General Report—Session VI: Stability of Slopes and Earth Dams Under Earthquakes

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INTRODUCTION

This General Report is presented in the following four sections. In the first section a brief state-of-the art review is given related to the following topics (covered by the papers presented in this session): (i) analysis of embankment stability during earthquakes; (ii) liquefaction potential of saturated soils during earthquakes; (iii) behaviour of tailings dams and waste disposals during seismic events; and (iv) assessment of failure of natural slopes during earthquakes. In the second section a summary of each paper is presented followed by general comments. The third section presents some future trends and the final section presents some remarks and topics for discussion.

Part. 1 - State of the Art

INTRODUCTION

In this section the embankment stability during earthquakes, the assessment of liquefaction potential of saturated soils, the behaviour of tailings dams and waste disposals during seismic events and the evaluation of failure of natural slopes during earthquakes are reviewed.

In dealing with this Part we should take into consideration:

"One should absorb the colour of life, but
one should never remember its details.
Details are always vulgar".
Oscar Wilde. The Picture of Dorian
Gray (1891).

ANALYSIS OF EMBANKMENT STABILITY DURING EARTHQUAKES

The behaviour of an embankment dam during an earthquake can be analyzed by experimental methods or mathematical methods.

Experimental Methods

Experimental methods are used to test predictive theories and to verify mathematical models. Despite some limitations they are useful in understanding the mechanisms of dynamic behaviour of embankments. The most common techniques are shaking table and centrifuge models.

Except for the existence of some difficulties to simulate the failure process of embankments with the law of similitude, there is a common nature in the dynamic phenomena observed from model tests and prototype dams (Han and Kong, 1987; Paskalow and Bojadzieu, 1990).

The influence of earthquake intensity on dynamic magnification (Steedman, 1991), the existence of a yield acceleration and a delayed failure can be observed in clay embankments subjected to simulated earthquakes in centrifuge tests (Kutter and James, 1989).

The failure mechanisms of earth dams during seismic loading observed in the centrifuge model tests is a boundary value problem with interacting soil elements (Muraleetharan and Arulanandan, 1991).

Mathematical Methods

The different methods of dynamic analysis of embankment dams are summarized so that their capabilities as well as their limitations may be better understood.

Pseudo-static analysis

In the pseudo-static analysis a horizontal force expressed as the product of a seismic coefficient K, and the weight W, of the potential sliding mass is applied at the center of the sliding mass and the minimum factor of safety against sliding is computed. It is assumed that the embankment dam behaves as a rigid body and that the accelerations will be uniform throughout the section and equal at all times the ground accelerations.

The deficiencies of a rigid body response have implemented the use of elastic response solutions for the determination of design seismic coefficients (Ambraseys, 1960; Koppula, 1984).

Simplified procedures to assess deformations

In order to overcome the severe limitations of pseudo-static analysis, a number of investigators have proposed simplified procedures for estimating induced deformations following Newmark (1965):

Sarma (1975) has proposed a method of computing the critical horizontal acceleration that is required to bring the mass of soil to a state of limiting equilibrium.

Makdisi and Seed (1977) presented a method where a failure occurs on a well defined slip surface and that the material behaves elastically at stress levels below yield stress but develops a perfectly plastic behaviour above yield.

Mineiro (1975) has proposed a method that takes into account the dynamic brittleness of soils and the excess pore pressures generated during an earthquake.

While these simplified methods have given reasonable answers in areas of relatively low to medium seismicity, it is important to analyse the behaviour of very large dams in zones where strong earthquakes have occurred by more sophisticated methods in order to obtain more reliable results.

Dynamic analysis procedures

The most widely used method of dynamic analysis for embankment dams involves the following steps (Seed , 1979b):

1) Determination of the initial stresses in the embankment before the earthquake.
2) Selection of an appropriate acceleration time history, expected to

develop in the rock foundation of the dam, for each earthquake under consideration.
3) Evaluation of the embankment response to the base rock excitation which includes the computation of induced shear stress-time histories and requires the determination of the dynamic soil properties.
4) Dynamic testing of representative soil samples under the combination of pre-earthquake stress conditions, and super-imposed dynamic stresses in order to determine the seismic strength and deformation characteristics of the soil.
5) Comparison of the laboratory cyclic shear stresses required to cause selected levels of strain with the computed shear stresses induced by the earthquake motions.
6) Evaluation of the overall strain potentials, deformations, and stability of cross sections of the embankment.

The dynamic analyses can be conducted in terms of total or effective stresses and considering elastic or plastic behavior of the soil.

Several finite element computer programs assuming an equivalent linear model in total stress have been developed for 1D (Schanabel et al., 1972), 2D (Idriss et al., 1973; Lysmer et al., 1974) and pseudo 3D (Lysmer et al., 1975).

Since these models are essentially elastic the permanent deformations cannot be computed by this type of analysis and are estimated from static and seismic stresses with the aid of strain data from laboratory tests (cyclic triaxial tests or cyclic simple shear tests).

To overcome these limitations, nonlinear hysteretic models with pore water pressure generation and dissipation have been developed using incremental elastic or plasticity theory.

The incremental elastic models have assumed a nonlinear and hysteretic behavior for soil and the unloading-reloading has been modeled using the Masing criterion and incorporate the effect of both transient and residual pore-water pressures generated by seismic loading (Lee et al., 1978; Finn, 1987).

