EARTHQUAKE RESISTANT DESIGN OF TAILINGS DAMS

by

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ABSTRACT

Tailings dams are large, critically important, hydraulic structures whose structural stability must be maintained under all possible design loads, including earthquake forces. In recent years rapid progress has been made in developing methods of analyses to evaluate the stability, under earthquake loading, of conventional water storage dams. This paper describes how these same methods of analyses may be applied to assessing the stability of tailings dams under earthquake loading.

Methods of analyzing the stability, under earthquake loading, of the downstream sand tailings dam are presented. To date, the authors' approach has been to carry out a three-stage analysis, starting with the relatively simple steady-state analysis, proceeding to a simplified dynamic analysis, and finishing with a rigorous finite element dynamic analysis. Each succeeding stage of the analysis is more complex and costly than its predecessor and is carried out only if the previous stage indicates that the tailings dam is not safe.

The paper presents the results obtained by applying the suggested three-stage analysis to three sand tailings dam sections. As anticipated, the first stage, steady-state analysis gave the most conservative assessment. On the other hand, the simplified dynamic analysis gave results that were only moderately more conservative than those obtained from the rigorous, finite element dynamic analysis. This is a very significant finding for, if verified by further comparative analyses on other tailings dams, it could provide a relatively simple alternative to time consuming and expensive finite element dynamic analysis.

INTRODUCTION

The recent trend towards mining very low grade ores has required the development of large-scale mining and milling operations which produce huge quantities of waste tailings. Safely storing these waste products of the mining operation requires the construction of extremely large tailings dams. Currently, dams are under construction which will have ultimate heights in the order of 200 metres and will retain billions of tonnes of tailings and lesser amounts of fluids. These dams are critically important hydraulic structures whose structural stability must be maintained under all possible design loads, including earthquake forces. Failure of a large tailings dam is completely unacceptable as it would cause the release of very large volumes of water and/or semi-fluid tailings. Such an event would pose a serious threat to life and property downstream of the dam as well as causing extensive pollution.

In recent years rapid progress has been made in developing methods of analyses to evaluate the stability, under earthquake loading, of conventional earthfill and rockfill water storage dams. This paper describes how these same methods of analyses may be applied to assessing the stability of sand tailings dams, under earthquake loading.

TYPES OF TAILINGS DAMS

General

A critically important difference between tailings dams and conventional water storage dams is the material stored behind the dams. The bulk of material stored behind a tailings dam is soft, loose, relatively impervious tailings rather than water. Figure 1 presents typical grain size curves for tailings. The consistency of these tailings may range between the solid state and the semi-fluid state, depending on their fineness, their age, and the location of the water table. Most important however, is the fact that under severe earthquake shock, a large portion of the saturated tailings are liable to liquefy, temporarily becoming a fluid of high unit weight. The dense fluid thus formed exerts a large, additional thrust on the tailings dam which the dam must be capable of resisting. This additional force is over and above any inertial forces that the earthquake itself induces in the dam.

There are a wide variety of tailings dam designs used throughout the world, however, the three most common types of structures currently used to retain tailings are:

1) "Upstream Tailings Dams" - This type of dam is constructed in the upstream direction, over previously deposited tailings, using tailings as the construction material.

2) "Conventional Water Storage Dams" - This type of dam is constructed on prepared foundations, using selected borrow materials, conventional dam building practices, and controls seepage with an impervious core.

3) "Downstream Sand Tailings Dams" - This type of dam is constructed in the downstream direction, on prepared foundations, using cycloned sand produced from the total tailings for construction material, and usually relies on a spigotted tailings beach for seepage control.

Many variations and combinations of the above three commonly used types of tailings retention structures are encountered in actual practice. However, to simplify the presentation of earthquake resistant design concepts, this paper limits itself to the above three basic structures. The reader is directed to References 1 and 2 for a more detailed discussion of tailings dam design and construction methods.

Upstream Tailings Dams

The oldest method of tailings dam design is the "upstream method" of dam building, which is illustrated in Figure 2. This method evolved as the natural development of the original mining procedures for disposing of the tailings as cheaply as possible. There are many variations of this method but they all involve constructing a small starter dam and then depositing the total tailings upstream of the dam. Subsequent raising of the starter dam is done in stages by constructing in the upstream direction, over the top of the previously deposited, loose, saturated tailings.

