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Dynamic Properties of Fine-Grained Coal Refuse

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SYNOPSIS: A simplified method of slope stability analysis is presented for upstream-constructed coal tailings dams subjected to earthquake shaking. The method employs a conventional method of slices approach, in which dynamic loads are represented as psuedostatic forces applied to each slice. Excess pore water pressures are estimated from cyclic triaxial tests performed on specimens of fine coal refuse.

Cyclic triaxial test results are presented for fine coal refuse materials from six sites in the western Appalachian region. Measured excess pore water pressure values appear to be influenced by fine coal processing procedures, although material plasticity and grain characteristics are also important. Additional studies are ongoing.

INTRODUCTION

A significant expense associated with coal mining is the safe disposal of waste products. Coarse coal refuse is generated during the coal excavation process and contains a sizable shale fraction. Fine coal refuse is generated during the coal scrubbing operation and, at the time of disposal, exists in slurry form.

A relatively inexpensive method to dispose of waste products is to construct a tailings impoundment. In mining operations where relatively small quantities of coarse refuse are produced, the upstream method of construction is preferred. As shown in Figure 1, a starter dam is constructed of coarse refuse and the fine refuse is pumped behind the starter dam. When fine refuse materials have consolidated under self weight, the dam can be raised in a second stage. After multiple raisings by the upstream method, a significant portion of the tailings dam consists of fine refuse.

The stability of an upstream-constructed tailings dam depends largely on shearing resistance generated within the fine refuse. Because fine refuse materials are fine sand- to silt-size and are deposited in a loose saturated condition, seismically induced pore water pressures must be considered in a stability analysis.

Since 1986, ERCE, Knoxville, Tennessee, and the University of Louisville have investigated the seismic stability of six upstream-constructed coal tailings dams in the western Appalachian region between eastern Tennessee and eastern Ohio. A simplified method of analyzing the stability of these dams was developed, which incorporates cyclic triaxial testing of fine coal refuse materials. In this paper, the method of stability analysis is described and results of laboratory tests performed on fine coal refuse materials are presented.

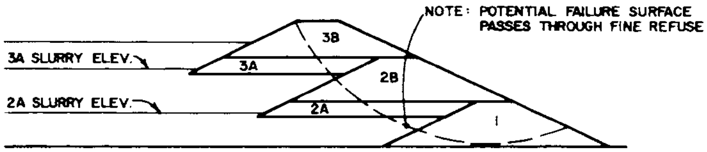

Fig. 1 Upstream Construction Method

STABILITY ANALYSIS

The method of analysis used to investigate the stability of the six tailings dams described in this paper has been presented by Thacker et al. (1988). The method is a variation of that developed by Klohn et al. (1978). The stability analysis is an effective stress analysis using a conventional method of slices slope stability technique, incorporating estimates of excess pore water pressure generated by earthquake shaking. The computer program STABR (Duncan and Wong, 1985), which employs the Bishop Modified Method of Slices, was used to analyze stresses along a slip surface passing mainly through fine coal refuse. An example cross-section is shown in Figure 2.

The computer program STABR calculated and output values of normal stress σ_n and shear stress τ on the base of each slice, as shown in the inset in Figure 2. The effective stress on the base of each slice was calculated as

$$\bar{\sigma}_n = \sigma_n - u_s \qquad (1)$$

where u_s is the static pore water pressure. Major and minor principal stresses, $\bar{\sigma}_{1s}$ and $\bar{\sigma}_{3s}$, were calculated for static conditions for each slice using the geometry of the Mohr circle shown in Figure 2. The consolidation ratio K_c was calculated for each slice using

