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Evaluation of Liquefaction Potential of Coal Slurry

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SYNOPSIS: Hundreds of coal refuse impoundments are constructed each year to dispose of coarse and fine coal refuse. As the need for more sites develops, the suitability of available sites decreases. This creates the need for alternative construction practices such as upstream tailings dam construction methods. These methods raise the question of how to analyze the seismic and liquefaction stability of these structures. The use of down hole nuclear density and moisture probes provides a reliable method for assessing the potential stability issues for these types of structures.

INTRODUCTION

Hundreds of coal refuse impoundments are constructed each year to dispose of coarse and fine coal refuse. These impoundments generally consist of an embankment constructed of coarse refuse and a fines product called coal slurry pumped upstream of the embankment. Generally, the two products are separated at the #28 or #100 sieve with the coarse refuse being #100 or #28 mesh up to about four inches and the fine refuse being -100 or -28 mesh material. Figure 1 shows the typical gradation range of these two materials.

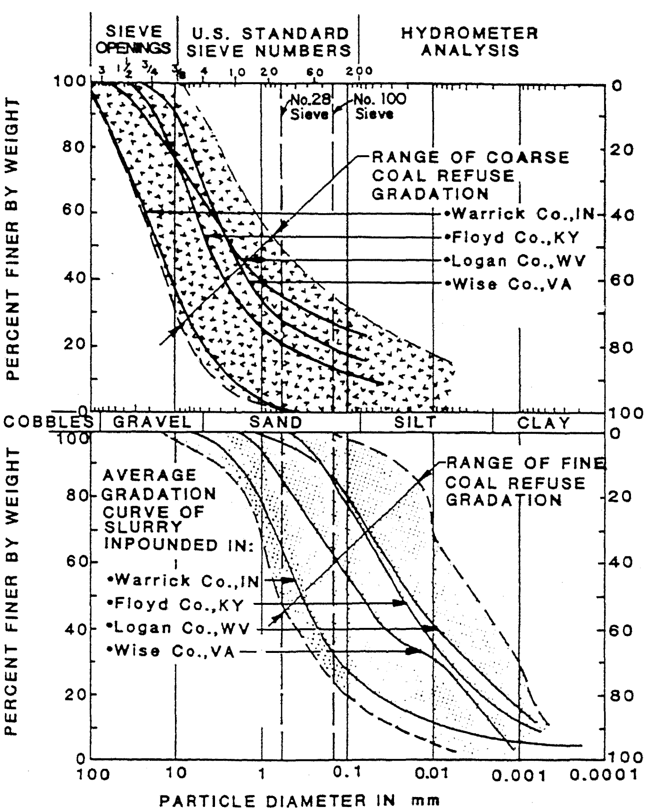

Figure 1. Typical Gradation of Coarse and Fine Refuse

Since both by-products are produced at the same time, it is necessary to sequence the construction such that the embankment constructed of coarse refuse stays ahead of the fine refuse deposited in the reservoir upstream of the embankment. It is also necessary to provide adequate freeboard for passage of the design storm, which is generally the probable maximum flood. Due to constraints of space and steepness of valleys, it is often necessary to construct in an upstream manner. Figure 2 shows the upstream construction of an embankment.

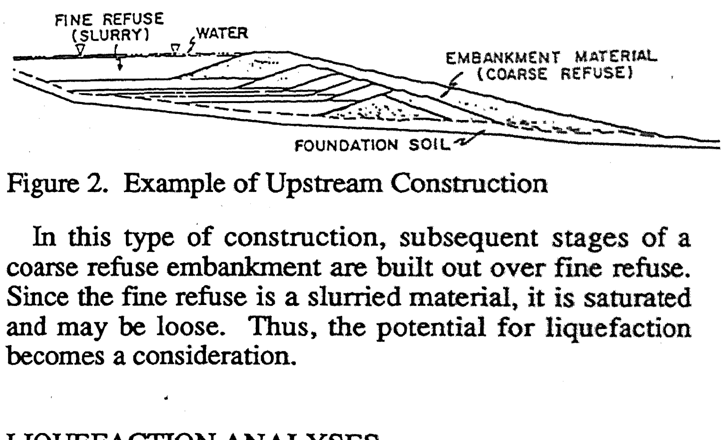

Figure 2. Example of Upstream Construction

In this type of construction, subsequent stages of a coarse refuse embankment are built out over fine refuse. Since the fine refuse is a slurried material, it is saturated and may be loose. Thus, the potential for liquefaction becomes a consideration.

LIQUEFACTION ANALYSES

There are two separate elements to consider in a liquefaction assessment:

1) the properties of the in-place potentially liquefiable material, and

2) the motions to which the structure will be subjected by the design earthquake.

