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DESIGN OF OIL SHALE DISPOSAL EMBANKMENTS

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Design of Oil Shale Disposal Embankments

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ABSTRACT

Mining processes and associated regulations for oil shale development in eastern United States are discussed with emphasis given to overburden and spent shale disposal at the mining site. Curves are presented which allow for quick determinaton of stripping ratios, overburden quantities and oil shale quantities. Procedures are outlined for determining quantities of materials to be disposed and graphs are given for sizing various zones of the disposal embankment. These procedures are demonstrated with an example.

Stability of slopes and magnitude of settlement are functions of the engineering properties of the embankment materials. Procedures for obtaining these data are from field exploration and laboratory tests are given. Some of these data can be estimated from inexpensive index tests.

Details of excavation, preparation of embankment foundation, and of construction are given. Compaction equipment, procedures, specifications, and control are all addressed.

Techniques for analyzing the stability of slopes are examined and several examples are provided. Finally, procedures for estimating magnitude and rate of settlement are given. Since oil shale operations are new to this region, it is recommended that initial embankment construction operations and embankment performance be monitored closely. Adjustments based on the observed performance should improve the economics of the disposal operation.

INTRODUCTION

Economics, responsible mining operations, and regulations dictate that disposal embankments associated with oil shale operations be properly designed. This paper approaches the design process of oil shale disposal embankments as they apply to Eastern United States. However, most of the data and examples used herein are associated with the oil shale regions in Kentucky. For these regions, stripping ratios are relatively low and the preferred method of mining is referred to as cross-ridge hill top removal. In this process, top soils and overburdens are removed and the oil shales mined with the excavation faces kept perpendicular to the axis of the ridge.

The retorting process generates significant quantities of waste products which are called spent shales. Usually all of the spent shales can be deposited on the plateau exposed by the mining operations. The overburden materials frequently can be used as cover or encapsulating materials to prevent contamination of surface and ground waters by the spent shales. Depending on local topography and stripping ratios, some of the overburden materials may have to be disposed elsewhere such as in head-of-the-hollow fills or valley fills. This paper will only address the disposal of spent shales and overburden materials on the surface exposed by the mining operations.

Information on mining processes in this region has been covered by a number of recent papers (1)[1], (2), (3). Extensive test data on oil shales were reported by Townsend and Peterson (4). Typical data used in the examples are taken from Drnevich, et al. (5), which is based on work reported in (6). The design procedures developed herein are done so with consideration given to regulations (7) and are based on significant experience in highway engineering in these regions. At the outset, it is recognized that each site has unique characteristics and that mining and retorting processes can differ widely; hence, the design of disposal embankments at each site should consider these as well.

REGULATIONS FOR DISPOSAL EMBANKMENTS

The primary purpose of regulations is to minimize the adverse effects of oil shale operations on persons and the environment. Typical regulations related to the topic of this paper usually require that waste is placed in a controlled manner to ensure: a) That leachate and surface runoff from the disposal site will not degrade surface or ground water or exceed effluent limitations; b) That the area designated as the disposal site is suitable for reclamation and revegetation; and c) That the waste is compacted and covered to prevent combustion and the probability of particulates becoming windborne (7). Acid-forming or toxic-forming materials must be covered with a minimum thickness of nontoxic, nonacid-forming material. In some cases, impermeable liners may be required to encapsulate the waste material. For some locations, only the spent shale is toxic or acid forming whereas in others, some of the overburdens that are removed in the mining process also may need to be covered with similar minimum thickness layers of nontoxic-forming and nonacid-forming materials.

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[1] The numbers in parentheses identify references in Appendix I.

Original top soil must be stripped off and stockpiled until it can be replaced on the completed fill. The fill itself usually must be engineered and constructed to be stable and not have any depressions. The placement of the material in the fills must be in lifts and monitoring of the fill placement usually is required. Final grading must be done to control surface runoff or channel it to retention areas designed to accommodate a 100-year, 24-hour or larger precipitation event.

TYPICAL DISPOSAL CONFIGURATIONS

Selection of a disposal configuration depends on: the nature of the mining operation, the nature of the retorting operation, the stripping ratio, the engineering characteristics of the materials to be disposed, and regulations that apply. The configuration of the disposal embankment may be symmetrical or nonsymmetrical. Quite frequently, a portion of the excavated surface will be needed as a haul road for the duration of the mining operation. This plus the economics of material handling often will make a nonsymmetrical embankment cross section more desirable. Nonsymmetrical embankments require more effort in design and analysis because slope stability and settlement may be different from one side of the embankment to the other.

Materials are placed in embankments in zones. At least five different zones may be used. Those considered herein are: top soil, unprocessed overburden, processed overburden, waste shale, and spent shale.

Processed overburden refers to overburden that has been processed by crushing or by being treated with additives so that it has special engineering properties when placed in the embankment (e.g., high shear strength or very low permeability). Obviously, zones containing these materials should be kept very small. Waste shale refers to the portion of the oil bearing shale that is not retorted due to not meeting specifications for the retorting process. Spent shale is the by-product of the retorting process. It is this material that generally has undesirable chemical characteristics and must be isolated from surface and ground water systems.

A typical symmetrical configuration is shown in Fig. 1 and unsymmetrical configurations are shown in Figs. 2, 3, and 4. Most of the dimensions in the configurations will vary with location, stripping ratio, etc. The unsymmetrical embankments may facilitate the handling of surface water at the site and also may allow a portion of the excavated surface to be used for haul roads while the remaining portion is used for material disposal. When mining is completed along a given ridge, the remaining part of the embankment may be completed. Material for complation may be obtained from temporary stockpiles or may come from the mining operation at a nearby ridge.

SUGGESTED DESIGN PROCEDURES

Establishing Idealized Cross Sections

Site geometry, material quantities, regulations, and mining methods must be considered when choosing a configuration for the disposal embankment. Consider the site geometry shown in Fig. 5. This is an idealized cross section of a

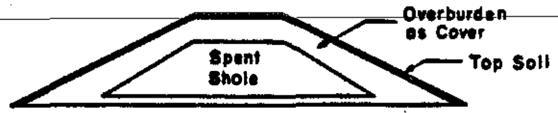


Figure 1. Symmetrical Configuration of Oil Shale Disposal Embankment (not to scale).

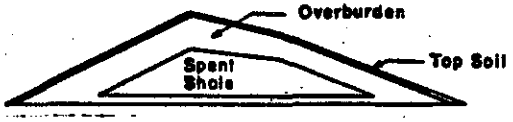


Figure 2. Unsymmetrical Configuration of Oil Shale Disposal Embankment to Control Surface Drainage (not to scale).

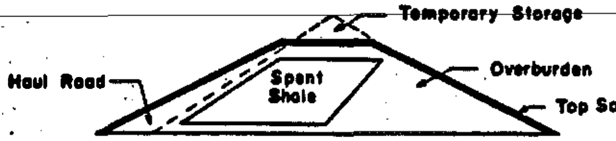


Figure 3. Unsymmetrical Configuration of Oil Shale Disposal Embankment to more Economically Accommodate Mining Methods (not to scale).

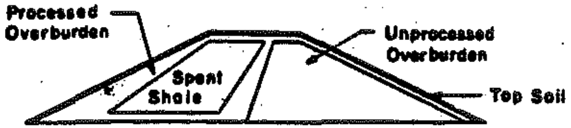


Figure 4. Unsymmetrical Configuration of Oil Shale Disposal Embankment to Accommodate Mining Process and Minimize Quantities of Processed Overburden.

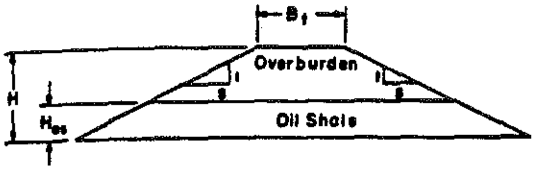


Figure 5. Idealized Cross Section of Ridge Top.

ridge top. This cross section may be used to simulate actual cross sections by the selection of parameters such that areas of the two materials in the actual cross section are approximately equal to the respective two areas in the idealized cross section.

Determination of Stripping Ratios and Areas of Cross Sections

Once the parameters of the idealized cross section are defined, unitless ratios, B_t/H_{os} and H/H_{os} are calculated. These ratios may be used in Fig. 6 to determine the stripping ratio associated with that cross section. To use Fig. 6, enter at the bottom with the ratio H/H_{os} and go vertically to the line associated with the ratio B_t/H_{os}. Interpolation may be necessary. Finally, go laterally to obtain the stripping ratio directly. This figure gives stripping ratios for values of slope (horizontal to vertical), S, between 2 and 3.

The unitless ratios also may be used to determine the areas of the overburden and oil shale in the cross section. Use Fig. 7a if the slope is 2, Fig. 7b if the slope is 2.5, or Fig. 7c if the slope is 3. To use these figures, enter at the bottom with the ratio, H/H_{os}, and go vertically to the dashed line associated with the ratio, B_t/H_{os}, and then go horizontally to the right to get the

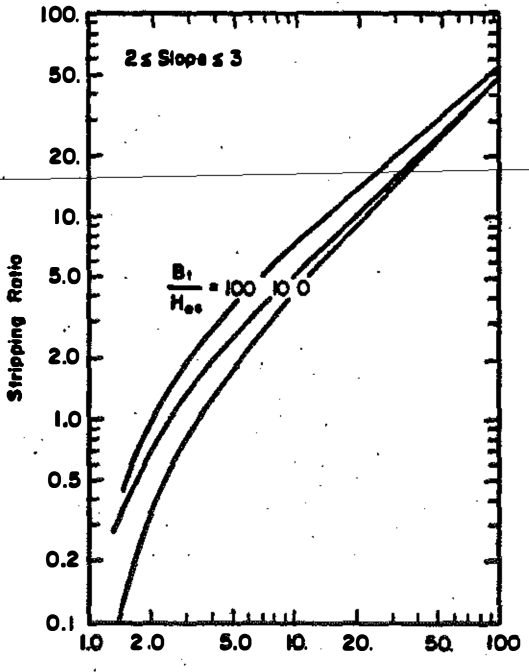


Figure 6. Stripping Ratio of Idealized Cross Section.