For the models based on the theory of plasticity two particular formulations appear to have a great potential for multidimensional analysis: the multi-yield surface model (Prevost, 1993) and the two--surface model (Mröz et al., 1979).

Endochronic models have been refined by the inclusion of jump-kinematic hardening to satisfy Drucker's postulate and achieve closure of the hysteresis loops (Bažant et al., 1982).

A modified cam-clay model for cyclic loading taking into account that when saturated clay is unloaded and then reloaded the permanent strains occur earlier than predicted by the cam-clay model was proposed by Carter et al. (1982). The predictions exhibit many of the same trends that have been observed in laboratory tests involving the repeated loading of saturated clays.

Observation methods

Full scale natural and man-made vibration tests accompanied by appropriate geophysical measurements can provide vital information regarding key material properties and dynamic characteristics of earth/rockfill dams.

The dam response to these vibrations are recorded on seismometers, along the crest and downstream slope of the dam, on the abutments and the various locations inside the dam. By analyzing the recorded motions, natural frequencies and associated 3-dimensional mode shapes as well as damping ratios are obtained.

The monitoring scheme of a dam provides: (i) the rational analysis of its structural behavior; and (ii) the monitoring of its safety against deterioration to failure. These data enable the engineer to undertake actions to achieve good maintenance and to avoid dam failure.

To obtain critical information regarding a dam's behaviour during an earthquake it is necessary to install seismic instrumentation in the region close to the dam and on the dam.

The strong-motion instrumentation networks shall be subdivided into the following categories (Fedock, 1984): (i) free-field motion instrumentation; (ii) input motion instrumentation; and (iii) response motion instrumentation.

LIQUEFACTION

The liquefaction potential of saturated soils during earthquakes has received a great deal of attention among the geotechnical community since 1964 when the earthquakes in Niigata and in Alaska caused unprecedented damages inducing liquefaction of the ground.

All the developments related to the mechanisms, to the factors influencing the triggering of liquefaction (such as: relative density, soil structure, grain characteristics, lateral earth pressure coefficient and overconsolidation, aging and previous strain history), to the laboratory tests, to the field tests and to the methods for estimating liquefaction potential have been described in detail in state-of-art papers by Seed (1976; 1979a), Yoshimi et al., (1977), Finn (1981, 1991), Ishihara (1990, 1993) and Sêco e Pinto (1993b).

The methods available for evaluating the cyclic liquefaction potential of a deposit of saturated sand are based on laboratory tests and field tests.

In general the following laboratory tests are used: (i) cyclic triaxial tests; (ii) cyclic simple shear tests; (iii) torsional cyclic shear tests; (iv) shaking table; (v) and centrifuge tests (Sêco e Pinto, 1991).

Extensive efforts have been undertaken to prepare representative samples. The most widely methods for the preparation of samples are: wet tamping, dry deposition and water sedimentation.

Attempts to recover high-quality undisturbed samples of sand have received a renewed importance in recent years with the use of: tube sampling, block sampling and in-situ freezing method.

The difficulties in obtaining high quality undisturbed samples and the limitations of laboratory testing technique related with membrane penetration and non-uniformity of strain distribution have increased the interest in field tests. The following tests are used: SPT tests, CPT tests, seismic cone, flat dilatometer and methods based on electrical properties of soil.

Although the basic aspects of the soil liquefaction phenomenon, influence factors and predictive methods have been thoroughly investigated the following topics have received considerable attention from researchers during the last decade.

The effect of fines and their plasticity on liquefaction susceptibility indicates that the sand with a large amount of fines are less susceptible to liquefaction than the sand without fines (Troncoso et al., 1985; Zhou, 1981).

It has been believed that gravelly deposits are less susceptible to liquefaction than sand deposits due to their higher permeability, greater dilatancy and larger stiffness. However the 1984 Borah Peak earthquake (USA) and 1987 Chibaken-Toko-Oki earthquake, have shown liquefaction of deposits of coarse grained sediments. To overcome these difficulties large diameter penetration test and the Becker penetration test (BPT) (Harder et al., 1986) are now used.

The assessment of liquefaction potential in engineering practice usually relies on in-situ penetration resistance measurements and is based in total stress analyses (Seed, 1987). In some critical facilities and important structures estimates of time histories of ground motions and dynamic and permanent ground deformations are required. This situation can be modelled using dynamic effective stress analysis (Finn, 1991). It is assumed a nonlinear and hysteretic behaviour for soil exhibiting Masing behaviour during unloading and reloading and the generated porewater pressures in saturated sands are of two types: transient and residual (due to plastic deformations).

Endochronic constitutive laws for the liquefaction of sands have been proposed by several authors (Bazant and Krizeh, 1976; Valanis and Read, 1982).

The common approach to assess the liquefaction of a site is by simply indicating that under certain ground-motion conditions a site does or does not liquefy.

Probabilistic approaches to liquefaction analysis using pore pressure generation models, variation of soil properties within a stratum combined with a stochastic description of the earthquake motion have been proposed by several authors (Liao et al., 1988; Pires et al., 1989; Finn, 1988) and are in a great state of development.

TAILINGS DAMS AND WASTE DISPOSALS

A brief summary of deposition method, stability analyses and design measures for tailings dams and waste disposal dams are outlined below.

Tailings dams

In the upstream construction method a starter dam is constructed of a 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. Because fine refuse materials are fine sand to silt size and are deposited in a loose saturated condition, seismically induced pore water pressure must be considered in a stability analysis. In the downstream method the sand dam is raised in a downstream direction and the fine tailings are spigotted off the upstream face of the dam to provide a low permeability beach between the sand dam and the free water in the tailings pond. The centerline method represents a compromise between the upstream and downstream method and offers the reduced fill volume advantages of the upstream method while exhibiting much greater stability.