This paper is concerned with the former and how to determine the characteristics of the in-place material for comparison with the ground motion generated by the design earthquake.

Historically, standard penetration "N" values have been used to assess liquefaction potential or relative density of in-situ materials in an empirical manner. Seed, Idriss, and Arango (1983) and others have developed charts and techniques for assessing the potential for liquefaction of clean sand materials based on the standard penetration test. The standard penetration test performed in silty sands, at best, gives an empirical value for the relative density of the material and it is extremely difficult to obtain an accurate standard penetration value for very fine-grain saturated materials. These difficulties are compounded by the variability of drilling techniques used today. For example, if the standard penetration test is to be consistent and accurate, a water head should be maintained in the boring or in the augers so that the appropriate pressure is maintained on the soil; otherwise, the standard penetration test will indicate a much lower relative density of the material than what actually exists. Seed, Idriss and Arango recognized this fact in their procedure and recommend adding 7.5 to any "N" value from silty sands plotting below the A-line and with a D_{50} less than .15mm.

A better method of assessing the in-place characteristics of the material throughout the entire deposit needs to be provided. The depth nuclear density/moisture gauges provide a reliable technique for determining the density and moisture content of slurry deposits (as well as other deposits) throughout the full depth of the deposit. Continuous determination of density and moisture content can be made throughout the full depth of a deposit by using the nuclear gauges. A steel access tube is inserted into the fine-grain material. This tubing is two inches outside diameter with a wall thickness of 0.172 inches. The tubing is provided with a point, and can be hydraulically pushed into the deposit to depths in excess of 100-150 feet. In denser materials, small solid augers can be used to penetrate to a depth where the tubes can be hydraulicly advanced and then install the tubing to the required depths. The tubing is inserted to the desirable depth and the probe is inserted to the bottom of the tubing. Density and moisture content readings are made as the probe is withdrawn from the bottom of the tube. The probe is raised in one-foot increments to the top of the boring (Figure 3).

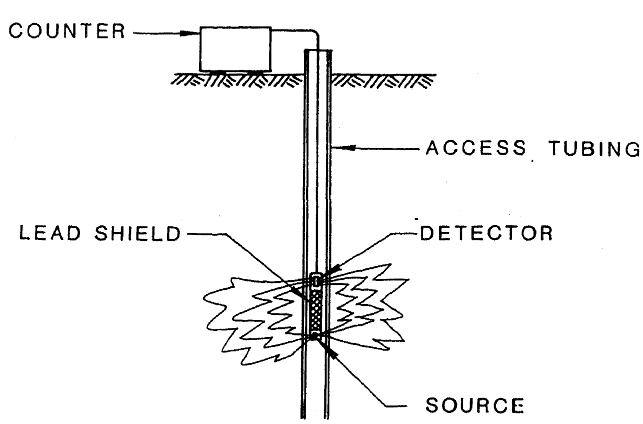

Figure 3. Nuclear Gauge

In this manner, density and moisture readings are continuously made throughout the entire depth of the deposit in one-foot increments. The insertion of the tube into the slurry creates very little disturbance as no material is removed. The probe measures the density of about 1 to 1 1/2 cubic feet of material; thereby, giving a relatively large volume measurement of density to enhance the accuracy. Both the moisture and density probes are calibrated in compatible materials to correlate the probe reading to actual physical measurements.

Since slurry deposits are generally saturated, this technique also allows the determination of the specific gravity and void ratio. If the saturation is one hundred percent and density and moisture contents are known, the specific gravity and void ratio can be calculated from the following equations.

$$G_s = \frac{\gamma_d}{\gamma_w - w\gamma_d}$$

$$e = wG_s$$

where:

G_s = Specific Gravity
e = Void Ratio
w = Saturated Moisture Content
γ_d = Dry Unit Weight
γ_w = Unit Weight of Water

Therefore, by determining the bulk unit weight and the moisture content throughout the full depth it is also possible to determine the specific gravity and void ratio for the full depth.

Once the determination of density and moisture content throughout the full depth of the deposit is known, it is possible to evaluate areas of loose and dense material. Relatively undisturbed samples can then be taken from areas revealed by the nuclear density testing to be either loose or dense material. It is recommended that samples be taken from dense areas of the deposit as well as loose areas so the entire range of density can be bracketed by the testing program. In addition, in order to more accurately assess the relative density of the particular materials, areas of materials with different specific gravities can be sampled for laboratory index testing to compare to the in-situ density for determination of relative density. Thus, in addition to determining the relative density throughout the full depth of the deposit, the nuclear density technique allows the design of a sampling and testing program to bracket the entire range of materials within the deposit.

