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Design and Behavior of Tailings Dams Under Seismic Conditions

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STATE OF THE ART (SOA5)
Design and Behavior of Tailings Dams Under Seismic Conditions

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1. INTRODUCTION

Seismic design of tailings dams in present times has to provide statisfactory solutions to fulfill environmental protection requirements and to assure proper behavior after closure and abandonment. The requirements to protect the environment include control of seepage and other forms of pollution of the air, waters and soils, under normal conditions, and also under the most extreme events which may be foreseen to occur. The worst possible form of pollution under such extreme conditions is a liquefaction failure envolving breaching of the dam and flooding of the valleys downstream.

The probability of ocurrence of maximum events obviously increases with the period of time considered, therefore, for the abandonment period of a tailings dam, a maximum credible earthquake has to be considered and a 500 year period is normally requested for such prediction.

Relatively large areas become endangered, under these conditions, around every tailings dam built in a seismic region. As time passes important parts of such areas shall be inhabited or developed for agricultural or industrial production, increasing their values, due to increase of population and growth of the economy. The combination of maximum earthquake, increasing demands for environmental protection and increasing values of the risks associated to tailings deposits, pose severe requirements for seismic design of the dams.

If these requirements are confronted with the dynamic properties determined by tests performed in laboratory prepared specimens of tailings soils, as is normal today for a new dam, they result in very expensive designs. On the other hand, recent observations of real seismic behavior of abandoned deposits of tailings and investigation of dynamic properties of tailings soils suggest that age has some favourable effects in the stability of these structures and that consideration of such effects may produce significative improvements in their design.

Therefore, the emphasis of this paper shall be placed on those aspects of seismic design specifically related with environmental protection, abandonment and time effects.

2. TIME EFFECTS IN TAILINGS SOILS

2.1 Nature of time effects

Tailings dams are soil structures which properties change as functions of time. This is a peculiar characteristic which is not commonly taken into consideration in the present state-of-the-art of seismic design because there is little knowledge about the real effects of time and about how to evaluate their consequences in order to include them in the structural models for design. However, there are many evidences of satisfactory seismic behaviors of old and abandoned deposits of tailings in countries where frequent and strong earthquakes do occur. Such behaviors are the natural consequences of several effects, some of them very well known, such as consolidation and dewatering, and others not so well known such as chemical changes, aging and seismic history effects.

Seismic design for abandonment stage does need to consider the effects of time, either favourable or unfavourable, if a realistic result is to be obtained.

2.2 Evidences of time effects

a) Cyclic strength as function of age

Troncoso et al (1988) found that cyclic strength of undisturbed samples obtained in deposits of tailings of different ages showed a strong favourable effect of time. Thirty year old specimens showed cyclic strengths which were about double the cyclic strength of one year old samples, as shown in Fig. 1. This important tendency is explained by long term chemical reactions between the minerals of the soil particles and the salts dissolved in the water. A fraction of the strength gain is also caused by consolidation: such increase has been determined to be no more than 30 percent for overconsolidation ratios of 2, and larger increases are, therefore, result of long aging effects (Troncoso and Jiménez, 1991).

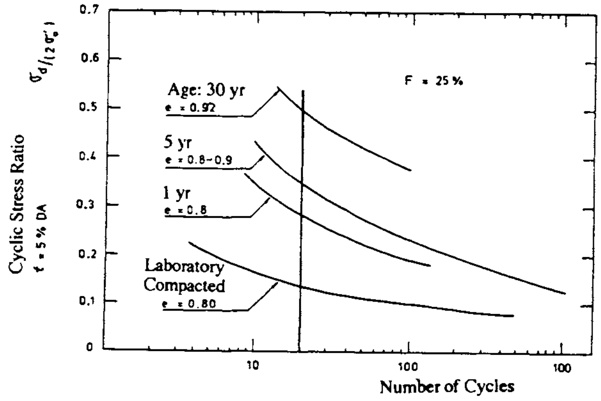


FIG. 1 AGING EFFECTS IN TAILINGS SANDS

b) Penetration resistance as function of age

Shear strengths, measured by cone penetration tests (CPTU) in tailings deposits of different ages, have shown tendencies to increase with time (Garga and Troncoso, 1991). Such CPTU measurements included point resistance, q_c, and lateral resistance, f_s, to penetration under hydraulic pressure. The effect of consolidation is excluded when comparisons are made for soils of same depths, as shown in Fig. 2.

