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ABSTRACT

During the early hours of 18-02-1995 a landslide occurred at Malakasa, on the 36th kilometer of the highway joining Greece's main cities, Athens and Thessaloniki. The computed deformed geometry using this model agrees reasonably well with that measured. The back-estimated soil strength of 16^o is in the range of the measured values (8-19^o). Finally, state-of-the-art stability analyses, using the back-estimated residual soil strength, illustrated that the location of the slip surface can be predicted if it is assumed that only the saturated soil below the water table loses its strength.

INTRODUCTION

During the early hours of 18-02-1995 a landslide occurred at Malakasa, on the 36th kilometer of the highway joining Greece's main cities, Athens and Thessaloniki. The slope movement cut off both the road and rail connection of Athens with northern Greece. A multi-block sliding system model that simulates slide movement has been proposed. In the paper, the multi-block sliding system model is used to simulate the Malakassa slide. A geotechnical investigation was performed to determine the cause of the failure (Kavounidis et al, 1997). Stability back analyses of the slide were performed to estimate the frictional resistance of the slide and compare it with the residual friction angle measured in laboratory tests (Kavounidis et al, 1997).

To analyze displacement of slopes, the sliding-block model is usually used (e.g. Davis et al., 1993). Yet, the conventional sliding-block model has shortcomings in back-analyzing slides when displacement is large. The reason is that the change in geometry of the sliding mass is not modeled. Thus, the sliding-block model cannot predict the finite slide displacement of slopes once the residual strength is reached, that is presumably a result of slide movement towards a more stable configuration.

Alternatively, to simulate slope movement when the displacement is large, two-block (Stamatopoulos, 1992, Ambraseys and Srbulov, 1995, Stamatopoulos et al., 2000) and multi-block (Sarma and Chlimintzas, 2001a and b) sliding models, that simulate the change in geometry of the sliding mass with displacement, have been proposed .

The multi-block model uses the Mohr-Coulomb strength model along the failure surface. Recently the multi-block model has been extended by using an elaborate soil model predicting the change in resistance with displacement along slip surfaces (Stamatopoulos, 2006). The extended multi-block model can be used to predict the triggering of slides. However, this improved model cannot be applied in the current study. The reason is that, unfortunately, results of laboratory tests giving the resistance along a slip surface in terms of displacement are not available for the soils of the Malakassa slide. The only information is the residual strength value. Thus, only slide deformation once the residual strength is reached, can be predicted.

The purpose of this paper is to investigate the ability of the multi-block model to predict the deformation pattern of the Malakassa slope. Furthermore, the paper investigates if state-of-the art stability methods can predict the location of the slip surface.

THE MALAKASSA SLIDE

Geometry

Fig. 1 gives the general topography of the Malakasa region after the slide. Fig. 2 gives a photo illustrating slide movement at its base. Fig. 3 gives a sketch of the distance moved by structural elements at the bottom of the slope.

Geology

The geology of the area is complicated due to the irregular stratigraphy of the rock formations. The alternating layers of clay-phyllite schists and of the older geological age Parnitha limestones form a complex geological structure. It can be said in general that the landslide took place within the clay schist in a previously sheared zone (Kavounidis et al., 1997). A panoramic picture of the mountain slope taken after the event of 18-02-1995.

Investigations (Kavounidis et al., 1997)

Thirty-one boreholes for sampling were performed within and out of the sliding mass . In the boreholes , inclinometers or piezometers were installed. Additionally, 23 piezometers were installed. In total 23 inclinometers and 47 piezometers of either open type or with ceramic head were installed. Also the surface cracks of the sliding mass were recorded. In total 166 cracks were detected and their movement was recorded. Four sets of pumping tests were also performed for estimating the soil permeability.

Subsoil Materials

The subsoil materials in the Malakasa region appear to be mixed due to the disturbed geological history of the region. They can roughly be classified as weathered schists and irregular limestones. The residual friction angle measured in the direct-shear device for c = 0 varied between 8 and 19 degrees.

Pore Pressures

Pore pressures are of particular importance. Based on the piezometers measurements, Fig 4 gives the water table elevation.

Determination of the Sliding Surface

The sliding surface was in some regions determined exactly, and in other regions it was assumed. There was accurate determination of its periphery on the surface at the points determined by the inclinometers. Estimation of the rest of the sliding surface was made on the basis of geotechnical observations (type of material, core description, index variation) and kinematic data (ability and shape of movement etc.) The final result was a very satisfactory determination of the sliding surface and given in Figs. 4 (Georgopoulos and Vardoulakis, 2001) and Fig. 5 (Kavounidis et al., 1997).