From the densities obtained from the nuclear readings, undisturbed samples and other types of samples for index testing can be taken from the depths of interest. It is recommended that undisturbed samples of the slurry material be taken to perform dynamic and static laboratory testing. Undisturbed samples are preferred to reconstituted samples as the fine coal slurry consists of angular particles created from the crushing of coal, and the material has a fabric which may or may not be reproduced in the laboratory reconstitution of the samples. It is, therefore, better to obtain relatively undisturbed samples of the materials in the field. This can generally be done with Shelby tube samplers, or fixed piston samplers can be used if necessary. Adequate measurements of the tube sample should be made in the field and lab to monitor any sample disturbance which may occur.

Once the samples are obtained, they can be subjected to a cyclic triaxial test to obtain plots of dynamic stress ratio versus number of cycles to failure. The samples should be consolidated to the effective overburden pressure which the slurry will be subjected to at the time liquefaction becomes a potential hazard in upstream construction. As long as the upstream platform does not increase the impounding capability of the structure, there would be no release of water if the upstream portion of the structure were to fail due to liquefaction. Therefore, no safety consequence would result from a liquefaction failure of the upstream bench prior to full consolidation of the underlying slurry (Figure 4).

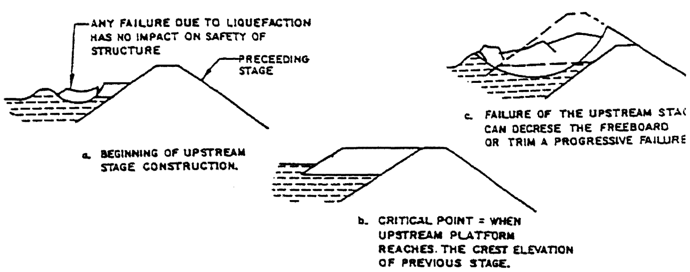

Figure 4. Possible Consequences of Upstream Stage Failure

It is, therefore, appropriate to consolidate the samples to the effective overburden pressure that will be placed on them by the upstream construction at the point at which a failure could create a release of water. Conservatively, this would be when the upstream portion of the construction reaches the crest elevation of the existing dam. There is no possibility of impounding any additional water until that point, and even after that point until the outlet is raised there is no possibility of releasing additional water. Figure 5 shows an example of dynamic triaxial testing performed at various density states. Using empirical equations (Seed and Idriss, 1971) the results translate or compare the tested densities to lower densities in the field. By using this technique, it is possible to convert the laboratory tested curves to field curves for any percent relative density and plots can be made that bracket the entire deposit in the field from a few laboratory tests.

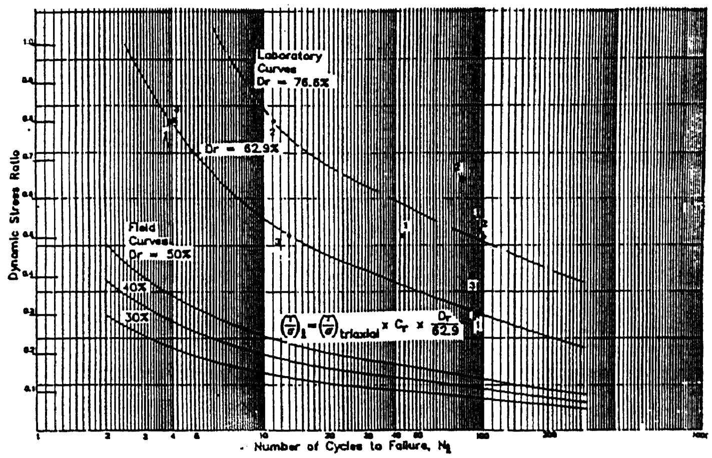

Figure 5. Results of Dynamic Triaxial Tests

In order to test the accuracy of the laboratory and design assumptions, instrumentation should be installed in the fine refuse to monitor the pore pressure buildup during and after construction. If the pore pressures dissipate during construction, then the design assumptions of consolidating the samples to the total overburden pressure created by the upstream platform are valid assumptions and no adjustments to the program are required. If the pore pressures indicate that there is a pore pressure buildup and the effective overburden pressure is less than the pressure created by the weight of the material placed on the slurry, than appropriate adjustments to the program can be made and values from dynamic tests made at lower degrees of consolidation can be utilized in the assessment. This would also allow construction to be slowed down to allow adequate consolidation to stay within design parameters.

