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SEISMIC DISPLACEMENT ANALYSIS OF SLOPES: COMPARISON BETWEEN A MULTI-BLOCK MODEL AND SHAKING TABLE TESTS

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ABSTRACT

In many real cases, due to different slope conditions, combined rotational and translational failure of slopes may occur along a slip surface formed by curved and planar segments. In these cases more blocks moving along different straight-line segments should be considered in the seismic analysis. A multi-block model for the evaluation of earthquake-induced displacements occurring along slip surfaces of general shape has been recently proposed. To verify the accuracy of the model and its capability to reproduce typical mechanisms of seismic-induced deformations of slopes, a shaking table test was modelled and a comparison between predicted and observed behaviour is described in the paper.

Keywords: multi-block model, shaking table test, clayey slopes, shear strength degradation.

INTRODUCTION

The occurrence of earthquake-induced landslides is documented in many post-earthquake damage reports. The experience of last decades, including field observations, showed that these phenomena represent one of the most damaging hazards associated with large earthquakes. During strong earthquakes soils develop significant deformations that may affect the stability condition of slopes and earth structures possibly causing failures and damages to the environment, structures and lifelines. Under seismic loading conditions, the assessment of earthquake-induced permanent displacements represents a suitable criterion for the evaluation of seismic slope response and post-seismic serviceability. Among the available procedures for seismic stability analysis of natural slopes, the sliding block approach (Newmark, 1965) is considered the better compromise between computational effort and results accuracy.
Sarma & Chlimintzas (2001) proposed a limit equilibrium multi-block model for the evaluation of seismic and post-seismic slope displacements occurring along slip surfaces of general shape. The procedure is based on an approximated method of slices with kinematically admissible failure mechanism. In the multi-block model a geometric transformation rule of the soil mass during sliding is proposed but no excess pore water pressure is accounted for and the analysis is carried out assuming that soil shear strength is constant during the motion.
The experiences of recent strong earthquakes reveal that the seismic response of slopes is greatly influenced by the soil cyclic behaviour. In particular, failure and large deformation may occur even for moderate earthquakes if the cyclic soil behaviour is characterized by significant strength and stiffness degradation. In this case a displacement analysis that does not consider these aspects could lead to an unsafe estimation of the slope response.

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The approach proposed by Sarma & Chlimintzas (2001) has been modified (Bandini & Cascone, 2008; Bandini *et al*., 2008) introducing the General Limit Equilibrium (*GLE*) Method (Fredlund & Krahn, 1977) for the evaluation of the critical acceleration coefficient, and accounting for the effect of soil shear strength degradation on the slope stability condition and on earthquake-induced permanent displacements. The effect of soil shear strength degradation can be accounted for in an effective stress analysis, by including pore-pressure build-up due to cyclic loading, and in a total stress analysis, introducing the cyclic reduction of the undrained shear strength.
To verify the accuracy of the model and its capability in reproducing typical mechanisms of seismically induced deformations of slopes, the results of a series of shaking table experiments carried out by Wartman *et al*. (2005) on small scale model slopes are considered and a comparison between observed and predicted behaviour of one of the slope model tests is discussed in the paper.
According to the available data, total stress analyses were carried out using peak or residual values of undrained shear strength or even accounting for the cyclic reduction of undrained shear resistance during seismic excitation, using the degradation parameter approach proposed by Idriss *et al*. (1978).
The comparison between observed and predicted slope behaviour is performed in terms of displacement time-histories, recorded at given locations in the slope, and in terms of deformed slope geometry at the end of the shaking. The results of the analyses show that only accounting for shear strength degradation it is possible to capture the main features of the slope behaviour.

