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PREDICTING LANDSLIDE RISK COMBINING SPACE MEASUREMENTS AND GEOTECHNICAL MODELING: APPLICATION AT KERASIA SLIDE

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ABSTRACT

The work developed and applied a methodology combining (a) space measurement of past displacement and (b) geotechnical modelling of displacement to predict and mitigate the risk of ground displacement cased by progressive slope instability. The area of study is in Kerasea village in Plastiras Lake Municipality. The problem under treatment is a creeping landslide in an inhabited area. Mitigation measures were analyzed.

1.INTRODUCTION

In Greek hilly and mountainous areas and particularly in zones of considerable precipitation, continuous "creeping" slides occur that are triggered principally by water movement and favored by soil composition and stratification, steep morphological gradients and not well studied human interventions. The 2003 heavy rain storm event that triggered many slides in Sifnos island in Greece is a typical case (Stamatopoulos and Stamatopoulos, 2003). Overall, in the last century, Europe has experienced many fatalities and economic losses caused by landslides: 16000 people have lost their lives. Annual landslides costs in Italy, Austria, Switzerland and France are estimated to 0.5-2 billion euros. As a consequence of climate change and increase in exposure in many parts of the world, the risk associated with landslides is growing. (Sassa and Canuti, 2008).

Differential interferometry radar (DInSAR) has proven an interesting tool for the measurement and observation of ground deformation (Hanssen, 2001). The basic idea of the method is the analysis of the phase of the reflected wave radar from two or more pictures which cover the same region to observe ground displacement. Basically, the phase represents the time needed for the signal to cover the distance from the satellite to the earth surface and return. The difference represents the difference in the distance covered and can be interpreted as displacement at the ground surface. The relatively small cost in the application of the method relative to the conventional ground methods of geodesy, and the ability to retrieve past displacement data, has allowed the application of the method in a number of scientific fields in which the information of ground displacement is needed. Indeed, from 1992 the conventional interferometry has been used in the study of natural phenomena which cause ground movement such as earthquakes, volcanoes, landslides and settlements which have direct economic and environment consequences (Le Mouélic et al., 2002; Raucoules et al., Stramondo et al., 2008).

As a result of the limited ability of the conventional interferometry to observe movements which do not exceed about 28 mm, in combination with the effect at the wave, especially from the atmosphere and the ionosphere, improved methods were developed to obtain more accuracy, decreasing also the effect of the factors producing error. Towards this direction, the method of interferometry of fixed reflectors (PSInSAR or PSI) (Ferretti et al., 2000, Pratti, 2010) was developed. The method PSI uses only point locations in which the characteristics of the reflections of the signals radar are not considerably affected from the geometry of the receiver and from other factors affecting scattering, giving high values of relevance and phase. Using only the specified reflectors, analysis is performed of the different phases eliminating the undesirable factors affecting the signal and allowing the estimation of linear and nonlinear rates of ground movement.

The PSI method utilizes the rich data base of satellite radar scenes from different satellites. The most important advantage of the method is the ability to construct maps of yearly rates of ground displacement or the change to the rates. The reflectors are located during the processing of the data and cannot be located a priori. In urban regions typically the number of reflectors is 200-600 points/km2. With the assistance of specific software, the response of different phases is analyzed in each reflector, in order to remove the undesirable effects, primarily as a result of the atmosphere, the topography and the curvature of the earth and predict ground movement with sub millimeter accuracy.

The objective of the work is to develop and apply a methodology combining (a) space measurement of past displacement and (b) geotechnical modeling of displacement to predict and mitigate the risk of ground displacement cased by continuous "creeping" slope instability on clays. The area of study is in the region of the Municipal Department of Kerasea in Plastiras Municipality. The problem under treatment is a creeping landslide in an inhabited area.

Below, after clay response along slip surfaces, the mechanism of progressive movement of slides and the multi-block model are described, a proposed approach combining geotechnical modeling and space measurements is given. Then, the area of interest is described and the proposed methodology is applied. The satellite measurements are also verified by their comparison with inclinometer measurements.