The pore pressure devices should be pneumatic devices providing rapid reaction to the pore pressures so that instantaneous response readings are obtained. The devices should be installed at multiple levels within the slurry, preferably deep within the slurry, at midpoint; and near the coarse refuse platform so that pore pressures throughout the deposit can be monitored during and after construction. It is recommended that the devices be rugged, preferably well-point devices on a point that can pushed into the slurry with a minimum of disturbance (Figure 6).

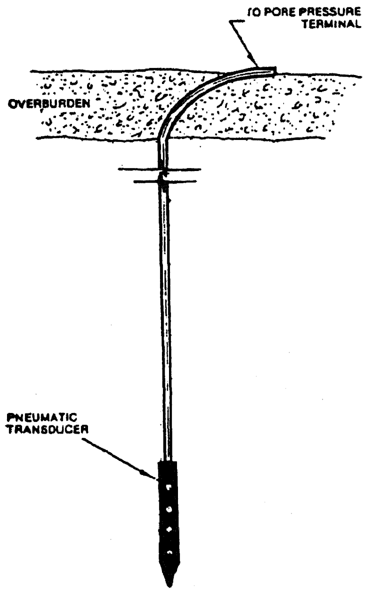

Figure 6. Well-Point Pneumatic Piezometer

CASE HISTORY

Figure 7 shows the proposed construction of an upstream stage for an embankment in West Virginia. The existing embankment had already undergone three upstream stage constructions. It was desirable to construct an additional stage, a total of some 80 feet in height above the slurry level. The design included an upstream berm to provide consolidating overburden pressure to increase the resistance to liquefaction at the toe of the upstream embankment. If this berm were to fail during an earthquake, it would not create a problem to the overall embankment.

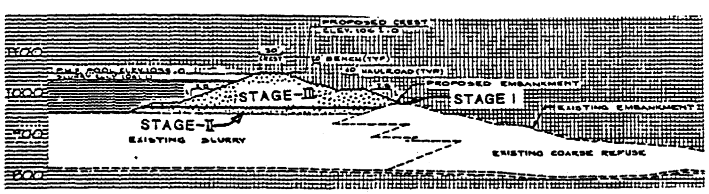

Figure. 7. Coal Refuse Disposal Site in Marshall County, West Virginia

Three borings were made to obtain in-situ density/moisture measurements utilizing the nuclear methods. The borings were made by temporarily raising the water level in the reservoir and placing a tripod on a pontoon boat. A steel tube was inserted into the deposited fine refuse to depths of 55-85 feet in depth. Nuclear probes were inserted and measurements were made at one-foot increments. Figure 8 shows the results of the readings in these borings along with the bulk unit weight, moisture content, dry unit weight, specific gravity, void ratio and relative density.

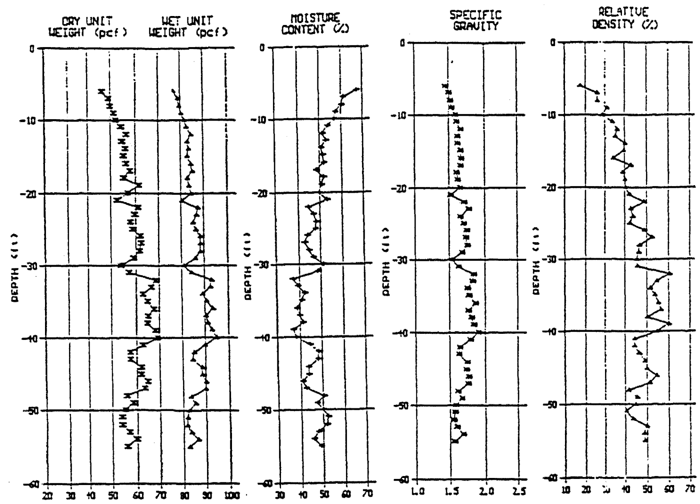

Figure 8. Results of Nuclear Measurements

Samples were obtained, index tests of maximum/minimum void ratios were prepared and the relative density was plotted as shown in Figure 8. Specimens were prepared to the field measured densities and samples were consolidated to an effective confining pressure of 35 psi corresponding to the pressure given by 50 feet of fill.

Failure in a dynamic triaxial test was considered to be when the dynamic strain reached ±5% under a constant dynamic stress ratio applied in undrained conditions. Two sets of laboratory curves were obtained, one for a relative density of 76.6%, the other 62.9%. Dynamic stress ratio was plotted versus number of cycles to failure and calculations were made to determine the dynamic stress ratio versus number of cycles to failure for 50, 40 and 30% relative density (Figure 5). The lowest relative density measured in the field below a depth of about 10 feet was about 30% with the average being well over 40%.

