

**Back analysis of the Lower San
Fernando Dam slide using a multi-
block model**

by

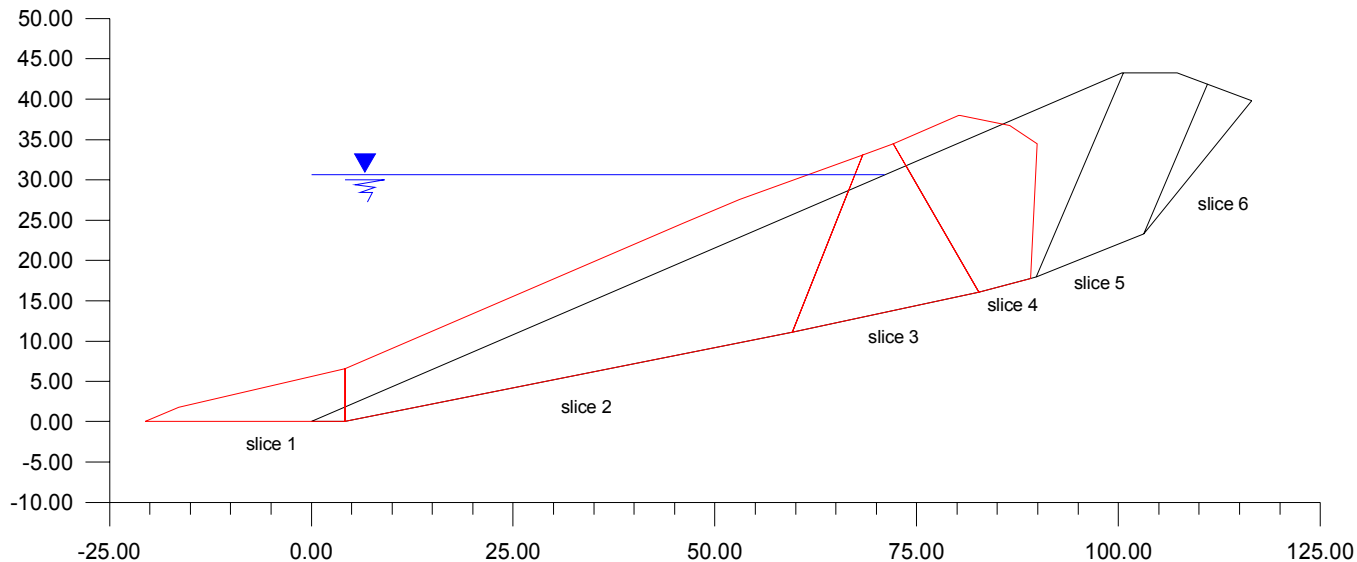
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Stamatopoulos and Associates Co.

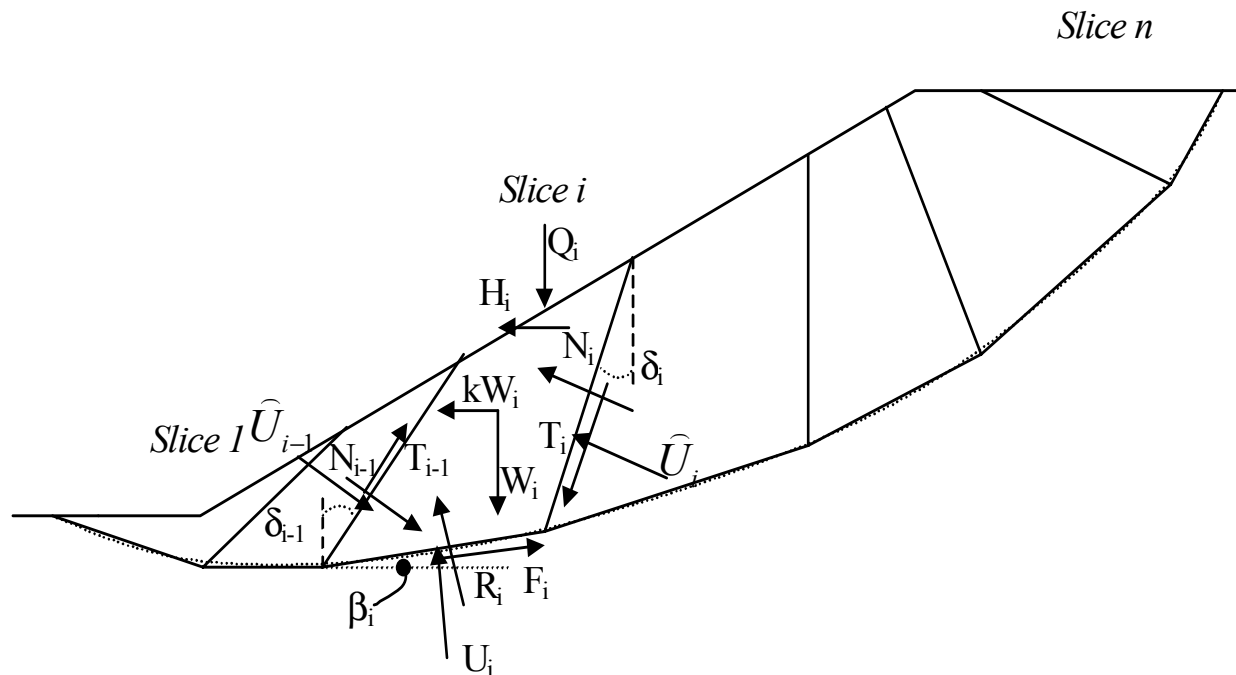
- A multi-block sliding system model has been developed to simulate the displacement of sliding geo-masses. This model is a useful tool, especially when displacements are very large and computer codes based on the Finite Element Method cannot be applied.
- The paper investigates the ability of the model to predict the response of the well-documented Lower San Fernando Dam slide.

1. The multi-block model

A two-block (Stamatopoulos et al, 2000) and multi-block (Sarma and Chlimintzas, 2001) sliding system has been developed during a previous EU project. This system is a useful tool to simulate slides, especially when displacements are very large and FEM computer codes cannot be applied.