2. CLAY RESPONSE ALONG SLIP SURFACES

Only in the ring shear device the deformation can be large, larger than a few centimeters or meters, as happens in situ. It is inferred that the most representative device to measure the response at a slip surface is the ring shear device. Undrained clay response towards peak strength is well known: Test results show that the response can be normalized in terms of the Overconsolidatio Ratio (OCR) and the initial vertical effective stress (Ladd and Foot 1974; Andersen et al. 1980). After the peak shear resistance is reached, at shear displacement of about 1mm, as shear displacement increases further, generation of additional excess pore-water pressures occurs, presumably as a result of a collapse of the soil structure. This generation of excess pore-water pressure results in a decrease in the effective stress towards a residual shear strength condition along the failure line. The residual shear strength is reached at shear displacement 1 to 100cm (Stark and Contreras, 1996, 1998, Elpekos et al, 1996). The displacement where the residual value of strength is reached is typically between 0.02 and 0.6m, while the ratio of residual to maximum strength equals 0.2 to 0.7. The residual friction angle typically varies from 35o for PI=10 to 10o for PI=40. Fig. 1 gives the shear stress and pore pressure versus displacement results of a constant-volume direct shear test on Drammen Clay (Stark and Contreras, 1996).

3. MECHANISM OF PROGRESSIVE MOVEMENT OF SLIDES

Based on the clay response described above the following mechanism of progressive movement of slides can be proposed: At each heavy rain occurence, the shear stress increases and thus failure occurs when the factor of safety is less than one. As a result of strain softening, the shear strength of the soil decreases. Furthermore, as a result of geometrical movement, the slope becomes more stable and the average shear stress decreases, and thus the factor of safety increases. Movement stops when the factor of safety equals one. This may occur when the water level again is lowered after the storm. In the next heavy rain interval, again when the shear stress increases, undrained failure occurs and again some displacement accumulates. Fig. 2 illustrates the mechanism of progressive failure of slides along clay slip surfaces at a shear stress versus displacement curve.

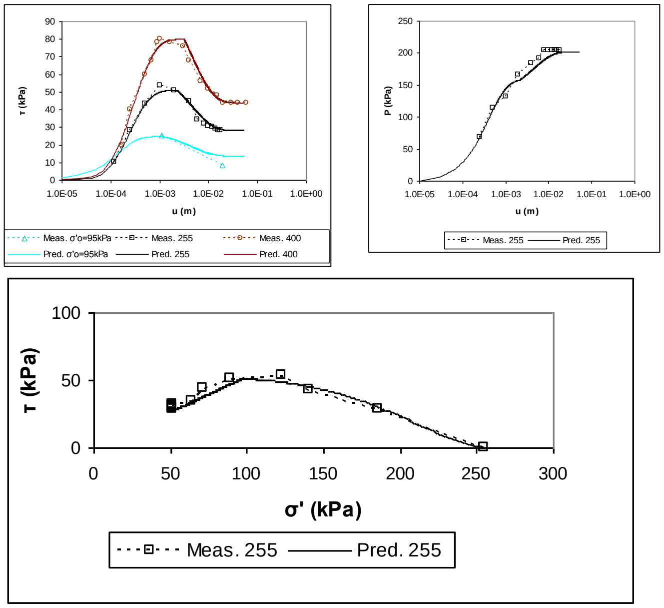


Fig. 1. Typical measured response and predictions of ring shear tests using the proposed constitutive model. Tests on Drammen clay are predicted.