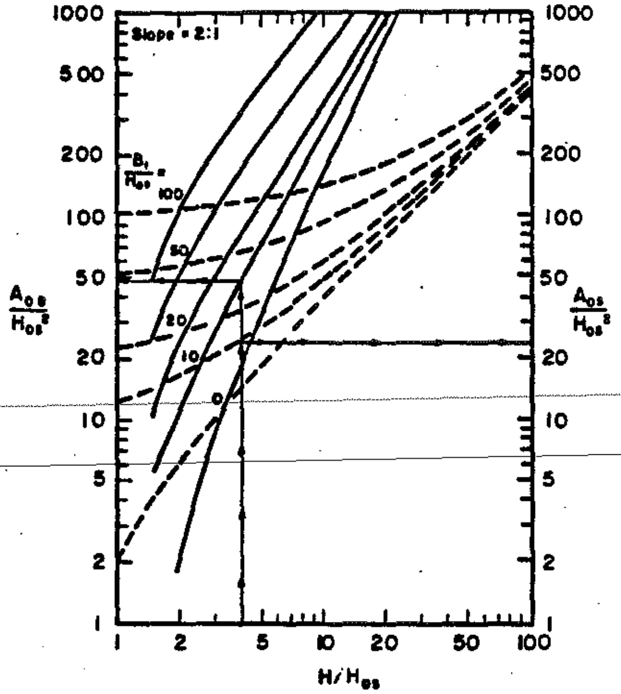


Figure 7a. Areas of Oil Shale and Overburden for Side Slopes of 2 Horizontal to 1 Vertical.

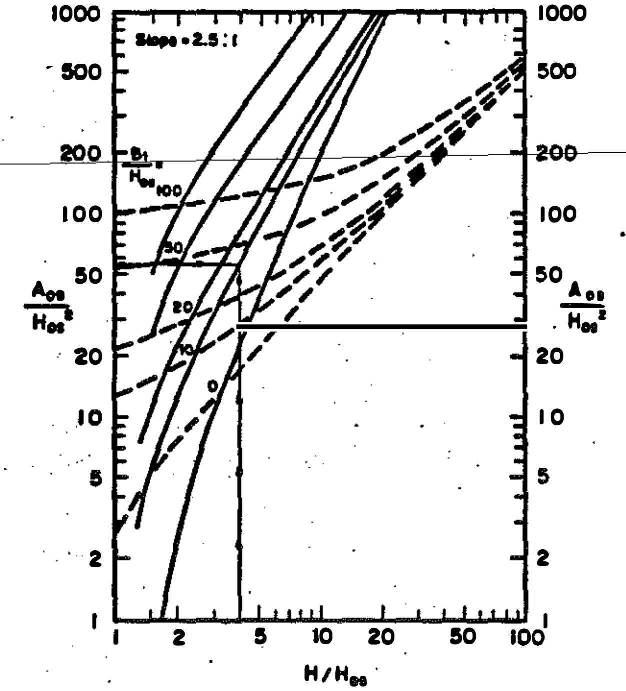


Figure 7b. Areas of Oil Shale and Overburden for Side Slopes of 2.5 Horizontal to 1 Vertical.

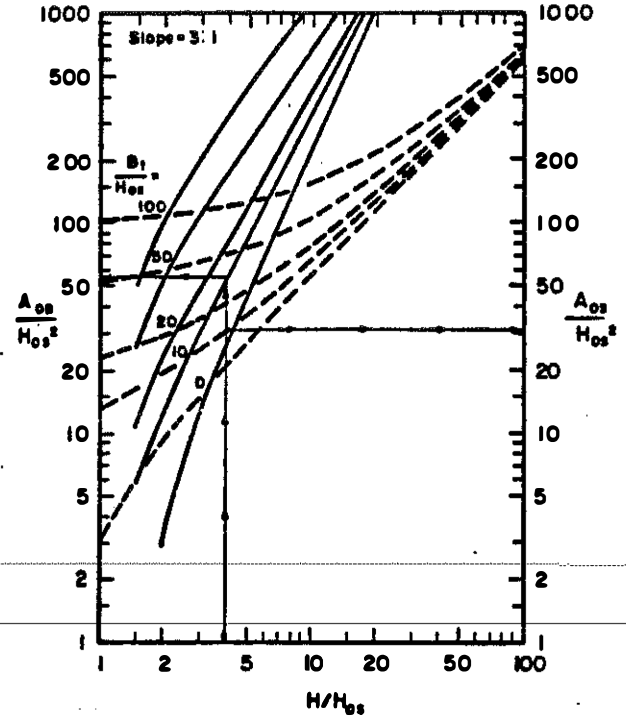


Figure 7c. Areas of Oil Shale and Overburden for Side Slopes of 3.0 Horizontal to 1 Vertical.

ratio, $A_{os}/(H_{os})^2$. The area of oil shale in the cross section is obtained by multiplying this ratio by H_{os}^2. In a similar fashion, if in going vertically to the solid curves in these figures and then going to the left, the ratio associated with the area of the overburden, $A_{ob}/(H_{os})^2$ is obtained. The area of the overburden for the cross section is obtained by multiplying this ratio by the H_{os}^2.

Determination of Material Quantities

Quantities of overburden and oil shale may be established if cross sections at various distances along the ridge are established. Quantities of material between each two cross sections can be determined by the average and area method,

$$V = 0.5(A_1 + A_2)(L/K) \qquad (1)$$

where: A_1 and A_2 are the respective areas at adjacent cross sections; L is the distance along the ridge between cross sections; and K is a factor to convert units (K = 27 for V in cubic yards from A in square feet and L in feet, K = 1 for V in cubic meters from A in square meters and L in meters).

Quantities determined above may be used directly in planning an oil shale operation. Volumes of oil shale may be converted to weights by multiplying the volumes by the unit weight of the oil shale in place. Values for these range from 120 pcf (19 kN/m^3) to 160 pcf (25.5 kN/m^3). Measurements from core samples or in place density tests should be used to establish values for a given site. In lieu of actual measurements, a conservative value of 125 pcf (20 kN/m^3) may be used for preliminary estimates.

Estimating Quantities of Materials for Disposal

Quantities of materials for disposal in embankments also can be established if appropriate volume change factors (sometimes called swell factors) are applied. For the overburden materials, this factor is dependent on: the nature of the overburden material; the excavation and handling procedures; types of processing (if done); the techniques of placement and compaction; and amount of settlement that takes place in the compacted material due to degradation and stress imposed from overlying materials. Factors can range from less than 1 to as much as 1.4 or more. Factors for a given site should be established early in the planning phases because these can significantly affect the economics of the operation. High factors mean that much of the overburden will have to be disposed of in head-of-the-hollow or valley fills. Details for determining these factors are given in the section on settlement. For preliminary estimates, a value of 1.25 is recommended for the volume change factor for overburden materials.

For the oil shales, volume increase takes place during mining but weight and volume decrease takes place during the retorting process. In addition to the factors which control volume change for the overburdens, the nature of the retorting process also significantly affects the volume change factor for oil shales. Actual factors for use at a given site must be determined from density measurements insitu before mining and from density measurements made in compacted spent shale embankments. Adjustments for these must be made to account for the loss of materials (mostly oils) in the retorting process and for settlement. These volume change factors may range from less than 1 to 1.5 with a value of 1.2 suggested for use in preliminary estimates.

Sizing the Spent Shale Embankment

Once the disposal quantities of spent shale are known, then the cross-sectional area of the spent shale at each section along the axis of the ridge can be determined. This is easily obtained by multiplying the oil shale cross-sectional area (determined by use of Fig. 7) by the appropriate volume change factor as discussed above. Next, the base width, B_b, of the spent shale disposal embankment must be chosen. This dimension must be less than the base width left by the mining process. In typical operations, it will be significantly less because of the space needed for haul roads and cover materials. The last parameters needed are the slopes at which the spent shale embankment will be placed. Because the spent shale will always be covered with other materials, these slopes may be quite steep. Further, the slope on one side of the cross section may be different from that on the other side. The notation with sizing a cross section is given in Fig. 8. If different slopes are used on each side, calculate an average slope from

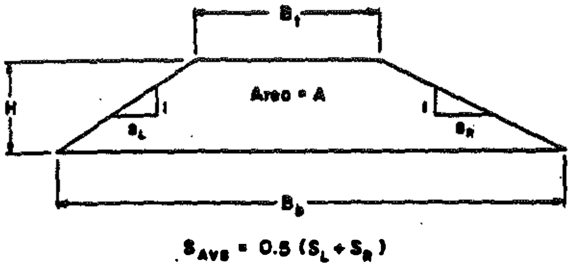


Figure 8. Notation for Determining Dimensions of Trapezoidal Cross Section.

$$S_{AVG} = 0.5(S_L + S_R) \qquad (2)$$

where S_L and S_R are the slopes of the left and right sides, respectively.

The spent shale cross-sectional area is then normalized by dividing it by the square of the base width. Figure 9 can then be used to determine the normalized height of the spent shale cross section. To use this figure, enter at the bottom with the normalized spent shale area and go vertically to the curve associated with the average slope value, S_{AVG}, and then go horizontally to the left to obtain the normalized spent shale cross section height. The actual height is obtained by multiplying the normalized height by the base width, B_b.

The dashed line in Fig. 9 represents the maximum normalized height of an embankment with chosen values of base width, cross-sectional area and slopes. At these heights, an embankment will have a ridge rather than a flat surface. Should the height determined be such that a flat surface exists, the width of the flat surface can be determined by use of Fig. 10 where a normalized top width, B_t/B_b is obtained. The top width is obtained by multiplying this normalized value by the base width, B_b.

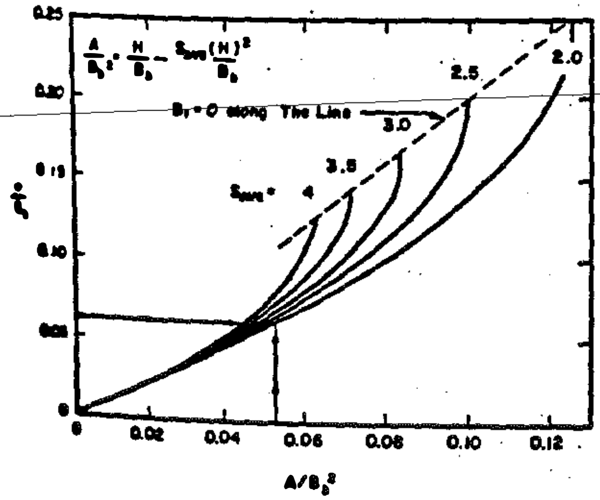


Figure 9. Height of Trapezoidal Cross Sections for Given Areas and Average Slopes (See Figure 8 for Notation).