The stability analysis is typically an effective stress approach using a conventional method of slices technique, incorporating estimates of excess pore water pressure generated by earthquake shaking. Excess pore water pressures are estimated from cyclic triaxial tests.

Conventional static methods are a useful tool to assess the seismic safety dams. However safety factors do not give a reliable value of permanent deformations which control the behaviour of tailings dams during the occurrence of earthquakes.

The definition of the limit of tolerable deformations plays an important role in the design of tailings dams. So nonlinear effective analyses to estimate induced porewater pressures are very important as they are capable of predicting deformations and assessing the consequences of liquefaction.

The dynamic response analysis method of waste dams is based on effective stresses.

The dynamic porewater pressure increment and residual deformations are evaluated.

The upstream construction of tailings dams should not be favoured in highly seismic zones (Troncoso and Vergara, 1993). Special provisions of design should be included to cover the following most important points:

- Residual shear strengths should be known for all soils involved in possible failure mechanism.
- Evolution of soil properties should be evaluated periodically, starting from the beginning of construction, to monitor shear strength gains due to consolidation and aging.
- Phreatic surface should be kept low by means of effective drainage systems.

Vibroflotation and drainage method are effective earthquake-resistance improvement methods.

Waste Disposals

In almost all major cities, solid waste landfill capacity and available new landfill sites are declining. Due to the demand high landfills have been built. In seismic zones there have been concerns regarding the stability of high refuse fills.

Dynamic strength properties of a material such as soil are determined by either laboratory testing or field test methods. Because of the highly heterogeneous composition of the refuse and the difficulty in obtaining representative samples of the in-place refuse, laboratory test data on the dynamic strength characteristics of refuse material has been seriously lacking.

The principles for seismic design of refuse landfills are similar to those used in the design of soil slopes. Both pseudo-static and deformational analysis methods are used.

The dynamic response analysis method of waste disposal dams is based on effective stresses.

The dynamic porewater pressure increment and residual deformation are evaluated.

NATURAL SLOPES

For the assessment of failure of natural slopes during earthquakes it is necessary to have a knowledge of geological and hydrological conditions. Case studies of slope failures during past earthquakes have indicated the existence of a well defined slip plane through a zone of weakness near the surface of the slope-forming soil deposits (Ishihara, 1985). This weak zone is generally created by water infiltration in the residual or weathered soil but in some cases this weak zone coincides with tectonically disturbed zones such as fault surfaces or contact surfaces.

Several landslides and rockfalls during earthquakes take place in areas near topographical prominences and the ground motions in such areas are significantly different from level ground.

The assessment of strength characteristics is difficult since general slopes are composed by partially saturated cohesive soils.

Part 2 - Paper Review

In order to provide some structure the papers were classified in topics.

The seventeen papers in this session are classified and listed in Table 1.

The papers are briefly summarized and their conclusions discussed in this section.

In dealing with this issue I remember.

"Mend your speech a little
Lest if (you) may mar your fortunes".
Shakespeare, King Lear, i,

Caldeira, Seco e Pinto and Bilé Serra (Paper 6.01) present a study with the purpose to improve the state of knowledge on the seismic behaviour of embankment dams for the following factors: seismic action, height of the dam, type of the material and core position. Three zoned earth dams were analyzed: (i) Borde Seco Dam located in Venezuela is a 122 m high dam with a thick central core and shells, a filter, a drain consisting essentially of granular materials; (ii) Las Cuevas Dam, located in Venezuela, is a 92 m high dam, with a thin upstream sloping clay core and shells and a drain zone of granular materials; (iii) Alvito Dam, located in Portugal, is a 40 m high dam with a cohesive central core, and shells of decomposed schist material.

The static and dynamic geotechnical characterization of the principal materials were based on triaxial monotonic compression tests, cyclic simple shear tests and crosshole shear wave velocity tests.

The linear equivalent model was used in a finite element analysis of plane strain equilibrium.

The following conclusions were pointed out: (i) the dominant frequencies are related to the height of the dam, with minimum values at Borde Seco Dam and maximum values of Alvito Dam; (ii) the

