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EVALUATION OF THE SEISMIC PERFORMANCE OF EARTH STRUCTURES

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ABSTRACT:

A number of simple and sophisiticated approaches have been developed and used for the assessment of the performance of embankments, earth dams and other geotechnical structures. In this paper reference is made to an extended sliding block model which enables the simulation of stability and deformations and to assess their variation with time during an earthquake. The shear strength of cohesionless soils decreases during an earthquake mainly due to the development of excess pore water pressures. Therefore, the factor of safety and the critical seismic coefficient decrease. This reduction has, in turn, a significant influence on the permanent deformations. Typical results for an embankment are presented for the factor of safety, the critical seismic coefficient and permanent deformations along a slip surface.

KEYWORDS:

Earthquake response, embankment performance, sliding block model, slip surfaces, safety factor, excess pore pressure, critical seismic coefficient, permanent deformations, shear strength decrease, liquefaction

INTRODUCTION:

Earthquakes often cause significant damage to embankments, earth dams and slopes. Many catastrophic failures of earth structures and natural slopes during earthquakes have caused considerable loss of life and property as well as damage to the environment. Geotechnical engineers are required to design new earth structures taking into consideration the effects of shaking due to earthquakes. It is also necessary to assess the stability of existing earth structures such as embankment dams. There are, of course, several important factors which control the response of an earth structure during the period of earthquake shaking. In addition to the nature and severity of the ground motion, the most important factors are those which contribute to the decrease in the shear strength of soil materials comprising an earth structure.

There are significant gaps in knowledge concerning the behaviour of earth structures under earthquake conditions. In spite of these gaps and uncertainties, it is necessary to assess the stability and integrity of such structures. Both simple and relatively complex methods of analysis have been developed and the choice of method depends on the importance of the project, the consequences of failure, the availability of accurate data on soil properties and the confidence in predicting the ground motions to which the structure will be subjected during its life. Considering the diversity of these factors and the uncertainties associated with them, geotechnical engineers prefer relatively simple methods of analysis.

As research concerning geotechnical earthquake engineering has progressed, sophisiticated methods of analysis have also been developed. Such approaches often involve dynamic finite - element analyses including those which are based on three-dimensional modelling of a soil structure. At the same time, studies with the Newmark sliding block approach (Newmark 1965) have been continued by various research workers including Sarma (1981), Hynes-Griffin and Franklin (1984), Tika et al (1993), Chowdhury and Xu (1994).

The approach pioneered by Professor Seed and his co-workers at the University of California, Berkeley, generally known as the Seed-Idriss-Lee approach, has been reported in many publications including Seed et al (1973) and Seed (1979). In this approach, the shear stresses imposed on soil elements during an earthquake are assessed from dynamic finite-element analyses. These shear stress increments are then applied to appropriate soil samples in dynamic triaxial or dynamic simple shear tests. The potential for liquefaction of samples, and hence of the soil zones they represent, is thus determined. Having identified liquefied and non-liquefied soil zones, stability analyses can be conducted to determined the static factors of safety considering either zero shear strength for the liquefied zones or the 'residual' shear strength.

The practice of adopting 'residual' shear strength for cohesionless soils, which have been assessed to have the potential for liquefaction, is a new trend which is receiving wide acceptance amongst geotechnical engineers who are required to assess the seismic response of earth structures. However, it should be noted that such an approach can only be appropriate for post-liquefaction stability. In particular, it can facilitate an assessment for the potential for the development of a flow slide after an earthquake has shaken an earthern structure.