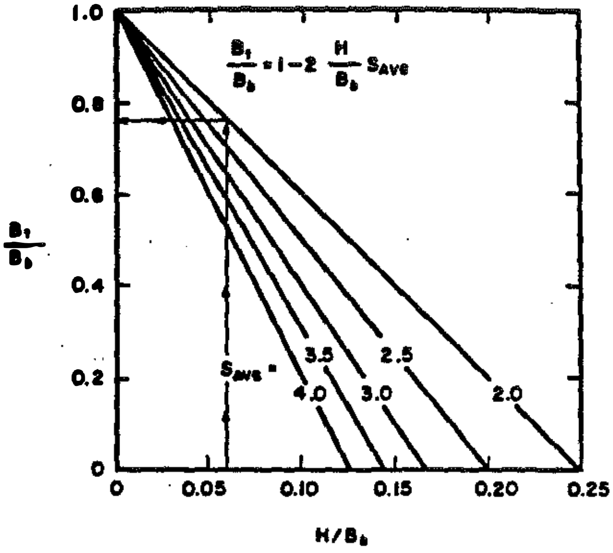
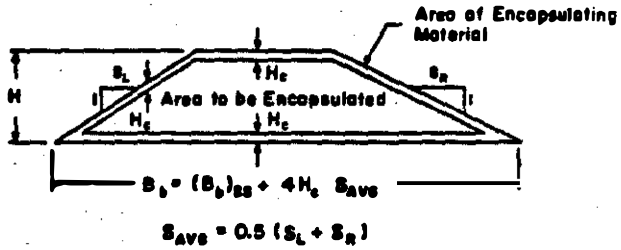


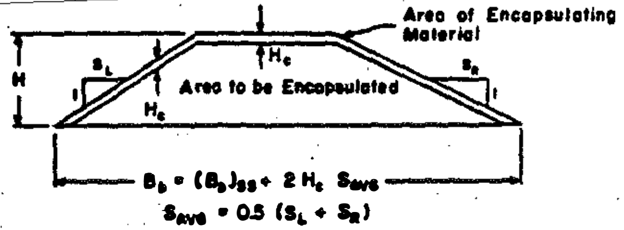
Figure 10. Relation of Top Width to Bottom Width of Trapezoidal Cross Section for Given Height and Average Slope (see Figure 8 for Notations).

Covering the Spent Shale

Good engineering practice and most regulations require that spent shale embankments be covered with nontoxic- and nonacid-forming material having a specified minimum thickness. Two schemes for this cover are shown in Fig. 11 where in part a) the spent shale embankment is



(a) Encapsulating Material Completely Surrounding Central Area.



(b) Encapsulating Material Only on Top Three Sides

Figure 11. Notation for Determining Area of Encapsulating Material for a Trapezoidal Cross Section.

(a) Encapsulating Material Competely Surrounding Central Area.

(b) Encapsulating Material Only on Top Three Sides.

completely encapsulated, while in part b) the cover is only on the top three sides. The base width required can be determined from

$$B_b = (B_b)_{ss} + 4H_cS_{AVG} \qquad (3)$$

for completely encapsulated spent shale and

$$B_b = (B_b)_{ss} + 2H_cS_{AVG} \qquad (4)$$

for cover only on the top three sides. In both of these equations, $(B_b)_{ss}$ is the base width of the spent shale cross section.

The cross-sectional area of the cover material is determined by use of Fig. 12 where the upper curve corresponds to the case where the spent shale embankment is completely surrounded by the cover and the lower curve corresponds to the case where the cover only is located on the top three sides. The use of this figure is similar to the previous figures where normalized parameters are used.

Sizing the Embankment for Overburden Disposal

The remaining part of the disposal embankment (except for top soil replacement) can be used for the disposal of overburden. The base width of the embankment is usually the overall width of the surface left in the mining operation unless it is desired to leave a bench or access road. The slopes of the embankment usually are selected as steep as possible and still maintain adequate stability. In practice, trial values of slope are selected, stability analyses are performed, and the slopes revised as necessary. Figures 8, 9, and 10 also apply to this situation. For maximum overburden disposal with a given average slope, use the dashed line in Fig. 9. Going horizontally to the left from the value of the slope on the dashed line will give the normalized height of the total embankment. Going vertically downward from the same point on the dashed line will give the normalized total area of the cross section. This is converted to total area of the section by multiplying by the square of the base width, $(B_b)^2$. The resulting area includes the area of the spent shale and the area of the cover. To get the cross-sectional area associated with overburden, these other areas must be subtracted from the total cross-sectional area:

$$A_{overburden} = A_{tot} - A_{ss} - A_{cover} \qquad (5)$$

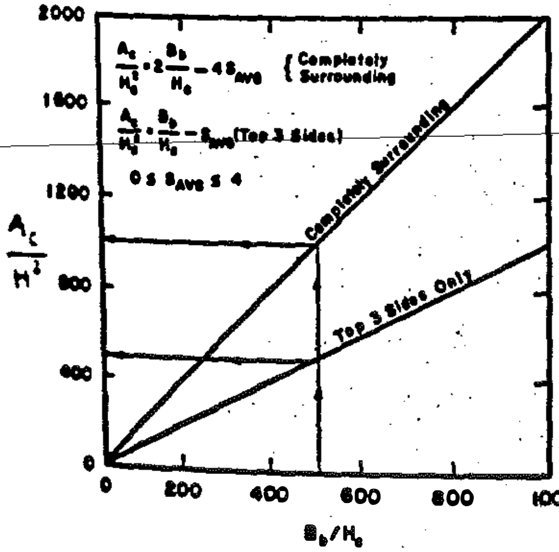


Figure 12. Cross Sectional Areas of Cover Materials for Trapezoidal Cross Sections (See Figure 11 for Notation).

Quantity of Excess Overburden

The total quantity of overburden to be disposed of equals the quantity determined from the original cross sections multiplied by the volume change factor for this material. These volumes are proportional to the individual cross-sectional areas (see Eq. (1)). Consequently, these areas multiplied by the appropriate volume change factors will provide volumes per unit length (areas) of material to be disposed. The volume of overburden material to be disposed of elsewhere (excess overburden) per unit length along the axis of the ridge can be determined from

$$A_{excess} = A_{ob} \times VCF_{ob} - A_{overburden} \qquad (6)$$

where VCF_{ob} is the volume change factor for the overburden and $A_{overburden}$ is obtained from Eq. 5.

Quantities of Top Soil

The quantity of top soil associated with a given cross section may be obtained by reference to Fig. 11 b) and use of the lower curve in Fig. 12. The procedure is identical to that for determining cover for the spent shale.

Example Problem

Let a given cross section be represented by the idealized cross section as shown in Fig. 13. Values of H, B_t and H_{os} are determined from field surveys and subsurface exploration. The width of the base, B_b, is determined from

$$B_b = 2\ H\ S + B_t \qquad (7)$$

For this cross section, B_t is 2400 ft. Next, the normalized parameters, $H/H_{os} = 4$ and $B_t/H_{os} = 10$ are determined. The slope in this example is 2.5 horizontal to 1 vertical. Use of Fig. 6 gives a stripping ratio of 1.9 for this cross section. From Fig. 7 b), $A_{ob}/(H_{os})^2$ equal to 56. Multi-

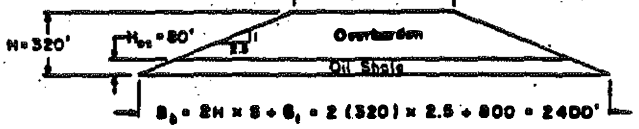


Figure 13. Example Problem of an Idealized Original Cross Section of Oil Shale and Overburden.

plying this normalized area by H_{oa}^2 gives a cross sectional area for the overburden, A_{ob}, of 358,400 ft². Also from Fig. 7 b), $A_{os}/(H_{os})^2$ equal to 27.5 and this yields a cross-sectional area of oil shale equal to 176,000 ft².

A cross section for disposal of materials at this same station is given in Fig. 14. The base width of the spent shale portion of the embankment of 2000 ft and slopes of 2 horizontal to 1 vertical were arbitrarily chosen. The cross sectional area of the spent shale is determined by multiplying the cross-sectional area of the raw shale by the volume change factor that accounts for the mining and retorting processes and for settlement due to its own weight. For this example, assume 1.2 for the volume change factor. The spent shale cross sectional area becomes 211,200 ft² (176,000 ft² x 1.2). Normalize this area by dividing it by B_b^2 to get 0.0528. From Fig. 9, H/B_b equals 0.06. Multiplying this by H_b gives a height of 120 ft for the spent shale embankment height. By use of Fig. 10 with H/B_b equal to 0.06 and S_{AVG} equal to 2, B_t/B_b equals 0.76 from which it can be determined that B_t equals 1520 ft.

Next, cover requirements are considered. Let the thickness of cover be 4 ft and assume that the spent shale embankment will be completely encapsulated with this cover. By Fig. 11 a), B_b equals 2032 ft (2000 + 4x4x2). Use Fig. 12 to get the cross-sectional area of the cover required. Enter with B_b/H_c equal to 508 (2032/4) and go to the upper line to get A_c/H_c^2 of 1008. Multiplying this by H_c^2 gives 16,128 ft² for the cover cross-sectional area.

The overburden is considered next. If a volume change factor of 1.25 is assumed to apply, then the area of the overburden to be disposed is 358,400 ft² multiplied by 1.25 which gives 448,000 ft². The base width for the entire disposal embankment is assumed to be the same as the original cross-sectional width, 2400 ft. Also, assume trial values of slope equal to 3 horizontal to 1 vertical. Before Fig. 9 can be used to determine the embankment height, the total embankment cross sectional area must be determined. This is calculated by use of Eq. 5 solved for A_{tot}.

$$A_{tot} = A_{overburden} + A_{ss} + A_{cover} \qquad (8)$$

For this example,

$$A_{tot} = 448{,}000ft^2 + 211{,}200ft^2 + 16{,}128ft^2$$
$$= 675{,}328\ ft^2.$$

If the overburden material can be used for the cover (special processing and placement may be required), then the A_{tot} may be reduced by A_{cover} (16,128 ft² in this example) and A_{tot} reduces to 659,200 ft². To use Fig. 9 a normalized area must be calculated and the value for this example becomes 659,200/(2400)² = 0.114. Upon entering Fig. 9 it is found that the slopes would have to be about 2.2 horizontal to 1 vertical to accommodate this quantity of overburden. These are far steeper than the 3.0 horizontal to 1 vertical assumed and most likely would not satisfy stability criteria. Hence, not all the overburden can be disposed at the mining site and some will have to be disposed elsewhere. To determine this quantity, use the dashed line in Fig. 9 and the assumed slope of 3. Starting again on the dashed line in Fig. 9 at the slope of 3 and going vertically downward gives a normalized cross-sectional area of 0.083 which corresponds to total cross sectional area of 478,080 ft² (0.083 x (2400 ft)²).