Table 1

Stability of slopes and earth dams under earthquakes

TOPIC	PAPER	DESCRIPTION	COUNTRY
EMBANKMENT DAMS	6.01	2D - EQUIVALENT LINEAR MODEL	PORTUGAL
	6.03	3D ANALYSIS LINEAR ELASTIC MODEL	CHINA
	6.06	EQUILIBRIUM ANALYSIS 1D-EQUIVALENT LINEAR MODEL	JORDAN, USA
	6.07	2D - EQUIVALENT LINEAR MODEL	USA
	6.08	2D - ELASTOPLASTIC MODEL	GREECE
	6.11	F.D.M - LINEAR ELASTIC PERFECTLY PLASTIC	USA
	6.12	CENTRIFUGE TESTS	USA
	6.14	PSEUDO-STATIC	VENEZUELA
	6.17	2D - LINEAR HYSTERETIC ELASTIC FEM - BEM ANALYSIS	USA
	6.18	2D - EQUIVALENT LINEAR MODEL FEM ANALYSIS	USA
	6.23	EMPIRICAL EQUATIONS	JAPAN
	6.24	SIMPLIFIED PSEUDO--DYNAMIC PROCEDURE. EXTENDED NEWMARK METHOD	CANADA
	6.25	EQUILIBRIUM ANALYSIS DEFORMATION ANALYSIS	USA
TAILINGS DAMS	6.02		USA
LIQUEFACTION	6.02 6.06 6.07 6.08 6.13 6.14 6.23 6.25		USA USA USA GREECE JAPAN VENEZUELA JAPAN USA
DYKE LEVEES	6.04 6.13	FEM 2D	NETHERLANDS JAPAN
REMEDIAL MEASURES	6.02 6.13		USA JAPAN
CONSTRUCTION METHODS	6.02		USA
CASE HISTORIES	6.01, 6.02, 6.08, 6.12, 6.14		PORTUGAL, USA, USA, JAPAN, VENEZUELA
MONITORING	6.10, 6.14, 6.18, 6.23		USA, VENEZUELA, USA, JAPAN
LABORATORY TESTS	6.01, 6.12, 6.25		PORTUGAL, USA, USA
IN SITU TESTS	6.01, 6.07, 6.10, 6.13, 6.25		PORTUGAL, USA, USA, JAPAN, USA
LANDFILLS LANDSLIDES	6.05 6.10 6.26	NEWMARK MODEL 2D NON LINEAR ANALYSIS SHAKE 91	USA USA USA

maximum accelerations took place at Las Cuevas Dam, due to the major stiffness associated with the larger seismic intensity and the amplification factor (ratio between crest acceleration and base acceleration) is maximum at Las Cuevas Dam and Alvito Dam for the faraway earthquake; (iii) the peak shear stress decreases with the increasing of the height of the dam, for the same height the seismic shear stresses are larger in the stiffer materials and the maximum shear stresses are lower for the faraway earthquakes in comparison with the nearby earthquakes; (iv) the equivalent number of uniform cycles increases for the faraway earthquakes in comparison with the nearby earthquakes as a consequence of its higher durations and increases with the duration of the stationary range of the acceleration time histories; (v) the seismic action plays an important role on the seismic behaviour of the dams (therefore on the potential deformation distribution) and for similar heights the type of the materials and the core position have a second order importance.

The paper presents good and interesting summaries about seismic response of embankment dams, but limitations of space has not allowed the inclusion of all the results. The parametric studies performed can be useful for predesign of other embankment dams.

Hallman and Dorey (Paper 6.02) discuss the characteristics of mine tailings resulting from different deposition practices. For the evaluation of liquefaction potential of tailing deposits the authors point the following differences from natural deposits: (i) tailings contain a large percentage of non-plastic or low plasticity fines; (ii) tailings typically exhibit thinly laminated grain size variations; (iii) tailings are initially deposited at lower relative densities; (iv) tailings tend to be composed of highly angular particles; (v) tailings exhibit a greater decrease in cyclic strength with increasing confining pressure; (vi) tailings are recent deposits and may not have a history of seismic shocks; and (vii) tailings are chemically active and aging related cementation can be significant. So tailings deposition practices can have a profound influence on their potential for liquefaction during earthquakes. Practices such as dump discharge versus carefully controlled, sub-aerial thin-lift deposition can result in wide variations in the behavior of the tailings.

The paper presents a valuable contribution related with mine tailings deposition practices. It is unfortunate that the authors do not provide details related with the residual strength values and the quantification of lateral deformations so persons interested in this subject could also have used the data.

Xu (Paper 6.03) presents a simplified method for 3D longitudinal dynamic analysis of earth dam in triangular canyons and investigates the effects of width to the height ratio of canyons on the longitudinal dynamic response of dam. For the shear wedge analysis the following assumptions were made: (i) the canyon wall is perfectly rigid; (ii) the direction of ground motion is horizontal and parallel to dam axis and there are no displacement in other directions; (iii) the dam is homogeneous and the dam materials are linearly elastic; (iv) interaction between water in the reservoir and the dam is negligible; and (v) only shear deformation is taken into account. The author have concluded that in narrow V-shaped canyons the computed maximum accelerations at midsection were about 30 to 50% higher in 3D analysis in comparison with 2D analysis but the maximum displacement, velocities and maximum shear stresses were one half to 2/3 lower.

The obtained results seem reasonable and are in accordance with the past experience of similar analyses.

The input motions should be assumed to act in the upstream-downstream direction of the dam since it constitutes the most severe condition of shaking.

The author may find useful the study performed by Mejia and Seed "Three dimensional dynamic response analysis of earth dams" - Report UCB/EERC 81/15.

Soydemir (Paper 6.05) reviews the currently practiced methodologies for seismic design of solid waste landfills with particular reference to the Northeastern United States (NEUS).

The author points out that the major difference from the procedures currently used for seismic stability evaluation of solid waste landfills and for embankment dams is that the critical liner and cover components of the landfill structures are relatively less tolerant to seismically induced permanent displacements because of the physical and mechanical limitations of the geosynthetic elements (i.e., geomembranes, geotextiles, geonets, etc) which are to be incorporated in those components to meet important environmental design requirements.

The author also presents charts which allow the design engineer to establish the required minimum yield acceleration in order to keep the permanent displacement at or below a level of 150 mm, a magnitude currently considered acceptable for bottom liners.

The author also presents charts to compute yield accelerations for the liner design based on the argument related to the seismically induced displacements in cover zones is that any surficial distress (e.g. cracking and ruptures) may be treated as a maintenance problem. As it is reasonable to adopt a more tolerant design criteria for the covers than for the bottom liners a 300 mm limiting displacement has been considered for cover liners.