Sliding

Landslide was of North-South approximate direction with maximum length about 300 m while in the direction East-West its maximum width was 240 m. Width was significantly reduced near its foot. The average depth of the sliding mass was of the order of 25-30 m. The landslide cannot be considered as 2-Dimensional because of the remarkable narrowing it exhibited in its foot. Most of the sliding surface passed through the weathered schist.

Along its major part, the landslide moved for about 7 m in plan view. The estimation of the movement (at 7 m) was based: (a) in measurements of the distance moved of structural elements such as walls, piles or the railway lines, (b) in comparisons of old survey with new survey maps and aerial photographs that illustrate the movement of the structural elements.

Causes of the Landslide (Kavounidis et al., 1997)

Ground water that was particularly high due to heavy rainfalls in 1994-1995 played significant role in the reduction of strength of the surface of sliding.

Permeability at the zone of sliding surface is low, of the order of $2x10^{-5}$ cm/sec. It is believed that the sliding surface was formed in a particularly impermeable zone of small thickness.

Excavation at the foot of the slope due to road construction had an impact on an already limiting state because it removed stabilizing loads.

At the foot and at low depths (0-5 m) a fairly weak material is present. Beyond the limits that define the landslide to the East and West, conditions favourable to instability seem not to exist.

Fig. 1. A panoramic picture of the mountain slope taken after the event of 18-02-1995 (Georgopoulos and Vardoulakis, 2001).

Fig. 2. Photo illustrating slide movement at its base (by Stamatopoulos)

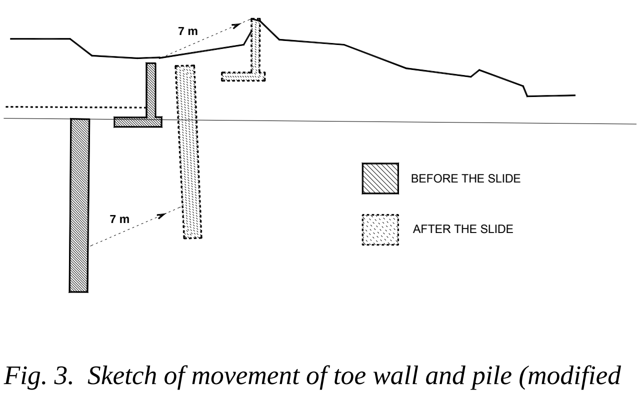


Fig. 3. Sketch of movement of toe wall and pile (modified from Kavounidis et al, 1997)

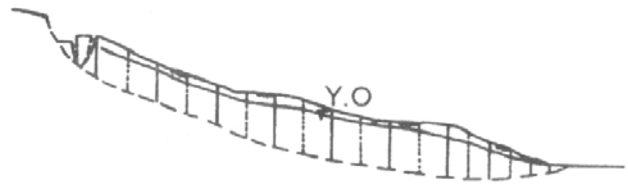


Fig. 4. The water table location (YO) and location of the slip surface at the slope (Georgopoulos and Vardoulakis, 2001)

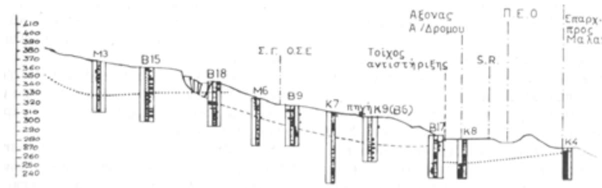


Fig 5. The location of the slip surface (Kavounidis et al., 1997)

THE MULTI-BLOCK SLIDING SYSTEM

Geometry

Similarly to the Sarma (1979) stability method, shown in Fig. 6, a general mass sliding on a slip surface that consists of n linear segments is considered. In order the mass to move, at the nodes between the linear segments, interfaces where resisting forces are exerted must be formed. Thus, the mass is divided into n blocks sliding in n different inclinations.

At the interface between two consecutive blocks, the velocity must be continuous. This principle gives that the relative displacement of the n blocks 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 is the displacement moved along a segment of the slip surface, the subscripts i and i+1 refer to blocks i and i+1 counting uphill, d refers to increment and β_i and $(90-\delta_i)$ are the inclinations of the segment and interface i respectively, shown in Fig. 6.