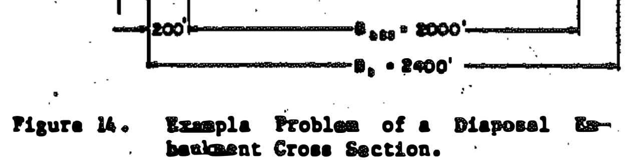


Figure 14. Example Problem of a Disposal Embankment Cross Section.

Going horizontally gives a normalized embankment height of 0.167 which corresponds to a height of 400 ft when this normalized height is multiplied by the base width (2400 ft for this case).

Since the area associated with disposal of spent shale is known (211,200 ft²), the quantity of overburden that can be disposed of in the embankment can be determined by use of Eq. 5 which for this example gives 266,880 ft². Thus, for this cross section, a quantity of overburden corresponding to 448,000 ft² minus 266,880 ft² equals 181,120 ft² must be disposed of elsewhere. Total quantities to be disposed elsewhere would be obtained by using the excess areas for each cross section in the average end area method (Eq. 1).

If the slope of the embankment were steepened to 2.5 horizontal to 1 vertical and the calculations above were repeated, the embankment would be 480 ft high and an excess area of overburden of 83,200 ft² would still exist.

Finally, the quantity of top soil needed to cover the embankment can be obtained by use of Fig. 11 b) and the lower line in Fig. 12. If a thickness of top soil of one foot is assumed, the normalized base width becomes 2400 ft divided by 1 foot which equals 2400. This is off the scale in Fig. 12 and the equation for the lower curve can be used to give the cross sectional area of the top soil which comes out to be 2397 ft².

DETERMINATION OF MATERIAL PROPERTIES

Site Exploration

A well planned and executed site exploration program will be invaluable for establishing the economics of potential mining sites. This program should be site specific and be performed by experienced geotechnical engineers and engineering geologists. In addition to establishing the stratigraphy at various locations, the program also should be designed to include some insitu testing and to procure samples for laboratory tests.

The most important insitu tests are associated with ground water location and permeability of strata. If the overburden materials and oil shales are relatively soft, tests such as the standard penetration test (8) may be quite helpful in planning excavation methods. Frequently, seismic refraction data are used to identify layering and give information on difficulty of excavation (9).

Bore holes should be carried well into the strata below the oil bearing shales because these lower strata have an influence on the behavior of the disposal embankments that replace the mined materials.

Laboratory Testing

Recent research (4, 5, 6) has shown that simple index tests carried out in the laboratory can go far toward establishing the suitability of disposal embankment schemes. Specifically, it is important to establish the natural moisture content of core samples from all levels in the stratum. For shales, the natural moisture content has correlated with shale durability (10). The economics of oil shale operations are related closely to the volume change factors associated with both the overburdens and the oil shales. To establish the volume change factors, accurate measurements of density on undisturbed specimens or intact cores is required. Since some shales degrade quickly when unstressed or subjected to an environmental change, the measurements of moisture content and density should be made very quickly (within a few days at most) after the sample or core has been obtained.

The simple tests needed to classify materials from each stratum should be performed. These include: specific gravity, particle-size distribution, and Atterberg limits. Specifications for these are available in ASTM (8). Several other simple tests are required. These include the compaction test (8) and the slake durability test (11,12). The former gives preliminary information on final in-place density so that volume change factors can be estimated and both give information on the durability of the materials.

If it is desired to utilize some of the overburden materials for encapsulating or covering spent shale, then permeability tests on compacted specimens of this material are required. If permeability levels are too high, some processing of the material (crushing, application of admixtures, etc.) may be required to reduce the permeability to acceptable levels.

Good engineering and most regulations require that stability and settlement analyses be performed on proposed embankments before completing their design. Stability analyses require: material unit weights, shear strength parameters, embankment geometry, and pore water pressure information. Unit weights can be estimated from the compaction data. Previous studies (4, 5, 6) have shown that drained triaxial compression tests give shear strength parameters, c' and ϕ', with reasonable accuracy. Most pore water pressure problems in embankments of this nature arise from stresses from overlying materials applied to soils having high initial moisture contents, very low permeability, and very great thickness or both. An experienced geotechnical engineer should be able to recognize the situations where this is likely to happen and to advise courses of action to maintain adequate stability in the embankments until these pressures dissipate.

For settlement estimates, usually one-dimensional analyses are used. One-dimensional compression tests can easily be conducted in the laboratory to give one-dimensional stress-strain data for compacted materials. If the materials are relatively free draining and are likely to degrade with wetting and stress application, a simple one- dimensional test (6) that gives stress-strain and behavior is recommended.

Interpretation of Data and Selection of Design Parameters

Materials in a given deposit can be very complicated and show significant variation from one location to another. For this reason, sufficient borings and samples must be studied to establish ranges in values. Recently, probabilistic methods are being used to guide in planning subsurface exploration and laboratory testing. If these methods are not used, then the program must be based on experience and judgement with a conservative interpretation of parameters.

It also is important to compare test results with published values on similar materials. The index tests and classification of materials are used to accomplish this. For some of the oil shale regions of Kentucky, work by Drnevich, et al. (6) should be quite useful. Their results may be applicable to other regions but local correlations must first be established.

All tests associated with subsurface exploration and laboratory testing have their limitations. Results from these tests, at best, can give good estimates of embankment performance. The design-construction process would be incomplete if some monitoring and evaluation of embankment performance were not scheduled. For example, consider in-place densities of the overburden material in the disposal embankment. The excavation, transport, placement, and compaction processes may produce significantly different in place densities than were predicted from laboratory compaction tests on samples gathered from borings or test pits. This could have a far reaching effect on volume change factors and quantities of materials to be disposed elsewhere. Some relatively small effort spent on construction monitoring and in-place testing could provide significant savings.

PLACEMENT OF MATERIALS

To obtain a stable disposal embankment and comply with regulations, placement of materials generated from oil shale mining operations will require proper attention to the following factors:

1. Site Preparation,
2. Excavation procedures,
3. Preparation of the foundation,
4. Sequence of constructing disposal embankments,
5. Compaction equipment and procedures,
6. Compaction specifications, control and monitoring, and
7. Final closure and reclamation.

Site Preparation

Site preparation for the surface mining of eastern oil shale entails the following: diversion of runoff from the mine area; clearing of vegetation from the site before the removal of topsoil; construction of access roads; and installation of power and communication lines.

Diversion of runoff water should be designed to keep as much water as possible from entering the exposed mine face. Water which leaves the mine area should be diverted to a sedimentation pond.

Clearing of vegetation from the stripping area should be performed in a staged operation so that large areas of exposed topsoil will be avoided. In addition, the burning of any cleared vegetation, if permitted, should be monitored closely.

Possibly the most important aspect of site preparation is the construction of access roads and the installation of utility lines. The roads should be constructed to give the best coverage of the site yet be easy to maintain. Access roads for the cross-ridge and hill-top removal method of mining will need to be continuously lengthened as the operation progresses.

Excavation Techniques

Both blasting and ripping techniques may be use to excavate the overburden materials and oil shales. Consider the Bedford and Borden materials in Eastern Kentucky. According to previous studies, these are clayey shales and the prospect exists that these might be rippable. These shales are spoken of as being "soil-like" materials (13) since their slake durability values are approximately 42 percent. Additionally, these materials slake or break down immediately when exposed to water. However, additional information such as jointing characteristics, bedding orientation, rock hardness, and seismic velocities are needed to fully assess the rippability of these materials at a particular site. Moreover, the rippability of these materials can best be determined by performing actual field tests (9) to assess ripping feasibility and economics.

Drilling and blasting are the most likely means of excavating oil shales. Slake durability indices of the oil shales associated with Eastern Kentucky are in excess of 95 % (6) and rippability of these materials is marginal at best. In fact, these oil shales are among the hardest shales found in the eastern formations and in Kentucky (10) and are characterized as "rock-like." Since the oil shales are very likely to require drilling and blasting to excavate, and drilling equipment will be required at a particular site, then drilling and blasting probably will be the most economical means of excavating both the oil shales and overburden materials.

Preparation of the Foundation

A major consideration in construction of the disposal embankment is proper preparation of the disposal foundation. If the disposal embankment is located on a sloping foundation, then an important aspect of foundation preparation is keying, or benching, the embankment into the sloping ground and installing drainage on the benches to intercept potential subsurface ground water (13). Use of sound, durable and free draining rock having no more than 10 % to 15 % fine material to form the drainage layer is essential. The thickness of the drainage layer on the benches should be approximately 2 to 4 feet. In certain cases, filter fabric can be used where graded filters might be required. Bench width normally will be dictated by the widths of the construction equipment (12 ft to 15 ft). If the sloping ground is fairly steep, then it may be necessary to use a rock berm, or buttress at the toe of the fill. Such a requirement would have to be determined from a slope stability analysis. In the mountain-top removal operation, a level foundation is most likely to be created. Consequently, little preparation of the foundation may be required. However, if seepage or springs are present, drainage blankets or drains may be required.

Sequence of Constructing Oil Shale Disposal Embankments

The sequence of construction of the oil shale disposal embankments will depend on the selected method of mining and removal of the overburden materials and oil shales. Symmetrical and unsymmetrical disposal embankment configurations which are envisioned and may be used are shown in Figures 1 through 4. In each of the figures, the spent shale is encapsulated with waste overburden materials. In Kentucky, the Borden and Bedford shales, found as overburdens, can be used. These shales are non-toxic and non-acid forming (14). Previous permeability studies (6) show that when the Borden and Bedford shales are broken-down and compacted to fairly high values of relative compaction (ratio of actual dry density of a material to the maximum dry density of the material obtained from ASTM D698-78), then the coefficient of permeability is less than 1×10^{-7} centimeter per second. Materials having coefficients of permeability of equal to or less than 1×10^{-7} centimeter per second can be classified as "practically impermeable (15)".

Based on Kentucky oil shale regulations (7), the minimum thickness of the encapsulating layer is four feet as shown in Figures 1 through 4. The four-foot cover (minimum) does not include the topsoil requirement. The degree of compaction of the four-foot thick layer formed of Borden and Bedford shales which may be required to make the layer impermeable will partly depend on whether the retorting process produces toxic- or/and acid-forming material. If the retorting process produces either type of material, then the spent shale should probably be encapsulated with an impermeable layer which would retard inflow of water and outflow of pollutants. The regulations do not necessarily specify that the minimum four-foot layer be made impermeable. Rather the regulations state that "all acid-forming or toxic-forming materials that are exposed, used, or produced during oil shale operations shall be covered with a minimum of four (4) feet of nontoxic and non-acid forming material.