This paper is a good contribution for a topic that is getting increased attention.

Well documented case histories related to the analyses of solid waste landfills behavior after the occurrence of earthquakes will be important to calibrate the presented charts.

Husein, Liang and Nusairat (Paper 6.06) present the seismic stability analysis of Karameh dam, situated in the Dead Sea Rift, which is to be constructed on an earthquake prone site. As the Dead Sea fault has slip rate ≥ 10 mm/year, slip per event ≥ 1 m, rupture length ≥ 100 km, magnitude $M_s \geq 7.5$ and recurrence interval ≥ 1000 years was classified as class IA.

The Karameh dam is zoned earth fill dam 41 m high, with central clayey core and a storage capacity of 55 million cubic meters.

The computed displacement of the critical failure circular surface assuming no strength losses during earthquake shaking ranged between 9 and 135 cm.

The computer code SHAKE was used to analyse the amplification through the embankment.

Due the existence of fine sand layers up to 500 mm thick the possibility of liquefaction was also assessed. Displacements resulting from liquefaction were estimated to be about 4.4 m.

Taking into account the possible spreading of the dam under earthquake event along with the wave effect and the possible fault movement, a high value of 7.0 m of freeboard was recommended.

This paper presents an interesting case history related with the design of an embankment dam located near an active fault. Details related with the procedure used to quantify the residual shear strength of sand layers should be given as this value has a great influence in the computed 4.4 m displacement. The authors also recommend a foundation treatment to avoid liquefaction but no details are given related with this issue.

Vessely and Deng (Paper 6.07) investigate the potential liquefaction of the downstream gravel filter of Bull Run Dam N°2 a 145 foot high zoned earth and rockfill embankment.

The relative density of the downstream gravel filter was analyzed by the Becker hammer and correlations with SPT have given an average value of 27 blows.

The dynamic response analysis was performed by the finite element program FLUSH and the comparison of the cyclic stress ratio with the cyclic shear strength of the gravel has indicated a factor of safety against liquefaction ranging from 1.6 to 2.6.

Residual excess pore pressure ratios were assigned to each element and static slope stability analyses to evaluate the post-earthquake stability of the embankment have indicated a minimum factor of safety against shear failure of 1.7.

This paper presents a well written description of the assessment of liquefaction of gravel filter materials. From correlations with SPT test a relative density of 70-75 percent was assumed for the downstream gravel filter. As the obtained factors of safety were reasonable it should be interesting to know if the authors recommend a relative density of 75 percent for gravel filters of new dams.

Yiagos (Paper 6.08) develops a simplified and efficient numerical model to perform the phenomenological elasto-plastic seismic response analysis of earth dams. The method is based on a two-dimensional Galerkin formulation of the equations of motion for the dam material, and accounts for the presence of water inside the dam. The soil skeleton elasto-plastic constitutive model, belonging to the family of Mohr-Coulomb models and based on the multi-yield function kinematic plasticity theory was used. The model can simulate observed nonlinear shear hysteretic behavior as well as shear stress induced anisotropic effects and reflects the dependency of the shear dilatancy on the effective stress ratio. The parameters used in this model can be derived entirely from the results of conventional triaxial soil tests.

The comparison between computed and recorded acceleration in the upstream-downstream direction at the crest of the Santa Felicia Dam and the Long Valley Dam is very favorable for the proposed model.

This paper shows the ability of the model to perform nonlinear effective analyses. It seems rather strange that for the analyses of liquefaction of the dam consisted by cohesionless material the author has considered a permeability value of 6.7×10^{-8} m/s the same as assumed for cohesive materials of the Long Valley dam.

Mars, Green, Kanakari, Boddie, Mejia and Weaver (Paper 6.10) have conducted a study to assess the potential risk of earthquake induced landslide movement beneath the Penitencia Water Treatment Plant. The analyses of the slope deformation were performed using a 2D non linear finite element code considering the non-linearity of the material by a multiple nested virtual surface plasticity model with a kinematic hardening rule. Simplified methods were also used to estimate the potential slide movement. The simplified procedures tend to predict larger ranges of deformation as opposed to the finite element method.

The estimated values for 1984 Morgan Hill earthquake and 1989 Loma Prieta earthquake are in agreement with the recorded displacements.

This paper presents a very interesting case history where material characterization, computer models and instrumentation readings are combined. Details related with the effects of initial shear stress on the stress-residual strain relationship would be welcome.

Law and Ko (Paper 6.12) have conducted a series of centrifuge tests on model embankment dams whose conditions were close to those of O'Neill Forebay Dam located in California. During the 1989 Loma Prieta earthquake, acceleration data were recorded of the dam. The motion similar to the recorded prototype base acceleration was used to excite the centrifuge models.

A total of 23 tests was conducted at the 125th scale. The model tests were carried out in the 400g-ton centrifuge at the University of Colorado, using the electro-hydraulic shaker.

The results have shown stronger response when the soil was compacted with a slightly higher unit weight due to an increase in shear stiffness of the structure. The addition of some gravel in the soil during the embankment construction also improved the dynamic behavior. The embankments with a reinforcing berm were somewhat stronger than those without berm. Related with different earthquake intensities, amplification of motions was generally observed in all tests and very large amplification occurred in the intense shaking test.

This study shows the advantages of centrifuge tests to perform parameter studies in order to obtain a better understanding of the dynamic behaviour of embankment dams.