DESCRIPTION OF REFERENCE SHAKING TABLE TEST

The tests by Wartman *et al*. (2005) were carried out on a 960 mm wide by 1219 mm long single-degree-of-freedom shaking table. Experiments were performed on four clayey slope models which were constructed and tested in a rigid box container bolted to the shaking table. The dynamic response and surface displacements of the models were measured using respectively solid-piezoresistive accelerometers and linear motion potentiometers. Uncooked durum semolina spaghetti strands (2mm diameter) were pushed vertically into the model, at regularly spaced intervals, and used as slope inclinometers.
The clayey slope models typically consisted of two layers: an upper soft clay layer underlain by stiffer clay in contact with the boundary walls. The stiff clay, which had a lower water content but was otherwise identical to the overlying softer material, was intended to minimize the influence of the container boundaries on the models by preventing development of shear surface in the vicinity of the container walls. The model clay used in the study was a saturated model clay mixture of 75% kaolinite and 25% bentonite; it had liquid limit of *LL*=133% and a plasticity index of *PI*=106%.
The small-scale slopes were not intended to model any single prototype-scale slope, but instead were designed so that the static and dynamic properties of the models were reasonably proportioned to a typical full-scale slope. For this reason, the observational data and analysis results were presented by Wartman *et al*. (2005) at the model scale. The frequency content of the input ground motions was increased to reflect the reduced-scale of the model tests.

In each test, the principal mode of permanent deformation was deep rotational/translational displacement in the upper clay layer. In contrast to Newmark's (1965) assumption that deformation occurs along a single well-defined slip surface, the model slopes typically displaced along two or more localized slip surfaces. In general, the multiple shear surfaces had a similar orientation and were located within close proximity to each other. Although shearing developed along multiple surfaces, it appears that nevertheless, the sliding block single surface assumption reasonably approximated the actual deformation observed in the models.

Surface deformations varied over the length of each model, with the largest displacements occurring at the toe or along the face of the slope. This behaviour contrasts the rigid block assumption, which presumes that the sliding mass has uniform deformations.

Test on model slope 4 was previously analysed by Bandini (2010). In this paper the multi-block model has been used to back-analyse the shaking table test on model slope 3 that showed a stick-slip sliding pattern of behaviour, with the soft clay moving as a relatively intact mass.
The model slope 3 is 26.5 cm high and has an inclination of 29.7°; the peak and residual undrained shear strength values of the upper soil layer, measured using a portable laboratory-scale mechanized vane shear, are respectively 2.68 kPa and 1.77 kPa. The geometry and the instrumentation of the model are shown in Figure 1. Figure 2 shows pre-test and post-test profiles of the model. Pre-test geometry is represented with a thin dashed line while localized shear displacement surfaces are shown with thick solid or dashed lines; vertical lines represent deformed spaghetti strands.

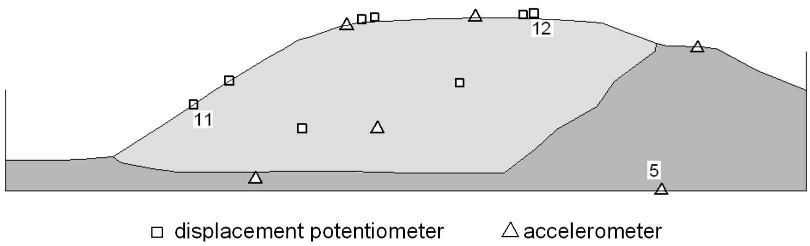

Figure 1. Slope 3: cross section and instrumentation (modified after Wartman *et al*., 2005).

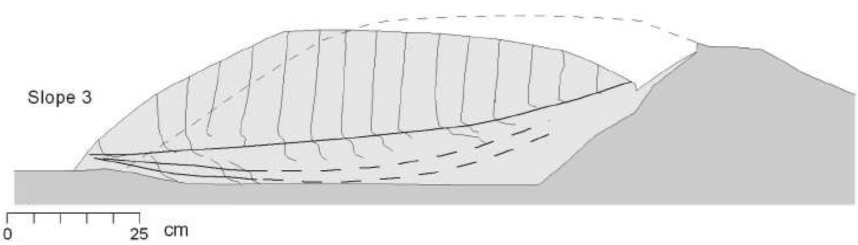

Figure 2. Pre- and post-shaking profiles of model test 3 (Wartman *et al*. 2005).