Covering the material with an impermeable liner(s) may be required by the Department." The regulations also state that "In addition, the Department may require an impermeable cover between the final layer of spent shale and the (4) feet of nontoxic- and nonacid-forming material." Hence, materials other than soil could be used to form the impermeable layer, provided such a layer is required.

Although such materials as synthetic membranes, asphaltic concrete, asphalt, and concrete could be used, compacted soils probably offer by far the longest service life of any of the above materials. For example, field experience with synthetic membranes does not extend beyond approximately 25 years (16,17). The service life of asphalt is thought to be on the order of about 40 years (18). Use of concrete as a liner or top cap is severely limited because of cracks that may develop during curing and when settlement occurs. The costs of asphaltic concrete, synthetic materials, and concrete also would be large.

Since large volumes of the Borden and Bedford will generally be available and must be wasted, then from a standpoint of economics, these shales offer the most logical choice of materials for use in constructing an impermeable liner when required. Compacted soil appears to be the best material to use in constructing hydraulic barriers with design lives on the order of 100 or more years. Compacted soil is relatively inexpensive, is resistant to chemical attacks and has a long service life. For instance, a properly compacted, four-foot thick layer of Borden shale subjected to a unit hydraulic gradient would have a containment time of approximately 133 years. Actually, the containment time would be larger if the soil layer is not completely saturated.

Regardless of whether an impermeable layer is used or required, the Borden and Bedford shales, when used in the processed zones of Figures 1 through 4, will require high values of relative compaction to obtain economical and stable slopes. Consequently, to obtain adequate stability, the Borden and Bedford must be compacted and as a result low values of permeability will be obtained. Another major consideration in making the cap impermeable is the effect of infiltration of rainfall and ground water on stability. Infiltration of water into the embankment would build-up pore pressures, decrease shear strength and lower the long-term factor of safety. Consequently, milder slopes would be required if pore pressure build-up develops.

Although the disposal embankment configurations of Figures 1 and 2 may be used in the mining operation, the configurations of Figures 3 and 4 would accommodate, more economically the cross-ridge mining operation. In Figure 4, the scheme contains a zone for unprocessed waste. As envisioned in Figures 3 and 4, the spent shales are placed on one side of the embankment cross-section while the overburden materials are placed on the opposite side. In this plan, the overburden removal would proceed ahead of the oil shale drilling, blasting, and excavation operation. In the scheme, trucks would be loaded at the face of the oil shale mining wall and would haul the oil shales to the rock crusher. At the rock crusher the trucks would be loaded with spent shales from a conveyor and circle back to a point near the oil shale mining wall. The spent shales would be dumped slightly behind the oil shale excavation operation. On the opposite side of the cross-section, trucks would be loaded with overburden materials at the excavation face. The overburden materials would be placed behind the overburden mining operation. The trucks hauling overburden materials would circle between the overburden mining wall and the overburden disposal embankment. By separating the excavation and hauling of the spent shales and oil shales and the overburden materials, traffic interference would be avoided.

Compaction Equipment and Procedures

Suggested lift thicknesses, type of compaction equipment, and number of coverages that will be required to obtain adequate compaction of the various zones of the disposal embankments are summarized in Table 1. Determinations of lift

Table 1. Suggested Guidelines for Compacting Oil Shale Disposal Materials**

Embankment	Loose Thickness of Lift (inches)	Type of Compaction Equipment	Minimum Roller Weight (pounds)	Number of Passes	Minimum Frequency of Density Tests
Topsoil*	8 - 10	• Sheepsfoot Roller	1.5 to 3.0 tons per linear foot; 60-inch diameter drum; foot contact pressure equal to 200 to 400 psi	4 to 6	1/1,000 to 1/3,000 cubic yards
Unprocessed Overburden and Waste Shales	20	• Heavy Tracked Dozer	D8 Minimum Weight	1 to 2	***
		• Static (Self-Propelled or Towed) Tamping Foot Roller	53,000	2 to 4	
		• Vibratory (Self-Propelled or Towed)	55,000	2 to 3	
Processed Overburden	8 - 10	• Heavy Tracked Dozer	D8 Minimum Weight	1 to 2	***
		• Water Tanker with Spray Bar		Variable**	
		• Heavy Duty Disk (36-inch)		Variable**	
		• Static (Self-Propelled or Towed) Tamping Foot Roller	53,000	2 to 4	
		• Vibratory (Self-Propelled or Towed)	55,000	2 to 3	
		• 4-Wheel, Pneumatic-Tired Roller	100,000	2 to 4	
Spent Shale	22-30	Heavy Crawler Tracker	D8 Minimum Weight	3 to 4	**

*If Borden and Bedford shales are used as a substitute for topsoil, then compact similarly to techniques described under "processed overburdens."

**Items in this table are guidelines. Test pads should be constructed during start-up of the oil-shale operations to determine the most suitable lift thicknesses, compaction equipment, spraying and mixing rates, and equipment coverages and to determine desired densities. Results obtained from test pads can be used to develop method-and-end-result specifications. Different blasting techniques should be tried to determine the method that produces (economically) the smallest fragmentation of the shales.

***Frequency of tests will depend on results obtained from test pads.

thicknesses of the various zones are based on slake-durability indices of the overburden shales, oil shales, and spent shales (6) and the chart shown in Figure 6. The chart was devised by Strohm, et al. (13) and is a preliminary lift thickness criterion for evaluating embankment construction based on slake-durability index and settlement performance data. The graph can be used to estimate suitable lift thickness for shales. Depending on post-construction problems that may be tolerated, the selection of a lift thickness varies and requires some engineering judgement decisions.

Overburden Disposal in the Processed Zone- Suitable lift thickness (Figure 15) of the Borden and Bedford shales, which have a slake-durability index of about 42 percent, ranges from about 8 inches to 24 inches. When these shales are placed in the processed zone, a lift thickness of not more than 8 inches should be used. To achieve proper compaction of the Borden and Bedford shales in the processed zone and satisfy permeability and stability requirements, special compactive efforts will be required. Since the Borden and Bedford shales have low slake-durability properties, then these shales should be treated as "soil-like" materials and essentially broken-down into soil-size particles during the compaction process. A relative compaction of 95 percent is recommended. To obtain high values of relative compaction of the Borden and Bedford shales, attention must be given to blasting (or ripping) methods and compaction techniques. The blasting (or ripping) methods should produce small fragments. Initially, trial and error blasting (or ripping) techniques may be required to increase fragmentation. General guidance on blasting practices is given by Konya (cf 13).

Alternatively, fragmentation of the shales might be obtained by processing the shales through the rock crusher which is used to crush the raw oil shales for the retorting process. However, this procedure would require additional handling. Furthermore, because of the high susceptibility of the Borden and Bedford shales to slaking when moisture is present, frequent "jamming" of the crusher could occur.

Since the insitu water contents of the Borden and Bedford shales are approximately 3 to 5 percent and considering that the optimum water contents, as obtained from ASTM D698-78, of the Borden and Bedford shales are about 15.8 and 12.3 percent, respectively, watering and disking will be required when these shales are placed in the processed zone. To obtain proper compaction, the following procedures may be necessary (13). The shales are placed in thin, loose lifts of about 8 inches; oversized particles are removed. Initially, heavy tracked dozers are used to roll the material and partially break-down the dry shale fragments. Following this, the layer is rolled with compactors having small area square feet to increase fragmentation of the nondurable shales. Using spray bar-equipped tankers or trucks, the layer is watered and then disked. The addition of water will aid in the break-down of the Borden and Bedford shales since these shales slake almost instantaneously when exposed to water. A heavy duty disk (36-inch) will be required to mix the entire loose lift. The water content of the compacted layer should not exceed optimum water content (ASTM D698-78). In cases where the processed shales may be subjected to fill heights in excess of 200 feet, the layer should be compacted slightly dry of optimum water content to minimize the possibility of high pore pressure build-up. Repeated cycles of watering and disking may be required to obtain good mixing and a breakdown of the dry, nondurable shales. After the mixing stage, the layer is compacted using a vibratory pad-drum roller. About 2 to 3 coverages should be made. Finally, compaction of the layer is obtained using a 50-ton 4-wheel pneumatic tired roller. About 2 to 5 passes should be made with this equipment. The use of test pads during the initial start-up of the mining operation to refine and determine the most efficient compaction procedures to obtain desired densities is recommended.

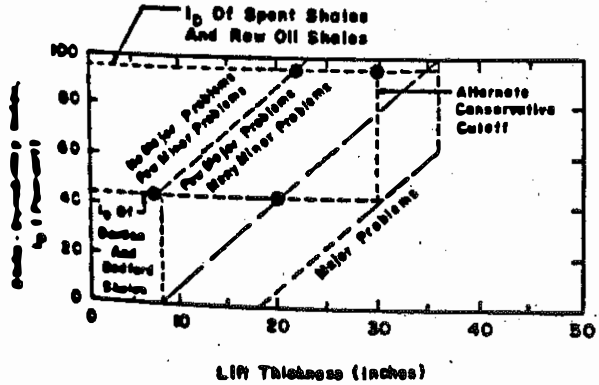


Figure 15. Preliminary Lift Thickness Criterion Based on Settlement Performance Data (83 Embankments) and Slake-Durability Index [After Strohm, et al. (13)].

Overburden Disposal in the Unprocessed Zone- When the Borden and Bedford overburden shales are placed in the unprocessed zone, lift thickness of up to about 24 inches could be used depending on the amount of settlement that can be tolerated. If settlements are not critical, the compaction requirements discussed above would not have to be as stringent when the nondurable shales are placed in the unprocessed zone. The 24-inch layer could be watered slightly to aid in obtaining some breakdown of the nondurable shales. Disking would aid in mixing and fragmenting the shales, although this might not be necessary. Use of the tamping roller would increase fragmentation. Finally, compaction could be obtained by using heavy duty crawler dozers. The unprocessed zone should be located in the interior of the embankment. Materials designated for the unprocessed zone should be placed "dry" of optimum water content. The minimum dry density for this zone should be such that 90 percent relative compaction is achieved.

When larger-sized particles are not broken down, laboratory values of maximum dry density and optimum moisture content must be adjusted. The method described in NAVFAC, DM-7.2 (19) is recommended. The adjusted maximum dry density is calculated from

$$[(\gamma_d)_{max}]_{adj} = \frac{1 - 0.05\,F}{\dfrac{F}{162} + \dfrac{1 - F}{[(\gamma_d)_{max}]_{lab}}} \left(\frac{\gamma_w}{62.4}\right) \qquad (9)$$

where: F is the fraction of oversized particles by weight (from field density tests) and γ_w is the unit weight of water in units consistent with the maximum dry densities. The adjusted optimum moisture content of the oversized materials is calculated from

$$[w_{opt}]_{adj} = F(w_g) + (1-F)[w_{opt}]_{lab} \qquad (10)$$

where: w_g is the moisture content of the oversized material (from field data).