The site is in an area where the strongest suspected earthquake event would be from a New Madrid, Missouri event with a body wave magnitude of 7.4, and a number of equivalent uniform cycles of 15 (Seed and DeAlba, 1986). This would induce a maximum acceleration at the site of 0.05g. The analysis shows that the fine refuse will not liquefy due to seismic loading. The dynamic stress ratio at 15 cycles for even 30% relative density was about 18. Dynamic stress ratio is not the same thing as the stress required to create failure. However, there are analytical methods of assessing the factor of safety knowing the stress ratio. The time history of shear stress at various depths was estimated by the simplified procedure of Seed and Idriss (1971). According to this procedure, the amplitude of the assumed average equivalent uniform dynamic shear stress leading is determined at any depth as a function of the total vertical stress at the ppoint of interest (taking into account the full loading by the embankment fill), the maximum credible acceleration at the site (0.05g), and a stress reduction coefficient (with a value gradually decreasing from 1.0 at the ground/fill surface to about 0.5 at depths in excess of 100 feet). The dynamic shear stress was divided by the effective stress (corresponding to full consolidation under the upstream stage fill, as determined by piezometric measurements) and compared to the dynamic stress ratio for yield conditions (see Figure 5). As a result, the number of uniform equivalent cycles to induce failure by liquefaction was determined.

It was concluded that the factor of safety against liquefaction was 1.6. The details of the analytical procedures used to evaluate the liquefaction potential warrants more discussion than what is presented herein, because this paper focuses on a site assessment technique leading up to the analytical procedure.

Analyses should be made to project the generation and dissipation of pore pressure during an earthquake. This can be performed by utilizing the computer program GADFLEA, developed by Booker, Robbin and Seed at the University of California at Berkeley. These analyses, taking into account the maximum post-earthquake pore pressure buildup, showed that the minimum factor of safety of the upstream slope with a stabilizing bench was 1.6

Pneumatic pore pressure devices were installed in the fine refuse at three different locations and two different depths at each location. The deepest was around 60 feet into the slurry below the level of the coarse refuse platform. The shallowest was about 30 feet below the coarse refuse platform. The pore pressures were monitored every seven days and have been monitored every seven days since installation. Figure 9 shows the readings of the piezometers plotted versus weight placed on the slurry expressed as an equivalent head of water in feet by the upstream overburden.

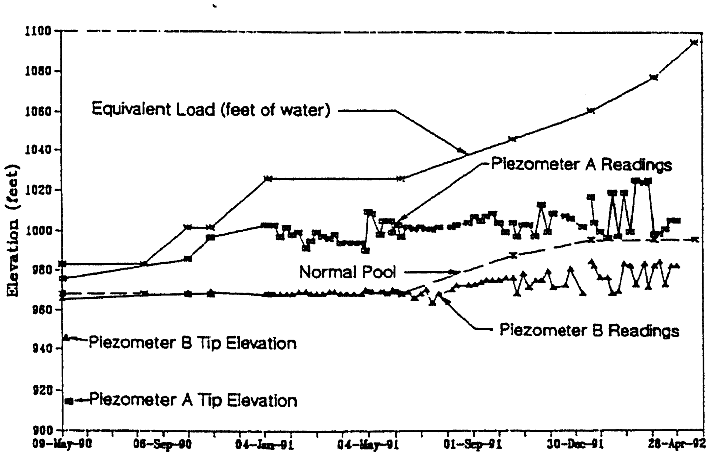

Figure 9. Pneumatic Pore Pressure Performance

It will be noted that the pore pressures never reached the equivalent waterhead indicating that pore pressures were dissipating quite readily. In fact, the upper piezometer levels indicate that the drainage is taking place quite rapidly into the coarse refuse.

CONCLUSIONS

Liquefaction potential assessments should be made at the in-situ confining stress expected to exist on the liquefiable material at the time of the dynamic event. The in-situ measurements are a very important part of the overall assessment; more important even than the determination of the design earthquake. The nuclear density/moisture method presents a reliable technique for determining the density and moisture contents as well as specific gravity and void ratio in saturated materials throughout the full depth of potentially liquefiable materials. They also present the opportunity to select and obtain relatively undisturbed and other types of samples at the appropriate and most critical locations for a laboratory testing program. This allows an examination of dynamic properties of the material at the actual density or range of densities expected within the potentially liquefiable deposit. The technique represents an improvement over standard penetration tests because it directly measures unit weight and moisture content of saturated samples. The technique is also preferable to cross-bore hole or plate seismic analyses as those types of analyses evaluate the material prior to the placement of the effective overburden pressure. The overburden pressure due to the upstream construction can provide a considerable stabilizing effect and should be taken into account in the dynamic response of the material.

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