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Back Analysis of the Lower San Fernando Dam Slide Using a Multi-block Model

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Abstract

A multi-block sliding system model has been developed to simulate the displacement of sliding geo-masses. This model is a useful tool, especially when displacements are very large and computer codes based on the Finite Element Method cannot be applied. The paper investigates the ability of the model to predict the response of the well-documented Lower San Fernando Dam slide. The predicted movement, and deformation agreed reasonably well with that of the upper part of the slide. Yet, the lower part of the slide slid more that the model prediction. The multi-block model was applied a second time. This 2-slide approach predicts movement, and deformation in very good agreement with that measured. In addition, the time duration of motion is in general agreement with the observed.

1 Introduction

The conventional sliding-block model has shortcomings in back-analyzing slides when displacement is large (larger than a few meters). The reason is that the change in geometry of the sliding mass, that greatly affects the displacement, is not modeled. Ambraseys and Srbulov (1995) proposed a two-body sliding system that simulates the displacement of slides. Stamatopoulos et al (2000) generalized the two-body sliding system. Sarma and Chlimintzas (2001) proposed a sliding system consisting of n bodies. Similarly to the Sarma (1979) stability analysis method, internal sub-planes are formed at the locations where the external slip surface changes inclination. Energy loss at these sub-planes is adequately modeled. As shear displacement occurs, mass is transferred between consecutive blocks.

This model is a useful tool, especially when displacements are very large and computer codes based on the Finite Element Method cannot be applied. The model has been validated by predicting the response of slides along pre-existing slip surfaces, such as the well-documented Vaiont landslide, which occurred in 1963 (Stamatopoulos and Aneroussis, 2006). The purpose of this paper is to investigate the ability of the model to predict the response of the liquefaction-induced slide of the Lower San Fernando Dam, triggered by the 1971 earthquake.

2 The multi-block model

We consider a general mass sliding in n slip surfaces. Similarly to the geometry considered in the Sarma's (1979) stability method, shown in figure 1, the mass is divided into n parts with (n-1) interfaces passing thru the nodes of the slip surface. Critical acceleration factor, k_c , is the minimum factor that when multiplied by the acceleration of gravity, g, gives the horizontal acceleration which is just sufficient to cause movement of the block. The inclinations of the interfaces correspond to the inclinations that produce failure at a minimum value of k_c. (This condition is preferred from the commonly-used factor of safety factor because it is better defined).

At the interface between two consecutive blocks, the velocity must be continuous. This principle gives that the relative displacement of the n bodies is related to each other as:

$$u_i/u_{i+1} = du_i/du_{i+1}= \cos(\delta_i+\beta_{i+1}) / \cos(\delta_i+\beta_i) \qquad (1)$$

where u_i is the displacement of body "i" along the slip surface. The forces that are exerted in body “i” are given in figure 1. As the body moves, the Mohr Coulomb failure criterion can be applied at both the external and internal slip segments. Thus, the equation of motion of body (i) along the direction of motion, is formulated. To eliminate the internal forces N_i (figure 1), equation (i) is multiplied by a factor. Summing all equations and expressing displacement of all blocks in terms of u_n, the equation of motion is obtained. As the equation is very long, it is not presented here. It is presented for two blocks by Stamatopoulos et al (2000) and for n blocks by Sarma and Chlimitzas (2001).

To solve the equations for large displacement, the masses and lengths of each body i are expressed in terms of the distance moved. The transformation rule, that when each block is displaced by $d\tilde{u}_i$, each point of the block including the ground surface (at the top of the block) is also displaced by $d\tilde{u}_i$, is applied incrementally. A point may move from one block to the previous, and thus its incremental displacement for given $d\tilde{u}_n$ will change from $d\tilde{u}_i$ to $d\tilde{u}_{i-1}$. Based on this rule, the masses, areas and lengths of the bodies "i" of the sliding system are continually updated as a function of the distance moved. The deformation that this rule predicts is illustrated later, in the case study (in figures 3c and 5c).

A computer program that solves the equations of motion of the model described above has been developed by Stamatopoulos. The input geometry is specified as the nodes of the linear segments defining the slip and ground surfaces. The inclinations of the internal slip surfaces are also defined. Soil strength and pore pressure are specified in each segment. The computer program includes graphics that illustrate (a) the acceleration, velocity and displacement in terms of time and (b) the initial and final deformation of the slides.