These results indicate that aging effects may be important but highly dependent on the mineralogy of the soils, chemical composition of the fluids, and environmental parameters, such as temperature and precipitations.

c) Effects of seismic loadings

Any tailings deposit built in an area of high seismicity will be subjected to frequent tremors and earthquakes, from the very beginning of construction, through several rise stages of operation and after closure. The vibrations induced by the seismic events shall affect the properties of the soil structures which form the deposit causing densification under dynamic inertia forces larger than resistances between soil particles.

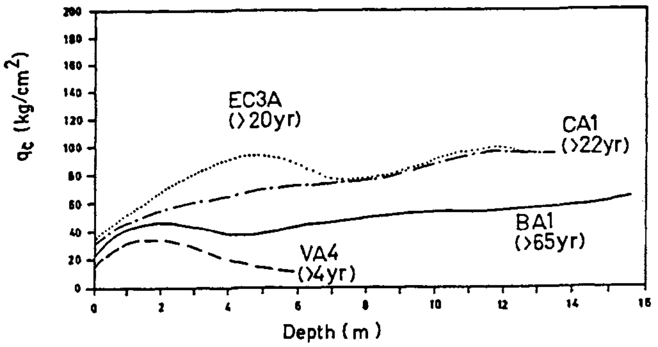
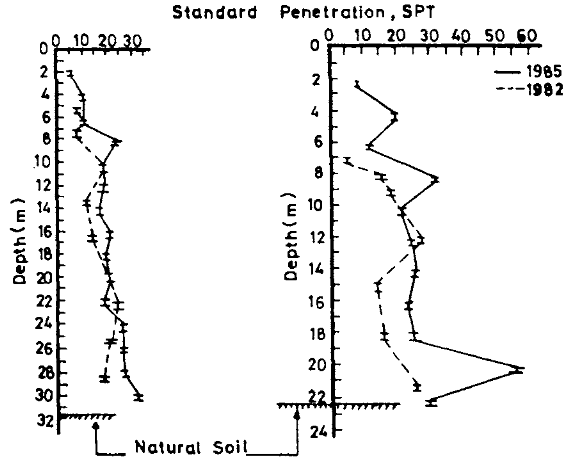


FIG. 2 POINT RESISTANCE VS AGE IN TAILINGS DAMS. CPTU

Densification of cohesionless soils, such as tailings sands and silts, obviously shall increase the shear strength and shall decrease the compressibility of the soil structures. Such favourable effects have been verified in tailings dams by means of standard penetration resistances (SPT) recorded before and after occurrence of a strong earthquake (Troncoso, 1992). As shown in Figs. 3 and 4, conversion of SPT values to relative densities (I_{rd}) indicate that silty sands looser than 50 percent densified under the seismic loadings, while those denser than 65 percent became looser. Such results are in very good agreement with previous data from triaxial tests which defined the critical relative density between 50 and 60 percent.

Increases in density also mean decreases in void ratios to become closer to the critical value, which for given effective stresses separate compressional from dilatational stress-strain behavior (Castro, 1969). Thus the soils densified by seismic loadings become stronger to support future earthquakes. In particular, liquefaction potential decreases and general factors of safety for stability increase.



a) Borehole G-4 b) Borehole C-6

FIG. 3 SPT RESISTANCE BEFORE AND AFTER EARTHQUAKE

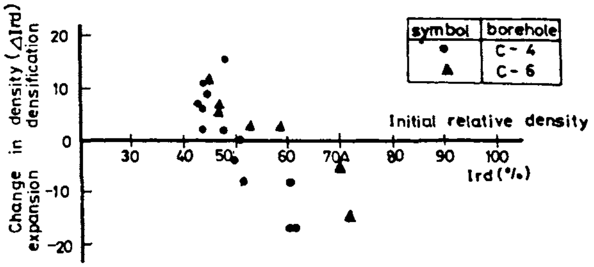


FIG. 4 SEISMIC CHANGES DETECTED BY IN-SITU TESTS

3. DESIGN FOR ABANDONMENT CONDITIONS

3.1 Methodology of design

The design for abandonment of tailings dams needs to use methodologies of integrated design and construction, more than any other geotechnical projects, due to the fact that the ways the dam is built, the reservoir is filled, the water is managed, are all important for the future behavior of the deposits. Further yet, observation and monitoring of the real behaviors of the soils constitute much needed sources of information to supplement data on long-term evolution of soil properties. Such informations should be properly fedback in the models utilized for initial design in order to improve the accuracy of predictions and quality of the project, both for environmental protection and for stability purposes. A summary of mathematical methods which are well known and used for design are included in the section on stability of slopes of these Proceedings, by Séco e Pinto et al (1995).