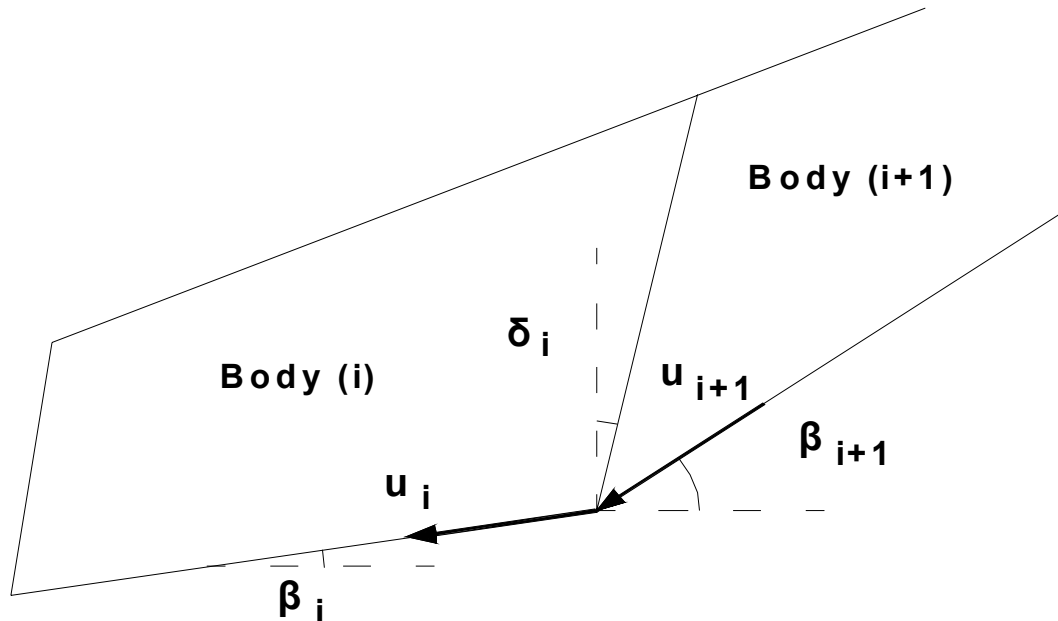


- The model considers a general mass defined by (m) nodes resting on a slip surface defined by (n) nodes. The mass is divided in (n) parts with (n-1) interfaces passing through the nodes of the slip surface.
- The inclination of the interfaces corresponds to the inclinations that produce a minimum value of critical acceleration.

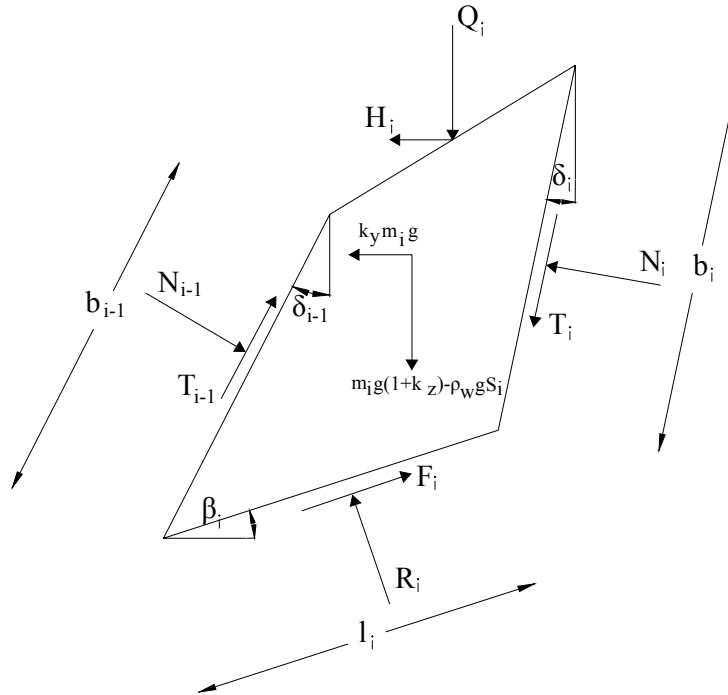


At the interface between two blocks, the velocity must be continuous. This principle gives that the relative displacement of two consecutive blocks is related to each other as:

$$u_{i+1} \cos(\beta_{i+1} + \delta_i) = u_i \cos(\beta_i + \delta_i) \quad (A)$$



The forces that are exerted on body "i" are given in the Figure below



As the body moves, at the external and internal slip surfaces, the Mohr Coulomb failure criterion gives

$$F_i = (R_i - U_i) \tan \phi_i + c_i l_i$$

$$T_i = (N_i - U_{in_i}) \tan \phi_{in_i} + c_{in_i} b_i$$

where U_i and U_{in_i} is the pore water force acting on slice i and along the interface between slices i and $i+1$ respectively

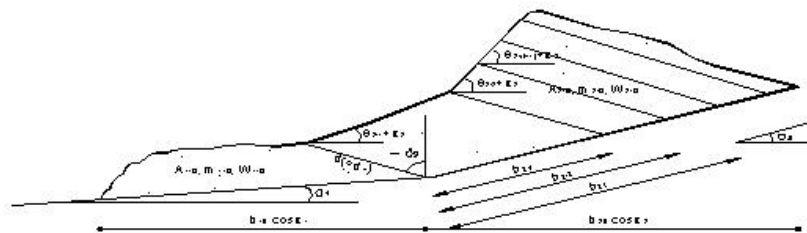
- From the above equations, the equation of motion of body (i) along the direction of motion, can be formulated using Newton's second law of motion.
- To eliminate the internal forces N_j we multiply each (i) equation by a factor. Summing all equations, we obtain the equation of motion.
(As the equations are very long, they are not presented here).

Change of masses, areas and lengths of the equation of motion in terms of the distance moved

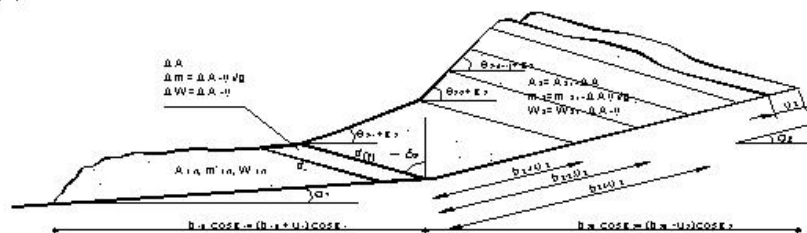
The transformation rule predicts that when each block is displaced by $d\tilde{u}_i$, each point of the block including the ground surface (at the top of the block) is also displaced by $d\tilde{u}_i$.