Equation of Motion

The forces that are exerted in block "i" are given in Fig. 7. Soil is assumed to behave as a Mohr-Coulomb material. As the body moves, the Mohr Coulomb failure criterion applies at both the slip surface and the interfaces. The equation of motion of block (i) along the direction of motion, for the case without seismic forces, is :

$$m_i (d^2u_n/ dt^2) q_i \cos\varphi_i \qquad (2)$$
$$= -U_i \sin\varphi_i + (m_i g Q_i)v_i - H_i x_i + c_i l_i \cos\varphi_i$$
$$+(1/ \cos\varphi in_{i-1}) N_{i-1} d_i - (1/ \cos\varphi in_i) N_i f_i$$
$$+ sa_i (cin_{i-1} b_{i-1} - \tan\varphi in_{i-1} Uin_{i-1}) - sb_i (cin_i b_i sb_i - \tan\varphi in_i Uin_i)$$

where

$v_i = \sin(\varphi_i - \beta_i)$, $x_i = \cos(\varphi_i - \beta_i)$,

$d_i = \cos(\delta_{i-1} + \beta_i - \varphi_i - \varphi in_{i-1})$, $f_i = \cos(\delta_{i-1} + \beta_i - \varphi_i - \varphi in_{i-1})$,

$sa_i = \sin(\delta_{i-1} + \beta_i - \varphi_i)$, $sb_i = \sin(\delta_i + \beta_i - \varphi_i)$,

$$q_i = \prod_{j=i}^{n-1} [\ \cos(\delta_i + \beta_{i+1}) / \cos(\delta_i + \beta_i))\ ]$$

and m_i is the mass of block i, φ_i, c_i, φin_i cin_i are the frictional and cohesional components of resistance at the i slip segment and interface respectively, l_i and d_i are the lengths of the i slip segment and interface respectively, U_i, Uin_i are the pore pressures at the i slip segment and interface respectively and Q_i and H_i are the vertical and horizontal external loads of block i respectively.

To eliminate the interslice forces, N_i, the (i) equation is multiplied by a factor. Summing all equations and expressing displacement of all blocks in terms of the displacement of the upper block, u_n, the equation of motion is obtained. It is a single second-order differential equation in terms of time. As it is very long, it is not presented here. It is given by Sarma and Chlimitzas (2001). Without seismic internal forces, it has the general form

$$du^2_n/dt^2 = A\ (a(t) - a_c)\ \text{ for } \quad du_n/dt>0 \qquad (3)$$

where A is a factor and a_c is the critical acceleration, defined as the horizontal acceleration which is just sufficient to start movement of the mass. The factors A and a_c depend of the geometry, the pore pressure and the strength of the n blocks of the sliding mass. The factor a_c is positive and negative when the sliding mass is stable and unstable respectively. According to the principle of limit equilibrium, the inclinations of the interfaces δ_i correspond to the inclinations that produce a minimum value of a_c.

For large displacement, the location of the interfaces does not change. To solve equation (3), the masses and lengths of each block i are updated in terms of the distance moved. The transformation rule, that states that when each block is displaced by du_i, each point of the block including the ground surface (corresponds to the top of the block) is also displaced by $d\mathbf{u}_i$, is applied. Incremental application is needed because a point may move from one block to the previous, and thus its incremental displacement for given $d\mathbf{u}_n$ will change from $d\mathbf{u}_i$ to $d\mathbf{u}_{i-1}$. The deformation that this rule predicts in a two-block system is illustrated in Fig. 8.

Multi-Block Model Extensions

Separation of blocks occurs when an interslice force, N_i, is negative. Fig. 9 illustrates a typical case where this occurs: when the angle $\beta_{m,1}$ representing the initial inclination of the first block of the system, is less than the angle $\beta_{m,0}$ representing the slope of the free ground surface immediately preceding the first block. In this case, the increased soil mass of the first block cannot maintain contact with the rest of the material and is detached from the system. For frictional materials, the angle of the internal sub-plane at the node of separation can be obtained from the resistance of the material inside block i, φin_i, according to what stability predicts as:

$$\delta_{i\text{-}separ} = 90^o - \varphi in_i \qquad (4)$$

Computer Program

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 pressures are specified in each segment. The computer program includes graphics that illustrate the final deformation of the slide that the model predicts.