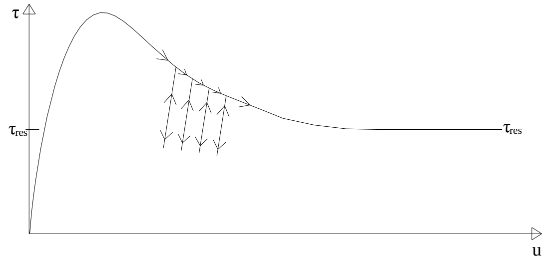


Fig. 2. Illustration of mechanism of progressive failure of slides along clay slip surfaces at a shear stress versus displacement curve

4. THE MULTI-BLOCK MODEL

As the current work deals with displacements, the proposed geotechnical models must predict ground displacement and not just a factor of safety. In addition, it is recommended that they are not very elaborate. Numerical effort must not be very large as simulation of different loading scenarios to predict future response must be performed. In addition, unlike other materials, such as steel and concrete, soil properties vary a lot not only in absolute value, but also with location. Furthermore, they are known less certainly, as soil testing, when it is performed, covers a very small portion of the total volume of the material. Thus, the use of elaborate models requiring the exact value of many soil properties that usually are not known with certainty is not justified.

The proposed work deals with landslides. For landslides, simple models predicting ground displacement are based on the sliding-block-model. When the displacement of slopes is large, the conventional sliding-block model has shortcomings. It predicts displacements that are larger than expected for similar input motion and soil strength. Alternatively, to simulate slope movement when the displacement is large, a multi-block sliding model has been proposed Stamatopoulos et al., 2011). This method will be used in the present work.

Similarly to the Sarma (1979) stability method, shown in Fig. 2a, a general mass resting on a slip surface that consists of n linear segments is considered. In order for 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 different inclinations. When the slide moves, at the interface between two consecutive blocks, the velocity must be continuous. This restriction predicts that the relative displacement of the n blocks is related to each other. For large displacement, the masses and lengths of each block sliding at each inclination are updated in terms of the distance moved, according to this restriction.

As discussed above, laboratory tests illustrate that the shear stress along slip surfaces depends on the shear displacement. Consistently, in addition to a Mohr'Coulomb model where the strength parameters are the frictional and cohesional resistances of the soil, a critical state model predicting the continuous change of shear stress with shear displacement. along slip surfaces depends is proposed (Stamatopoulos, 2009). The model uses the following equations

$$\tau = \sigma' \, r \, f \qquad (1)$$

$$dP = -d\sigma' = K \, du_t \, (\tan\varphi_{cs} - \tau/\sigma') \qquad \text{where}$$

$$f = 1 - b \ln [\, \tan\varphi_{cs} \, \sigma'/(\sigma'_o \tan\varphi_{res})]$$

$$r = \tan\varphi_{cs} \, u_t \, / \, (a + u_t)$$

In the above equations τ is the shear stress, σ' is the effective normal stress, compressive positive, σ'o is the initial effective normal stress, P is the excess pore pressure, ut is the shear displacement along the slip surface, φcs is the final steady-state effective friction angle, φres corresponds to the final residual friction angle and a, K, b are fitting parameters. Shear displacement is in m and stresses and pressures in kPa. Unloading is not modelled, as it is assumed that relative motion of slides is only downslope. Fig. 1 illustrates typical predictions of the above model.

A computer program that solves the equations of the multi-block model has been developed by C. Stamatopoulos. The second order differential equation of motion is solved numerically by the Euler method.

Application of the multi-block model requires determination, in addition to the external interfaces, internal interfaces within the sliding mass. According to the principle of limit equilibrium, the inclinations of the internal interfaces correspond to the inclinations that produce failure at a minimum value of the horizontal acceleration required for relative motion.

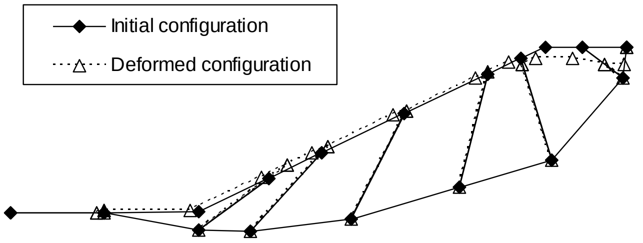


Fig. 3. The multi-block model. (a) The multi-block stability method proposed by Sarma (1979) and deformation assumed. The x-axis gives the horizontal distance, while the y-axis gives the elevation.