Monitoring the evolution during construction and operation of a tailings dam is further necessary because the composition of the disposed soil may change during operation due to changes in the minerals and/or in the metallurgical and extraction processes. A proposed flow chart for the integrated methodology of design and construction is shown in Table 1. In this chart the stages are: exploration, design, construction and evalution. Each one of these stages include performance of several tasks; the most relevant tasks for the seismic design for abandonment are detailed in next sections.

Table 1. Seismic design for abandonment.

STAGE	TASKS
EXPLORATION	Investigations & Compilation of Data necessary to define the project to prepare the analytical models of the tailings dam, impoundment and foundations, and to determine the risks of the site and basin.
DESIGN	Preparation of analytical models, calculations of behaviors for normal and eventual loadings, including maximum credible events, and designs of structures, reinforcements, remedial and mitigation works. Stability and dynamic analyses by staged approach.
CONSTRUCTION	Building and operation of the deposit in accordance with specifications; controlling the works to assure the quality of the structures and auxilliary installations.
EVALUATION	Monitoring of behavior since the beginning of construction, through operation and after closure, feeding back results in Design models and improving the project according with results (expansions, reinforcement).

3.2 Seismic loadings

In high seismicity countries the maximum credible earthquake (MCE) should be used as the maximum design event. The design criteria for such strong event should be based on: 1) a realistic assessment of the seismicity of the site, 2) a precise knowledge of dynamic properties of the foundation materials, and 3) a knowledgeable prediction of the consequences of unfavourable behavior of the dam.

The effects of an MCE in a tailings dam will depend of the characteristics of the ground motions at the base of the dam. The ground motions are the result of: the source location and magnitude of the event, the nature of the seismic path of the seismic waves to the dam site and the dynamic properties of the geotechnical materials encountered between the bedrock and the base of the dam.

The deterministic procedures to select the MCE include the preparation of regional maps with all the informations gathered on tectonic and geologic data plus locations of epicenters and magnitudes of recorded earthquakes. The potential source is thus identified, the closest distance to the site is determined and the maximum magnitude is assigned. These procedures are usually difficult to complete satisfactorily due to lack of records of strong earthquakes (Lo & Klohn, 1991).

Installation of adequate accelerographs at every important tailings dam is a most needed improvement in the present state of the art because there are no substitutes for them in any design-behavior analysis. The purpose of seismic instrumentation is to record events from the beginning of the life of a tailings dam and to assist in monitoring behavior and evolution, including seismic history, so helping to predict future seismic behaviors and to adopt improvements as they may become really necessary.

The characteristics of the seismic movements at the base of a dam may be analyzed, once the bedrock motions are well established, only if the dynamic properties of the foundation materials become known with a degree of precision satisfactory for the preparation of good representative mathematical models. As it is known that dynamic properties of soils are strain dependent, representative models for seismic analyses have to be constituted with variable shear moduli and damping ratios as functions of shear strain values comparable to those generated by strong earthquakes.

3.2 Dynamic properties of foundation soils

The characteristics of the ground movements at foundation level are different from those at bedrock underlying the dam site because soil layers in between act as filters for the wave propagation phenomena. The predominant period of the ground motions, T_o, is a function of the shear wave velocity, V_s, as it is easily found for a uniform soil deposit of thickness H:

$$T_o = \frac{4H}{V_s}$$

Larger amplification of the dynamic response of the dam to the seismic ground motions occur when the natural period of the structure coincides with the predominant period of the ground and an effect of resonance is thus created.