Under static loading conditions there is a limiting height to which such a dam can be safely built. Under earthquake loading, this type of dam may be subject to failure by liquefaction, at any height. The authors consider that the "upstream method" of tailings dam design should not be used except perhaps for small structures located in areas of low seismicity. Consequently, the paper contains no further discussion of the method of construction.

Conventional Water Storage Dams

In areas of very high seismicity and/or where large volumes of water must be stored along with the tailings, construction of a conventional water storage type dam to retain the tailings often provides the only satisfactory solution. Where waste rock or overburden materials are available from the open-pit, stripping operations these are usually used for construction. Figure 3 illustrates a conventional water storage dam that might be constructed for storing tailings.

The advantages of using a conventional water storage dam for the retainment of tailings are obvious. The structure can be designed and constructed to safely resist any desired earthquake event, and, in addition, adds a great deal of flexibility to the operation of the tailings pond. Unfortunately, this method of tailings dam construction is usually the most expensive.

Downstream Sand Tailings Dam

The "downstream methods" of sand tailings dam design have evolved as acceptable alternatives to the generally unsatisfactory "upstream methods". The sand required for dam construction is usually produced by cycloning the total waste tailings. The cycloned sand thus produced is a very cheap construction material that extracts up to 50% of the total tailings as dam building material. A commonly used method of downstream sand tailings dam construction (centreline method) is illustrated on Figure 4. All of the downstream sand tailings dams have two features in common: the sand dam is raised in a downstream direction and consequently is not underlain by previously deposited tailings; and the tailings are spigotted off the upstream face of the dam to provide a lower permeability beach between the sand dam and the water in the tailings pond. Other advantages of this method of construction include the ability to: prepare the foundation and install drainage; and control placement and compaction of the sand. Consequently the sand tailings dam can be designed and constructed to whatever degree of competency is required, including earthquake resistance.

EARTHQUAKE DESIGN CONSIDERATIONS

Selection of Design Earthquake

In areas where seismic disturbances may occur, analyses are required to determine the effects of the design earthquake on the proposed tailings dam. Selection of the magnitude of the design earthquake normally involves obtaining the recorded data and/or historical descriptions for all known earthquakes in the area together with statistical analyses predicting earthquake magnitudes for various return periods. Also required is a detailed geological assessment of the structural geology and tectonic setting for the area, with particular attention to existing faults and their history of movement. The exact procedures used to estimate the design earthquake for a particular site vary, and may utilize either deterministic or probabilistic methods (3). However, all methods involve a large degree of judgment and require extensive experience in this field.

A method commonly used to determine the parameters appropriate for the selected design earthquake at a particular site, is to assume that the design earthquake occurs on the closest known, possible active fault. The fault is selected on the basis of the geological studies that have been made for the area. Suitable attenuation curves (4, 5, 6) are used to estimate the peak acceleration of the earthquake forces reaching the site. These values together with duration evaluations based on the assumed magnitude, are then used to assess the behaviour of the structure under the design earthquake. For the finite element dynamic analysis, selection of an appropriate acceleration record with proper frequency content for use in the computations is a difficult task requiring considerable experience (7).

Effects of Earthquake Forces on Dams

Conventional Water Storage Dams - When a dam is subjected to earthquake forces there are three distinct aspects of the problem that must be considered over and above those considered for the conventional static analysis. These are: earthquake inertial forces, loss of strength due to strain or remolding, and loss of strength due to pore pressure development.

Where a conventional water storage dam is used to retain tailings, a fourth factor, the potential liquefaction of the slimes in the pond, must also be considered. This occurrence places a sudden, additional shear force on the tailings dam which does not occur when water only is stored behind the dam.

Compacted earthfill or rockfill water storage dams, built to present-day engineering standards, will not lose appreciable strength due to strain nor will they develop significant, excess pore pressures during an earthquake. Consequently, where such a structure is used over a competent foundation to retain tailings, no appreciable loss of strength should occur and the earthquake stability analysis can usually be simplified to evaluate the combined effects on the dam of: the normal static forces, the inertial forces caused by the earthquake; and the additional shear force caused by the liquefaction of the tailings in the pond. Procedures for such analyses are described in detail by Seed (8) and will not be discussed further in this paper.