It is important to distinguish between a 'total stress' and an 'effective stress' approach for the analysis of an earth mass or a geotechnical structure. For pre-earthquake stability of an embankment or an earth dam, one must adopt an approach appropriate to the soil types and the environmental conditions. 'Effective stress' analysis would be appropriate for cohesionless soils and either a 'total stress' or an 'effective stress' analysis may be used for cohesive soils depending on the loading conditions and design objectives. For an analysis simulating conditions during earthquake shaking, the use of a 'total stress' approach has been justified on the basis of 'undrained' loading conditions which are expected to prevail. Similarly, for post-earthquake stability immediately after an earthquake, 'undrained' loading conditions can be expected to prevail and, therefore, the use of a 'total stress' analysis can be justified. Consequently, residual shear strength of a cohesionless soil, which has been assessed to have the potential for liquefaction, is considered as a 'total stress' parameter. It is important to distinguish this concept of residual shear strength from the traditional concept relevant to cohesive soils under static loading conditions. The traditional approach is applicable to shear surfaces or zones in cohesionless soils which have been subjected to significant relative deformations and not just large strains.

In spite of the practice often adopted of a 'total stress' analysis approach within the framework of a limit equilibrium concept, it is widely recognised that an 'effective stress' approach would be more soundly based on the principles of modern soil mechanics. The real cause of shear strength decrease in a saturated cohesionless soil during earthquake shaking is the development of excess pore water pressure. Therefore, effective stresses decrease and an analysis which simulates the process of such strength decrease would be more realistic than a 'total stress' analytical approach. Accordingly, in this paper an extended sliding block approach is advocated in which the slope stability part of the analysis, based on the concept of limit equilibrium, is performed in terms of effective stresses.

THE PROPOSED APPROACH

The basic sliding block approach proposed by Newmark (1965) was a marked improvement on the pseudo-static analysis approach. The concept of critical seismic acceleration coefficient K_c was introduced. It is defined as the seismic acceleration coefficient which corresponds to critical equilibrium of a slope (factor of safety $F = 1$) and its value is determined from an appropriate limit equilibrium analysis. The method of analysis chosen simple or rigorous, would depend on the assumed shape of the potential slip surface within the slope, e.g., planar, bi-planar, circular and arbitrary or non-circular.

Having determined the value of K_c, the potential sliding mass is considered as a block, resting on an inclined plane, and subjected to an acceleration coefficient $K(t)$ which is a function of time t. At a particular instant of time, the applied acceleration coefficient $K(t)$ may have a value greater than the critical seismic coefficient K_c. If this is so, the sliding mass will have an acceleration and its relative displacement may be estimated from basic principles of dynamics. These permanent deformations can thus be estimated by integration for the whole of a given acceleration-time history.

The original sliding block approach and many subsequent extensions assume that the critical seismic coefficient remains constant during the period of earthquake ground motion. The proposed extension (Chowdhury and Xu, 1993) considers both the static factor of safety and the critical seismic coefficient to be functions of time t after the start of an earthquake.

$$F = F(t), \quad K_c = K_c(t) \qquad (1)$$

The reason for this extension is that shear strength of soils within an earth structure may decrease during earthquake shaking either due to strain-softening of soil materials or due to the development of excess pore water pressure or both. These processes would lead to decrease in the overall safety margin of the earth structure.

The expression for the resultant acceleration, a, of a block subjected to an applied acceleration K(t) may now be written as follows:

$$a = g\frac{\cos(\alpha - \theta - \phi)}{\cos(\phi)}\,[K(t) - K_c(t)] \qquad (2)$$

in which, g is the gravitational acceleration, α is the inclination of the inclined plane to the horizontal, θ is the inclination of applied acceleration vector to the horizontal and ϕ is the internal angle of friction at the interface between the base of the block (soil mass) and the inclined plane. In other words, ϕ is the internal friction angle along a potential slip surface.

In this paper, shear strength decrease is considered to be due only to the development of excess pore water pressure which may occur in some zones of an embankment or soil structure. Any strength decrease due to strain-softening phenomena is not included here.

SIMULATION OF EXCESS PORE WATER PRESSURE

The development of the Seed-Idriss-Lee approach mentioned earlier was a consequence of research concerning the behaviour of soils under cyclic loading conditions. The importance of such studies is now widely appreciated. However, simple approaches for using the results of such studies have not been widely adopted in practice.