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

(a)



(b)

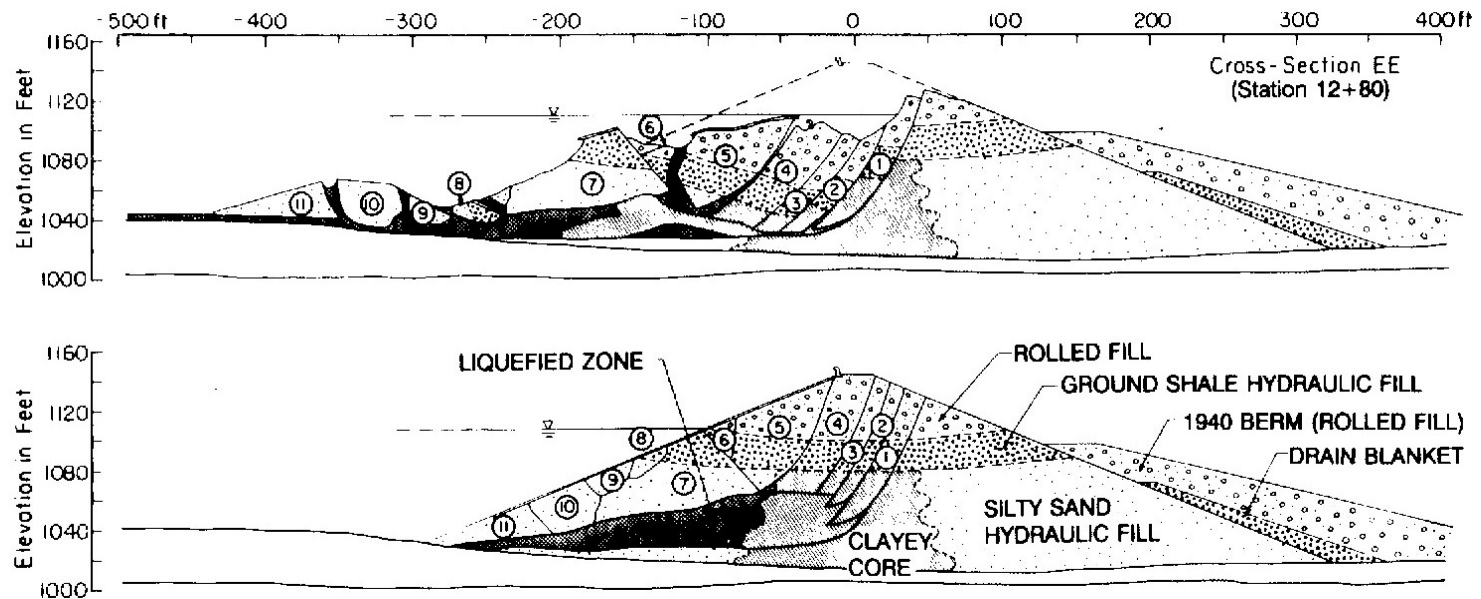


- **Computer program**

- A computer program was written based on the above model by C. Stamatopoulos.
- The input geometry is specified as the nodes defining the slip surface consisting of linear segments and the ground surface.
- The computer program includes graphics that illustrate the deformation that the model predicts.

2. 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).



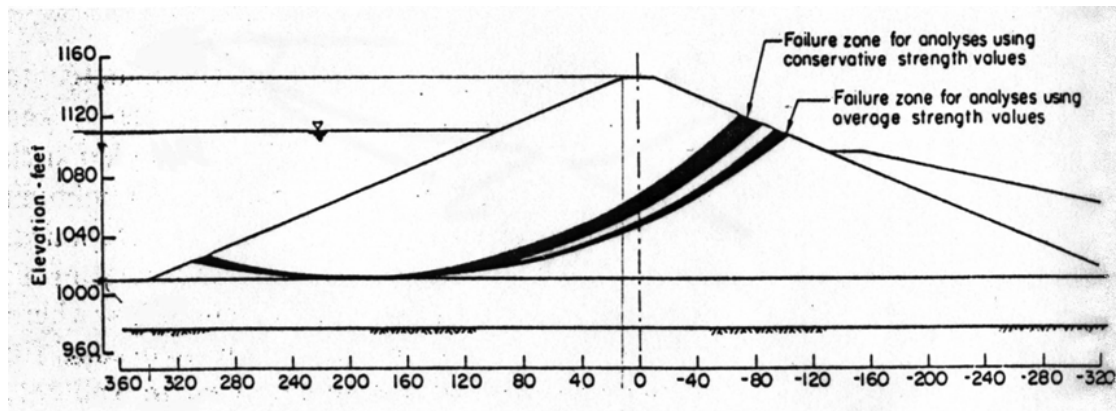
- The residual resistance of the sandy liquefied materials has been measured by various investigators in the laboratory; Baziar and Dobry (1995) report that $c_{u\text{-sand}}/\sigma'_v$ equals 0.12 to 0.19. The corresponding total strength friction angle equals 6 to 11 degrees.
- The steady-state strength 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/m³ (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).