The wave velocity is related to the shear modulus, G, and to the mas density, ρ, by the relationship:

$$V_s = \sqrt{\frac{G}{\rho}}$$

and, therefore, it is a parameter representative of the soil structure. As such it is very important that direct measurements be made in the complete soil deposit which shall become the foundation for a tailings dam. The measurements at different layers of the stratigraphic profile of wave velocities should be performed in the undisturbed structures, under the real prevailing state of stress and at the strain range corresponding to the strong earthquakes predictable for the site.

The stress history of the soil deposits changes the structural dynamic properties of the soils, such as shear wave velocity and damping ratio, as well as the standard penetration resistance, SPT, as it has been measured by in-situ tests (Troncoso, 1975) for strata of silty sands and clays of different degress of overconsolidation. Comparisons of shear moduli and damping ratios, as function of penetration resistances serve to illustrate the effect of stress history: 1) slightly overconsolidated soils have smaller shear moduli and smaller rates of increase with SPT than highly overconsolidated soils, 2) higher degrees of overconsolidation lead to higher damping ratios. These measurements were made with in-situ cross-hole wave propagation tests where polarized shear waves were generated by impacts at the high strain level of strong earthquakes. Such type of in-situ tests should be performed at every prospective site of large dams in order to obtain truly representative profiles of dynamic properties recorded in undisturbed structures, for the analyses of seismic behavior.

3.3 Dynamic properties of tailings soils

Seismic behaviors of tailings dams are mainly controlled by pore pressure increases and corresponding shear strength reductions in the tailings soils. Such behaviors have lead to catastrophic flow failures or to liquefaction failures in several tailings dams in seismic countries (Moshikoshi, Japan, 1978; Barahona, Chile, 1928; El Cobre, Chile, 1965; Veta del Agua, Cerro Negro, Chile, 1985). The mechanisms of shear strength reductions associated to seismic conditions are well known, at present, after the comprehensive laboratory investigations of Casagrande (1975) Castro (1977) and Seed (1977) among many other researchers.

Triaxial compression loadings on consolidated-undrained specimens are used to determine the steady-state strength, under monothonic stress controlled conditions, or the cyclic strength, under reversible cyclic stress conditions.

Laboratory tests have advantages in: the control of boundary conditons, the repeatability, the possibilities to perform numerous tests and to undergo parametric studies. They have disadvantages in the reproduction of real in-situ conditions, in relation with the natural soil structures and with the initial states of stress. Tailings soils generate structures which are particularly difficult to reproduce in the laboratory due to segregation of particles of different sizes and to stratification proper of hydraulic fill structures. On the other hand, it is difficult to obtain undisturbed samples of noncohesive tailings and to try to correct the errors introduced by volume changes produced by sampling.

In-situ tests are useful tools to obtain soil properties of natural structures under real stress conditions. The following in-situ tests are normally used to investigate dynamic properties of tailings soils:

a) Standard penetration tests, SPT. This method to measure shear strength through resistance to penetration keeps today the advantages of universal use and of the many studies performed to correlate SPT results with relative density and liquefaction potential. It is simple to perform but it is subject to errors introduced both by the mechanical equipments and by the operators. For instance, one inherent disadvantage of SPT is that the resistance of the soils at different dephts are measured at the surface of the deposit by counting the number of blows of a hammer falling "freely" 30 in. to hit the driving head, without discounting the losses of energy which occur along the rods between the head and the split spoon sampler; whichever those losses may be, it is a fact that deeper strata are always tested with lower energies than the shallower ones, therefore invalidating any direct comparison. Another problem of SPT refers to the insuficient resolution (one test over 45 cm) which prevents to detect thin layers of weaker soils, typical of tailings dams.

b) Cone penetration test, CPTU. This type of test permits to determine shear strength by two simultaneous measurements of cone tip resistance, q_c, and lateral resistance, f_s, plus an independent record of the pore pressures generated during each test, u_d. These measurements are recorded every one cm of penetration under static hydraulic pressure.

3.4 Evaluation stage of design

Main objective of the Evaluation stage is to obtain additional information in order to: decrease the costs of construction of dams through a better knowledge of the real behavior of tailings soils, specially in relation with seismic loadings; decide about reinforcing works if they become strictly necessary, and improve the design of future deposits and expansions of the facilities. Evaluation is necessary to optimize designs through more realistic models of soil behavior and to supplement present state of knowledge in very imporant subjects, such as pore pressure build up and liquefaction potential.