Downstream Sand Tailings Dams - The magnitude of the pore pressures that build up in a saturated, sandfill dam for a given earthquake, is a function of the density of the sand. The denser the sand the less the pore pressure build-up. On the other hand, if the sand is dry, pore pressure build-up will be negligible, even if the sand is very loose. Therefore the two main design protections against the development of significant excess pore pressures are drainage and compaction.

Where the earthquake risk is very high and cycloned tailings sands are used to construct the tailings dam they are normally heavily compacted to produce a very dense sand fill. These structures will not develop significant, excess pore pressures during an earthquake and consequently are normally assessed as outlined in the previous section for conventional water storage dams that retain tailings.

However, at most tailings dam sites the earthquake risk is low to moderate and designs that combine good drainage with construction procedures that produce a medium-dense sand fill are often selected as the most economical tailings dam design. As such medium-dense sand dams may undergo appreciable pore pressure build-up under earthquake loading, with subsequent loss of strength, the decision to use this method must be carefully evaluated by the designer. The earthquake stability analysis required to assess such a sand tailings dam must include a means of evaluating the magnitude of the excess pore pressure build-up in addition to evaluating the combined effects of the normal static forces, the earthquakes inertial forces, and the liquefied pond shear forces. Methods for carrying out such analyses are discussed following.

STABILITY OF DOWNSTREAM SAND TAILINGS DAMS UNDER EARTHQUAKE FORCES

General

A recent paper by Lo et al (9) sets out a general approach developed by the authors' firm for evaluating the stability of sand tailings dams when subjected to earthquake forces. The method follows a staged process, with each successive stage involving a more complex and costly type of analysis. In ascending order of cost and complexity the three stages of dynamic analyses used are:

1) Steady-State Strength Analysis (10)
2) Simplified Dynamic Analysis (11, 12, 13)
3) Finite Element Dynamic Analysis (7, 8)

As each of these analyses has been extensively described in the literature only a very brief description will be given in this paper.

Steady-State Strength Analysis - The concepts of the steady-state strength type of analysis have been described by Castro (10). In effect, the steady-state undrained strength is the lowest possible strength which a given sand, in a contractive state, at a given density and under a given confining pressure could reach if it were subjected to an earthquake of sufficient magnitude and duration to force the sand to lose enough strength that it reaches the steady-state condition. In this type of analysis the steady-state undrained strength along the potential failure surface, as determined from laboratory tests, is used in a conventional static limit equilibrium stability analysis. The analysis must include the increase in the horizontal thrust due to the liquefied tailings in the pond. The inertial forces caused by the earthquake are not included as these are of very short duration and the dam is assumed capable of safely absorbing the related brief horizontal movements.

The steady-state method is a quick and relatively inexpensive form of analysis and represents the worst possible conditions that could develop for the dam of low to medium density during an earthquake. At sites involving loose, saturated materials where the seismic risk is high, the method is considered to provide a reasonable assessment of the tailings dam's stability under earthquake loading. However, for medium-dense sands at sites of low to moderate seismicity the extent of seismic loading is usually insufficient to force the materials completely into a steady-state condition. For these conditions the steady-state analysis is considered to provide an overly conservative assessment of the dam's seismic stability. Sand tailings dams constructed using the centreline or downstream methods of construction usually fall into this medium density category. If such a tailings dam successfully passes the steady-state analysis, more sophisticated analysis are obviously not required. On the other hand, if the steady-state analysis indicates that a problem in stability might exist, then the next stage in the evaluation would be to run either a simplified dynamic analysis or a finite-element dynamic analysis.