3. Steps used to apply the multi-block model

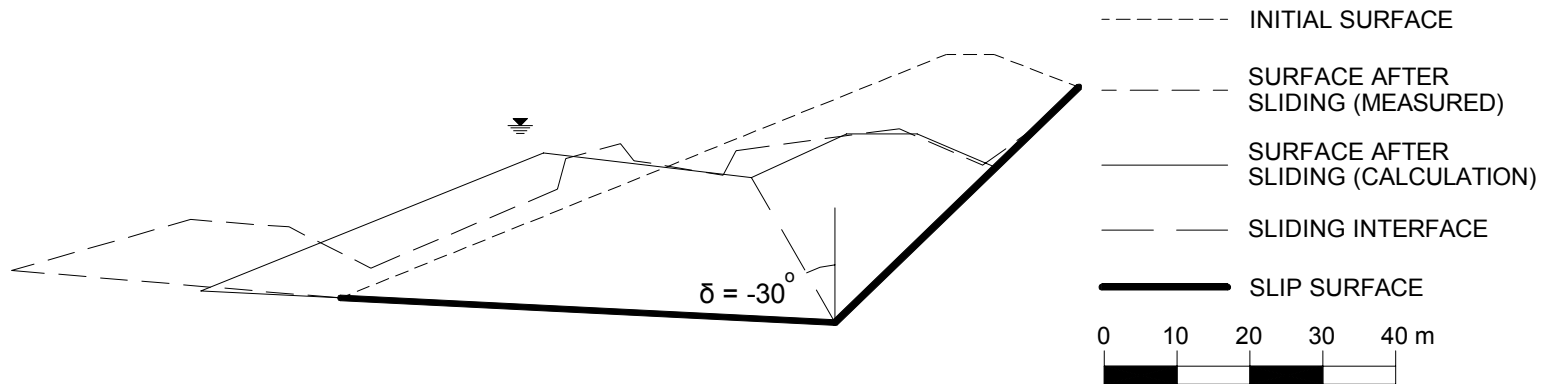
- The steps required to apply the multi-block model in back analyses of slides are: (a) The slip surface is established and simulated as a series of linear segments, (b) the inclination of the internal linear segments is established according to the condition of minimum critical acceleration value and (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 followed: (1) Select a soil resistance, (2) Estimate the inclinations of the internal sub-planes, (3) Apply the multi-block model and produce the deformed geometry, (4) Compare the deformed geometry with the actual displacements and (5) perform again steps (2) to (4) until convergence is achieved.

4. Prediction

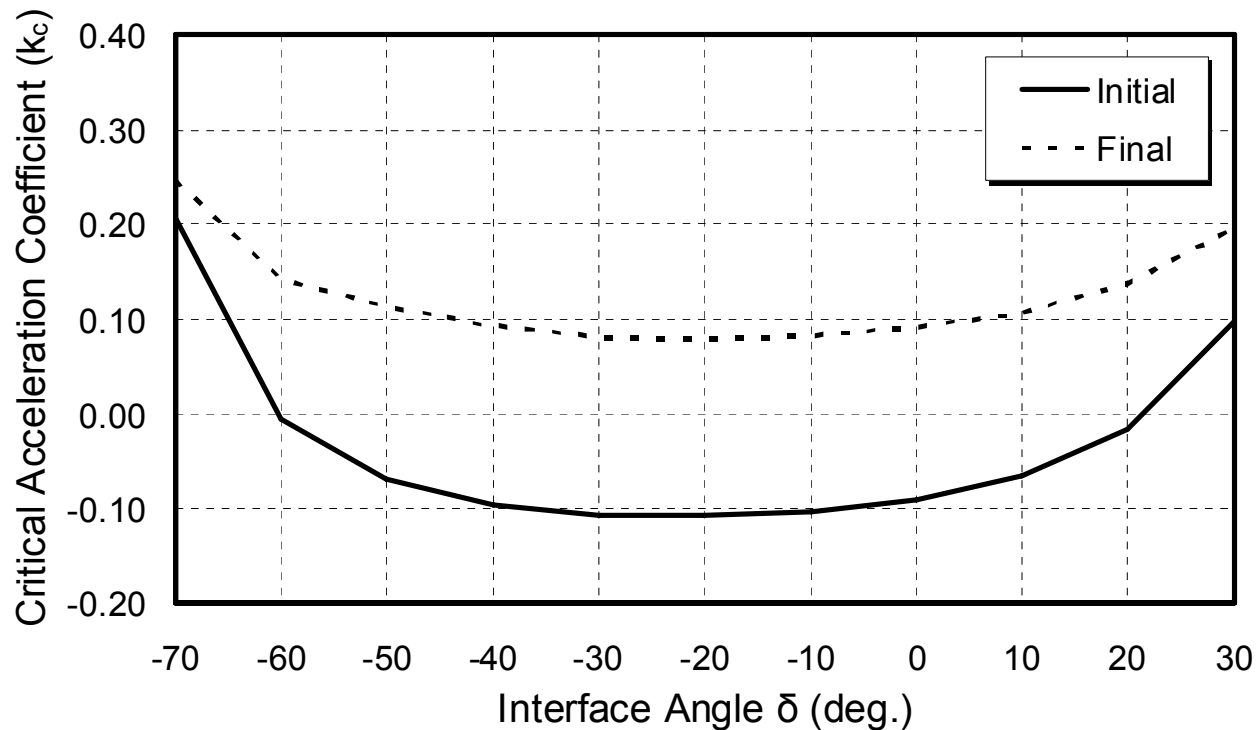
- Stability analysis reported by Seed et al (1975) (see figure below) illustrates that the critical slip surface may be represented approximately by two linear segments.



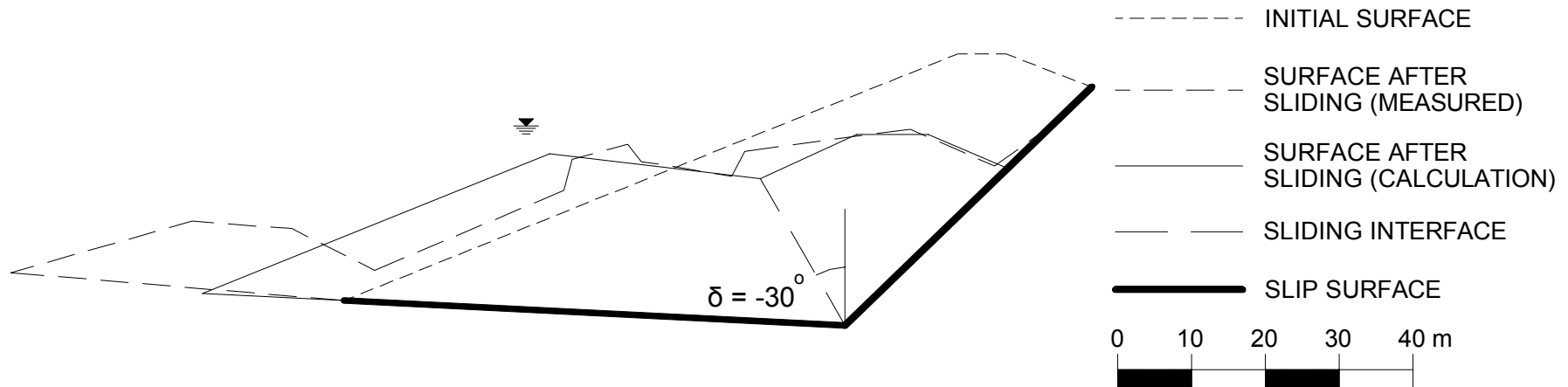
This is illustrated below:



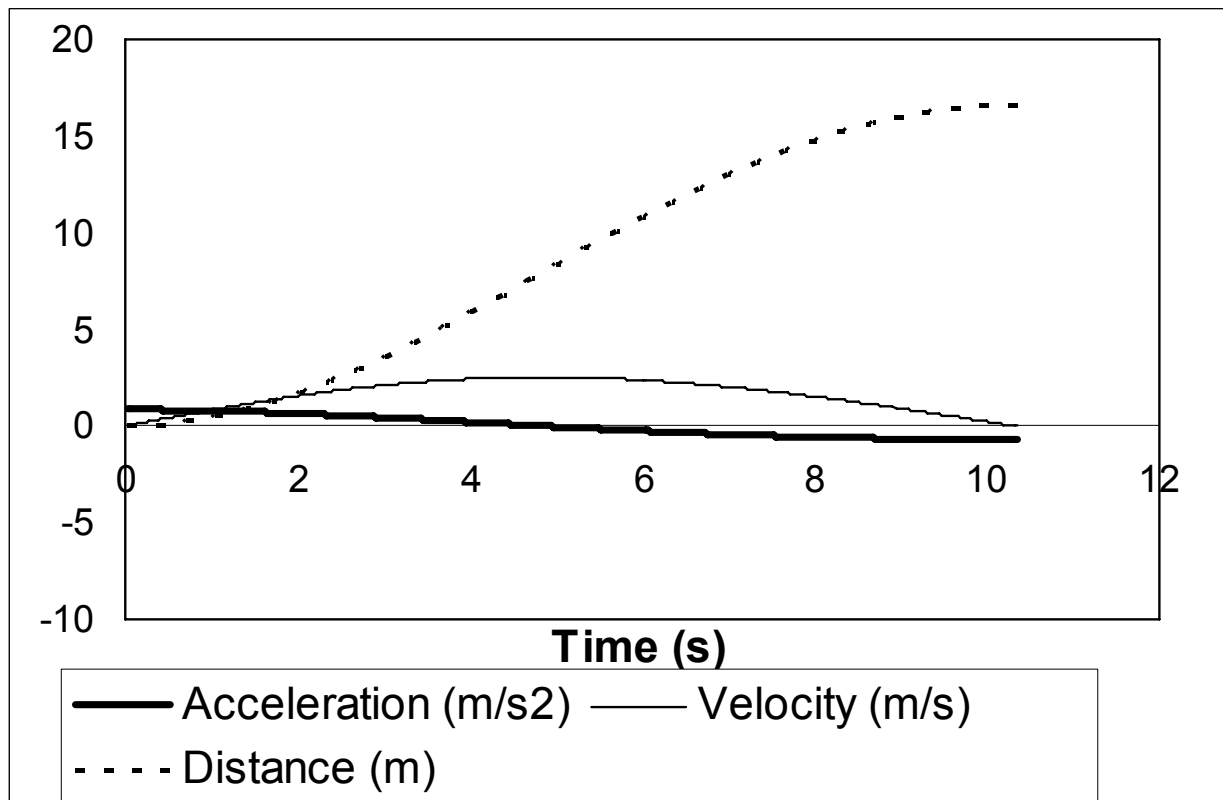
- The Figure below gives the critical acceleration coefficient for relative motion at the initial and final configurations of the two-block model in terms of the interface angle. It can be observed that the average interface angle that produces minimum critical acceleration value is $\delta = -30^\circ$.



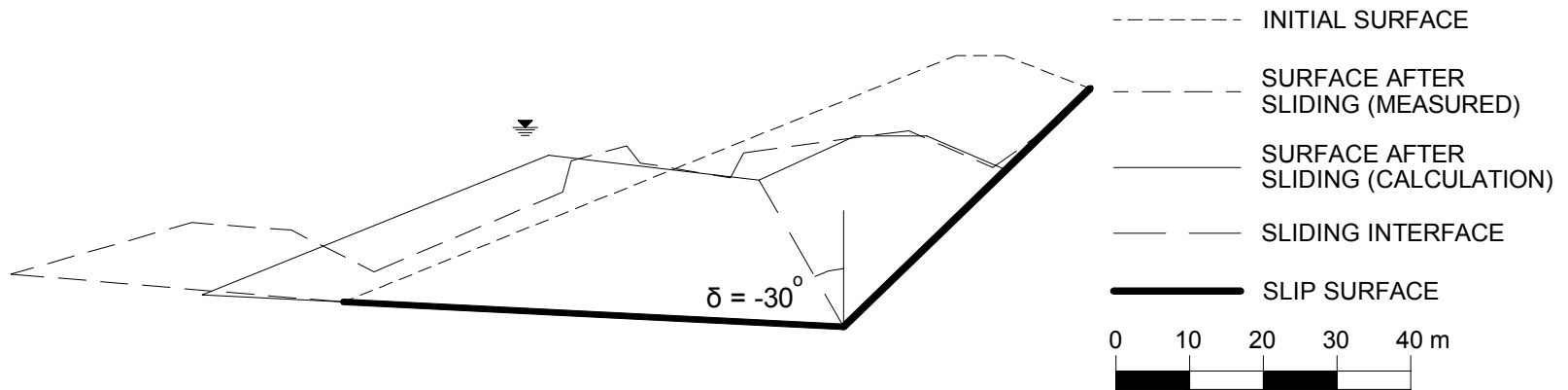
- For this value, the computed geometry that best fits the observed displacements is achieved with a value of frictional angle $(\varphi)_{res} = 9^\circ$ at the liquefied portion of the dam. The rest of the dam slide geometry, is considered with a purely cohesive strength $c_u = 29$ kPa.