The use of digital signal procession to manipulate and extract more information about the models from the data given by the instrumentation and the advances of blast effects have greatly contributed for the implementation of centrifuge model in the last decade.

Kaneko, Nishikawa, Sasaki, Nagase and Mamiya (Paper 6.13) have analyzed river dikes failure in Japan due to Kushiro-Oki Earthquake and Hokkaido Nansei-Oki Earthquake occurred in 1993. The damages were caused by liquefaction of subsided dike materials and liquefaction of sand of the foundation bed. An assessment of liquefaction resistance factor was done based on SPT values. To improve the seismic behaviour the use of PVC sheet, sand bags were recommended. In addition piling was used to improve sand compaction.

It is unfortunate that the authors do not provide details related to the determination of liquefaction resistance factor. The lack of available details makes it difficult to understand the recommended measures to improve the seismic behaviour.

Sully, Fernandez and Zalzman (Paper 6.14) have performed back analyses of La Marquesa dam and Lake Ackerman Roadway Embankment to provide information on the possible range of values for the soil moduli at or near liquefaction. Slope deformation have occurred as a result of loss of strength in the foundation soils due to liquefaction. The vertical deformations predicted by the Dynard program are in good agreement with the magnitudes measured in the field and the calculated horizontal displacements are considerably less than the measured values. The results of the deformation studies were combined with those from stability analyses to design remedial measures for the dyke system.

Studies for la Marquesa dam ignore inertial loading effects, which would be significant for a magnitude 8 event. The authors point that the residual strength and liquefied modulus were obtained by undrained triaxial tests. It will be interesting to know if the authors do not consider that cyclic simple shear tests would give more reliable results and perhaps a better agreement between calculated and measured horizontal displacements.

Abouseeda and Dakoulas (Paper 6.17) analyse the effects of dam - foundation interaction on the response of earth dams to obliquely incident P and SV waves. The numerical formulation combines the FEM and BEM in a powerful hybrid technique. An idealized dam with 100 m has been analyzed as a plane strain linearly hysteretic elastic body founded on an elastic halfspace. The authors have concluded from the limited results presented that the effects of the spatial variability of the ground motion for P and SV waves travelling across the width of the dam seem to be important but less dramatic than those reported in previous studies, which concluded that such effects may lead to response values substantially higher than those caused by coherent ground motion.

It seems that some of the model improvements, presently under way, such as the incorporation of soil nonlinearity in the study of 2D and 3D dams using the hybrid formulation in time domain should provide significant advances along this direction.

Deng, Ostadan, Arango and Marrone (Paper 6.18) present a seismic stability analysis of a 555 ft high earth and rockfill dam in central California, constructed in 1960, using the FLUSH program. The results showed a significant amplification of the ground motion. Permanent deformations were evaluated by simplified procedures and the computed values ranging from 6 to 50 cm were judged to be small and tolerable considering the height of the dam and of the same order of measured crest movements of the other high earth and rockfill dams during earthquake shaking.

This is a well written paper. It is unfortunate that the authors did not provide more quantitative information related with dynamic properties of shell materials such as the variation G/G_{max} and damping ratio versus strain used in the equivalent linear model so those interested in dynamic analyses could also use the data.

Iwashita, Japan, Nakamura and Yasuda (Paper 6.23) evaluate the maximum acceleration dam site rock values, the maximum acceleration application ratios at crest and the natural periods of the dam bodies by the analyses of the acceleration records at dams during the two big earthquakes which hit in Hokkaido in 1993 and compared with the results given by empirical equations. The authors have concluded that this study confirmed that the dams constructed on rock foundations using modern design and construction technologies were able to survive these powerful earthquakes without any threat to the safety and that they had remained in good condition.

With maximum acceleration values lower than 0.2g the dams were not significantly tested and so this study does not give a sound support to the conclusions.

Jitno and Byrne (Paper 6.24) present a simplified pseudo-dynamic procedure to predict the liquefaction induced deformation of La Palma dam. The Newmark's method is extended to incorporate the effects of stiffness reduction in liquefied soils. The procedure is capable of predicting movements of the upstream slope of the dam due to liquefaction of silty sand layer beneath the shell. The results show that the predicted displacements are in general agreement with field observations both in terms of magnitude and pattern of deformations.

The methodology presented in this paper seems promising and should be applied in more history cases in order to gain a sound support. Numerous more detailed observations were made and are included in a number of referenced companion papers. The work deserves serious study.

Pillai, Plewes and Stewart (Paper 6.25) analyse the liquefaction potential of the foundation soils and the performance under seismic loading of Duncan Dam located in British Columbia. The dam is a zoned earthfill embankment founded on a thick sequence of sands, silts and gravels.

The post liquefaction stability and deformation of the dam was based on two approaches: one laboratory "direct method" and the other an "indirect method" (Seed's method) which is based on field penetration data. The paper describes some advanced aspects of the field and laboratory investigations including laboratory testing of undisturbed soil samples obtained after freezing the ground in situ.

Application of this methodology to seismic assessment of Duncan Dam has resulted in the conclusion that post-liquefaction deformations will be tolerable and no remedial work is required for the maximum design earthquake. Whereas the simpler and more conventional assessment predicted a flow-slide and remedial requirements.

This paper provides an excellent overall description of a challenging dam project where the authors stress the advantages of sophisticated sampling techniques and field and laboratory investigations associated with more recent models in comparison with classical techniques and commonly used models to provide sound and practical approaches to liquefaction evaluation and mitigation.