Simplified Dynamic Analysis

There are a number of simplified dynamic methods available for analyzing earth dams and tailings dams (8). Of these methods, one was developed especially for evaluating sandfill tailings dams (11, 12), using a modified pseudo-static stability analysis computer program (SEISLOP, Ref. 13). The authors use this program for making simplified dynamic analyses of sand tailings dams. Briefly, this simplified analysis involves the following steps:

1. A design earthquake and its related parameters are selected for the site.
2. Static stress conditions on an assumed failure surface are evaluated using a conventional limit-equilibrium form of analysis.
3. The limit-equilibrium analysis is then repeated to determine the increases in static stresses on the failure surface, due to the additional horizontal thrust of the pond caused by its liquefaction. This thrust is assumed to be applied rapidly. Skempton's pore pressure parameter $\underline{A}$ is used to determine the pore pressure caused by this loading along the saturated portion of the failure surface.
4. Inertia forces are then applied to the dam, using a conventional limit-equilibrium analysis to determine the resulting cyclic shear stresses on the assumed failure surface. The inertia forces are calculated using appropriate seismic coefficients. These coefficients may be computed from the graphs given in Ref. 11, which is based on the work by Seed and Martin (14).
5. Using the design earthquake parameters, the physical properties of the sand, and the cyclic triaxial test data, the pore pressure increases caused by the cyclic inertia forces are determined. These cyclic pore pressures are then added to the original pore pressures developed by the steady seepage and the increased static pore pressures resulting from liquefaction of the pond at the onset of the earthquake (Step 3 above).
6. Finally, the resulting increased pore pressures are used to calculate the reduced effective normal stresses on the failure surface for the condition immediately following the last cycle of the earthquake. At this time the inertia forces are equal to zero and the full horizontal thrust of the liquefied pond is assumed to be acting on the dam.

The SEISLOP simplified dynamic method of analysis requires more field and laboratory data than does the steady-state analysis, and also requires the selection of a design earthquake. However, the SEISLOP analysis program is simpler and less costly to run than are the programs for the finite-element analysis, while at the same time acknowledging the importance of energy input levels from the earthquake. Moreoever, it attempts to approximate pore pressure conditions that would likely fall somewhere in the gap between those corresponding to the fully drained static state and those associated with the fully developed, undrained, steady-state. It does, of course, also include many more approximations than does the finite-element method, which approximations have been discussed elsewhere (11).

Finite Element Dynamic Analysis

Finite element dynamic analysis procedures for analyzing the earth and rockfill dams and tailings dams have been described by Seed (8) and Finn (7). These solutions, which represent our best current state-of-the-art engineering knowledge on this subject are complex; involve complicated, finite element, computer programs; require the input of a broad spectrum of engineering skills and experience; and are time consuming and expensive. A detailed discussion of such analyses is far beyond the scope of this presentation and the following comments are intended mainly to highlight the necessary steps:

1. Determine the static and dynamic properties of the soils comprising the dam, the upstream tailings beach, and the foundation.
2. Subject representative samples of the embankment materials to laboratory tests simluating the combined effects of the initial static stresses and the superimposed dynamic stresses and determine their effects in terms of the generation of porewater pressures and the development of strains.
3. Determine the static, pre-earthquake stresses within the dams.
4. Determine the time history of base excitation to which the dam and its foundation may be subjected by the design earthquake.
5. Determine the dynamic response for the dams and its foundation to the seismic loading from Step 4 above. (This step might need adjustments to compensate for the additional shear forces caused by potential liquefaction of the tailings pond).
6. Evaluate the overall strain potential and performance of the dam.
7. Carry out a post-earthquake limit equilibrium analysis using: the effective friction angle for the sand obtained from consolidated undrained static traixial tests; the effective normal stress on a potential failure surface which has been computed by subtracting from the total stress on the failure surface the sum of the following pore pressures: (1) the original static pore pressures established by the steady seepage condition; (2) the pore pressure caused by the pond liquefaction; (3) the pore pressure rise caused by earthquake shaking. In making this post-earthquake analysis it is also assumed that the lower limiting value of the shear strength along the failure surface is defined by the steady-state undrained strength regardless of the pore pressure values calculated from the dynamic finite element analyses.

Obviously, a complete and detailed dynamic analysis is a major undertaking which requires an extensive data base and specialized skills to perform satisfactorily. For these reasons such analyses should be reserved for major tailings dams where failure would pose a serious threat to life and property downstream and where the Stage 1 (steady-state) and/or Stage 2 (simplified dynamic) analyses have indicated that a more detailed review of the stability problem is required.