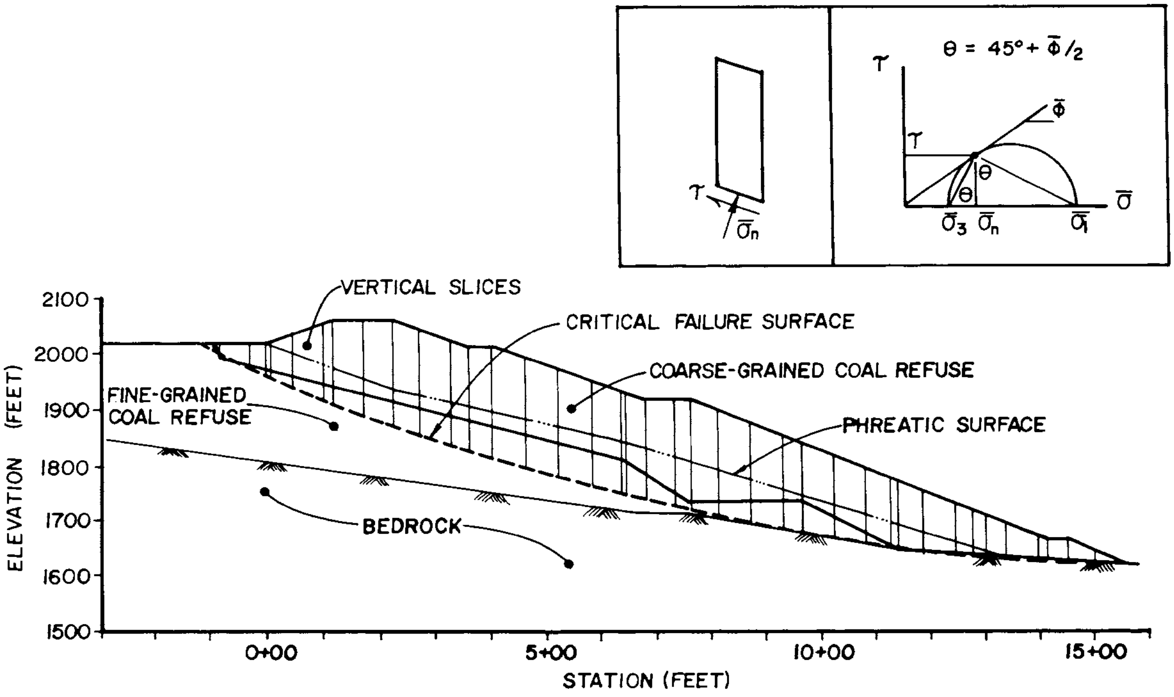

Fig. 2 Cross-Section of Abner Fork Impoundment

the equation

$$K_c = \bar{\sigma}_{1s}/\bar{\sigma}_{3s} \qquad (2)$$

The range of values of $\bar{\sigma}_{3s}$ for all slices analyzed was used to select consolidation pressures for cyclic triaxial testing. All triaxial test specimens were consolidated anisotropically using an average value of K_c for each analysis.

The psuedostatic approach was used to estimate dynamic stresses along the slip surface. A psuedostatic force kW was applied at mid-height of each slice having weight W. The seismic coefficient k was chosen using regional charts of k, such as that presented by Donovan et al. (1978). The computer program STABR was used to perform a psuedostatic slope stability analysis using the appropriate value of k and to calculate σ_n and τ on the base of each slice. Values of dynamic principal stresses $\bar{\sigma}_{1d}$ and $\bar{\sigma}_{3d}$ were calculated for each slice using values of σ_n and τ. The cyclic stress ratio SR was calculated for each slice using the equation

$$SR = \frac{(\bar{\sigma}_{1d}-\bar{\sigma}_{3d})-(\bar{\sigma}_{1s}-\bar{\sigma}_{3s})}{2\,\bar{\sigma}_{3s}} \qquad (3)$$

The average value of SR for all slices was used to dynamically load cyclic triaxial test specimens.

Cyclic triaxial tests were performed on each of the six fine refuse types to estimate excess pore water pressures generated during earthquake shaking. All tests were performed on saturated specimens consolidated from thick slurries. Four tests were performed on each refuse type using a CKC e/p Cyclic Loader (Chan, 1981). Values of effective confining pressure, consolidation ratio, and cyclic stress ratio were chosen as described above. Specimens were dynamically loaded by uniform cycles of stress using a frequency of one cycle per second. The number of cycles of loading was chosen as follows: The 50-year, 95% probable earthquake magnitude was estimated using data presented by Algermissen et al. (1982). The number of equivalent uniform cycles corresponding to an earthquake of this magnitude was estimated using data presented by Seed et al. (1975). Parameters used in cyclic triaxial testing of each refuse type are listed in Table I.

Each cyclic triaxial test produced a record of pore water pressure build up versus time, from which the maximum excess pore water pressure was normalized by dividing $\bar{u}_{max}$ by the consolidation pressure $\bar{\sigma}_{3c}$. Values of pore pressure ratio ($\bar{u}_{max}/\bar{\sigma}_{3c}$) were plotted versus $\bar{\sigma}_{3c}$, which permitted estimation of excess pore water pressure on the base of each slice.

A final slope stability analysis was performed, in which a psuedostatic force kW was applied to each slice and pore water pressures were estimated by adding excess pore water pressures from cyclic triaxial testing to static pore water pressures. In each of the six cases analyzed, the dynamic factor of safety was at least 1.2.