Chang, Wei, Chang and Hall (Paper 6.26) have calculated lateral displacements induced by a design earthquake in landfills in the Memphis Tennessee by Newmark method. The authors have concluded that lateral displacement is proportional to the slope angle of the landfill, peak acceleration and time duration of bedrock motion and is inversely proportional to the average unit weight of the landfill refuse.

The authors do not provide specific quantitive data related to the geosynthetic interface strength. This issue is important when selecting a material for bottom liner and top cover and plays an important role on factor of safety.

Any misunderstanding or misinterpretation of the papers reviewed for this session are the responsibility of the General Report and to those Authors whose papers may be misrepresented, apologies are offered. Comments regarding the papers have been expressed from the perspective of stimulating lively discussions during the session.

Part. 3 - Future Trends

The following topics that are in an initial state of development and raise very real challenges will have a great growth in a near future.

In dealing with this subject we should always have in mind that:

"Discovery consists of seeing what everybody
has seen and thinking what nobody has thought"
A. Szent-Gyorgoyi, (American Scientist, 1971).

ANALYSIS OF EMBANKMENT STABILITY DURING EARTHQUAKES

The dynamic response analysis of embankment dams is a very complex problem. First, dams are large nonhomogeneous structures and the material is a multi-phase solid-fluid medium. Second, the behaviour of the soil skeleton is highly nonlinear, anisotropic and hysteretic. Finally, the interaction of the dam with its boundaries including the underlying foundation and the water in the reservoir further complicates the problem.

Current dynamic analyses of embankment dams use total stresses and treat nonlinear behaviour by iterative linear-elastic procedures. These analyses do not require prohibitive time computer costs and are valid when pore water pressures do not exceed 30% of the effective overburden pressure. Since they are elastic methods they cannot provide information on permanent displacements and deformations, strong interest has developed in nonlinear effective stress methods.

Despite the high computer costs of nonlinear effective analyses they provide a very clear overall picture of the dam response to the design earthquake as well as helping the designer with all the details necessary in zones of potential concern.

More experience in the application of these models is necessary and, for their calibration, centrifuge models seem very useful.

Uncertainties in soil parameters in analyzing the seismic response of earth dams have been incorporated in probabilistic approaches. Comparisons with Monte-Carlo type simulations has shown the suitability of the method.

LIQUEFACTION

(i) The assessment of liquefaction induced deformations has become an important issue in evaluating seismic risks of structures and underground structures.

A relationship between cyclic stress ratio (τ/σ_o), $(N_1)_{60}$ (SPT) and volumetric strain was proposed by Tokimatsu and Seed (1984). A different approach was proposed by Ishihara (1990) correlating the post-liquefaction volumetric strain with maximum shear strain for different values of relative density.

(ii) The determination of the loss of strength of soils i.e. the residual strength is important for the assessment of lateral flow of sand deposits following liquefaction.

A correlation between SPT value and the residual strength of sand based on case studies of failure of embankment dams was proposed by De Alba et al. (1987).

A similar correlation was proposed by Ishihara et al. (1990) between CPT value and residual strength based on several failures of embankments and sloping grounds composed of sandy silts or silty sands.

(iii) Static penetration tests like vibratory CPT test and Becker hammer are very promising in the assessment of liquefaction potential of gravel materials.

(iv) The spectral-analysis-of-surface wave (SASW) method for measuring in-situ shear wave velocity is having increasing interest. This method which requires no boreholes, can obtain data on soil layering including thickness of layers and shear modulus of layers.

(v) The probabilistic analysis of liquefaction incorporating the uncertainties in soil properties and the probabilistic nature of earthquake is also becoming an active area of research.

TAILINGS DAMS AND WASTE DISPOSALS

Analyses of post-liquefaction behavior of tailings dams are becoming an important issue. It is important to assess the deformations of the dam as the strength of the liquefied material drops towards the steady state strength as well as a comprehensive picture of the consequences of liquefaction.

Dynamic strength characteristics of refuse materials are not yet adequately defined; there is a large scatter on the dynamic strength data obtained from laboratory testing and in situ testing reported in the literature.

NATURAL SLOPES

The definition of strength-deformation characteristics of natural soil deposits under slopes is important. The effect of initial shear stress and confining pressure deserve more consideration.

To improve the understanding of the above topics and to calibrate the proposed correlation, analyses of well documented records and comparisons between predicted and observed values in case histories will be fundamental.

Part. 4 - Final Remarks and Topics for Discussion

The papers presented in this session cover a wide range of important topics in the design, construction, and monitoring of slopes and earth dams under earthquakes. They illustrate many of the impressive advances that have been made in the mentioned fields. Nevertheless, we feel that several questions still remain without a definitive answer.

Some questions that deserve further discussion are outlined below.

The purpose is to establish a systematic communication between the authors and the delegates of this Conference in order to create a dialogue between everyone and to explore the interactions, the developments and the structural conditions to further implement this subject and to live a thrilling adventure.

It seems that this is the best way to provoke a wide discussion using open questions with the purpose of creating new propositions and to contribute to the advancement of the knowledge.

ANALYSIS OF EMBANKMENT STABILITY DURING EARTHQUAKES

(i) In zones of low to moderate seismicity, steep slopes of the order of 1.0 on 1.3 to 1 on 1.45 for concrete faced rockfill dams have been used. The assessment of potential permanent deformations of these rockfill dams has shown acceptable levels of seismic performance. For areas of high seismicity where high acceleration will be developed near the crest, downstream slopes of the order 1 on 1.6 to 1 on 1.8 are recommended (Seed et al., 1985) at the top of 1/4 of the dam where high values of acceleration will occur.