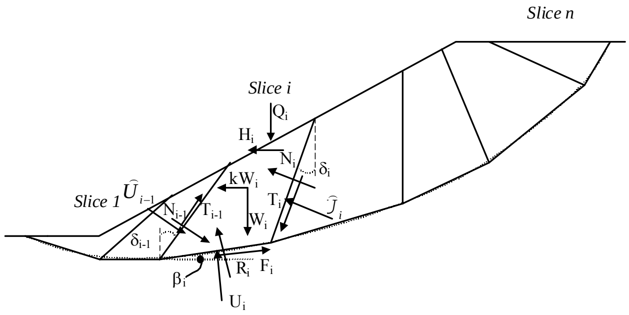


Figure 1. The multi-block stability method proposed by Sarma (1979).

3 The Lower San-Fernando slide

A well-documented case of a liquefaction-induced slide is the one of the Lower San Fernando Dam, triggered by the 1971 earthquake. Figure 2 gives a typical cross-section showing the geometry before and after the slide (Seed et al., 1971). The residual resistance of the sandy liquefied materials has been measured by various investigators in the laboratory; the value ranges from 29 to 38 kPa (Baziar and Dobry, 1995). However, Baziar and Dobry (1995) state that during the process of movement the hydraulic fill may have lost part of its original microlayering, approaching the remoulded homogeneous steady-state and decreasing the residual strength to the final value of about $c_{u\text{-sand}}$= 19 kPa. In addition, the same authors report that $c_{u\text{-sand}}/\sigma'_v$ equals 0.12 to 0.19. The corresponding total strength friction angle equals 6 to 11 degrees. The steady-state strength of the clay core material has also been measured as $c_{u\text{-clay}}$ = 29 kPa (Castro et al., 1992). The total unit weight of the hydraulic fill was 20 kN/m^3 (Seed et al., 1971).

Analysis of the seismoscope record on the dam crest indicated that the major slide started about 25 sec after the earthquake shaking had stopped and lasted for about 50sec. (Seed, 1975).

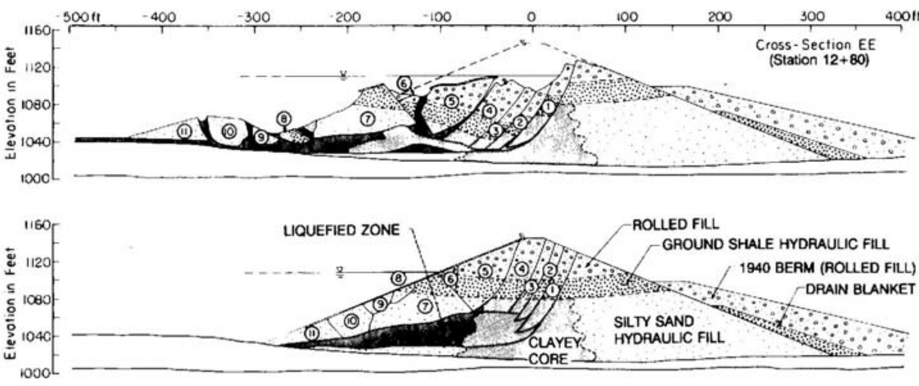


Figure 2. The Lower San Fernando Dam Landslide. Cross-section of the slide (Seed et al., 1975).

4 Steps used to apply the multi-block model

The steps required to apply the multi-block model in back analyses of slides are: (a) The slip surface is located and simulated as a series of linear segments, (b) the inclination of the internal linear segments is established according to the condition of minimum critical acceleration value and (c) the distance moved and slide deformation is estimated using the multi-block model.

The above procedure assumes that soil strength is known. In the present study a range of measured soil strength values exists. For this reason, for steps (b) and (c) the following procedure is used: (1) Guess a soil resistance, (2) Estimate the inclinations of the internal sub-planes based on the theory of limit equilibrium for this resistance, (3) Back-estimate the soil strength that best predicts the final deformed geometry, (4) Compare the back-estimated resistance with the resistance assumed in (1) and if it is different, perform again steps (2) to (4) until convergence is achieved. In (2) it should be noted that, as the geometry changes by the slide movement, the inclination of the internal sub-planes should be the average of those at the initial and final configurations in the cases where considerable slide deformation occurs. Finally, compare the back-estimated resistance with the measured range of strength values.