TABLE I. Parameters for Cyclic Triaxial Testing

Site	Location	ϕ for Fine Refuse,deg.	Range of $\bar{\sigma}_{3s}$ for Tests,kPa	Consolidation Ratio,Kc	Cyclic Stress Ratio,SR	Number of Cycles	Frequency, cps
Abner Fork	Eastern Kentucky	30	100-500	2	0.2	8	1
Bennetts Branch	Eastern Kentucky	30	100-400	2	0.2	8	1
Gum Branch	Eastern Tennessee	31	60-660	2	0.2	8	1
TCC No.1	Eastern Tennessee	30	60-600	2	0.2	8	1
Meigs	Eastern Ohio	29	60-600	2	0.2	8	1
Muskingum	Eastern Ohio	32	60-600	2	0.2	8	1

PHYSICAL PROPERTIES

Index tests, including specific gravity tests, grain size analyses, and Atterberg Limits tests, were performed on fine coal refuse specimens from each site. Results of these tests are summarized in Table II (right). Grain size distributions are shown in Figure 3.

Dynamic slope stability analyses performed for each site resulted in the following parameters being used for all tests: consolidation ratio = 2, cyclic stress ratio = 0.2, number of uniform stress cycles = 8, and frequency of stress cycles = 1 cps. Since sites were grouped closely in the western Appalachian region, a seismic coefficient of 0.1 was used in each slope stability analysis. Also, the 50-year, 95% probable earthquake magnitude was 6.1 for each site. Finally, values of angle of internal friction were similar for all six materials (Table I). Therefore, it is not surprising

TABLE II. Index Properties of Fine Coal Refuse

Site	Specific Gravity	Percent Fines	Liquid Limit	Plastic Limit
Abner Fork	1.85	82%	35.9%	26.6%
Bennetts Branch	-	76	43.6	30.9
Gum Branch	1.87	31	nonplastic	
TCC No.1	1.97	86	nonplastic	
Meigs	2.49	24	nonplastic	
Muskingum	1.79	44	31.1	23.5

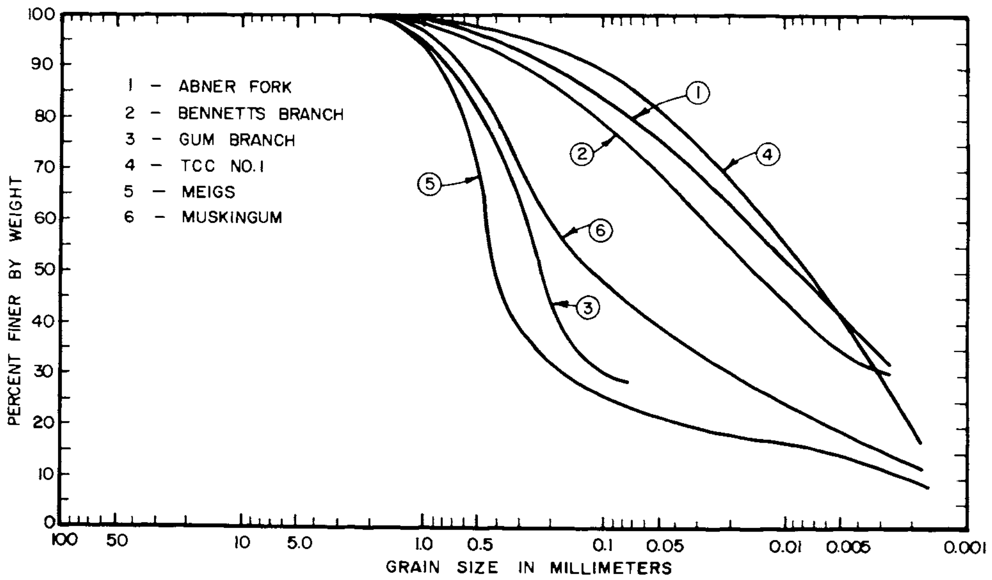

Fig. 3 Grain Size Distributions for Fine Coal Refuse

that specifications for cyclic triaxial tests would be the same for all six materials. This circumstance permitted direct comparison of cyclic triaxial test results to investigate similarities and differences in behavior.