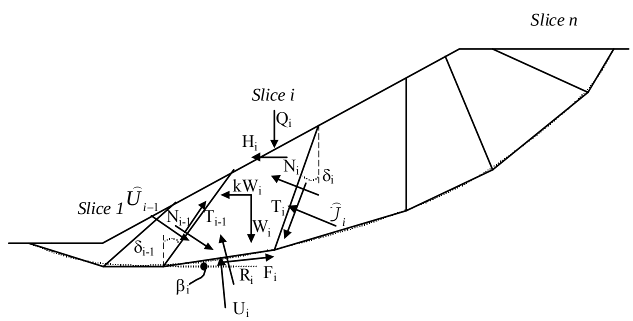


Fig. 6. The multi-block stability method proposed by Sarma (1979).

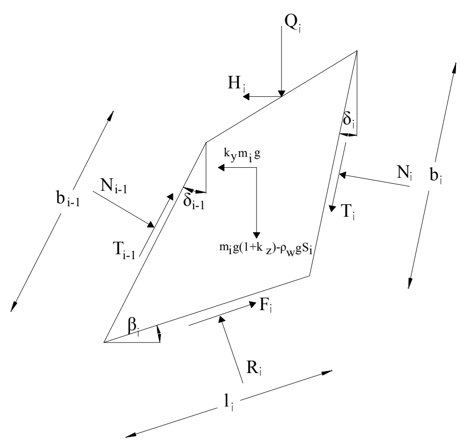


Fig. 7. Forces at body 'i'.

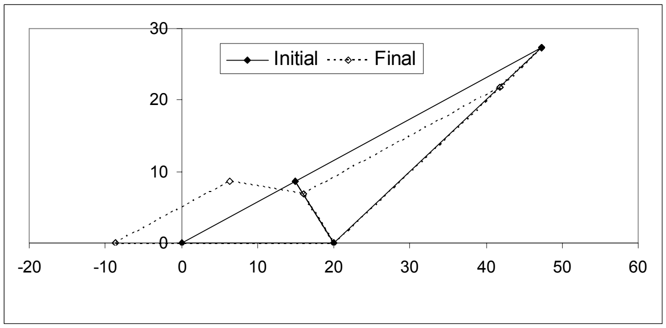


Fig. 8. Deformation assumed in the model. The case of a 2-body system sliding at level ground is given.

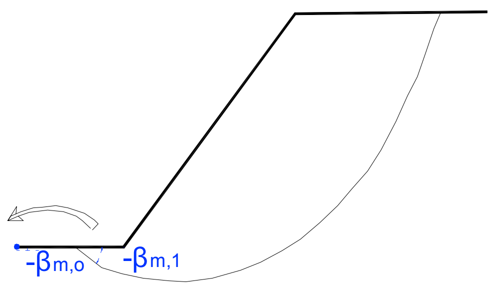


Fig. 9. Typical case where separation of blocks occurs (Sarma and Chlimintzas, 2001).

PREDICTIONS OF THE MULTI-BLOCK MODEL

Steps Required for Applying the Model and Procedure Used in the Present Study

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 are 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, in the present study it is first assumed that the slip surface is known, and for steps (b) and (c) the following procedure is used: (1) guess a soil strength, (2) estimate the inclinations of the internal sub-planes based on the condition of minimum critical acceleration value, (3) obtain the prediction of deformation and (4) compare the distance moved with the measured and if it is different, perform again steps (1) to (4) until convergence is achieved. Finally, (a) compare the back-estimated resistance with the measured range of values and (b) investigate, using the back-estimated residual soil strength, if state-of-the-art stability methods can predict the location of the slip surface.

Multi-Block Predictions

The landslide geometry (initial ground surface and the slip surface) was taken from Fig. 4, as shown in Fig. 10. The slide is represented by a six-block system. However, the front block is dummy, with zero mass, and its purpose is to define a horizontal slip surface along which the sliding of the toe takes place.

Consistently with the triggering factor, pore pressures were applied. Their magnitude, was taken from the water table given in fig. 4. In particular, pore pressures of 0, 50, 125, 220, 190, 1200kPa were applied at the mid-point of the segments from left to right, of the slip surface of Fig. 4. The unit weight of the soil was taken as $2T/m^3$.

Uniform strength was taken along the slip surface, corresponding to the residual strength value. At the interfaces, for shearing to occur, the peak strength must be reached. Thus, according to measurements, a value of soil strength equal to c=0 and $\varphi=30^o$ was used.