Proper evaluation requires to measure relevant parameters of soil structures and to monitor the changes they may experiment with time. For this purpose instruments have to be installed in the soils to record pore pressures, water flows, deformations and stresses, as well as seismic ground motions. The analyses of the recorded data permits to backcalculate the mechanic and dynamic properties of the soils, including compression moduli and pore pressure parameters. Furthermore, proper or deficient behavior of drains may be verified.

Instrumentation requirements for tailings dams would depend of the importance of the structure, the natural hazards of the site and the consequences of eventual failures for the endangered areas. As an example, a tailings dam built in a seismic site, 75 m high, located 30 km upstream and 1,000 m above the elevation of a populated valley, should have the following instruments:

a) Three accelerographs to record seismic motions of: bedrock at one of the abutments; surface of natural soils, at base of the dam; and crest of dam, at central part. Each of these sensors record ground motions in directions parallel and normal to the valley and vertical; they are interconected for triggering at same time, yet independent in recording to provide redundancy against malfunctioning. Comparisons of all records should permit to evaluate amplification effects from baserock to top of foundation soils and from there to crest of the dam. IC digital cards capable to secure most relevant data even after saturation are preferable for records.

b) Ten electric piezometers connected to an intelligent data adquisition system, programmed to record periodically plus any time a seismic event occurs with a predetermined intensity.

c) Six vertical axis with inclinometer and settlements sensors, to record horizontal and vertical deformations.

The instrumentation system should be designed such that maintenance and operation requirements be minimal and that retrieval, analyses and interpretation of data be easy and fast. These characteristics plus the indispensable proper training of operation personnel and the supervision of the designer should permit to feedback the results in the design models and to proceed with remedial measures if necessary.

Remedial measures which may be implemented in the evaluation stage include: construction of reinforcement berms to improve factors of safety for downstream slope, relief wells to reduce pore pressures and diversions of water courses.

4. SEISMIC BEHAVIOR OF TAILINGS DAMS

The analysis of real behaviors of deposits of tailings soils under seismic loadings is an useful way to evaluate the design methods which are presently in use in accordance with the state of the art. In this respect, several experiences gathered in chilean earthquakes will be presented herein with the purpose of illustrating the advantages and limitations of different aspects of design and to expose them to the revision of the profession in relation with the experiences of other seismic countries.

4.1 Pore water pressures

Seismic variations of pore water pressures are being recorded in Veta del Agua Tailings Dam since June 1990 (Troncoso et al, 1990). The recording system consists in one digital strong motion triaxial accelerograph, Model SMAC-MD, and three dynamic piezometers, Model Dam-122, interconected to record simultaneously the three components of ground motions at the base of the dam plus the pore pressures in silts and sands located below the phreatic surface, as shown schematically in Fig. 5.

The purpose of this seismic instrumentation is to monitor the pore pressure build-up in the soils of the dam induced by ground movements. About 20 events, identified by maximum ground accelerations between 4 and 40 gal, have been recorded in 4 years. Results of these measurements, expressed as pore pressure increment divided by maximum base acceleration versus date of event, are presented in Fig. 6. for piezometer N° 3 installed in sandy silts. These results suggest that for a given intensity of seismic movements the corresponding pore pressure increments may tend to decrease with time. Therefore, the idea is to keep the seismic recording system in operation for a long period of time to permit capture of stronger earthquakes and to define realistic in-situ relationships between characteristics of ground motions and induced pore water pressures. On addition, effects of age of the deposit in the generation of dynamic pore pressure increments is expected to be shown.