Adjustments by equations (9) and (10) can be significant and should be made whenever the percentage, by weight, of particles with sizes greater than 3/4-inch exceeds 30 percent.

Spent Shales- The spent shales, as shown by previous studies (6), have slake-durability indices in excess of 95 percent. Based on Figure 15, the spent shale could be placed in lift thicknesses ranging from about 22 inches to 30 inches. Since the spent shale classifies as a coarse-grained material and contains almost no fines, the material could be spread and compacted with crawler tractors. The tractor should be no smaller than a D8. Approximately 3 or 4 coverages should be used. The addition of some water to this material would aid the compaction process.

Waste Shales- Waste shales which consist of rejected oil-bearing shales have slake-durability indices in excess of 95 percent. Hence, these materials classify as "rock-like" and could be placed in the spent shale zone, or the unprocessed zone. Compaction of these materials could be the same as described above for the unprocessed zone, or the spent shale zone.

Topsoil Cover- Soil normally used as a topsoil cover will be a clay or silty clay material. Compaction of the topsoil cover is essential so that erosion is controlled. If such a material is used, then a sheepsfoot roller should be used to obtain a relative compaction of 95 percent. Maximum loose thickness should be no more than about 8 inches. Suggested specifications with regard to the sheepsfoot equipment are shown in Table 1. About 4 to 6 passes of the sheepsfoot roller should be made to obtain good compaction. Foot contact pressure should be on the order of 200 to 400 pounds per square foot. As discussed in a companion paper to this conference (14), the Borden and Bedford shales may be used as a topsoil substitute. These shales weather rapidly to produce a fine-grained soil and contain enough clayey material to support plantlife. The compaction procedures described above for the processed zone can be used to achieve good compaction and produce a breakdown of these shales.

Compaction Specifications, Control, and Monitoring

The type of compaction specification used to obtain desired results will depend on the character and nature of the materials that will be placed in the various zones of the disposal embankment. For example, merely specifying that shales placed and compacted in the processed zone have a relative compaction of 95 percent—end result specification—may not be sufficient to obtain desired results. In-place density tests would be performed to determine if compaction specifications were met. Because of the dry nature of the Borden and Bedford shales insitu and considering that some difficulty will be encountered in fragmenting and compacting these shales, a method-and-end-result type of specification would be more likely to obtain desired results than merely specifying that an end-result density and water content be obtained. In-place densities of coarse-grained (fragments) shales, as discussed by Strohm, et al. (13), indicate that end-result specifications may be misleading when shales are compacted as soil. An exception to this is the compaction of soft shales that break-down into soil when placed and compacted in the processed zone. However, adequate break down of these shales in the unprocessed or semi-processed zone may not be obtained. Consequently, when placement of the Borden and Bedford shales must be made the method-and-end-result type of specification as described above may be required, that is, the specification not only describes the type of equipment that must be used but also specifies the lift thickness, the number of coverages, a range of water contents that the materials can be placed, and the relative compaction that must be achieved. The types of equipment shown in Table 1 and, compaction procedures described above are, in the opinion of the authors (based on available information), those that will be required to meet minimum settlement and stability criteria. Placement and compaction of the spent shales and rejected raw oil shales may also require a method-and-end-result type specification.

To effectively determine the best type of equipment and procedures to use to obtain desired compaction results of the various zones of the disposal embankment and to determine maximum lift thicknesses, shale test pads should be made an integral part of the initial start-up phase of an oil-shale mining operation. The discussion above should be viewed as "guidelines" and will serve as a "starting point" toward obtaining reasonable compaction results. By establishing method-and-end-result specifications from test pad results, the number of insitu density tests required for proper monitoring of the disposal embankments could be reduced. Recommended test procedures for shale test pads are described elsewhere (13). Depending on the size of fragments of spent shale produced by the retorting process, large-scale, field density tests of the magnitude described by (19) may be required during test pad tests to effectively design compaction specifications.

Control and monitoring of compaction of the materials in the various zones will depend on the type of specification required to obtain desired results. As mentioned above, the best compaction procedures can be determined from test pads. End-result specifications can probably be used for the topsoil zone when this material is constructed of clayey soil. In this case, in-place density and moisture content tests are performed; the results are compared to maximum dry density and optimum moisture content obtained from ASTM D698-78 (or AASHTO T-99) to determine relative compaction. Nuclear density gages (direct transmission) or sand-cone density tests are used to obtain in-place density and moisture contents. Nuclear density gages should be properly calibrated and adjusted to the shales that will be tested. Use of sand cone tests and speedy moisture content measurements are recommended to adjust the manufacturer's calibrations (13). Without these adjustments, the nuclear gages may yield erroneous results.

SLOPE STABILITY CONSIDERATIONS

In designing the slopes of the mountain top disposal embankments, the following factors must be considered:

1. Selection of design shear strength parameters,
2. Selection of design safety factors,
3. Estimation or prediction of pore pressures,
4. Selection of a model(s) to estimate stability and likely failure mode(s)
5. Examination of foundation conditions
6. Estimation of earthquake loadings

Selection of Design Shear Strength Parameters

Shear strengths of the raw oil shales, the Borden and Bedford shales, and spent shales which were obtained from consolidated-undrained triaxial tests with pore pressure measurements have been established from previous studies (6). Selection of design shale strength parameters are discussed in those studies. For example, design angles of shearing resistance and cohesion (in terms of effective stresses) for the Borden and Bedford shales are 26.5 degrees and zero, respectively. Recommended design parameters, effective angle of shearing resistance and cohesion, of the raw oil shales were 40.0 degrees and zero cohesion. Triaxial tests gave a curved envelope for the spent shales. The curved envelope gave a cohesion of 280 pounds per square foot and an angle of shearing resistance (in terms of effective stress) ranging from slightly over 45 degrees at low confining stresses to 26 degrees at very large confining pressures. Based on considerations of the range of stresses which will be imposed on the spent shales in the potential failure zone, an effective angle of shearing resistance of 30.5 degrees and effective cohesion of zero are selected for design purposes.

Selection of Design Safety Factors

Normally, for long-term stability a design safety factor (20, 21, 22, 23, 24) of 1.5 is selected. Long-term stability is a condition in which the pore pressures have reached a steady-state condition; excess pore pressures have dissipated. The safety factor in limit equilibrium methods, which are the most frequently used methods to determine slope stability, is assumed to be constant along the length of the trial shear surface and is an average value. Hence, as noted by Johnson (23), the safety factor obtained from limit equilibrium methods does not constitute a reserve of unused strength; rather, the safety factor is a working element of the design process. Moreover, a long-term safety factor of 1.5 is generally successful in guarding against failures and has a very reasonable success record.

For short-term stability (or temporary loadings), a safety factor as low as 1.25 or 1.30 is frequently used, provided good quality strength tests are available, and a good knowledge of the characteristics (such as fabric, fissures, anisotropy, etc.) of the materials are known. Selection of a design safety factor must be balanced against the cost of repairs that will be required if a failure of the oil shale embankment occurs and the level of risk that can be safely assumed. For instance, based on previous histories of highway embankment failures (embankment heights on the order of 50 feet), repairs may range from 500 to 1000 dollars per linear foot of slide and typically, for small embankments, repair costs may be on the order of 250,000 dollars. For embankments with heights in excess of 200 feet, costs of repairs may be on the order of 2500 dollars per linear foot with corresponding total costs for repair on the order of 1 million dollars.

Normally, for embankment loading, the short-term stability is more critical than the long-term stability. Short-term stability is generally investigated using the ϕ-equal-zero analysis and undrained shear strength (unconsolidated-undrained triaxial tests or unconfined compression tests). However, undrained shear strength should be used cautiously when overconsolidated soils, such as compacted dry shales, are involved. A summary discussion of this design aspect is presented elsewhere by Hopkins, et al.(24). The short term stability is normally lower in embankment loadings than the long-term stability because, generally, pore pressures are larger during construction than after construction.

Estimation or Prediction of Pore Pressures

High pore pressures due to seepage are not anticipated in the disposal embankments provided measures are adopted to prevent infiltration of ground water and surface water. However, high excess pore pressures may be generated during construction in certain zones of the disposal embankment because of the large stresses resulting from large heights of the disposal embankments. Since the spent shales and the materials (mainly the Borden and Bedford shales) placed in the waste zone will likely be compacted in a relatively "dry" state (dry of standard optimum water content), then excess pore pressure build-up in those zones will probably not be a problem. However, the build-up of excess pore pressures in the four foot compacted layer of Borden and Bedford shales, which may be used to encapsulate the spent shales, may occur when fill heights are approximately in the range of 200 to 500 feet. Although the short-term stability may be estimated using the ϕ-equal-zero analysis and undrained strength, total reliance upon the ϕ-equal-zero method to estimate the short-term stability should not be made. Rather, the short-term stability should also be investigated using an effective stress analysis based on effective stress strength parameters and predicted (or measured) pore pressures. Methods, including laboratory techniques, for estimating excess pore pressures have been given by Bishop and Henkel (25) and Skempton (26). Possible effects of excess pore pressures on the design of disposal embankments is illustrated below. Piezometers should be installed early during start-up of the oil shale operations.

Models to Estimate Stability and Likely Failure Modes

Several methods are available for determining the stability of earth slopes; many of these models have been programmed for the computer (27, 28, 29, 30). Practically all of the methods are based on limit plastic equilibrium and the slices technique. Capabilities and limitations of these methods have been discussed by Wright (30), Johnson (23) and Hopkins, et al.(24). The so-called "accurate" methods include Bishop's methods (31), Spencer's methods (32, 33), Morgenstern-Price (34), Janbu's (35), and a new method by Hopkins (36).

In selecting a trial slope of a disposal embankment, the infinite slope technique and stability charts are useful. Charts presented by Bishop and Morgenstern (37) are quite suitable for this purpose. Once a trial slope has been selected, the design can be checked using one of the "accurate" methods. For the examples shown below, the method by Hopkins is used. This method is useful since circular, wedge, and composite failure modes can be investigated rapidly using the same computer program. This method yields safety factors that are almost identical (based on many comparisons) to those from the other "accurate" methods listed above.