COMPARISON OF STABILITY ANALYSES RESULTS

The three dam sections presented on Figure 5 were selected for comparative analyses, using each stage of the recommended three-stage approach for analyzing a sand tailings dam under earthquake loading. These analyses used static and dynamic parameters that were obtained from extensive field and laboratory testing programs on sands from a typical, large, downstream sand tailings dam. Space limitations preclude the presentation of the laboratory and field data as well as a detailed discussion of the three stability analyses, however, these data will be covered in a subsequent publication.

All analyses are "immediate post-earthquake" and assume that the maximum pore pressures developed during the earthquake are present. They also assume that the pond has liquefied to its full depth and therefore adds a significant thrust on the dam, a very conservative assumption. No inertial forces due to the earthquake are included in the "post-earthquake" analysis.

All the stability analyses have been carried out using a computer program based on the limit equilibrium procedures described by Janbu (15). The design earthquake used for all analyses was a Richter magnitude 6.5 producing a maximum horizontal acceleration of 0.38 g at the bedrock foundation about 100 ft below the base of the dam.

A summary of the factors of safety obtained from the earthquake stability analyses is presented in Table 1. An examination of these data indicates that:

1. The factors of safety obtained using the "steady-state" analysis are significantly lower than those obtained from the other two methods of analysis.
2. The factors of safety obtained from the "simplified dynamic" analysis (SEISLOP) closely approximate those obtained from the more rigorous "finite element dynamic" analysis.

The steady-state method of analysis does not consider the magnitude of the earthquake to which a given dam might be subjected. Consequently, the values for factor of safety given in Table 1, would be the same whether the earthquake magnitude was 5.5 or 7.5. On the other hand, the factors of safety presented for the SEISLOP and Finite Element Dynamic analyses would both become larger for the M=5.5 earthquake and smaller for the M=7.5 earthquake.

CONCLUSIONS

The results of these analyses, which are presented in Table 1, demonstrate that the steady-state analysis provides the most conservative assessment of the stability of the downstream sand tailings dam and provides the "bottom-line" factor of safety for the dam. These results also suggest that the simplified dynamic analysis using the SEISLOP program provides an assessment of the stability of a sand tailings dam, under earthquake loading, which closely approximates the results obtained using the more rigorous, time consuming, and expensive, finite element dynamic analysis. Although further correlating analyses are required to compare the two methods over a wider range of variables before a definitive relationship can be established, the initial results are very encouraging and suggest that the SEISLOP method will provide a viable alternative to the finite element dynamic analysis for medium-dense sand tailings dams, located in areas of low to moderate seismicity.

In the event that further studies should confirm these preliminary results, the authors would propose dropping the finite element dynamic analysis for all but the most unusual and/or critical downstream sand tailings dams and going to a two-stage analysis using only the steady-state and SEISLOP procedures.

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TABLE 1

FACTORS OF SAFETY FOR DOWNSTREAM SAND TAILINGS DAMS UNDER EARTHQUAKE LOADING

(Using Three Methods of Analysis(1))

			Computed Factors of Safety		
Dam Section	Height	D/S Slope	Steady-State Analysis	Simplified Dynamic Analysis(2)	F.E.M. Dynamic Analysis
A	107 m (350 ft)	3:1	1.1	1.2	1.4
B	146 m (480 ft)	3:1	0.8	0.9	1.2
C	152 m (500 ft)	3:1	0.9	1.1	1.1

NOTES

(1) All analyses were carried out for the immediate post-earthquake condition.

(2) SEISLOP program was used for the simplified dynamic analysis.