The procedure described above was used to obtain the solution of the problem. The interface angles that produce minimum critical acceleration value at the initial slide configurations are given in fig 11. Any of these four curves is produced by holding constant the critical value of the other angles. The corresponding values of the interface angles (defined in Fig. 6) are $\delta_1=28^o$, $\delta_2=-2^o$, $\delta_3=33^o$, $\delta_4=-4^o$. The best-fit final geometry obtained is given in fig 10. The strength corresponds to $(\varphi)_{res}=16^o$. Fig 12 gives the computed acceleration, velocity and distance moved of the upper body in terms of time of the solution above. The computed time duration of motion and peak velocity are 17s and 0.5m/s respectively.

Figs. 11 illustrates that initially (or when the residual soil strength is reached in the actual slide), the critical acceleration of the slide is negative. Thus, initial instability exists and, as illustrated in Fig. 12, the initial acceleration of the slide is positive. As shown in Fig. 12, slide velocity starts to increase and ground displacement to accumulate. The slide moves gradually to a more stable configuration, and the slide acceleration decreases and eventually becomes negative. Then, the slide velocity decreases and gradually becomes zero. At this time, displacement stops to accumulate.

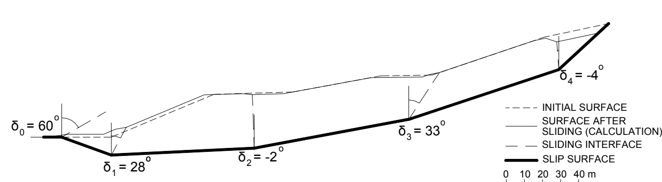


Fig. 10. Initial slide configuration assumed and computed final configuration and comparison of the predicted with the measured deformation.

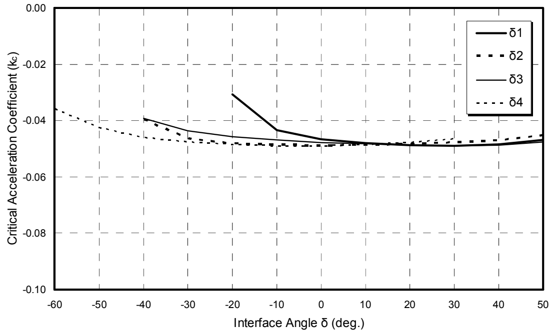


Fig. 11. Critical acceleration coefficient for relative motion at the initial configuration in terms of the three interface angles.

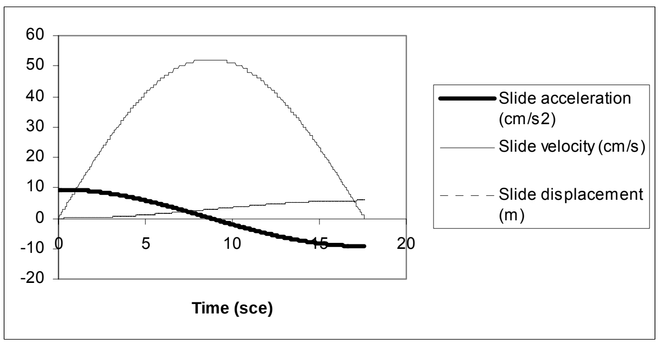


Fig. 12. Computed acceleration, velocity and distance moved of the upper body in terms of time.

ESTIMATION OF THE LOCATION OF THE SLIP SURFACE

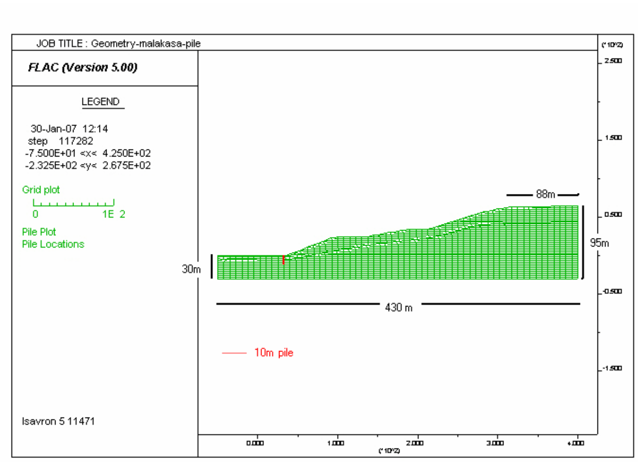
State-of-the-art stability analyses were performed, using the back-estimated residual soil strength to investigate if the location of the slip surface can be predicted. The stability method described by Dawson et al. (1999), as implemented by the code FLAC-v.5 (ITASCA Consultants, 2005), was used. The method performs a full solution of the coupled stress/displacement, equilibium using the Mohr-Coulomb constitutive equations. For a set of properties, the system is determined to be stable or unstable. By automatically performing simulations for different strength properties, the Factor of Safety can be found, and the critical slip surface can be located.