The crest retaining wall is a very vulnerable feature of the dam as large permanent deformations of the wall will take place (Gazetas and Dakoulas, 1991). An example of the vulnerability of crest walls is the collapse of the wall on the crest of the Douhe Dam, in China, during the 1976 Tangshan earthquake.

Is there a need to reanalyse the behaviour of existing dams? Should the above measures be incorporated in the design of new dams?

(ii) The seismic response of dams has been analyzed considering synchronous (in phase) oscillations to provide the excitation. However seismic shaking is the result of a multitude of body and surface waves with resulting oscillations that differ in phase and amplitude from point to point along the dam-valley interface. Is it important to analyse the response of a canyon to incident SH waves impinging at different angles in the vertical plane of the dams axis?.

(iii) The hydrodynamic effects of the reservoir water upon concrete face rockfill dams have received more attention as these dams have slopes of 1(V): 1.3 (H) and water pressures are applied directly to the concrete facing, concentrating the loads in that area (Bureau et al., 1985).

The more effective approach is to treat the dam-water system as composed of two substructures: dam and fluid domain coupled through the interaction forces and appropriate continuity conditions at the face of the dam? Two formulations can be used: Westergaard method and Galerkin method (Sêco e Pinto, 1993a). What will be the adequate procedure to deal with this subject?

(iv) What time-acceleration data should be used in estimating permanent deformations of an embankment dam using Newmark procedure. Since the acceleration response varies throughout the embankment the engineering practice in the selection and use of time-acceleration data is not consistent.

LIQUEFACTION

(i) The CPT gives a reliable continuous penetration resistance in comparison with SPT tests. Should efforts be increased in order to increase the CPT data base for liquefaction correlations?

(ii) Has field experience in using the CPT shown that the fines content can be adequately determined for the purpose of assessing liquefaction potential?

(iii) In order to assess the liquefaction of gravel materials should correlation between BPT-SPT and the use of shear wave velocity be encouraged?

(iv) Should nonlinear elastic or plastic models for predicting liquefaction to assess the permanent deformations be implemented?

TAILINGS DAMS

Is it important to establish a data base for static and dynamic strength characteristics of refuse material?

NATURAL SLOPES

What is the influence of initial shear stress in the stability of natural slopes?

With this discussion the following benefits are expected:
- a better evaluation of soil dynamic properties with the use of new laboratory and field equipments.
- a better definition of construction specifications related with the compaction of filter and drain materials and the bounds of fine percentage.
- a better support for the definition of monitoring plans.
- development of new criteria for the design of embankment dams, slopes and tailings dams under earthquakes.

In dealing with this subject we should never forget the memorable lines:

"The important thing in science is not
so much to obtain new facts as to discover
new ways of thinking about them".
(Sir W. Bragg, British Scientist, 1968)

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Papers presented at this Session

6.01 Caldeira, L., Sêco e Pinto, P.S. and Bilé Serra, J.P. "Seismic Response of Embankment Dams".

6.02 Hallman, D.S. and Dorey, R. "Mine Tailings Deposition Practices, Liquefaction Potential and Stability Implications".

6.03 Xu, Z. "Effect of Canyon Shape on Longitudinal Vibration of Earth Dam".

6.05 Soydemir, C. "Seismic Design of Landfills for NE United States".

6.06 Husein, A.I., Liang, R.Y. and Nusairat, J.H. "Karameh Earth Dam. Challenging Project".

6.07 Vesseley, D.A. and Deng, N. "Gravel liquefaction Anlysis of an Embankment Dam".

6.08 Yiagos, A.N. "Elasto-Plastic Seismic Response Analysis of Earth Dams".

6.10 Mars, S.S., Green, R.K., Kanakari, H., Boddie, P.J., Mejia, L.H. and Weaver, K.D. "Evaluation of Earthquake-Induced Slope".

6.12 Law, H.K. and Ko, H.Y. "Model Parametric Studies of Earthquake Response of the Embankment Dam".

6.13 Kaneko, M., Nishihawa, J., Sasaki, Y., Nagase, M. and Mamiya, K. "River Failure in Japan by Earthquakes".

6.14 Sully, J.P., Fernandez, A. L. and Zalzman, S. "Back--Analyses of Deformations for Case Histories Involving Flow-Type Failures".

6.17 Abousseda, H.M. and Dakoulas, P. "Response of earth Dams Subjected to Obliquely Incident P and SV Waves".

6.18 Deng, N., Ostadan, F., Arango, I. and Marrone, J. "Seismic Stability Analysis of High Rockfill".

6.23 Iwashita, T., Japan, T., Nakamura, A. and Yasuda, N. "Behaviour and Damage of Dams During 1993 Kushiro Oki Earthquake and 1993 Hokkaido Nansei Earthquake".

6.24 Jitno, H. and Byrne, P.M. "Predicted and Observed Liquefaction Induced Deformations of La Palma Dam".

6.25 Pillai, V.S., Plewes, H.D., and Stewart, R.A. "Some Aspects of Liquefaction Assessment of Duncan Dam".

6.26 Chang, T.S., Wei, B.Z., Chang, K.P. and Hall, K.M. "Earthquake-Induced Lateral Displacement of a Landfill".