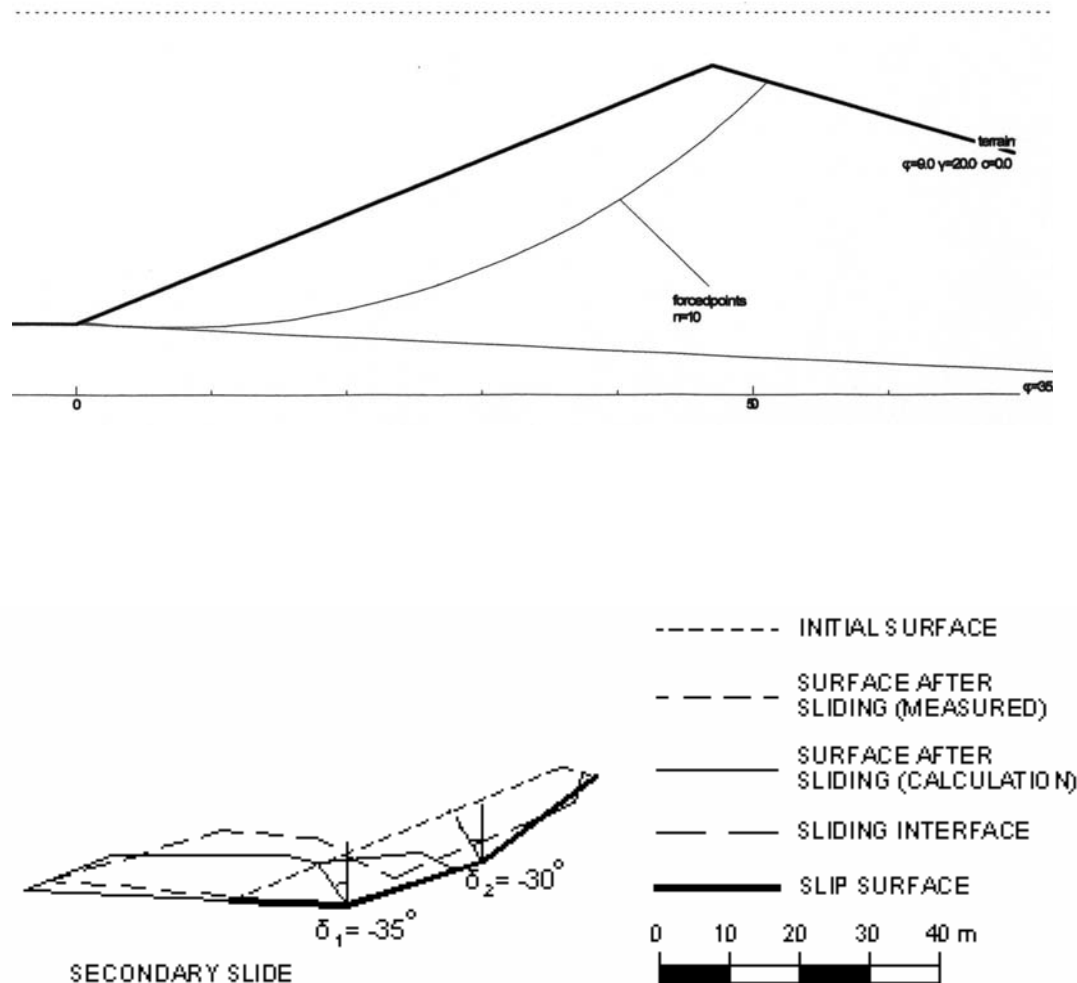
The graph below gives the computed acceleration, velocity and distance moved of the lower body in terms of time of the solution above. The computed time duration of motion is 10.4s.



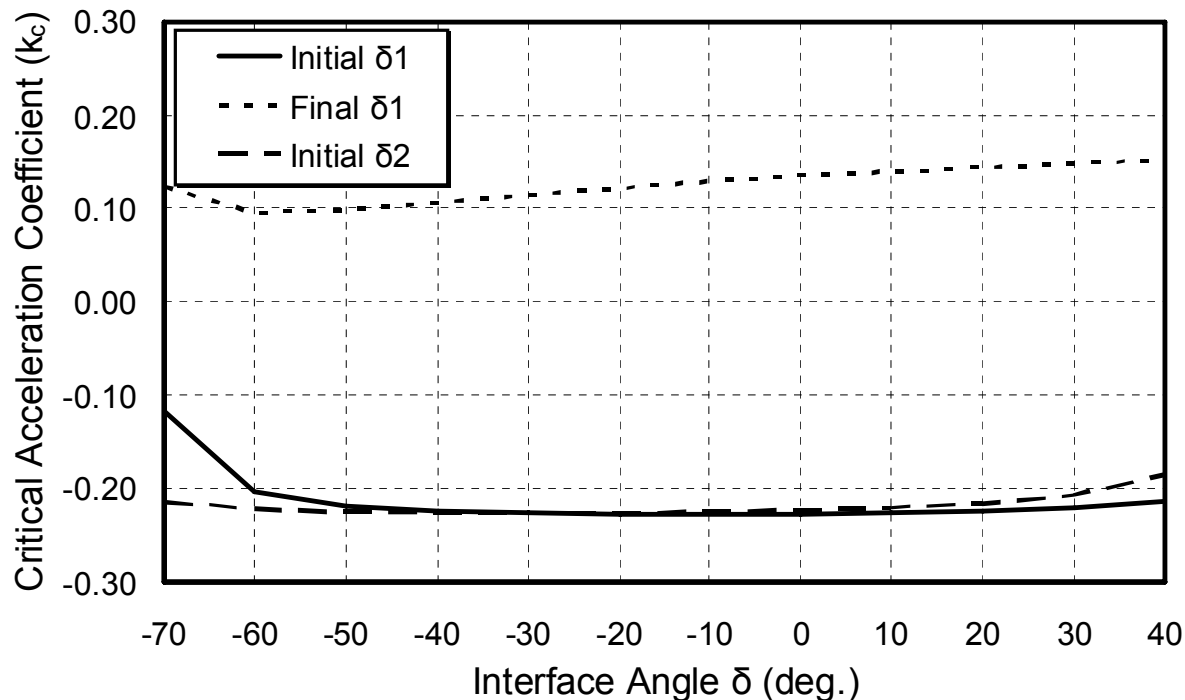
- The predicted movement of the lower body and deformation agreed reasonably well with that of the upper part of the slide. Yet, the lower part of the slide slid more than the model prediction. This discrepancy between field observation and model simulation was attributed to the existence of two slides. Thus the calculation was repeated for a second time.