The initial topography was taken from Fig. 4. The region was divided in two layers: the soil (1) above and (2) below the water table. It is assumed that only saturated soil can lose its strength due to build-up of pore pressures. Accordingly, for layer 1 strength parameters used are c=0 kPa, φ = 30° and for layer 2, residual strength parameters used are c=0 kPa, φ= 16°. Furthermore, the wet density is taken as 2.0 T/m^3 and the dry density is taken as 1.8 T/m^3.

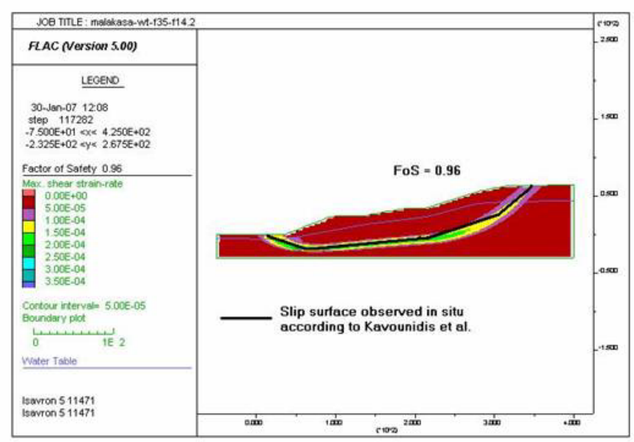
The shear (G) and bulk (K) moduli of the layers, needed in the analysis, are taken as G=3.6*10^4 kPa, K=10^5 kPa. Yet, parametric anlyses have illustrated that these parameters do not affect the results.

The grid used for the stability calculations is shown in Fig. 13a. It is a uniform grid consisting of 60X40 elements. The horizontal distance of the grid is 430m, the plateau has a length of 88m and the left and right vertical boundaries are 30m and 95m respectively. As shown in Fig. 13a, near the toe of the slope the 10m pile is considered. Typical pile properties are used.

The calculations gave a factor of safety equal to 0.9 and a slip surface as shown in Fig. 13b. Fig. 13b compares the computed with the measured slip surface. It can be observed that: (a) the factor of safety is considerably less than one, something that explains the catastrophic landslide and (b) the estimated slip surface does not differ considerably from the measured.



(a)



(b)

Fig. 13. (a) Grid used in the numerical stability analysis and (b) soil layers used and comparison of FLAC and observed in situ Sliding Surface.

DISCUSSION

The computed deformed geometry using the multi-block model agrees reasonably well with that measured: Similarly to the observed response of Fig 4, the computed final geometry at the top of the slide predicts that as a result of downward movement, a gap is formed. Furthermore, similarly to the observed response of Fig 3, the computed final geometry predicts upward movement at the bottom of the slide.

The back-estimated soil strength of 16^o is in the range of the measured values (8-19^o). The fact that it is on the high side of this range is consistent with observations of previous slides where the estimated value for the residual internal friction angle is systematically higher than the real (Georgopoulos and Vardoulakis, 2001). The reason for this is that analyses are 2-Dimensional and 3-Dimensional effects are not considered. The computed time duration of motion and peak velocity agree with the observed rapid occurrence of the Malakassa slide.

Finally, state-of-the-art stability analyses, using the back-estimated residual soil strength, illustrated that the location of the slip surface can be predicted if it is assumed that only saturated soil below the water table can lose its strength (due to build-up of pore pressures).

CONCLUSIONS

A multi-block sliding system model that simulates slide movement has been proposed. In the paper, this model is used to simulate the Malakassa slide.

The computed deformed geometry using the multi-block model agrees reasonably well with that measured. Similarly to the observed response, the computed final geometry at the top of the slide predicts that as a result of downward movement, a gap is formed. Furthermore, similarly to the observed response, the computed final geometry predicts upward movement at the bottom of the slide. The back-estimated soil strength of 16^o is in the range of the measured values (8-19^o).

Finally, state-of-the-art stability analyses, using the back-estimated residual soil strength, illustrated that the location of the slip surface can be predicted if it is assumed that only saturated soil below the water table can lose its strength.

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