting in less borrow material required for construction. Low permeability provides for less loss of water from the impoundment to meet a key design consideration for water-retention dams. High strength and low permeability are achieved in conventional earthen embankment materials by placing them in thin lifts and compacting them 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. In coal refuse dams, roads are typically required to provide access for coarse refuse disposal which result in flatter slopes than would otherwise be required to meet minimum stability criteria. 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 construction of the dam.

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 the shallow depth of water that is typically less than about 5 feet deep and impounded above the fine refuse. 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).

In applying the information contained in the previous references to the selection of minimum placement criteria for a coal refuse dam being built by the MUSC method, statistical data from existing coal refuse disposal sites are presented. Figure 12 presents statistical compaction data from sites with different minimum allowable compaction criteria. Typically, when a minimum 90% compaction criteria is specified for a given test, 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, the statistical median of the data will be on the order of 100% compaction. As a result, data from testing of samples compacted to a minimum 95% criteria may not be representative of the coarse refuse in the dam if a minimum 95% compaction criteria is specified for each field density test.

Figure 13 presents statistical placement moisture content data from existing coal refuse disposal sites obtained during different seasons of the year. Generally, the moisture content of coarse refuse as it comes from a given preparation plant will be fairly constant over the various seasons of the year. Variations in placement moisture content will be caused primarily by varying weather conditions. Specifying a narrow moisture range for all field density tests precludes year-round placement which is one of the key design considerations required of most coal refuse disposal impoundments. As shown by the data presented in Figures 8 through 11 and as will be demonstrated by the results of the following analyses, restricting the moisture content at placement to a narrow range may not be necessary to achieve the desired engineering characteristics.

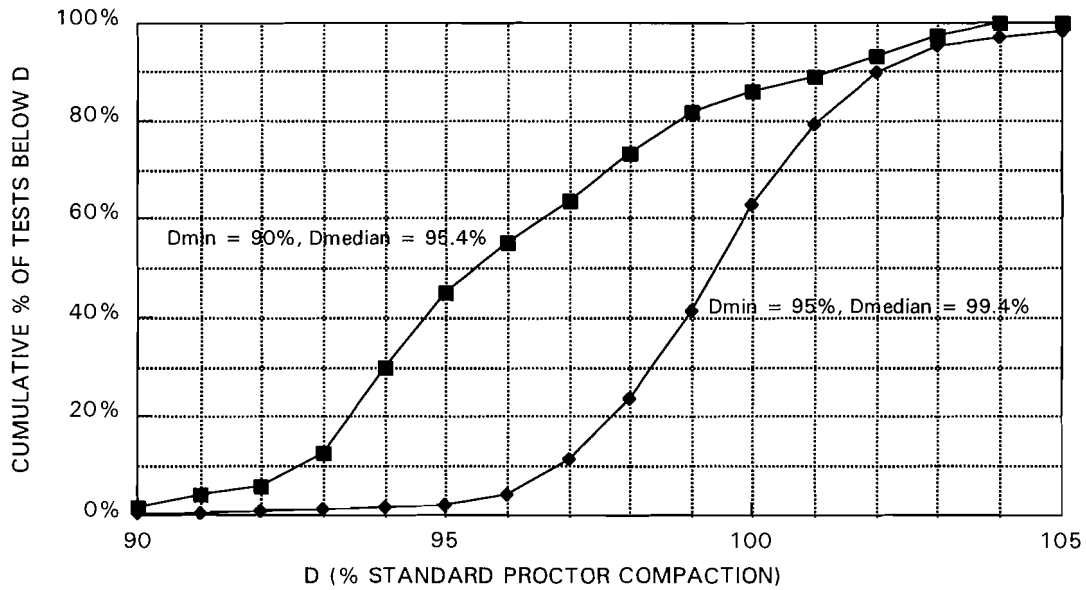


Figure 12. Statistical Analysis of Field Density Test Data for Coarse Refuse from Sites with Different Minimum Compaction Criteria for a Given Test