Although values of excess pore pressure after eight cycles of deviator stress were required for dynamic slope stability analyses, many cyclic triaxial tests were continued through as many as 50 cycles of loading. Further, although test results in which a cyclic stress ratio of 0.2 was used were required for dynamic slope stability analyses, additional cyclic triaxial tests were performed in which other cyclic stress ratio values were used. An example of a test series in which cyclic stress ratio was varied is shown in Figure 4 for the Muskingum material. In this figure, pore pressure ratio at the end of each cycle $(\bar{u}/\bar{\sigma}_{3c})$ is plotted versus number of cycles for four cyclic triaxial tests in which cyclic stress ratio was varied. Each test specimen was consolidated under stresses 400 kPa (vertical) and 200 kPa (lateral). Each specimen was subjected to 50 cycles of deviator stress at a frequency of 1 cps. Two features shown in Figure 4 are significant: First, pore pressure ratio increases gradually with number of cycles for cyclic stress ratio values of 0.1, 0.15, and 0.2, indicating a progressive breakdown in specimen fabric when subjected to cycles of deviator stress small in comparison to consolidation pressure. Pore pressure ratio increases rapidly with number of cycles for SR = 0.3, indicating a rapid fabric breakdown under cycles of deviator stress large in comparison to consolidation pressure. Secondly, pore pressure ratio reaches a constant value of about 0.72 after about 20 cycles of stress for a cyclic stress ratio of 0.3; i.e., liquefaction did not occur.

As mentioned above, values of pore pressure ratio of interest in dynamic stability analyses corresponded to eight cycles of loading using a cyclic stress ratio of 0.2. None of the materials tested liquefied under these test conditions. Values of pore pressure ratio are plotted versus confining pressure in Figure 5 for all materials tested. Test conditions were those outlined in Table I. Test results shown in Figure 5 may be divided into two groups by site: One group of sites consists of sites in eastern Kentucky and Ohio. Pore pressure ratios measured for materials from these sites fall between 0.01 and 0.20. At these sites, a fine coal cleaning process is employed, which removes sand-size coal particles from the fine coal refuse. Also, three of the four materials from eastern Kentucky/Ohio sites possess measurable plasticity, which serves to limit pore water pressure build up under cyclic loading.

The second group of sites consists of two sites in eastern Tennessee where fine coal cleaning is not employed. Pore pressure ratios for these materials range from 0.40 to 0.60. Neither of these materials possesses measurable plasticity, although the TCC No. 1 material contained 86% fines.

Although the groups of sites described above and shown in Figure 5 imply that pore pressure ratio is controlled by the use or nonuse of fine coal cleaning, it is obvious that other factors influence pore pressure ratio, notably material plasticity. As shown by the specific gravity values listed in Table II, all materials contain an appreciable amount of coal. Also, all materials contain a significant percentage of fines, although this parameter bears no apparent relation to pore pressure ratio. It is hoped that as additional cyclic triaxial tests are done on materials from other sites and more data points are added to Figure 5, a clear pattern of behavior will emerge which will allow