5. PROPOSED APPROACH COMBINING GEOTECHNICAL MODELING AND SPACE MEASUREMENTS

Conventional methods of ground deformation monitoring present many disadvantages such as high costs and time consuming. The space based Differential Interferometry SAR (DInSAR) techniques could present a valuable tool for detecting, monitoring, quantifying the deformation and with fieldwork contribution can identify causes which may induce deformation. DInSAR has already proven its potential for mapping ground deformation phenomena, e.g. earthquakes, volcano dynamics, etc and to cover in continuity large areas. 00).

The following approach is proposed combining geotechnical analysis and space measurements to predict and mitigate landslide risk under heavy rain for typical landslides based on the mechanism of progressive movement of slides described above. Regarding space measurements, it is proposed to use the Persistent or Permanent Scatterers Interferometry (PSI) technique, which, as described in the introduction, overcomes several limitations of repeat-pass interferometry. Two cases are differentiated: results of ring shear tests of the soil along the slip surface (a) are and (b) are not available.

For (a) the following is proposed:
(a1).Determine the location of the slip surface and displacement already moved, based on space displacement measurements
(a2). Estimate from (a1) and from the shear stress-displacement curves measured in ring shear tests, by applying the multi-block model, the shear stress-displacement relations of the slide
(a3). From (a1) and (a2) obtain the additional shear displacement for different loading scenarios, as the existing slip surface and the shear stress displacement so far along the slip surface are known.

For (b) the following is proposed:
(b1).Determine the location of the slip surface and displacement already moved, based on space displacement measurements. Determine the displacement already moved by the slide based on space measurements
(b2). Estimate by applying the multi-block by back analysis the current strength of the soil
(b3). From the measured displacement from space measurements, guess whether the residual soil strength has probably already been reached, or the soil along the slip surface is still strain-softening
(b4). Based on (b3), if the residual soil strength has already been reached, obtain the additional shear displacement for different loading scenarios by assigning the residual soil strength along the slip surface. Based on (b3), if the residual soil strength is not reached, propose mitigation measures ensuring that the maximum past shear strength will not be reached.

6. THE AREA OF INTEREST

The area of study is in the Kerasea village in Plastiras Municipality in Northern Greece (Fig. 4). The problem under treatment is landslide in inhabited area. The broad area belongs to the lower part of Agrafa mountain range with an average altitude of 910 m. Average slope in this zone is of the order of 20o or 35%. The broad area is characterized by one of the highest rainfall-snowfall quantities in Greece: the average annual equivalent rainfall height is about 1200 mm with the 80% of this fall between months of October to April. The area of study is classified as belonging to Category II of seismic action with ground acceleration A = a x g = 0.24 g (OASP, 1999). Landslides have caused ruptures in walls and floors of buildings, wall turnings, cracks on the road surfaces of the municipal road network, the creation of soil cracks , tilting and uprooting of trees (Figs. 5, 6).