As noted above, the foundation created by the mountaintop removal mining operation will likely be level or flat. Provided that the disposal embankment is constructed on a portion of unmined oil shale formations, foundation problems may be nominal. However, if the operation cuts into the underlying "problem" shales, e.g., Crab Orchard shales, then serious stability problems could develop. This formation has caused numerous highway failures in Kentucky (24) and every effort should be made to avoid these shales, if possible. These shales contain a high clay content, weather rapidly (slake-durability index is less than approximately 55 percent), and have very low shearing strengths (especially along bedding planes). Construction of disposal embankments on the Crab Orchard Formation should be avoided. (However, haul and access roads may have to be constructed through these shales.)

A major portion of the eastern oil-shale deposits are generally located in low seismic zones. Consequently, advanced earthquake analysis, such as dynamic response analysis, will generally not be required on a routine basis. However, considering the large sizes of the disposal embankments that the oil shale operation may generate and the large costs of repairs that may be involved if an earthquake occurred, limited studies using advanced techniques might be considered.

Based on the idealized, original cross section in Figure 13, two trial disposal embankment cross-sections were established for stability analyses, as shown in Figures 16 and 17. To establish preliminary slopes of the oil shale disposal embankment, infinite slope analysis and stability charts are used. In Figure 17 a trial slope having a slope of 3:1 was selected. To obtain an approximate value of the safety factor of this slope an infinite slope analysis was made and yielded a value of 1.50. This type of analysis can be used in this case since the shear strength of the spent shales is larger than the overburden shales and the effective cohesion of the overburden shales is zero. Hence, the critical shear surface lies entirely within the overburden shales. Stability charts developed by Bishop and Morgenstern have a broader application than the infinite slope analysis since the charts can handle soils which have a cohesion and can take into account the effects of pore pressures on the safety factor. However, stability charts are developed for specific slope geometries and pore pressure conditions. Also, the charts are applicable only to problems involving a homogeneous soil.

Many slope stability problems involve irregular ground surfaces, several soil layers, soil layers having different pore pressures, and irregular-shaped shear surfaces. Consequently, in designing slopes that contain complex soil conditions and pore pressures, such as those encountered with the oil shale disposal embankments, more accurate analytical methods must be used.

Stability calculations for the trial sections shown in Figures 16 and 17 were made using a generalized, limit equilibrium method of slices and computer program developed by Hopkins (publication pending). Potential failure modes, as well as long-term and short-term stability, were investigated to determine the most critical shear surface having the lowest safety factor.

For long-term stability of the slope in Figure 16 (pore pressures are assumed to equal zero in all zones of the disposal embankment), a safety factor of 1.57 was obtained. The critical shear surface lies entirely in the overburden material, is tangent to the outer slope of the spent shale zone and passes through the toe of the disposal embankment. Circles passing through both the spent shale and overburden waste zones have much higher values of safety factor because the shear strength of the spent shale is larger than the shear strength of the overburden shales. To determine if a wedge-shaped mass might yield a

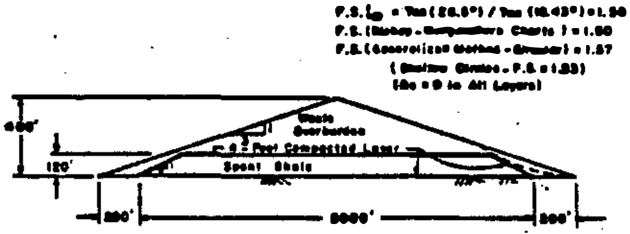


Figure 16. Trial Slope of 3:1 and a Comparison of Factors of Safety Obtained from an Infinite Slope Analysis, Bishop and Morgenstern's Charts, and a Circular Search Analysis.

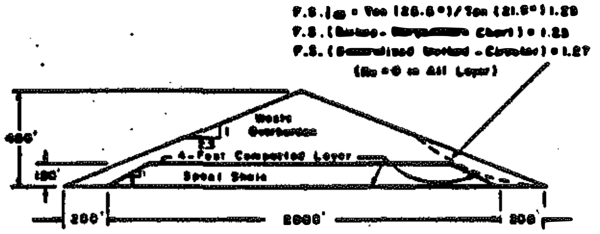


Figure 17. Trial Slope of 2.5:1 and a Comparison of Factors of Safety Obtained from an Infinite Slope Analysis, Bishop and Morgenstern's Charts, and a Circular Search Analysis.

lower safety factor than the value obtained from a circular analysis, different wedge configurations near the toe of the disposal embankment, as shown in Figure 18, were examined. A safety factor of 1.51 was obtained. The circular and wedge analysis of the 3:1 slope gave similar results.

Similar analyses were made for the 2.5:1 slope. An effective stress analysis gave a minimum, long-term safety factor of 1.27 as shown in Figure 17. As shown in Figure 19 wedge analyses gave an identical result. Normally, the shear surfaces in Figures 16 through 19 would be considered shallow failures. However, the depths of the failure masses range up to about 60 feet. Consequently, a failure near the toe of the embankment would be costly to repair. Protection of the toe area of the embankment is extremely vital because of the high concentration of stresses in this area. Even slight erosion at the embankment toe can activate a large landslide (24). Once a small slip occurs at the toe, then a multiple retrogressive series of slides may develop. Sound, durable rock can be very effective in protecting the embankment toe.

Short-term (or end-of-construction) stability, of the trial sections were not investigated using the ϕ-equal-zero (total stress) analysis because undrained shear strength data were not available. However, an assessment of the short-term stability can be examined using an effective stress analysis. To investigate the short-term stability using an effective stress analysis requires a knowledge of pore pressures. If adequate drainage measures are adopted, ground water seepage into the disposal embankment is not likely. Excess pore pressures in the four-foot compacted layer may occur, since the clayey materials in this zone will have a degree of saturation close to 80 to 90 percent and will be subjected to enormous stresses—the degree of saturation will approach 100 percent and excess pore pressure will develop. Additionally, these clayey shales when compacted have low permeabilities. Hence, excess pore pressures will dissipate slowly during and after construction. Since the spent shale is granular, this zone of material will act as a good drainage boundary and aid to dissipate excess pore pressures. Moreover, the placement (when feasible) of a layer of rejected oil shales (which are granular) on top of the four-foot compacted zone would also speedup dissipation of excess pore pressures.

The likelihood of a deep failure occurring during or immediately after construction through the four-foot compacted layer increases with the build-up of excess pore pressures. The deep failure mass will be wedge shaped and consist of two blocks—an active wedge and passive wedge.

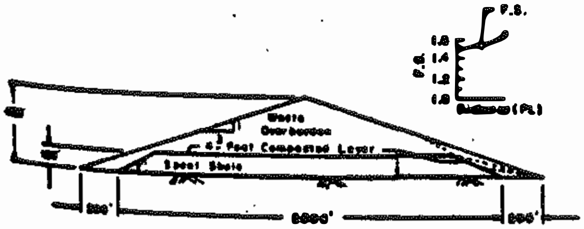


Figure 18. Wedge Analysis of Trial Slope of 3:1.

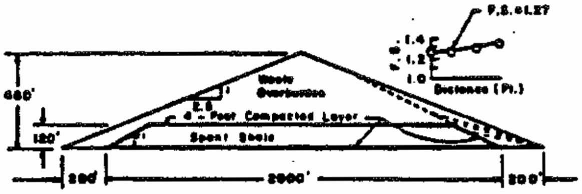


Figure 19. Wedge Analysis of Trial Slope of 2.5:1.

For purposes of analysis of this case, it is convenient to express the pore pressures at any point of the embankment in terms of the pore-pressure ratio, R_u. The pore pressure ratio is defined as the ratio of pore pressure and the bulk unit weight multiplied by the depth of the point in the soil mass below the soil surface. Many compacted soils have a pore pressure ratio approaching 0.6. In the examples below, the ratio was varied in the four-foot layer to determine the effect of pore pressures on stability of the disposal embankment. Pore pressures were assumed to be zero in all other zones.

Deep failure shear surfaces were investigated for the two trial slopes. In these examples, the failure mass is assumed to be wedge-shaped—two blocks are involved. In each of these figures, the safety factors of several trial shear surfaces were determined. The failure angle, θ, of the shear surface of the active block in each of the examples was estimated from

$$\theta = 45 + \phi'/2 \qquad (11)$$

In this case, the angle of shearing resistance, ϕ', used in this equation was 26.5 degrees. The shear surface of the passive block was assumed to pass through the middle of the four-foot compacted layer. In Figure 20, failure is assumed to occur through the four-foot compacted layer at the bottom of the spent shales. Safety factors for a range of different assumed R_u-values and different wedge-type shear surfaces of the slope of 3:1 are shown in the top right portion of Figure 20. The minimum safety factor is plotted as a function of each assumed R_u-value in the top left portion of Figure 20. The minimum safety factor of the deep shear surfaces ranges from 2.26 (long-term) for a R_u-value of zero to 1.32 for a R_u-value of 0.6.

In Figure 21, failure is assumed to occur in the four-foot layer lying on top of the spent shales. In this case, the minimum safety factor ranges from 2.33 (R_u=0, long-term) to 1.29 (short-term). In the later case, the disposal embankment is constructed on an impermeable foundation which contains no fractures.

Similar analyses are shown for the slope of 2.5:1 in Figures 22 and 23. The minimum safety factors of shear surfaces passing below the spent shale and through the four-foot compacted layer are 1.95 for a R_u-value of zero and 1.15 for a R_u-value of 0.6. For the upper failure surface, Figure 23, the minimum safety factor ranges from 1.98 for R_u equal zero to 1.16 for R_u equal 0.6.

Based on the analyses in Figures 20 through 23, deep failure surfaces could develop during construction of either trial slopes. Development of such shear surfaces is dependent on excess pore pressures which may be generated during construction. The long-term safety factors (R_u=0) of both trial slopes are sufficiently large to guard

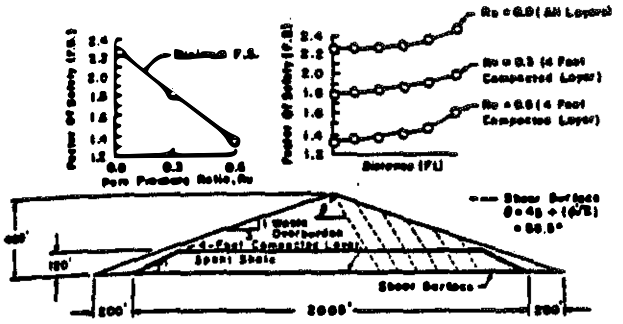


Figure 20. Stability Analysis of Deep Shear Surfaces Assuming Two-Block Wedge Failure Masses of the Trial Slope of 3:1. Shear Surfaces Pass below the Spent Shale Zone through 4-Foot Compacted Layer.