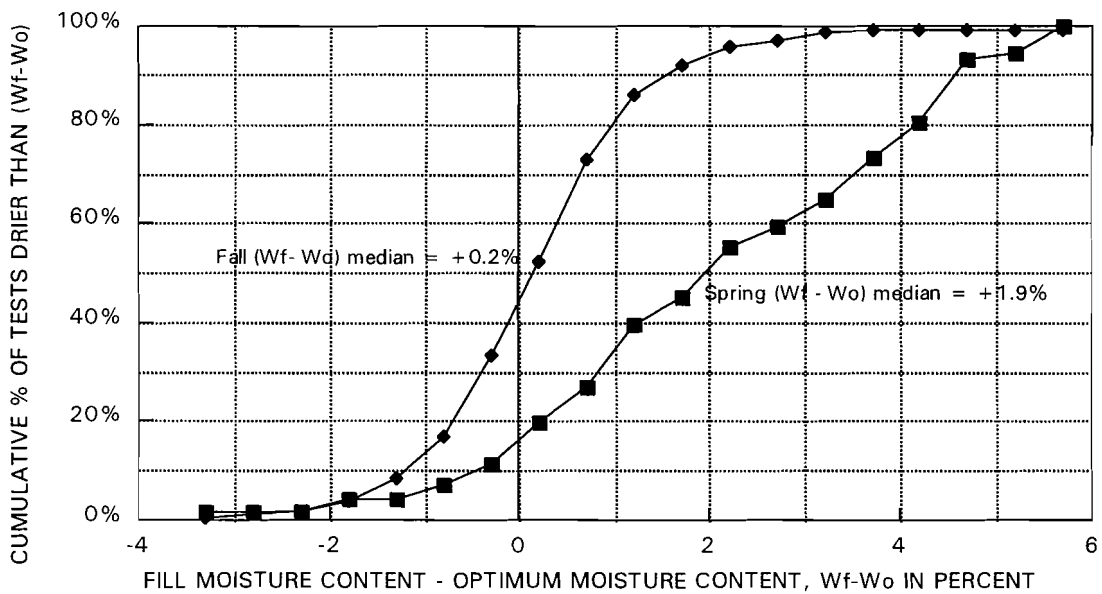


Figure 13. Statistical Analysis of Field Moisture Content Test Data for Coarse Refuse During Different Seasons of the Year

The paradigm that embankment materials must always be placed in thin lifts and compacted to a high density near optimum moisture content is not applicable for coal refuse dams built by the MUSC method. The selection of placement criteria for coarse refuse should be based on site specific design considerations and engineering characteristics of the actual embankment materials. For the facility shown in Figures 3 and 4 with coarse refuse characteristics representative of the data shown in Figures 8 through 11, coarse refuse placement criteria are proposed as follows:

1. Coarse refuse should be placed in the lower structural zone of the embankment (i.e. Stages 2 through 12) in maximum 1-foot thick lifts and compacted to a minimum of 92.5% of the standard Proctor maximum dry density for a given test. Field density testing should be performed to document that a statistical median of at least 95% of the standard Proctor maximum dry density is achieved on at least a quarterly basis. The statistical median moisture content at the time of placement should be within a range of -2% and +3% of optimum as documented on at least a quarterly basis. The moisture content for a given sample can be outside this range provided that the required statistical median is achieved.
2. Coarse refuse should be placed in the buttress zone of the embankment in maximum 2-foot thick lifts and compacted to a minimum of 90% of the standard Proctor maximum dry density for a given test. The statistical median moisture content at the time of placement should be within a range of -3% and +4% of optimum as documented on at least a quarterly basis.
3. Coarse refuse should be placed in the combined structural/buttress zone of the embankment (i.e. Stages 13 and 14) in maximum 18-inch thick lifts and compacted to a minimum of 90% of the standard Proctor maximum dry density for a given test. Field density testing should be performed to document that a statistical median of at least 93% of the standard Proctor maximum dry density is achieved on at least a quarterly basis. The statistical median moisture content at the time of placement should be within a range of -2% and +3% of optimum as documented on at least a quarterly basis.
4. A 3 to 5 feet thick pad of coarse refuse will need to be placed over the fine refuse as the initial phase of an upstream stage to serve as a working base. Afterwards, the previous criteria will apply for coarse refuse placement.

Justifications for the proposed coarse refuse placement criteria are presented in the following sections.

Seepage Analyses

Because the validity in using laboratory permeability tests to predict field conditions can be questioned, results of seepage simulations of existing sites are presented to supplement the laboratory data. In these simulations, phreatic levels and seepage rates are measured in the existing embankments. Finite element seepage analyses are then performed with varying coefficients of permeability for the various coal refuse materials until the model simulates the measured field boundary conditions. Table 1 summarizes the results of seepage simulation analyses at four existing coal refuse impounding sites.