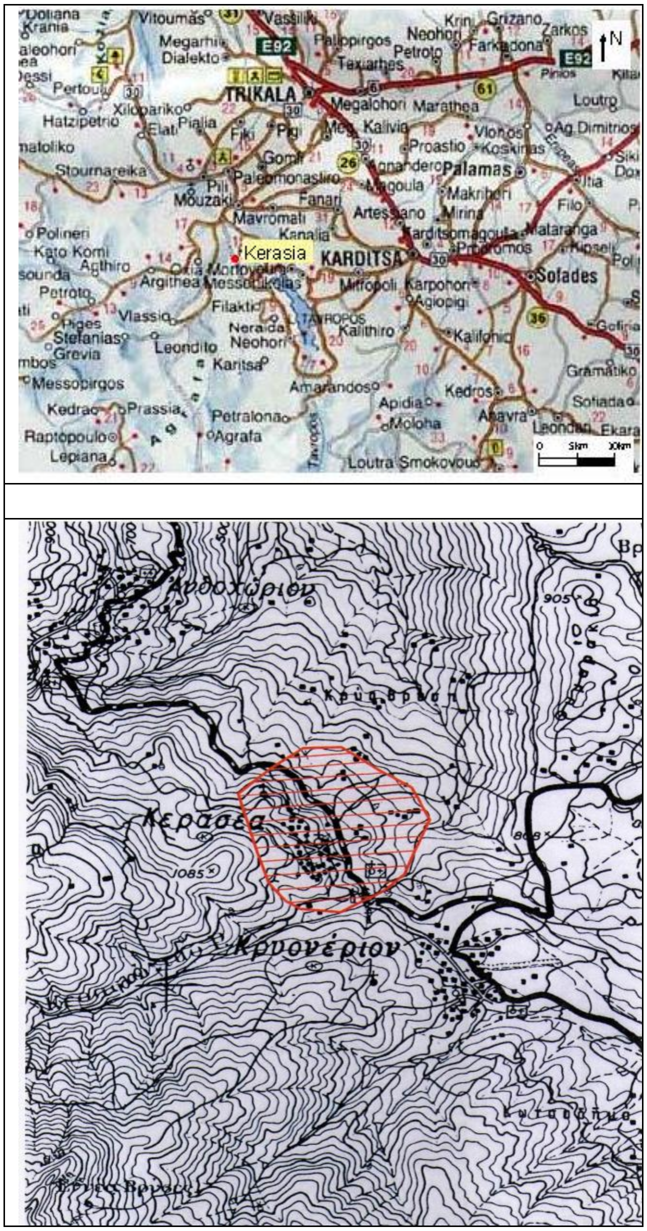
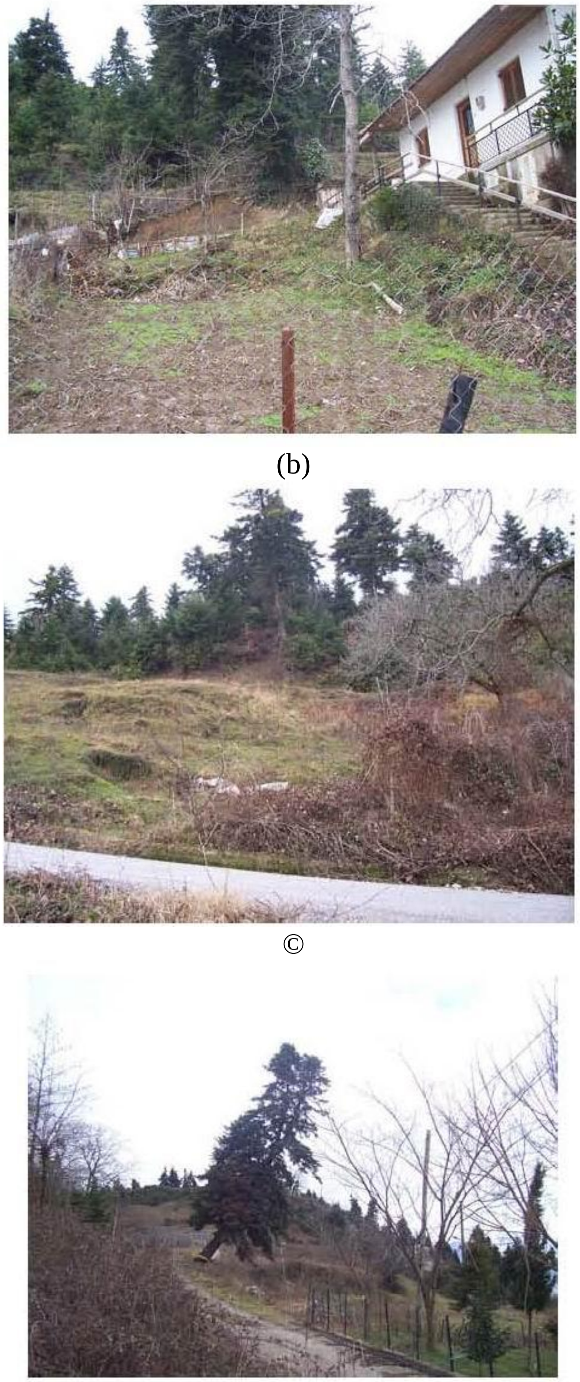