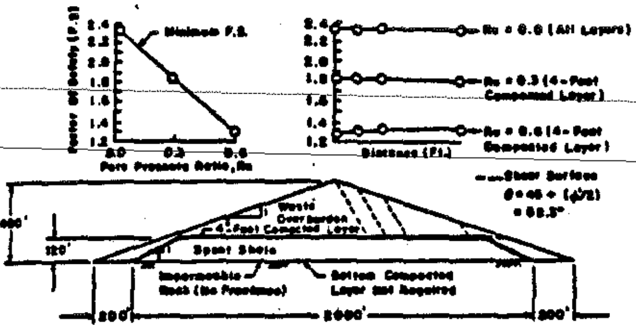


Figure 21. Stability Analysis of Deep Shear Surfaces Assuming Two-Block Wedge Failure Masses of the Trial Slope of 3:1. Shear Surfaces Pass above the Spent Shale Zone through the 4-Foot Compacted Layer.

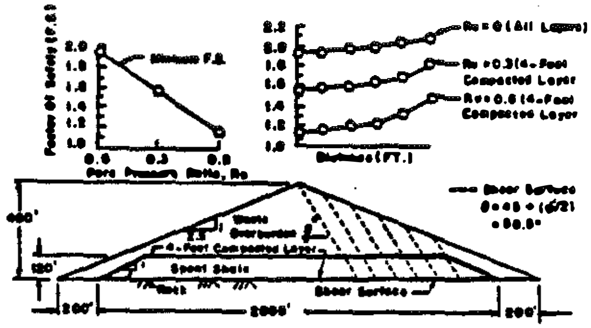


Figure 22. Stability Analysis of Deep Shear Surfaces Assuming Two-Block Wedge Failure Masses of the Trial Slope of 2.5:1. Shear Surfaces Pass below the Spent Shale Zone through the 4-Foot Compacted Layer.

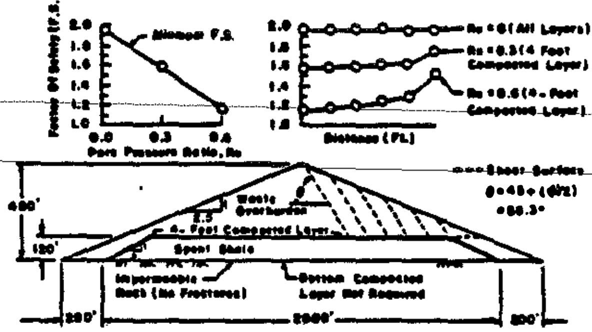


Figure 23. Stability Analysis of Deep Shear Surfaces Assuming Two-Block Wedge Failure Masses of the Trial Slope of 2.5:1. Shear Surfaces Pass above Spent Shale Zone Through the 4-Foot Compacted Layer.

against a deep failure after construction. If large excess pore pressures build-up on the order of R_u equal 0.6, then the slope of 2.5:1 would be unacceptable because of the low safety factor (1.15 or 1.16). For R_u-values on the order of 0.6, the slope of 3:1 would be acceptable. This slope would also be acceptable with regard to shallow, toe failures. However, the embankment with a slope of 2.5:1 would not be acceptable.

SETTLEMENT CONSIDERATIONS

Factors Affecting Estimates of Settlement

Settlements in fills are most difficult to estimate accurately. A number of reasons may be advanced to account for this. Among the more important are: a) time dependent nature of the phenomenon; b) variability of techniques and conditions of placement of fill material relative to those used to determine settlement parameters; and c) inadequacies of methods used.

The time dependent nature of settlement is especially significant for shales and other overburdens which are degradeable, i.e. weather and breakdown with time after placement. Settlement rates are impossible to predict in these cases because they are a function of the weathering rates which, in turn, are functions of the parent material and the environment. The time dependent component of settlement associated with degradation can be minimized by increasing the degree of compaction when the material is placed in the fill.

If in placement, some of the fill becomes saturated, the increase of stresses from placement of additional fill may generate excess pore pressures that may require significant time to dissipate. This process of consolidation always has settlement associated with it.

When estimates of settlement are made, they are usually based on results of laboratory compression tests made on samples of the fill material. Quite frequently, the actual specimen tested is very small, does not contain any large particles, and hence, does not accurately reflect the macroscopic behavior of the material. Very few, if any, laboratories are equipped to test large enough specimen sizes to accurately reflect the particle size range likely to be encountered in oil shale disposal embankments. Even if the tests existed to obtain good data, the variation in techniques of fill placement from those used in creating the test specimen would be sufficient to cause inaccuracies in the estimates.

Finally, the theories commonly used are somewhat limited. For example, these theories generally assume that one dimensional compression exists, i.e., that there is no strain in the lateral direction. While this may be true for fills of wide lateral extent relative to their height, it is not generally true for ridge fills as discussed earlier in this paper.

As a consequence of the above discussion, estimates of settlement from conventional laboratory test data will quite frequently be considerably different from actually observed settlement. However, estimation of settlement is helpful in locating the zones of large settlement, rates of settlement, and volume change factors. All are important for design purposes.

If settlement rates are high, then much of the total settlement may occur during the construction of the embankment. This is ideal because it means that final grade elevations and surface water handling schemes will not change once they are established.

Example Calculation of Embankment Settlement

Consider the embankment shown in Fig. 16. This embankment consists of a four-foot thick blanket of processed overburden over which a 120-ft thick layer of spent shale is placed. The spent shale is covered with another four-foot thick blanket of processed overburden. The remaining thickness of 272 ft is of waste overburden.

The assumptions made associated with this example are: a) there is no settlement in the foundation beneath the first blanket of processed overburden; b) relative compaction is 95 percent in the two four-foot thick zones of processed overburdens; c) the spent shale and the waste overburden are placed to achieve 90 percent relative compaction; d) except for the four-foot thick blankets which are placed at near optimum moisture contents, the other materials are placed at their natural moisture contents which is assumed to be less than the optimum moisture contents; and e) one dimensional compression applies.

Either void ratio or axial strain as a function of axial stress for one dimensional compression loading is required. Data for these materials were taken from reference (6), Figs. 6 and 8. The total settlement is the sum of the settlement in each layer or sublayer. If a layer is greater than 40 ft it should be divided into sublayers such that each sublayer has a maximum thickness of 20 ft or so. The equation for settlement in a layer or sublayer is

$$S_i = \frac{e_o - e}{1 + e_o} H_i \qquad (12)$$

where: S_i is the settlement in layer or sublayer i; e_o is the void ratio of the material as compacted; e is the void ratio of the material when the embankment is completed; and H_i is the thickness of layer or sublayer i.

The void ratio, e, is a function of the vertical stress due to the overburden above the mid-height of the layer or sublayer in question. To obtain this stress, it is necessary to know the total unit weight and thickness of each layer or sublayer above the layer or sublayer in question.

For the example under consideration, each of the four-foot thick blanket layers was considered as a layer, the 120-ft thick spent shale layer was divided into three sublayers of 40 ft each, and the 272-ft thick layer of waste overburden was divided into ten sublayers of 27.2 ft each.

Settlements in each waste overburden sublayer with 27.2-ft thickness ranged from one foot for the sublayer closest to the surface to five feet for the sublayer nearest the spent shale. The three sublayers in the spent shale with thickness of 40 ft had settlements ranging from 4.8 ft to 5.4 ft. The total expected settlement (assuming that none took place during construction) was calculated to be 56 ft. However, all materials in the embankment, with the exception of the two four-foot thick blanket layers, would be partially saturated and would settle as construction of the embankment took place. The total amount of settlement taking place during construction depends on the materials and degree of breakdown of materials during placement. For this situation, it is estimated that at least 90 percent or more of the total expected settlement could take place during construction. This estimate is based on the results of the one dimensional compression and creep tests on these materials (5). Consequently, subsequent to completion of construction, settlements less than 10 ft would likely occur in this 400-foot high embankment.

Effect of Settlement on Volume Change Factors

As heights of disposal embankments become large, the settlements become large even though they occur quite quickly. Large settlements significantly affect the volume change factors which must be used to estimate quantities of materials placed. These factors may be calculated from

$$VCF = \frac{(\gamma_d)_{insitu}}{(\gamma_d)_{compaction}} (1 - P_L/100) (1 - S/H) \qquad (13)$$

where: $(\gamma_d)_{insitu}$ is the dry unit weight insitu before excavation; $(\gamma_d)_{compaction}$ is the dry unit weight of the material after placement and compaction; P_L is the percentage of the material weight lost due to processing or retorting; S is the average settlement in this material after embankment is complete; and H is the thickness of this material in the embankment.

For overburden materials, the value of P_L is near zero whereas for Eastern oil shales, the value of P_L is approximately 15 percent. For typical disposal embankments, values of S/H range from less than 0.02 to more than 0.20. Thus, settlement has a significant effect on the volume change factor.

SUMMARY AND CONCLUSIONS

The design and construction of oil shale disposal embankments has been covered in detail. Techniques have been developed for estimating the stripping ratios and the the quantities of overburden and oil shales. Design charts have been produced that allow for the sizing of disposal embankments, including the sizes of the various zones that may exist within the embankment. Provisions are given to account for volume change in the mining and placement processes. The procedure is quite general and easy to apply as shown by the example problem.

The procedures for obtaining the engineering properties of the various materials are covered.

It is shown that careful determination of these is important if economical and stable embankments are to be constructed.

Details of construction of embankments are provided. Specific requirements are illustrated by use of material properties typical of sites in central Kentucky. Special attention is given to compaction procedures for overburden materials used as cover for the spent shale. These materials are often "soil-like" and must be processed properly to ensure low permeability, low settlement, and stability.

For overburden materials that may have large particle sizes (greater than 3/4-inch), a method is presented to adjust results of laboratory compaction tests such that they apply to field conditions. These adjustments are significant and can have a major impact on the long-term stability and settlement of embankments.

Methods and examples for establishing stability and settlement are given. Initial design of slopes can be made by use of published charts. However, analyses by use of more accurate methods are required for zoned embankments cause many modes of failure are possible.

For settlement, a simple, one-dimensional method is described. The accuracy of this method is not very good but utilization of more accurate methods is not warranted because accurate data on material behavior is usually not available. Magnitudes of settlement can be very large (tens of feet). However, for most materials in the central Kentucky region, settlements should occur during construction if proper construction procedures are followed and long-term settlements should not be a problem.

It is clear that detailed knowledge and experience is lacking for construction of oil shale disposal embankments in this region. In view of this, it is strongly recommended that the initial phases of any mining and disposal process include test embankments and test sections (test pads) within the embankment as it is being constructed. These can have a major impact on the efficiency of embankment construction, the long term performance, and on the cost of subsequent embankments.

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