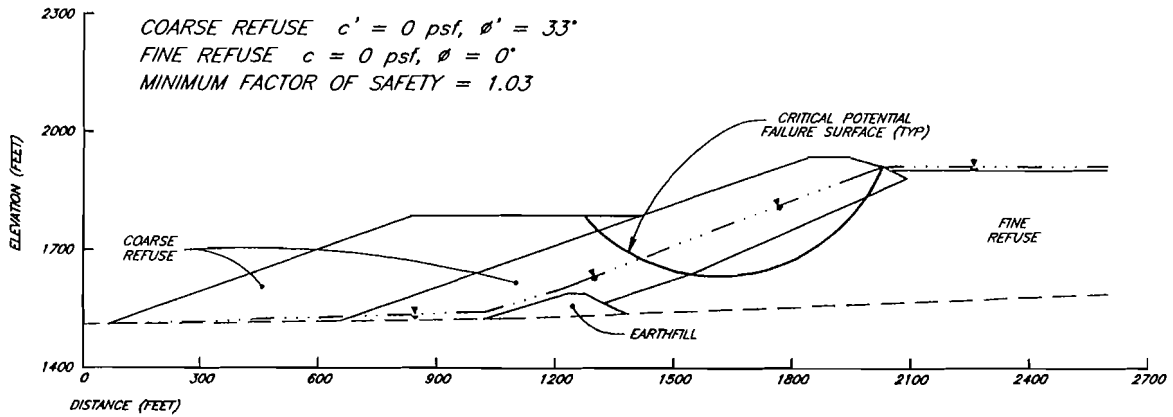
TABLE 1. Back-Calculation of Coefficients of Permeability Required to Simulate Boundary Conditions in Existing Coal Refuse Dams

<u>Site Location</u>	<u>Vertical Coefficient of Permeability, cm/sec</u>	
	<u>Coarse Refuse</u>	<u>Fine Refuse</u>
Ohio	5×10^{-4}	1×10^{-6}
Kentucky	3×10^{-5}	3×10^{-7}
Tennessee	5×10^{-5}	5×10^{-7}
Virginia	1×10^{-5}	1×10^{-7}

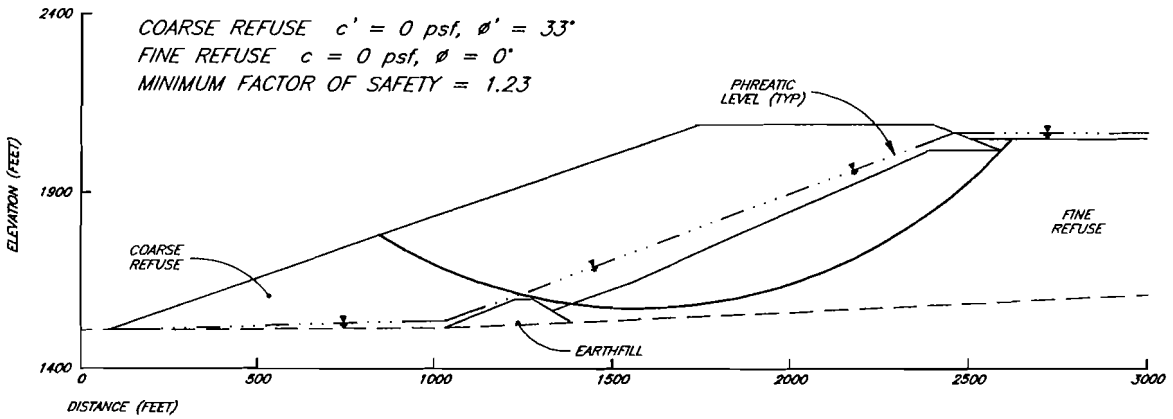
Ratios of horizontal to vertical coefficients of permeability of 9 to 1 for coarse refuse and 100 to 1 for fine refuse were used in the simulations to back-calculate the vertical coefficients of permeability. As shown by Table 1, the vertical coefficient of permeability for coarse refuse at the sites examined ranges from about 1×10^{-5} to 5×10^{-4} cm/sec. These values are within the ranges measured in the laboratory as shown in Figures 6 and 10. The vertical coefficient of permeability for fine refuse at the four sites ranges from about 1×10^{-6} to 1×10^{-7} cm/sec.