For step (a), an algorithm searching for the critical slip surface associated with the multi-block stability method does not exist at present in the literature. Previous work reported in the literature, or an algorithm associated with the Bishop method of slices included in the computer software Larix 2S (Cubus Software, 1995), was used instead.

5 Prediction

The strength properties are non-uniform. Consistently with section 3 above, for the clay layer $c_{u\text{-}clay}$=29 kPa was assumed. For the liquefied layer, the frictional resistance is taken to vary. The total unit weight of the hydraulic fill was 20 kN/m^3. As the slide occurred after the earthquake, seismic forces were not applied in the analysis.

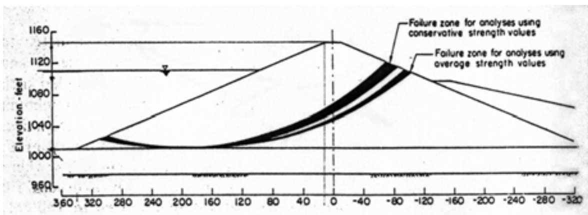
The procedure described in section 4 above was used to obtain the solution of the problem. Stability analysis reported by Seed et al (1975) (figure 3a) illustrates that the critical slip surface may be represented by two linear segments, as given in figure 3c. Figure 3b gives the critical acceleration coefficient for relative motion at the initial and final configurations of the two-block model in terms of the interface angle. As the strength along the slip segments is nonuniform, average values obtained by interpolation were used. It can be observed that the average interface angle that produces minimum critical acceleration value is δ_1=-30^o. For this value, the best-fit final geometry obtained is given in figure 3c. The strength of the liquefied layer corresponds to $(\varphi)_{res}$=9^o. Figure 4a gives the computed acceleration, velocity and distance moved of the lower body in terms of time of the solution above. The computed time duration of motion is 10.4s.

The predicted movement, and deformation agreed reasonably well with that of the upper part of the slide. Yet, the lower part of the slide slid more than the model prediction. This discrepancy between field observation and model simulation was attributed to the existence of two slides firstly a "primary" slide affecting the total height of the slide and secondly a "secondary" slide affecting only the lower part. Thus the calculation was repeated for a second time. The strength of the soil above the liquefied zone is not given in the literature. As all the mass is below the water table, soil is sandy and has been already sheared, it is assumed that if has a frictional resistance equal to that of the liquefied layer.

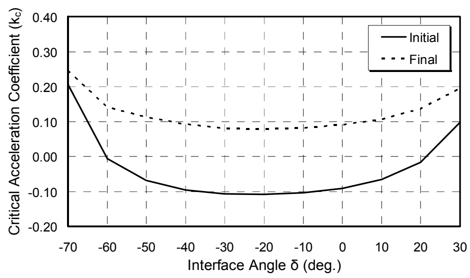
The procedure described in section 4 above, was applied for a secondary slide. Stability analysis on the deformed configuration of figure 3c, using the Bishop method, illustrated that (a) the deformed configuration produces a factor of safety less than unity for a friction angle equal to 9^o, and thus a second slide can be triggered and (b) the critical slip surface of this secondary slide, given in figure 5a, can be represented by three blocks, as shown in figure 5c. Figure 5b gives the critical acceleration coefficient for relative motion at the initial and final configurations in terms of the interface angle. It can be observed that the average interface angles that produce minimum critical acceleration values are δ_1=-35^o, δ_2=-30^o. For these values, the best-fit final geometry obtained is given in figure 5c. The strength of the liquefied layer corresponds again to $(\varphi)_{res}$=9^o. Figure 4b gives the computed acceleration, velocity and distance moved of the lower body in terms of time of the solution above. The computed time duration of motion is 8.7s.

Figure 6 gives the deformed geometry considering both slides. Finally, stability analysis illustrated that the final configuration for $(\varphi)_{res}$=9^o for the liquefied layer is stable.