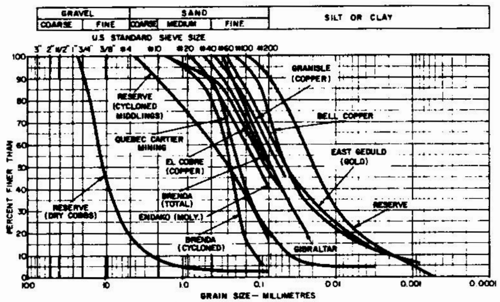

FIG. 1 - TYPICAL GRAIN SIZE CURVES FOR TAILINGS

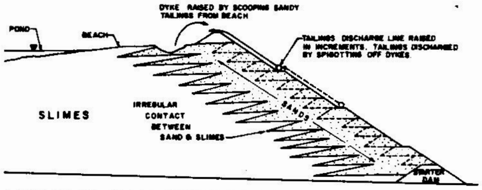

FIG. 2 - TAILINGS DAM CONSTRUCTED BY UPSTREAM METHOD

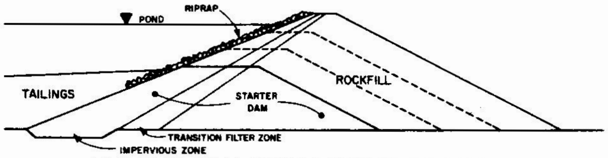

FIG. 3 - TAILINGS DAM CONSTRUCTED AS CONVENTIONAL WATER STORAGE DAM

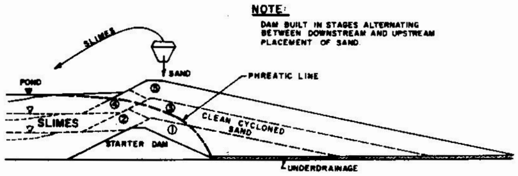
NOTE:
DAM BUILT IN STAGES ALTERNATING BETWEEN DOWNSTREAM AND UPSTREAM PLACEMENT OF SAND.

FIG. 4 - SAND TAILINGS DAM CONSTRUCTED BY DOWNSTREAM (CENTRELINE) METHOD

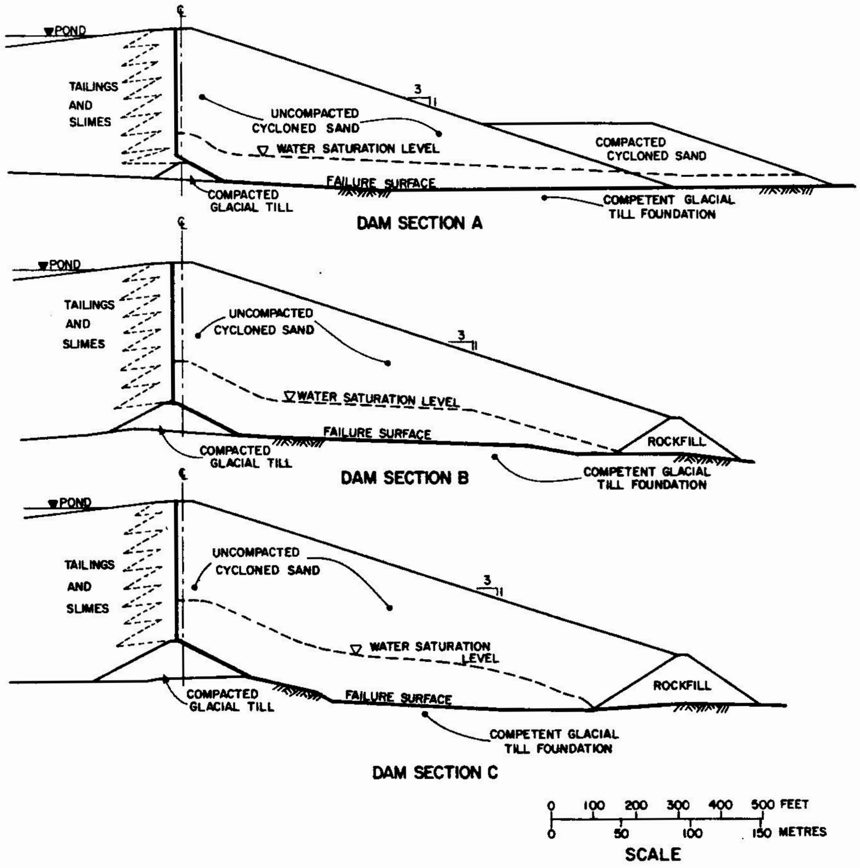

FIG.5 - DAM SECTIONS USED FOR COMPARATIVE STABILITY ANALYSES