Fig. 4. Location of Kerasia Village in Plastiras Municipality, near Trikala town, Nothern Greece and topography of the area of study (Pirgiotis L., Apostolidis Emm., 2007)

(a)



(b)

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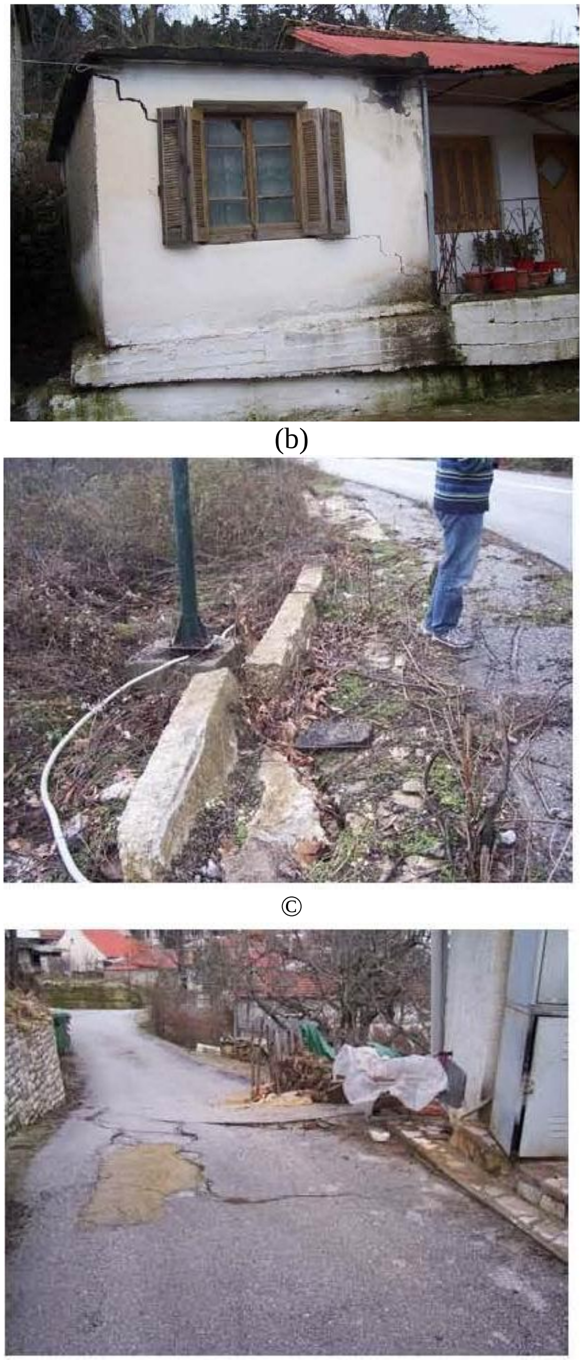
Fig. 5. Kerasia slide. Photos at 28/12/2010. (a)-(b) Top of the slide, (c) oblique tree illustrating slide movement.

(a)



(b)

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Fig. 6. Kerasia slide. Photos at 28/12/2010. (a) . Typical damage at house. (b). Damage at wall illustrating differential movement. (c). Differential movement at road

7. APPLICATION OF THE PROPOSED METHODOLOGY

A PSI study of Kerasia village was performed. The number of PSI points is 22. Fig. 7 gives the location of the measured PSI displacements. Satellite measurements vary from 5.4 mm/ year to 16.4 mm/year with an average value of 8.4 mm/year.

According to the previous discussion and as ring shear test results of the clay along the slip surface are not available at the studied study, the method (b) of analysis above will be applied. According to the space displacement measurements, the maximum rate of displacement per year equals 8mm. Since, the area is moving for at least 20 years, movement can be at least of the order of 20cm. Furthermore, the photographs of Figs. 5 and 6 illustrate maximum displacement about 10cm. As on the soil of the slip surface ring shear test results do not exist, the in-situ residual soil strength, and the displacement that it is reached are not known. Yet, as in clays the residual strength is reached at displacement of about 0.04 to 0.6m, it is inferred that the residual strength is probably not reached. Thus, according to the above procedure, first the existing strength will be assessed by back analysis and then mitigation measures will be studied.