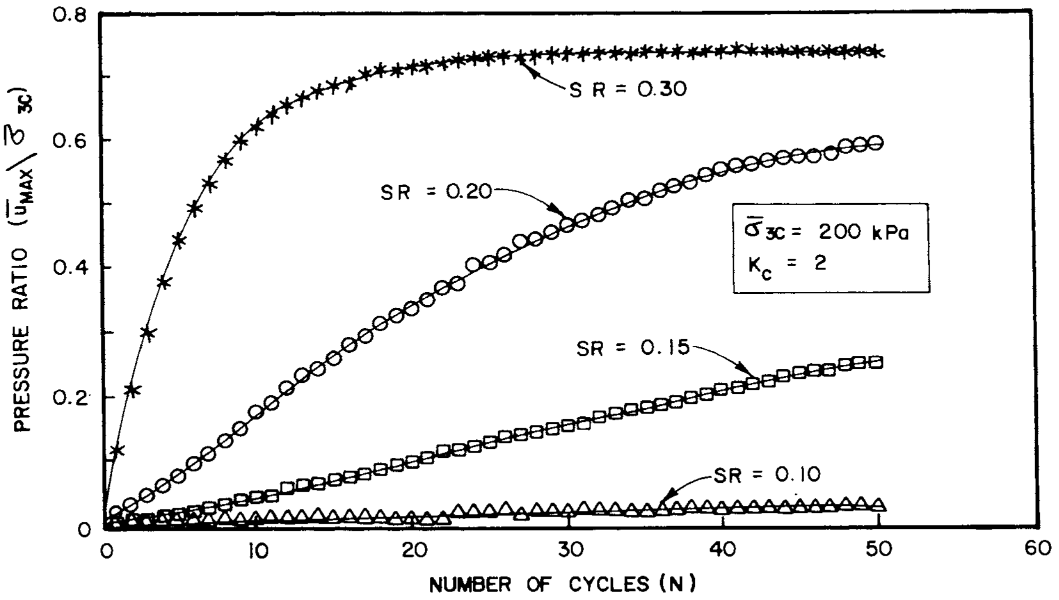

Fig. 4 Cyclic Triaxial Test Results for Muskingum Material

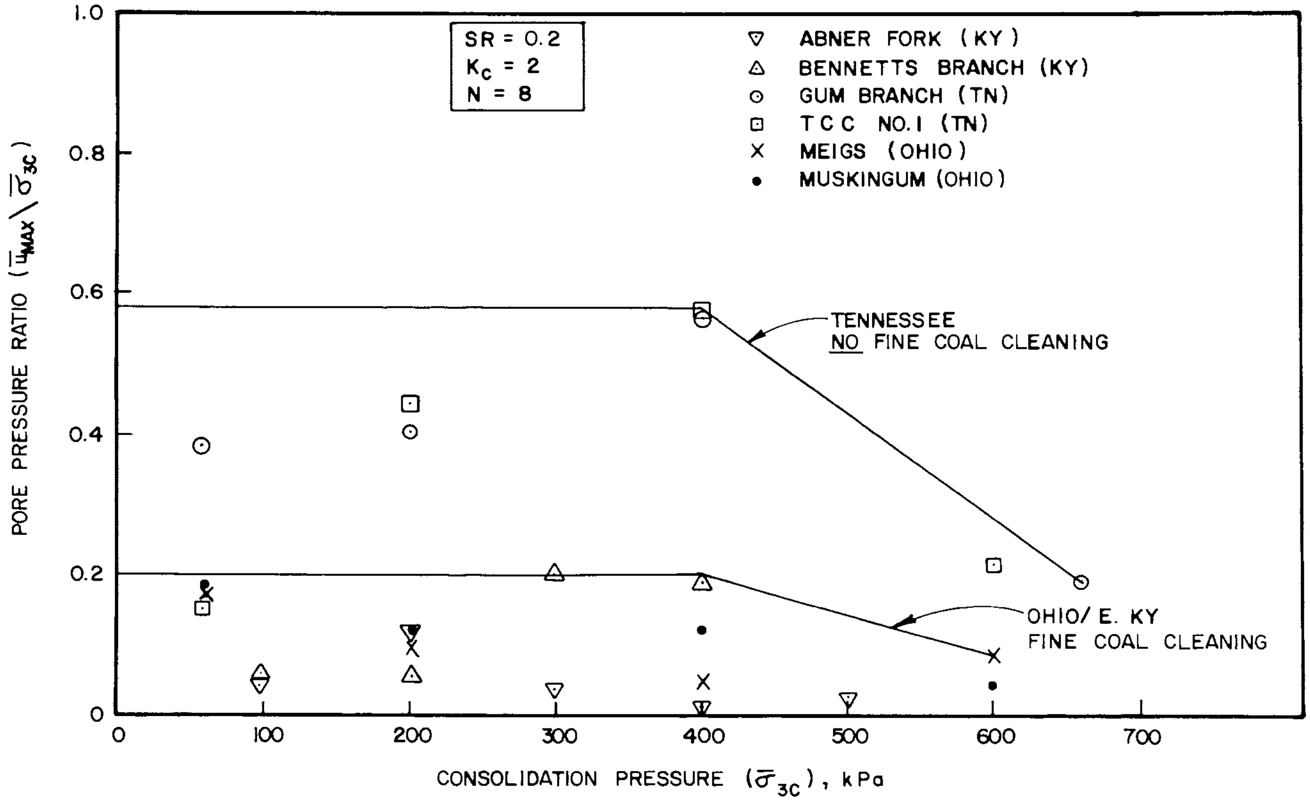

Fig. 5 Pore Pressure Ratio Values for All Sites

designers of coal tailings dams to estimate excess pore water pressures generated by seismic shaking.

CONCLUSIONS

A simplified method of slope stability analysis for coal tailings dams has been presented which accounts for earthquake loading and accompanying build up of excess pore water pressure within the embankment. The slope stability analysis uses a conventional method of slices approach in which the effect of the dynamic loading is represented as a psuedostatic force applied to each slice. Excess pore water pressure values are estimated on the basis of cyclic triaxial tests done on fine coal refuse materials. The procedure for specifying cyclic triaxial test parameters is explained in this paper.

Cyclic triaxial test results were presented for fine coal refuse materials from six sites. Although none of these materials may be expected to liquefy under conditions of dynamic loading at each site, two types of behavior were noted: for sites at which fine coal cleaning was used, measured pore pressure ratios varied from 1% to 20%. For sites without fine coal cleaning, pore pressure ratios varied from 40% to 60%. Other factors, such as plasticity, character of fines, and percentage of fines, are thought to influence pore pressure ratio; however, more data is needed and further studies are in progress.

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