Finite element seepage models were developed for the various stages of the embankment shown in Figure 14. Sensitivity studies were then performed using the ranges in coefficients of permeability included in Figure 10 and Table 1 for coarse refuse and fine refuse. The phreatic levels included in Figure 14 show the highest phreatic levels for each phase of construction as predicted by the results of the seepage analyses. In addition to estimating phreatic levels, seepage rates estimated from the analyses can be used to size the various drains.

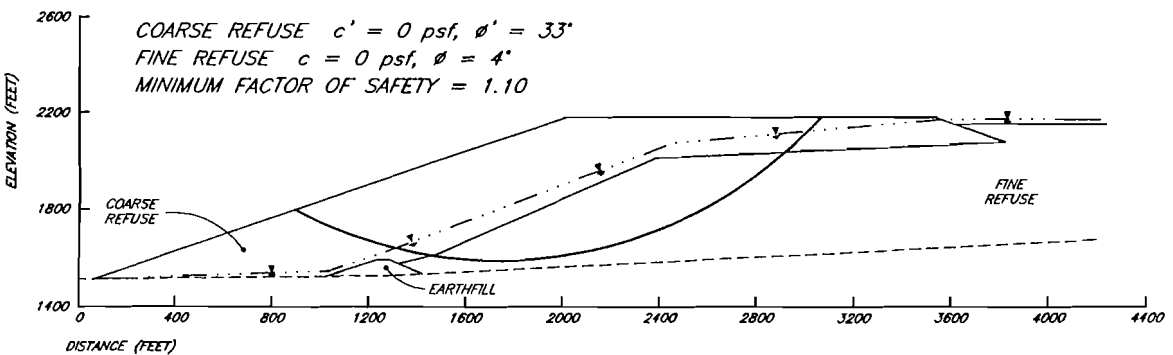
Because the fine refuse in the impoundment controls the rate of seepage through a dam built by the MUSC method, the highest phreatic level was estimated for the case where the coefficient of permeability of the coarse refuse was the lowest. Cedergren (1973) reported a similar observation for sloping core dams with different relative permeabilities between the upstream



a) Partial Buttress Zone Phase



b) Completed Buttress Zone Phase



c) Reclamation Phase

Figure 14. Results of Seepage and Stability Analyses for Various Phases of a MUSC Dam

core and the downstream shell. 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.

Stability Analyses

Static stability analysis methods for coal refuse dams built by the upstream construction method are well documented (Thacker 1985, Huang 1994). These methods should be utilized to verify that a dam to be built by the MUSC method will meet regulatory requirements for stability. With regard to the potential impact of a design earthquake on the strength of fine refuse, a post-earthquake static stability analysis can be performed initially presuming that the fine refuse has liquefied during the design earthquake.

Figures 14 a) and 14 b) show the critical potential failure surfaces and factors of safety presuming complete liquefaction (i.e. no strength) for the fine refuse. With such a conservative analysis, an acceptable factor of safety in excess of 1.0 is recommended. For the phases of construction shown in Figures 14 a) and 14 b), no field verification of the fine refuse strength would be required. In the phase of construction shown by Figure 14 c), a nominal undrained steady-state angle of internal friction of 4° with no cohesion is required to provide the required resistance to a failure during an earthquake. As a result, in-situ vane shear testing would be required to verify the available strength of the fine refuse in a completely remolded state as described previously. The vane shear testing could be performed during the phase of construction shown in Figure 14 b) to verify that the required strength of fine refuse could be mobilized prior to achieving the critical phase of construction shown by Figure 14 c).

If the required strength of fine refuse cannot be verified by vane shear testing during the phase of construction shown in Figure 14 b), then a more detailed liquefaction study would be required. Specifically, cross-borehole shear wave velocity and/or cyclic triaxial testing with more detailed analyses would be required (Thacker et al. 1988, Ullrich et al. 1991). If the more detailed analyses still indicated that the required strength of fine refuse could not be mobilized during earthquake conditions, then design modifications would be required prior to achieving the critical phase of construction.

Figure 14 shows that an effective angle of internal friction of 33° with no cohesion was used in the stability analyses for the coarse refuse. The strength of coarse refuse used in the stability analyses is lower than the values measured in the laboratory over the anticipated range of moisture contents and densities as shown in Figures 8 and 9. The phreatic level used in these analyses was the highest phreatic level estimated from the sensitivity study of impacts over the measured ranges in permeability for the coarse refuse and fine refuse represented by the previous

data. Therefore, justification is provided for the previously proposed placement criteria for coarse refuse with regard to strength and permeability characteristics even though it deviates from the recommendations of Saxena et al.