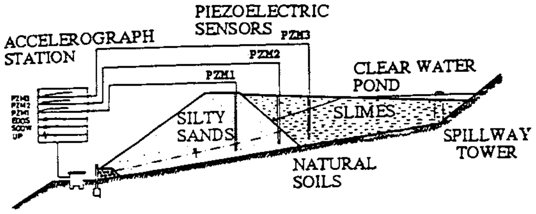


FIG. 5 SEISMIC AND PORE PRESSURE ACELEROGRAPH STATION FOR VETA DEL AGUA

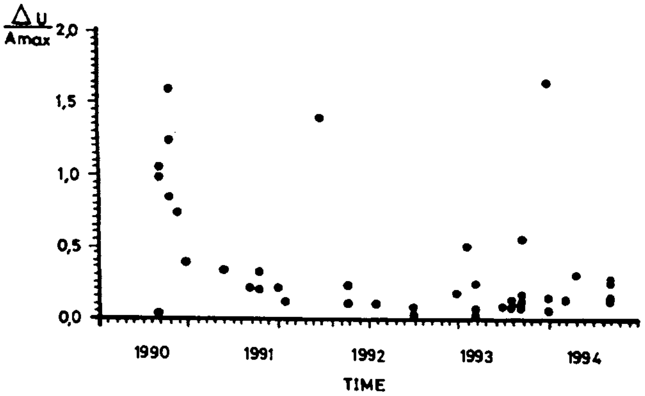


FIG. 6 EVOLUTION OF SEISMIC PORE PRESSURE INCREMENT (ΔU)/MAXIMUM SEISMIC ACCELERATION (A_{max}) RATIO. PIEZOMETER 3 - VETA DEL AGUA

4.2 Critical density

Curves of critical relative density, which separate compressional and dilatational behaviors, as functions of effective confining stress, have been defined for sands and silty sands of El Cobre N° 4 Tailings Dam, by means of undrained monothonic triaxial tests, as shown in Fig. 7 (Troncoso & Verdugo, 1985). In the range of confining stresses corresponding to depths between 5 and 30 meters inside the dam, critical relative densities ranged between 25 to 30 percent, for clean sands, and between 50 to 60 percent in sands with 15 percent silt content. These results indicate a very important influence of the silt content in the dynamic behavior of silty sands, suggesting the need for higher compaction to achieve stable deposits in siltier sands than in clean sands. Silty sands, with higher potential for densification under drained loading, will have a corresponding higher potential for pore pressure build up and liquefaction under undrained loading.

The above results of laboratory tests have been further validated by in-situ standard penetration measurements performed before and after same tailings soils were strongly shaken by an earthquake (Troncoso, 1992). Densification was detected and verified by increases in SPT indexes in silty sands with initial penetration resistances corresponding to relative densities (Gibbs and Holtz, 1957) below 50 percent, as shown in Fig. 4.

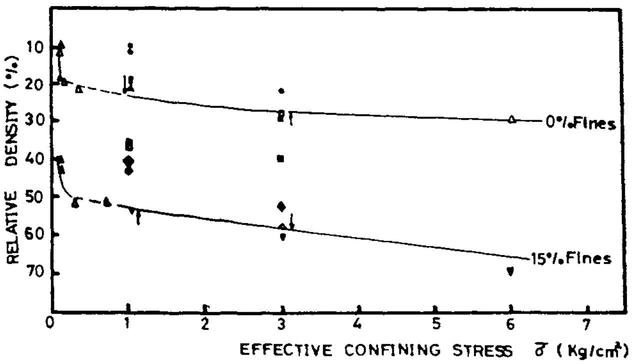


FIG. 7 STEADY STATE CURVES OF TAILINGS SANDS

4.3 Undrained shear strength of tailings soils

The seismic failure of Cerro Negro CN4 Tailings Dam, which ocurred on March 3, 1985, has been investigated by Castro and Troncoso (1989). Shear strength of tailings sands were measured in undisturbed samples carefully recovered with stationary piston, keeping precise records of all foreseeable changes in volume. Shear strengths of silty slimes were measured in laboratory specimen sedimented from slurry and consolidated to simulate impoundment conditions. The results have indicated that the seismic behavior of tailings deposits is mainly controlled by the undrained shear strength of the soils which form the retaining dams and the adjacent volumes of the impoundment. Seismic loadings and strains produce changes in the microstructures of the soils, including reorientation and breakage of particles, towards a condition of steady state of deformation in which the mass deforms continuosly, at constant volume, constant normal effective stress, constant shear stress and constant velocity (Poulos, 1981). The shear strength under these conditions is the undrained steady state strength, S_{us}, (Castro, 1987). Mass failure would then occur if the driving stresses acting in the soils would exceed the steady state strength.

Determinations of S_{us} on undisturbed samples of sands from Cerro Negro, as summarized in Fig. 8, indicate relatively high S_{us} values with one exception, ranging between 1.3 and 3.5 kg/cm2. The sands of this dam, and of many other typical tailings dams are slightly dilative, due to the angularity of the particles, and the steady state strength is about equal to the drained strength. However the steady state strength decreases as the fine content increases. The friction angle at steady state ranges between 34 to 38 degress.