Seven (7) borings were performed with purpose to determine subsoil composition and to perform field and laboratory tests by Greek Institute of Geology & Mineral Exploitation (IGME) (2007).

Based on the space measurements the three sections illustrated in Fig. 7 were considered in the analysis. It should be noted that these cross-sections are in agreement with IGME observations of past slide movements by IGME, as well as the past geotechnical analysis. First, the critical slip surface section must be determined in all sections. Stability analyses were performed for this purpose. The geotechnical cross-section assumed by IGME with corresponding geotechnical parameters. As the slip surfaces are not necessarily circular, the Jambu method was applied. The critical slip surfaces computed in each critical section is given in Fig. 8. The others were similar but are not given in the present publication due to space limitations.

As described in the section dealing with the mechanism of slide movement, the critical situation is the case that the water table line is in the ground surface. Furthermore, as ring shear tests were not performed at soil along the slip surface, the soil strength during movement, is not really known. Back analysis is performed using the multi-block model for this purpose to determine the residual soil strength under the condition of only (total-not effective) frictional resistance. It should be noted that the back analyses predictions of the multi-block model were compared with the predictions of the Jambu stability method and were found identical. Fig. 8 presents the results for section 11' (Fig. 7). The obtained residual friction angle was 30^o, 40^o, 37^o for cross-sections AA', 11', 22' respectively. These values are in general agreement with values reported in the bibliography in terms of the PI of the soil, described above.

As the movement of the slides are associated with the water table rise, it is inferred that the most effective mitigation measure to eliminate slide movement is the lowering of the water table line by drainage. The analysis of the needed lowering of the water table line concerns the performance of stability analyses under different depths of the water table line to estimate the depth of the water table line needed for the required safety. The stability analyses will be performed using the back-estimated soil strength. The needed safety requires: (a) an adequate factor of safety under static loading for design, that for period of 50 years equals to 1.3 (e.g. the German code DIN 4084, article12) and (b) the condition of zero seismic displacement under the condition of earthquake loading. Condition (b) is conservative, but in accordance to the strain-softening response of the soil that must ensure that triggering of the slide must not occur. In addition, as the area of study is classified as belonging to Category II of seismic action in Greece with ground acceleration A = a x g = 0.24, condition (b) requires that the critical acceleration is larger than 0.24g.

Water table lowering at depths 2, 4, 6, 8m were considered for all three sections. The corresponding Safety Factor (FS) and critical horizontal acceleration required for motion (a_c) are given in table 1. It can be observed that water table depth of 8m is needed for the requited safety described in section 2 above.

8. COMPARISON OF SATTELITE MEASUREMENTS WITH H INCLINOMETER MEASUREMENTS

Satellite measurements vary from 5.4 mm/year to 16.4 mm/year with an average value of 8.4 mm/year. This average value by taking an average slope of 20 corresponds to an average yearly vertical displacement of $8.4/\tan(20^o) = 23.0$ mm/year. On site measurements performed by the Greek Institute of Geology & Mineral Exploitation (IGME) (2007) at two locations between March 2006 and March 2007 (11.5 months period) recorded surface vertical displacements: (a) At boring K1:7 mm, or 7.3 mm/year and (b) At boring K2:22 mm or 23.0 mm/year.

The average value measured by satellite is just equal to the larger recorded on ground displacement. It is inferred that even though the time and location of the satellite and inclinometer recordings are different, the methods are in reasonable agreement. Furthermore, the space measurement rates in houses of the Kerasia village are in general qualitative agreement with the measured damage of theses houses, illustrated in Fig. 6.

Fig.7. The location of the measured PSI displacements at Kerasia village and the sections studied

Table 1. Factor of safety and critical acceleration value in terms of water table lowering for the three sections considered.