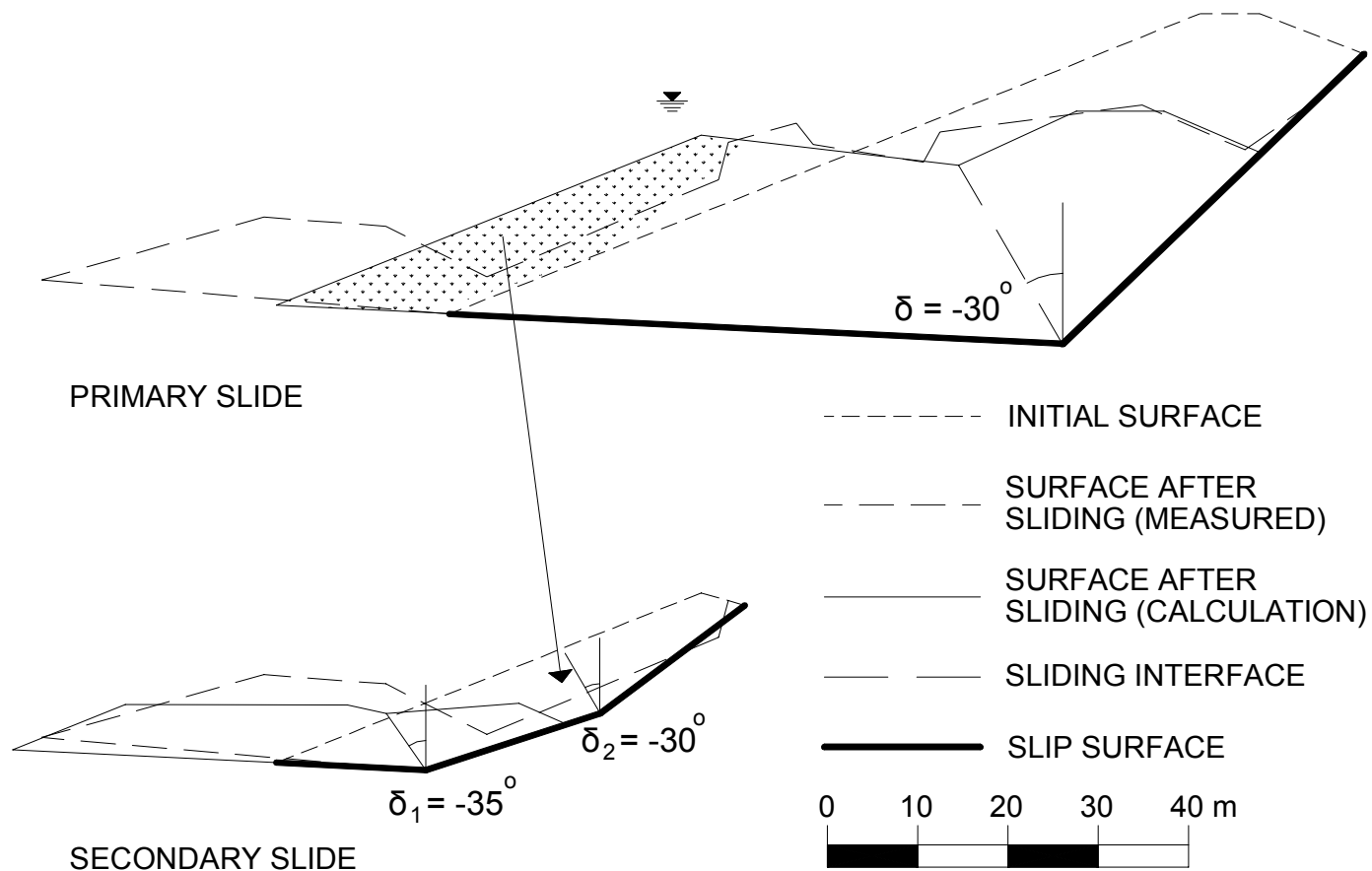
Stability analysis on the deformed configuration of the previous figure, using the Bishop method, illustrated that (a) the deformed configuration produces a factor of safety less than unity for a friction angle equal to 9° , and thus a second slide can be triggered and (b) the critical slip surface of this secondary slide, can be represented by three segments, as shown in the figure.



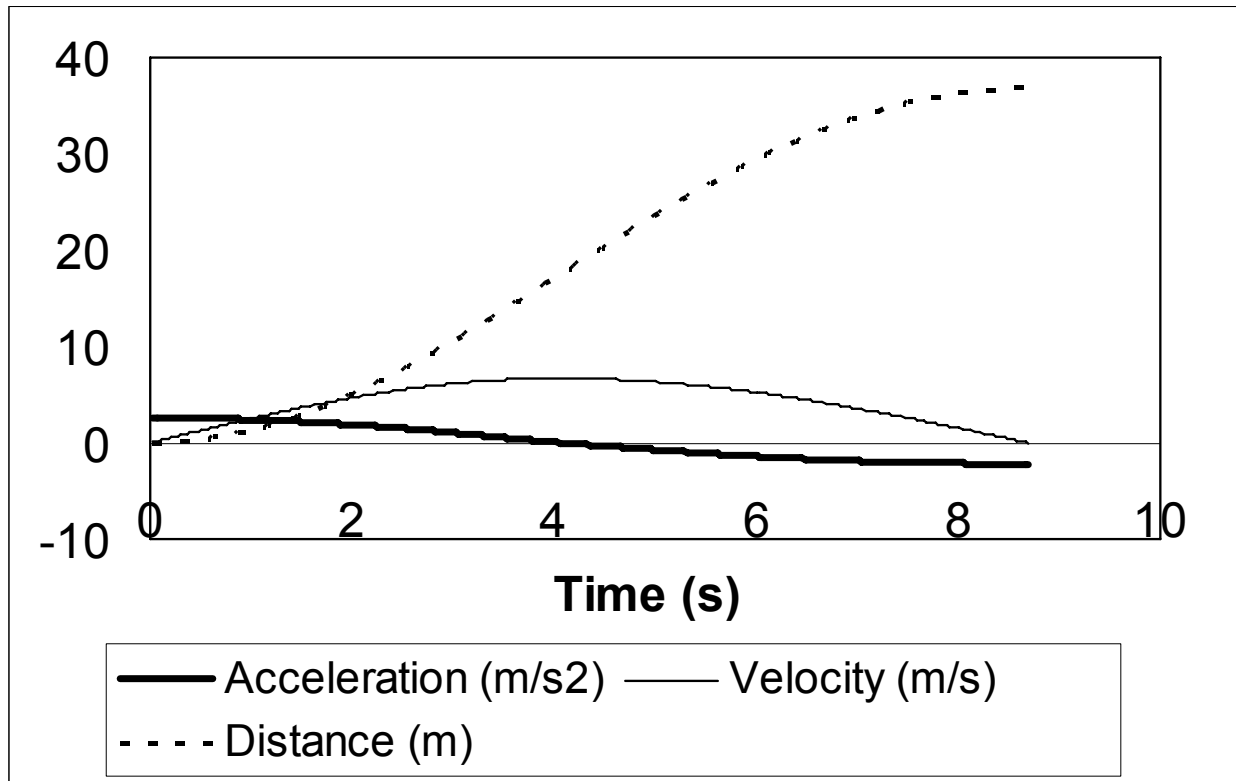
- The graph below gives the critical acceleration coefficient for relative motion at the initial and final configurations in terms of the interface angle. It can be observed that the average interface angles that produce minimum critical acceleration values are $\delta_1 = -35^\circ$, $\delta_2 = -30^\circ$.