Pore pressure coefficients A and B proposed by Skempton to estimate excess pore water pressures under static loading have been widely adopted in geotechnical practice. Sarma and Jennings (1980) proposed the use of dynamic pore pressure coefficients under earthquake loading conditions. They analysed published experimental data from different sources and found that the following simple equation could be used to estimate excess pore water pressure Δu from the results of cyclic triaxial tests.

$$\frac{\Delta u}{\sigma'_{3c}} = A_n \frac{\Delta\sigma_1}{\sigma'_{3c}} \qquad (3)$$

in which $\Delta\sigma_1$ is the increment of cyclic major principal stress, σ'_{3c} is the minor principal consolidation stress and A_n is a pore water pressure coefficient appropriate to n cycles of loading.

Based on their analysis, the following relationship between A_n and A_1 was also proposed:

$$A_n^{\frac{1}{2}} = A_1^{\frac{1}{2}} + \beta \log n \qquad (4)$$

in which A_1 is the pore water pressure coefficient for one cycle of loading and β is another soil parameter.

Considering the results of cyclic simple shear tests, the proposed equation corresponding to Eq.(3) is the following:

$$\frac{\Delta u}{\sigma_{vo}'} = A_n \frac{\Delta\tau}{\sigma_{vo}'} \qquad (5)$$

in which $\Delta\tau$ is the increment of cyclic shear stress and σ_{vo}' is the effective vertical overburden stress on the sample.

NUMERICAL APPROACH

A potential slip surface is selected within the earth structure and an appropriate method of slices for slip surface of either a circular shape or an arbitrary shape is chosen.

It is also desirable to locate the critical slip surface using a search technique or an optimisation approach. Based on the geometry of the earth structure, the shape of the slip surface and the appropriate geotechnical parameters, the initial values of the factor of safety F and the critical seismic coefficient K_c are then calculated. Each vertical slice is considered as a block on an inclined plane for the dynamic part of the analysis.

The design ground motion or acceleration time-history must be known before the full analysis can be carried out. The numerical solution for the extended sliding block model is carried out in very small and sequential time steps. A dynamic analysis based on the simple, single-degree-of-freedom-system represented by Eq.(2) is carried out for each of vertical slices for the first time step. The increments in principal stresses at the base of each block can then be estimated. Using these values and the given values of dynamic pore pressure coefficients, the excess pore water pressure can be calculated.

Before carrying out the dynamic analysis for the next time step, the limit equilibrium part of the analysis is repeated with the values of the excess pore water pressure so that a new value of K_c can be obtained. In this way, the analysis is carried out for all the time steps covering the whole period of earthquake ground motion.

ILLUSTRATIVE EXAMPLE

The new and extended sliding block approach was used for an analysis of the Lower San Fernando Dam, a cross section of which is shown in Fig. 1. The results presented in this paper have been obtained for the arbitrary slip surface shown in Fig.1. Some results for the critical slip surface have been presented elsewhere (Chowdhury, 1995).

A simulated acceleration-time history was used for the analysis and this is shown as Fig. 2. This time-history is similar to the one used for previous analysis of this dam by Seed and his co-workers from the University of California, Berkeley.

There are several soil zones in the dam as shown in Fig.1. The geotechnical properties of these soil zones are presented in Table 1. The analyses were carried out considering the reservoir water level shown in Fig. 1. The soil mass above the slip surface was divided into 13 vertical slices as shown in Fig.1.