(a)



(b)



(c)

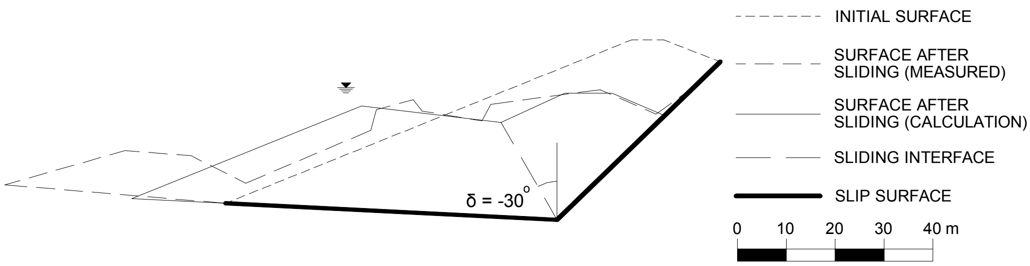


Figure 3. First slide. (a) The slip surface as predicted by Seed et al (1975), (b) critical acceleration coefficient for relative motion at the initial and final configurations in terms of the interface angle and (c) initial slide configuration assumed, computed final configuration and measured final configuration.

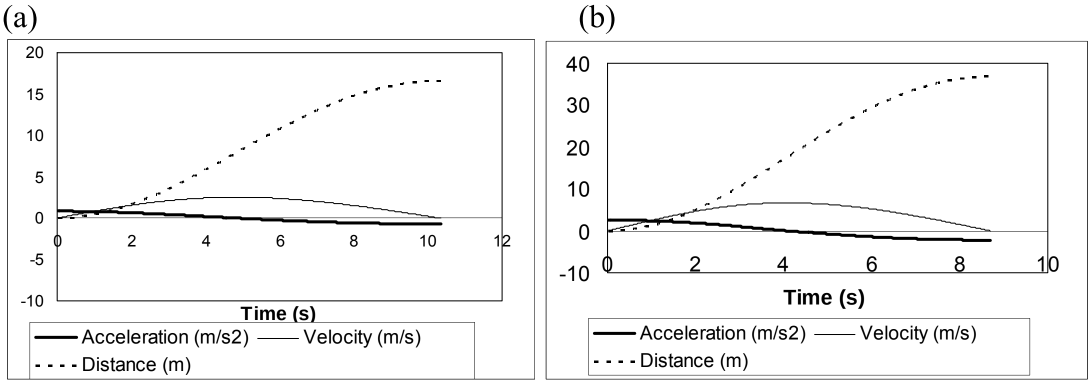


Figure 4. Computed acceleration, velocity and distance moved of the lower body (a) of the first slide and (b) of the second slide in terms of time.