- For these values, the best-fit final geometry obtained is given below. The strength of the liquefied layer corresponds to $(\varphi)_{res} = 7^\circ$.

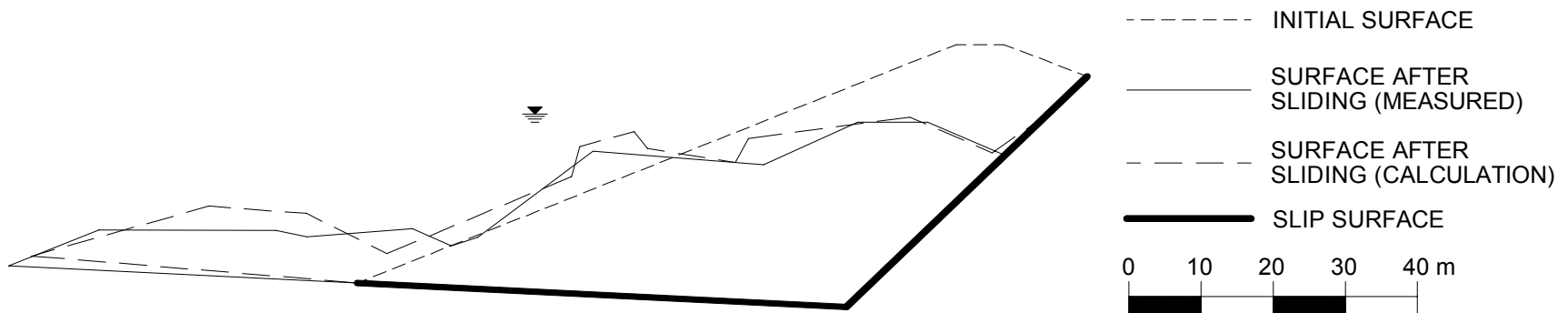


The Figure gives the computed acceleration, velocity and distance moved of the lower body in terms of time of the solution above. The computed time duration of motion is 8.7s.

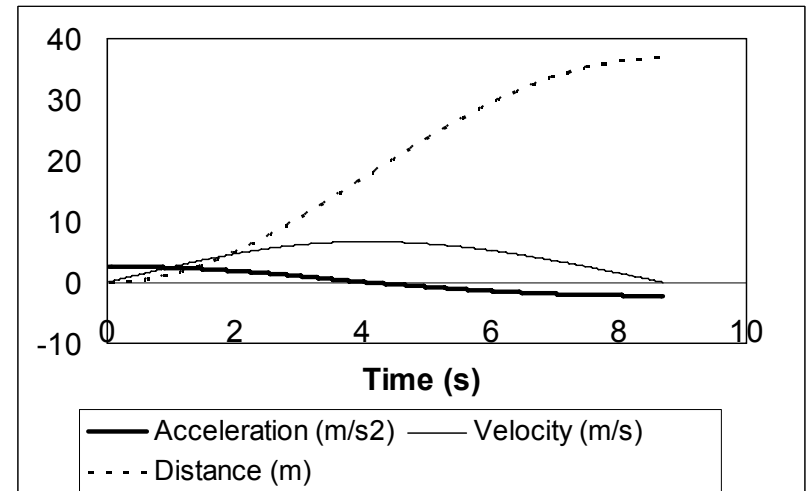
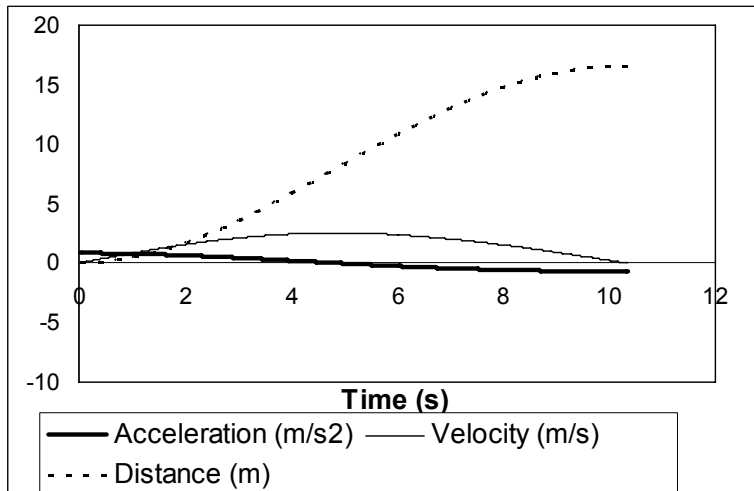


5. Discussion

- As illustrated in the figure, the 2-slide approach predicts movement, and deformation in very good agreement with that measured. The iteratively-estimated soil strength of the liquefied sand equals 9° for the primary and 7° for the secondary slide. 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 apparent 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.