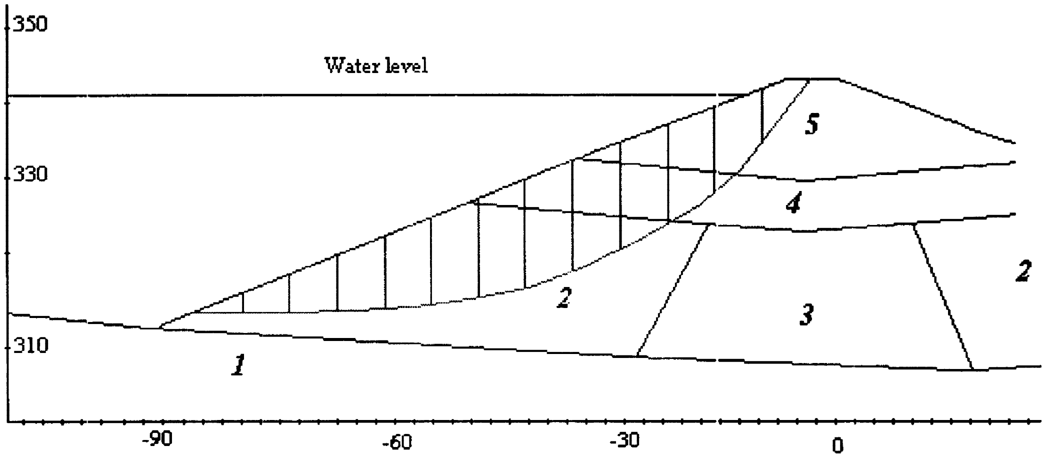

Fig 1 Cross section of dam with arbitrary slip surface

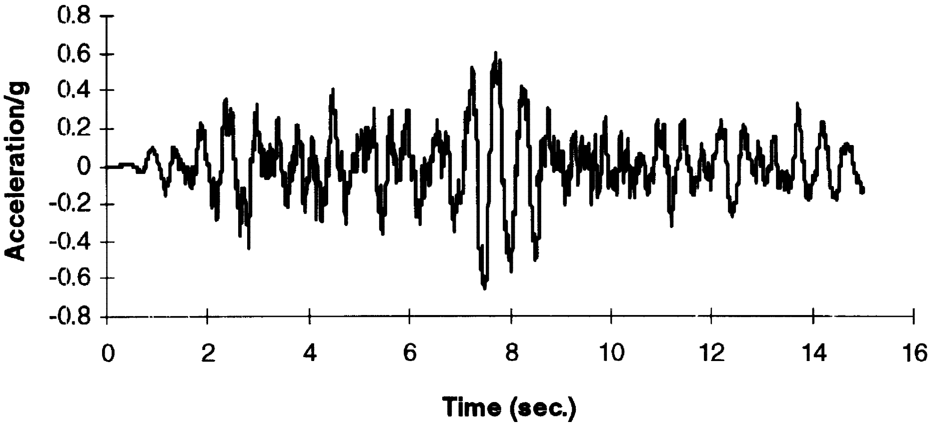

Fig 2 A generated earthquake for 15 seconds

Table 1 Soil Properties used in the analysis

Zone	γ (KN/m^3)	c' (KN/m^2)	ϕ' (Degrees)	c_u (KN/m^2)
1	17.3	0	38	-
2	20.5	0	37	-
3	19	-	-	81.4
4	20	0	33	-
5	19	-	-	81.4

The values of dynamic pore pressure coefficients used for the analysis were:

$A_l = 0.67$, $A_n = 1.6$

$A_l = 0.67$, $A_n = 2.4$

These values are well within the range estimated from experimental data for the soils from Lower and Upper San Fernando Dams.

The initial and final values of F and K_c for these two sets are shown in Table 2.

Table 2 Initial and final values of F and K_c for two sets of values of dynamic pore pressure coefficients

A_n	A_n	Initial		Final	
		F	K_c	F	K_c
0.67	1.6	2.24	0.45	1.65	0.23
0.67	2.4	2.24	0.45	1.33	0.1

It is clear that, while the reductions in the safety margin are substantial, failure is not predicted during the earthquake even with the higher value of A_n.

An important advantage of the new sliding block approach is that the variations of factor of safety and critical seismic coefficient with time, during the earthquake, can be simulated.