Determinations of Sus on consolidated samples of slimes, indicated that the ratio of undrained steady state strength to effective consolidation stress (S_{us}/σ_{vc}) was 0.07, while undrained peak strength ratio was 0.27, considerably lower than the strengths of the sands.

The march 3, 1985 earthquake induced more than 10 cycles of peak accelerations larger than the calculated yield acceleration, which was 0.1 g, in Cerro Negro Dam. Therefore, peak shear strength of saturated sands and slimes was overcome leading to a reduction of the strength to the undrained steady state value. Post-earthquake stability analyses revealed factors of safey of 0.97 for this condition and larger than one for the undrained peak strengths; therefore, the failure of the dam was explained by the seismic reduction in shear strength of the slimes.

In summary, it is important to evaluate properly the undrained shear strength of the slimes for seismic design of tailings dams. Consolidation increases the shear strength, both at peak and at steady state condition, and, therefore, the stability of dams is critical during operation and it improves after closure. Once the evolution of undrained strength is well determined it is easy to calculate the minimum dimensions of the sand structures which are necessary to retain the impounded slimes under seismic conditions.

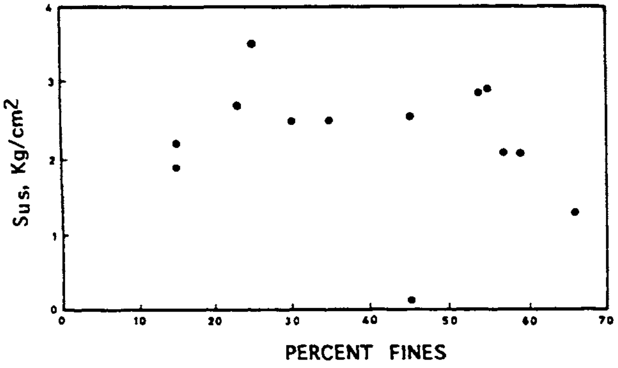


FIG. 8 IN SITU S_{us} VERSUS PERCENT FINES FOR SANDS CERRO NEGRO TAILINGS DAMS N° 4 (Castro and Troncoso, 1989)

5. ENVIRONMENTAL DESIGN CONSIDERATIONS

5.1 Environmental impacts of tailigns dams

Toxic fluids contained in talings deposits may affect the environment due to some damaging processes caused by leakages of contaminated fluids from the reservoir, seepages through the dam, abutments or foundations and infiltration into aquifer sources of potable or irrigation waters.

Fine sands and silts of dry deposits may be eroded and transported by wind actions and deposited as eolic sediments over adjacent lands.

Breaching of a dam may cause catstrophic floods of tailings over lands and surface water courses.

The agencies which grant the permissions to build and control the operations of the deposits of mineral residues, and their environmental protection departments, are aware of these impacts and they are requesting strict countermeasures to prevent them. Such requirements may become too expensive and sometimes they may seriously complicate the tailings disposal operations. This fact is specially serious when the seismicity of the site imposes strong loadings in the structure which form the deposit and its auxilliary installations.

5.2 Environmental damages caused by seismic failures

Seismic failures of tailings dams normally result in extensive damages to the environment when the modes of failure involve the flow of liquefied soils over vast areas. Prediction of the extension of the endangered areas is a crucial issue of design since it determines wether a site is acceptable or not bo build a deposit, how much money should be spent in order to make a deposit safe or how to protect the population, structures and lands located downstream of an existing tailings dam.

The worst possible damages to the environment are those caused by flow failures. The damages of a flow failure depend first upon the potential energy of the soil mass which fails; this energy is equal to the weight of the soil which may flow multiplied by the difference in elevation between the location of the deposit and the endangered areas. The maximum distance of the flow is limited by the obstacles existing along the flow path and by the possibilities to dissipate energy as the flow hits such obstacles. A flat and wide valley with a steep slope shall permit a flow at high speed to cover a very wide area. On the other hand, a narrow valley shall concentrate the flow and lead it for longer distances.