Settlement Analyses

Figure 15 presents long-term surface settlement monitoring data from two existing coal refuse disposal impoundments. The site in Tennessee was built by the upstream construction method and the settlement data are representative of conditions that would exist at Station 4+00 in Figure 3 b). The site in Ohio was built by the downstream construction method initially and then converted to the upstream construction method during the "reclamation stage". Settlement data from the Ohio site are representative of conditions that would exist at Station 14+00 in Figure 3 b).

As shown in Figures 7 and 11, primary consolidation characteristics of coarse coal refuse are dependent on the degree of compaction. Figure 16 shows the estimated maximum settlement for the embankment shown in Figure 3 b) at Station 14+00 using the data presented in Figure 7 for various levels of compaction of the coarse refuse. Even though Figure 16 shows relatively large estimates of maximum potential settlement, consolidation is typically rapid in coarse coal refuse such that primary consolidation is finished by the time a given stage of construction is completed. Primary consolidation of fine coal refuse typically requires a much longer period of time. However, in most cases, field measurements have shown that primary consolidation is completed by the time a given stage of construction is completed and that secondary consolidation settlement is small as indicated by the data included in Figure 15.

The sequence of construction for a dam built by the MUSC method helps to mitigate the impacts of settlement. Specifically, upstream construction stages are built early in the project to begin loading of the fine refuse. After the dam achieves a given level, the buttress stage is started to allow pore pressures to dissipate in the fine refuse beneath the previous upstream construction stages. The buttress stage eventually covers the previous stages and the remaining construction proceeds at a slower rate due to the amount of coarse refuse required to build the massive combined buttress/structural zone of the embankment.

Even though increasing the degree of compactive effort of the coarse refuse could reduce the maximum total settlement that would be predicted, this potential advantage is not significant if the rate of consolidation is more rapid than the rate of construction as illustrated by Figure 15. If the rate of pore pressure dissipation in the fine refuse is slower than desired for stability and settlement considerations, then mitigative measures such as the installation of internal wick

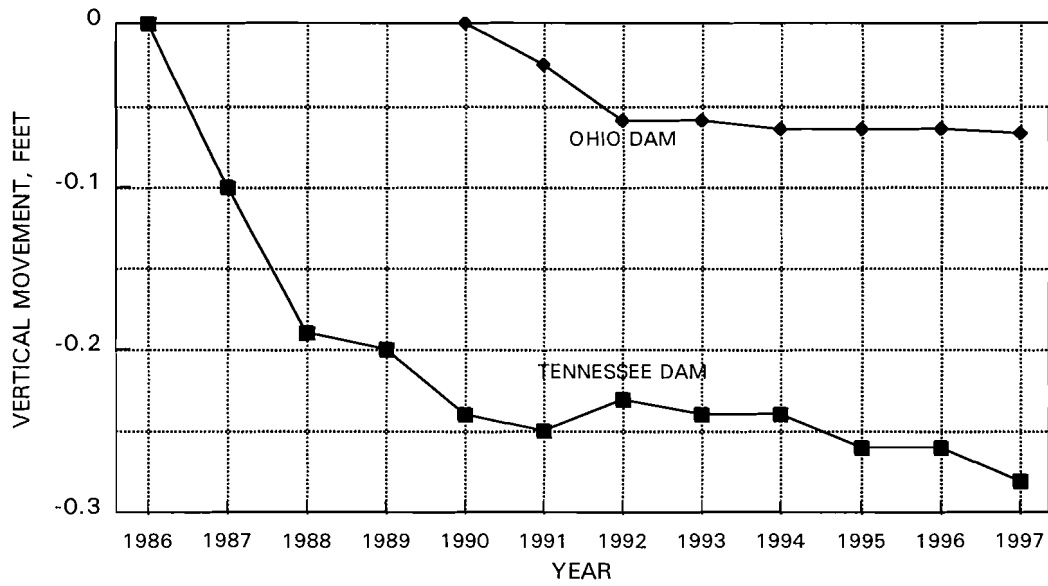


Figure 15. Post-Construction Settlement Monitoring Data for Existing Coal Refuse Dams