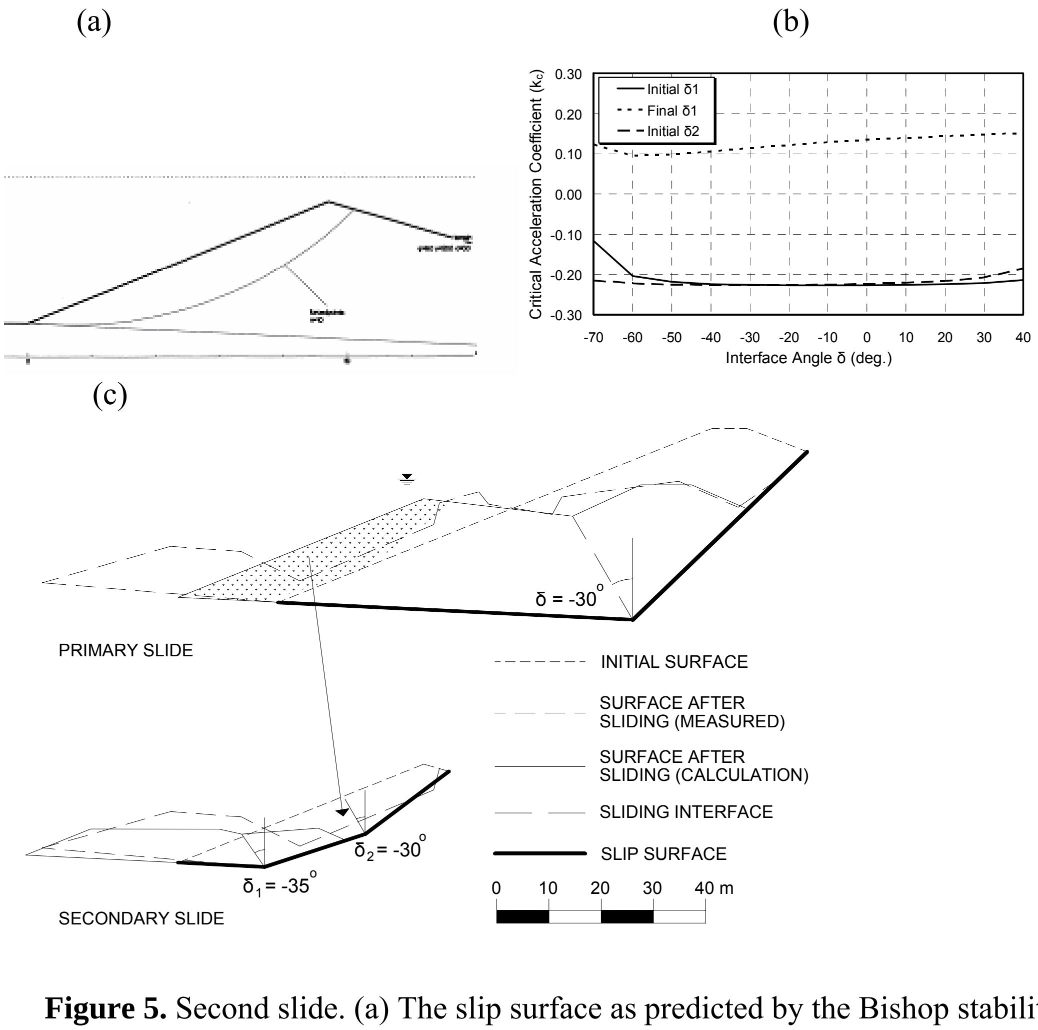


Figure 5. Second slide. (a) The slip surface as predicted by the Bishop stability method, (b) the critical acceleration coefficient at the initial and final configurations in terms of the interface angles and (c) the initial slide configuration assumed, computed final configuration and measured final configuration. In (b) for each case the other interface angle equals its critical value.

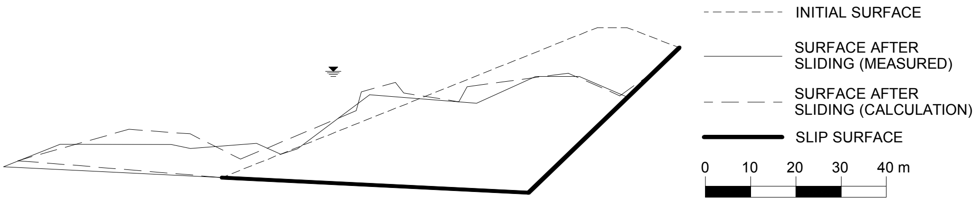


Figure 6. Initial configuration, computed final configuration with the 2-slide analysis and measured final configuration.

6 Discussion

As illustrated in figure 6, the 2-slide approach predicts movement, and deformation in very good agreement with that measured. The back-estimated soil strength of the liquefied sand equals 9^{o} for both the primary and secondary slides. This is within the range of the measured total friction angle of the liquefied material. The computed time duration of the primary slide equals 10.4s and of the secondary slide 8.8s. The two slides have a total duration of 19s, less than the observed total duration of the slide of 50s. This difference may be due to a time interval of stability between the two slides.

From all the above it is inferred that the multi-block model with two assumed slides can be used to simulate the motion and deformation of the Lower San Fernando Dam slide.

7 Conclusions

A multi-block sliding system model and associated computer code has been developed to simulate the displacement of sliding geo-masses. The paper investigated the ability of the model to predict the response of the well-documented Lower San Fernando Dam slide. As illustrated in figure 6, the 2-slide approach predicts movement, and deformation in very good agreement with that measured. The back-estimated soil strength of the liquefied soil equals 9^{o} for both slides. This is within the range of the measured total friction angle of the liquefied material. The computed time duration of the primary slide equals 10.4s and of the secondary slide 8.8s. The two slides have a total duration of 19s, less than the observed total duration of the slide of 50s. It could be that between the two slides there was a time interval of stability. From all the above it is inferred that the multi-block model with two consecutive assumed slides can be used to simulate the motion and deformation of the Lower San Fernando Dam slide.

Acknowledgement

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