Other environmental damages result when the earthquake causes ruptures or destruction of some elements designed to minimize the impacts under normal loadings, as follows:

a) Impermeable liners may be cut if seismic tension stresses exceed the strength of the geomembranes.
b) Interception and diversion ditches may be cut or may be filled with debris after earthquake-induced landslides.
c) Diversion tunnels or ducts may collapse under seismic loadings.

6. CLOSING REMARS

The abandonment condition and the correspondingly very long term environmental effects control the seismic design of tailings dams in the present state of the art. This is so because the worst forms of pollution are related to the catastrophic failures under seismic loadings, such as liquefaction and flow failures, and the ruptures of impermeable barriers or ducts.

Maximum credible events have to be considered in design for abandonment; therefore, very large magnitudes of loadings have to be imposed in the retaining structures. On the other hand, time affects favourably the dynamic properties of the soils as evidenced by the observation of real seismic behavior of abandoned tailings dams. Evaluation of behavior as function of time is an important stage of design because it permits to quantify the effects that aging, seismic history and dessication may have, on addition to consolidation, in the dynamic resistance of tailings soils.

Feeding back the results of evaluation permits to improve design in an integrated methodology of design, construction and operation.

Environmental protection and abandonment condition have to be considered from the very beginning of a project in order to properly incorporate all the necessary elements in the most efficient manner.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Casagrande, A. 1975. Liquefaction and cyclic deformation of sands-A critical review. V Pan Am Conference on Soil Mechanics and Foundation Engineering, Buenos Aires, Argentina.

Castro, G. & J.H. Troncoso 1989. Seismic behavior of three tailings dams during the march 3, 1985 earthquake. 5th Chilean Conference on Seismology and Earthquake Engineering, Santiago.

Castro, G. 1969. Liquefaction of Sands. Harvard Soil Mechanics Series N° 81, Cambridge, USA.

Castro, G. 1975. Liquefaction and cyclic mobility of saturated sands. Journal of the Geot. Eng. Div. ASCE 101 (GT6): 551-569.

Gàrga, V. & J.H. Troncoso 1991. Seismic design and evaluation of tailings dams. IX Pan Am Conference on Soil Mechanics and Foundation Engineering, Viña del Mar, Chile.

Gibbs, H.J. & W.G. Holtz 1957. Research on determining the density of sands by spoon penetration testing. IV International Conference on Soil Mechanics and Foundation Engineering, London, England.

Lo, R.C. & Klohn, E.J. 1991. Design and analysis of tailings dams for earthquake conditions. Int. Seminar on Seismic Design, Abandonment and Rehabilitation of Tailings Dams, Viña del Mar, Chile.

Poulos, S.J. 1981. The steady state of deformation. Journal Geot. Eng. Div. ASCE 107 (GT5): 553-562.

Séco e Pinto, P.S., P.C. Dakoulas, L. Harder, H. Watanabe & A. Chugh 1995. Stability of slopes and earth dams under earthquakes. Third Int. Conf. on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, USA.

Seed, H.B., K. Mori & C.K. Chan 1977. Influence of seismic history on liquefaction of sands. Journal of the Geotech. Eng. Div. ASCE 102 (GT4): 246-270.

Troncoso, J.H. 1975. In-situ impulse test for determination of soil shear modulus as a function of strain, Ph. D. Thesis University of Illinois at Urbana-Champaign, USA.

Troncoso, J.H., K. Ishihara & R. Verdugo 1988. Aging effects on cyclic shear strength of tailings materials. 9th World Conference on Earthquake Engineering, Tokyo, Japan.

Troncoso, J.H., S. Yasuda, F. Rodríguez 1990. In-situ measurements of pore water pressures during earthquakes. Pontificia Universidad Católica de Chile, DIE N° 90-10.

Troncoso, J.H. & C. Jimenez 1991. Effects of overconsolidation ratio in cyclic strength of tailings sands (in spanish) Apuntes de Ingeniería 43, p 41-54, Santiago, U. Católica.

Troncoso, J.H. & Lobos 1991. Limit strength of sands and static and seismic stability of tailings dams (in spanish). Final Report of Fondecyt Project N°. 334-88, Santiago.

Troncoso, J.H. 1992. Fundamentals of geotechnical earthquake engineering (in spanish). Book, Ediciones Universidad Católica de Chile, Santiago, Chile.