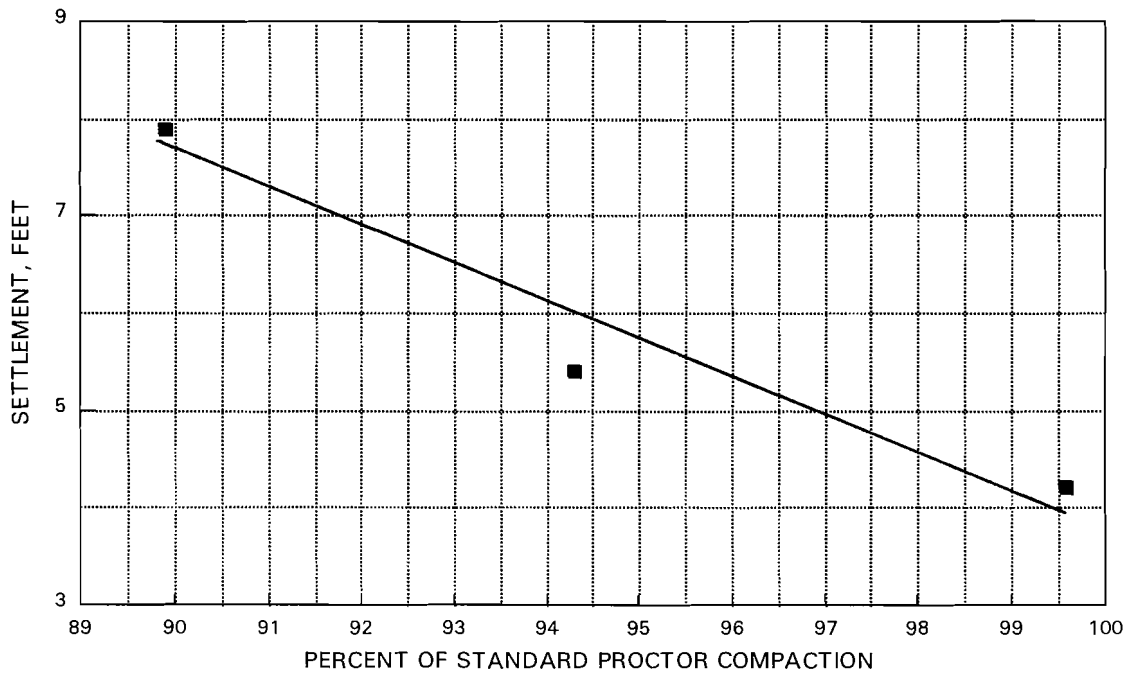


Figure 16. Maximum Predicted Settlement for Dam in Figure 3 b) at Station 14+00 Using Consolidation Data from Figure 7

drains can be incorporated into the design to reduce the drainage distances in the fine refuse and provide for more rapid pore pressure dissipation (Thacker 1985). As a result, settlement is usually not a major design consideration in dams built by the MUSC method. Therefore, justification is provided for the previously proposed placement criteria for coarse refuse with regard to consolidation characteristics and settlement, even though it deviates from the recommendations of Saxena et al.

PERFORMANCE MONITORING OF MUSC DAMS

As with any dam, performance monitoring of MUSC dams is required to verify the validity of the design assumptions. Performance monitoring can include such items as:

1. field moisture and density testing to verify compliance with the minimum and statistical median requirements;
2. phreatic levels as measured from standpipe piezometers installed in the coarse refuse embankment and pore pressure levels measured from pneumatic piezometers installed beneath the upstream stages in the fine refuse to verify that design levels are not exceeded;
3. flow rate measurements from the underdrains and French drains to verify drain size design calculations and to validate the finite element seepage model;
4. settlement measurements determined from settlement monuments installed on completed portions of the embankment to verify that primary consolidation has been completed and that the magnitude of secondary consolidation is within acceptable limits; and
5. general site reconnaissance of the embankment slopes and appurtenant structures to identify seeps, sloughing, settlement cracks, erosion, and related conditions that may need to be addressed.

In addition, annual strength, permeability, and consolidation testing are suggested for coarse refuse samples remolded to the statistical median moisture content and the statistical median compaction for the previous year to confirm that the engineering characteristics have remained consistent with the design values. The level of required fine refuse testing would depend on the level of reliance that is placed on the fine refuse to maintain stability during the design earthquake as discussed previously.

ABANDONMENT OF MUSC DAMS

Large coal refuse disposal impoundments may have a surface area in excess of 100 acres during the later stages of construction. An owner who waits until active mining and processing operations have ceased to cap the impoundment could be faced with a multi-million dollar expense. The expense of abandonment can be reduced by building a "reclamation stage" as the last active phase of the disposal facility as shown by Figures 2 and 4 b).