The variation of factor of safety is shown in Fig. 3 and the variation of critical seismic coefficient is shown in Fig. 4.

The permanent deformations of the bases of slices 5 and 10 are shown as functions of time in Figs. 5 and 6 respectively.

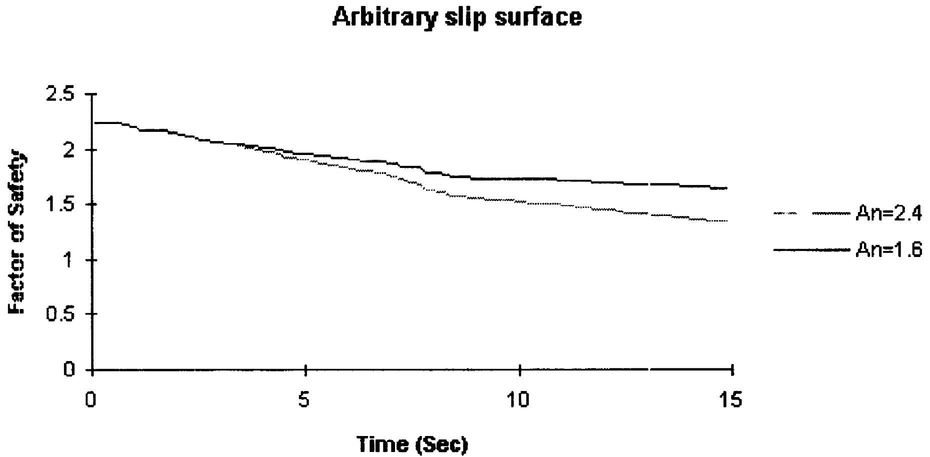

Fig 3 Variation of factor of safety with time

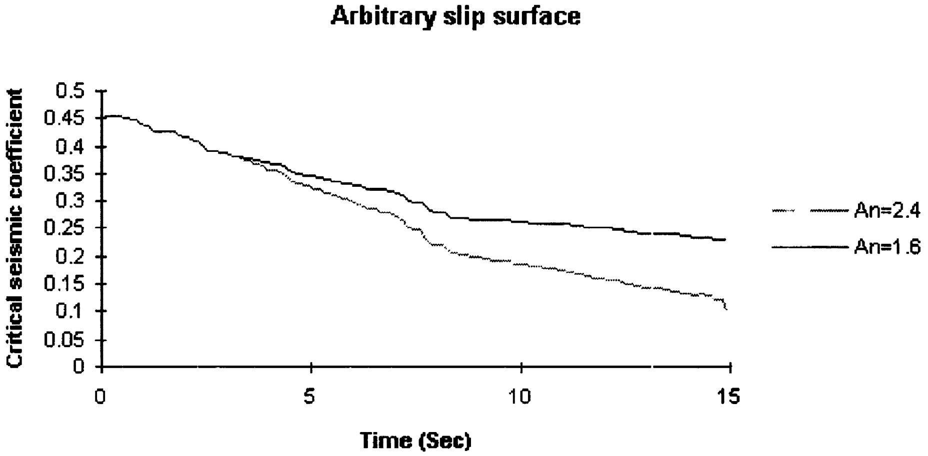

Fig 4 Variation of critical seismic coefficient with time

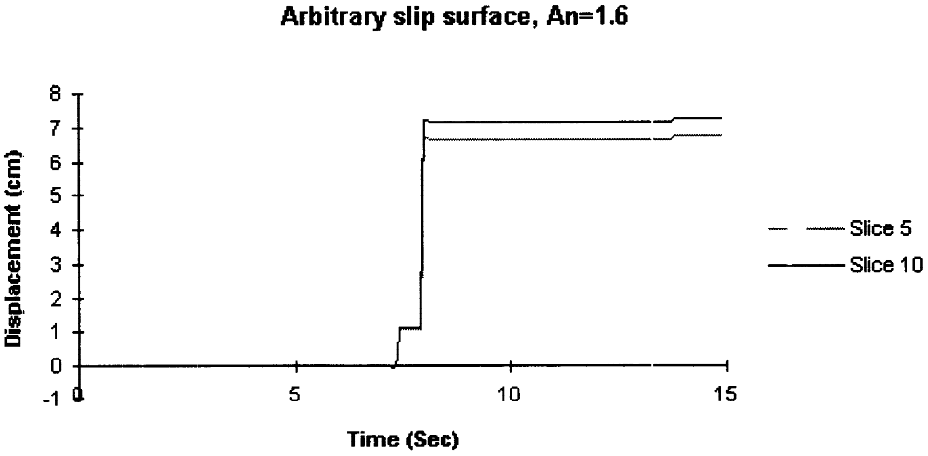

Fig 5 Increase of permanent displacement with time for $A_n = 1.6$

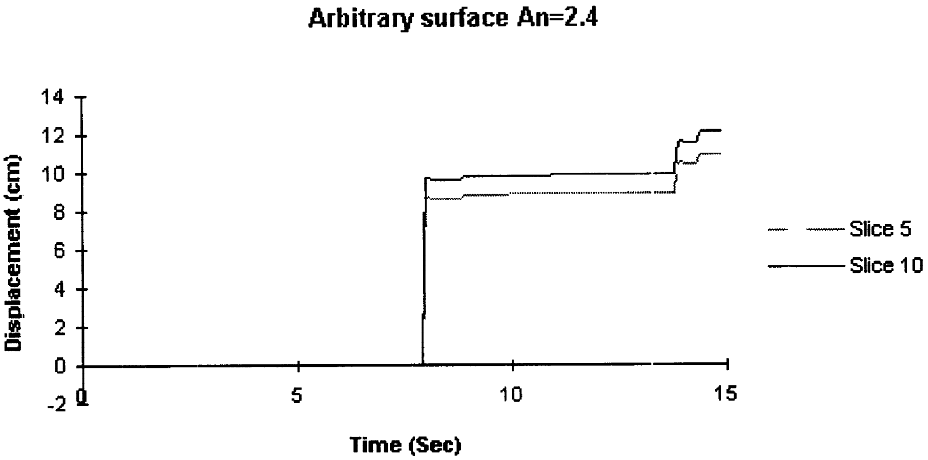

Fig 6 Increase of permanent displacement with time for A_n = 2.4

DISCUSSION

The key elements of an extended sliding block model have been presented in this paper. Simple equations, proposed in the literature on the basis of experimental data, can be used to simulate the increases in excess pore water pressure during an earthquake. Values of dynamic pore water pressure coefficients for any cohesionless soil are required for the analysis.

Typical results are presented considering an arbitrary slip surface at a relatively shallow depth within the Lower San Fernando Dam. From additional studies presented elsewhere it is known that lower factors of safety and larger deformations are predicted for deeper slip surfaces. A comprehensive comparison of the results from different slip surfaces is to be published after further studies.

The way in which factor of safety and critical seismic coefficient change during an earthquake can be studied by using this method. Similarly, the increase of permanent deformations with time can be studied on a systematic basis.

CONCLUSIONS

Relatively simple methods are very useful for studying the seismic response of earth structures. However, such methods must be realistic and, therefore, capable of simulating the decreases in safety margins during earthquake shaking. In order to achieve this, simple and realistic equations must be used for the relationship between excess pore water pressure developed in a cohesionless soil and the cyclic stresses applied during earthquake shaking to elements of that soil. The proposed new approach is an extension of the sliding block approach. In relation to the state-of-the-art of geotechnical earthquake engineering, it is important to note that new approach enables analyses to be carried out in terms of effective stresses. With the development of such effective stress approaches, desirable improvements can be expected in the state-of-practice of geotechnical earthquake engineering.

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