Section	Water table depth	2m	4m	6m
AA'	FS	1.3	1.61	1.82
	ac (g)	0.09	0.18	0.24
11'	FS	1.08	1.18	1.28
	ac (g)	0.06	0.13	0.2
22'	FS	1.28	1.55	1.84
	ac (g)	0.09	0.19	0.28

9. DISCUSSION

The availability of ring shear tests would have allowed a much more accurate geotechnical analysis. The availability of PSI during the period 2000-2010 would have allowed a more accurate analysis and comparison between displacements measured in-situ and from space.

10. CONCLUSIONS

The work developed and applied a methodology combining (a) space measurement of past displacement and (b) geotechnical modeling of displacement to predict and mitigate the risk of ground displacement cased by slope instability. The area of study is in the region of the Municipal Department of Kerasea in Plastiras Municipality. The problem under treatment is a creeping landslide in an inhabited area.

Mitigation measures were analyzed and proposed. As the movement of the slides are associated with the water table rise, it is inferred that the most effective mitigation measure to eliminate slide movement is the lowering of the water table. The analysis illustrated that the needed lowering of the water table line is 8m.

The measured space displacement was in agreement with displacement measurements in-situ from inclinometers. The availability of ring shear tests would have allowed a much more accurate analysis. The availability of PSI during the period 2000-2010 would have allowed a more accurate analysis and comparison between displacements measured in-situ and from space

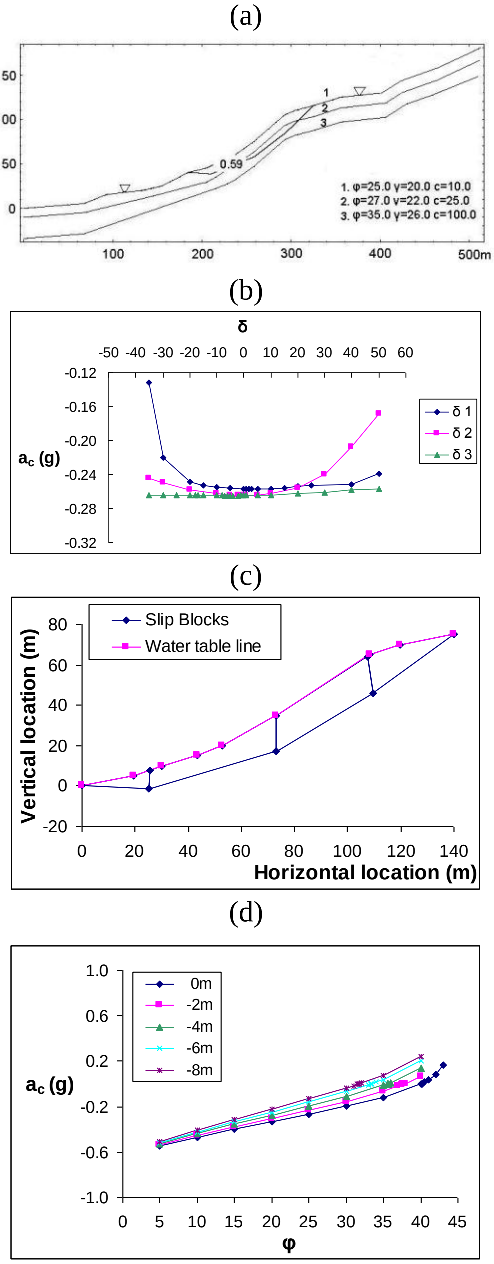

Fig. 8. Typical results of the analysis. Critical section 11'. (a) Determination of the critical slip surface by the search using the Jambu method, (b) Determination of the critical angles of the interfaces of the multi-block model, the inclinations of the internal interfaces to the vertical, δi (defined as the acute angle between the vertical and the interslice surface of blocks i and i+1, measured from the vertical, positive clockwise) (c) The simulation of the slide using the multi-block model. The case of the water table at the ground surface is given, (d) the friction angle and the critical horizontal acceleration (in g) for relative motion in terms of the elevation of the water table.

10. ACKNOWLEDGEMENT

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