One of the advantages of a dam built by the MUSC method is that it is conducive to allowing for construction of a "reclamation stage" as the last active phase of disposal. Near the end of the life of the facility, construction of the buttress zone can cease to enable the structural zone to be raised and thereby create excess disposal capacity in the impoundment. Afterwards, coarse refuse can be placed over the fine refuse in the gradual elimination of impounding capabilities.

Alternatively, the coarse refuse can be crushed, if needed, and pumped to the impoundment for disposal along with the fine refuse. The surface of the impoundment can then be capped by simply moving the discharge end of the pumping line to fill in the impoundment. Experience has shown that the coarse refuse will settle immediately at the end of the pumping line. Specific areas can then be regraded with a dozer to achieve the desired grade and that area can then be covered with soil and vegetated. Using this method, abandonment costs can be significantly reduced and distributed over a several year period during the life of the "reclamation stage".

OBSERVATIONS AND CONCLUSIONS

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

1. The MUSC method for constructing a coal refuse dam combines the advantages of upstream construction in lower operating costs and concurrent reclamation with the liquefaction resistance of downstream construction.
2. The sequence of construction for a dam built by the MUSC method allows the fine refuse to be loaded with coarse refuse early in the project. Subsequent placement of coarse refuse in the downstream buttress zone can provide time for dissipation of excess pore pressures in the previously loaded fine refuse.
3. The proposed design procedure presented for the MUSC method 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. If no strength is required, then no testing is needed.

4. The engineering characteristics of coarse coal refuse are dependent on a combination of density, the amount of particle breakage (i.e. particle size), and fabric. For example, the data show a general decrease in permeability and compressibility and an increase in the lower limit of strength with increasing density. A decrease in strength with increased confining pressures as shown in Figure 5 can be explained by particle breakage during shearing. The combined dependency on density, particle breakage, and fabric might explain why the sample compacted to the 95% standard level at a moisture content of 6% above optimum moisture content had a higher strength than the samples compacted to the 100% standard level over a range in moisture contents as shown in Figure 8.
5. Specifying minimum compaction criteria for coarse refuse will result in an embankment composed of material that can be significantly denser than the specified minimum compaction level. Performing laboratory testing on coarse refuse samples remolded to the minimum compaction level may not be representative of the material in the dam.
6. Broader standards than those recommended in the literature can be justified for coarse refuse placement in the MUSC method by incorporating engineering characteristics based on site-specific data, performing statistical analysis of the field moisture content and density data, and by using mitigative measures such as drains at various levels of the construction.
7. A smaller quantity of coarse refuse is required to build a coal refuse dam to a given height by the MUSC method than by the downstream construction method. The coarse refuse that is "saved" by the MUSC method can be used in the final covering of the impoundment during abandonment.
8. Use of the MUSC method in the construction of a coal refuse dam is conducive to economic placement of a large percentage of the coarse refuse using conveyors.
9. Many designers of water-retention dams share the paradigm that "considerations which are valid for water-retention dams must be valid for coal refuse dams". These individuals believe that the downstream construction method, placement of embankment materials in thin lifts, and compacting them to a high density near their optimum moisture content are always "good". The presence of this paradigm is evidenced by Saxena et al. (1984) in their stringent recommendation for coarse refuse placement in the eastern United States even though their data provided little or no justification for this recommendation.

10. The proposed MUSC design procedures and supporting data presented in this paper offer justification for a paradigm shift with regard to the design and construction of coarse coal refuse dams that impound fine coal refuse.

REFERENCES

BUREAU OF RECLAMATION (1987)

Design of Small Dams. U.S. Department of Interior, 860 pp.

CEDERGREN, H. R. (1973)

Seepage Control in Earth Dams. Embankment-Dam Engineering, Casagrande Volume, John Wiley and Sons, New York, NY, pp 21-45.

HUANG, Y. H. (1994)

User's Manual on REAME and REAME3D, Two- and Three-Dimensional Analysis on Stability of Slopes. University of Kentucky, Lexington, KY, 131 pp.

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.

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.

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.

SAXENA, S. K., LOURIE, D. E., and RAO, J. S. (1984)

Compaction Criteria for Eastern Coal Waste Embankments. Journal of Geotechnical Engineering of ASCE, Vol. 110, No. 2, pp. 262-284.

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.

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.

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.