MULTI-BLOCK MODEL ANALYSES

Analysis with peak and residual values of undrained soil shear strength

The deep shear surface observed at the end of test on model slope 3 was approximated with 11 straight-line segments and consequently the slope was subdivided into 11 blocks moving each parallel to its own failure surface segment (Fig. 3).
In Figure 4a the time-history of the measured base motion acceleration coefficient (accelerometer n. 5) is superimposed to the predicted yield acceleration coefficients, $k_{c,P} = 1.07$ and $k_{c,R} = 0.64$, respectively computed for the peak and residual values of the undrained soil shear strength. The input motion is a synthetic motion with spectral frequency content in the range 1–20 Hz, maximum recorded acceleration coefficient of 3.46 and a significant duration of 19.3 s. The acceleration time history recorded at accelerometer n.5 best represents the accelerations along the bottom of the slip surface, and was therefore used as input acceleration in the displacement analysis.

Displacements observed close to the toe and the top of the slope (potentiometers n. 11 and n. 12) are compared with those predicted by the model for blocks n. 3 and n. 10 (Fig. 4b).
During the shaking table test slope deformations exceeded the range of the displacement potentiometers and therefore only the initial portion of the displacement-time history was recorded, with maximum displacement after 21 s of dynamic excitation of about 6.5 cm. Final measurements of surface deformation observed at survey monuments located on the model surface, varying in a range of 12-14 cm, are shown on the figure with a dashed area to supplement the recorded displacements from the potentiometers. The figure shows that similar displacements were measured at the toe and top of slope and near the back of the model, suggesting once again that the soft clay moved as a relatively intact mass after the slip surface was fully developed.

The same behaviour is caught by the multi-block analysis. The final displacements predicted for block n.3 and n.10 are respectively 5.3 cm and 5.9 cm in the analysis carried out assuming that the peak undrained shear strength $C_{u,P} = 2.68$ kPa was mobilised along the failure surface; displacement as large as 18.9 cm and 20.8 cm were predicted by the multi-block analysis assuming that the undrained shear strength had attained its residual value $C_{u,R} = 1.77$ kPa. From Figure 4b it is apparent that the multi-block analysis performed using constant peak or constant residual values of undrained shear strength is not able to reproduce the observed displacements. Measured displacements on the sliding mass were effectively bounded by deformations computed using peak and residual soil strengths; however, this bounding range was quite large. Similar considerations could be done in terms of observed and predicted post-test profile, as shown in Figure 5. The predicted final deformed configurations show that slope displacements are underestimated if the peak strength is assumed constant in the analysis and overestimated if the residual strength is adopted.

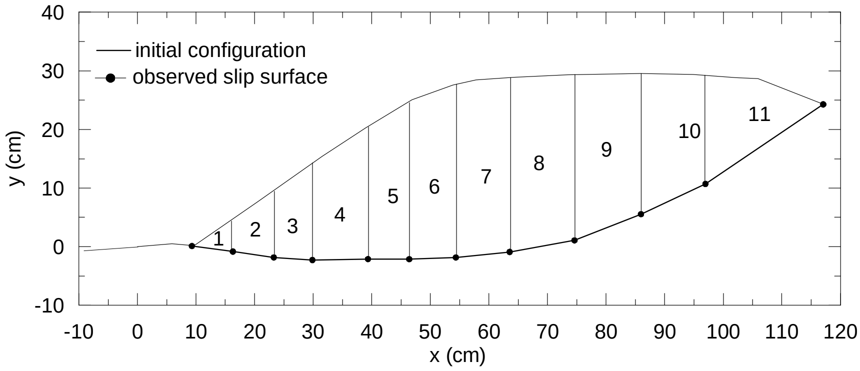

Figure 3. Discretization of observed shear surface and multi-block system

Analysis accounting for the cyclic reduction of undrained shear strength
Under cyclic loading stiffness and strength of clayey soils degrade, and pore water pressures develop. To quantify such degradation Idriss *et al.* (1978) introduced the concepts of degradation index δ and degradation parameter *t*. Experimental results obtained in cyclic strain-controlled tests can be expressed either in terms of shear modulus G or cyclic shear stress τ_c introducing the degradation index δ:

$$\delta = \frac{G_N}{G_1} = \frac{\tau_{c,N}/\gamma_c}{\tau_{c,1}/\gamma_c} = \frac{\tau_{c,N}}{\tau_{c,1}} \tag{1}$$

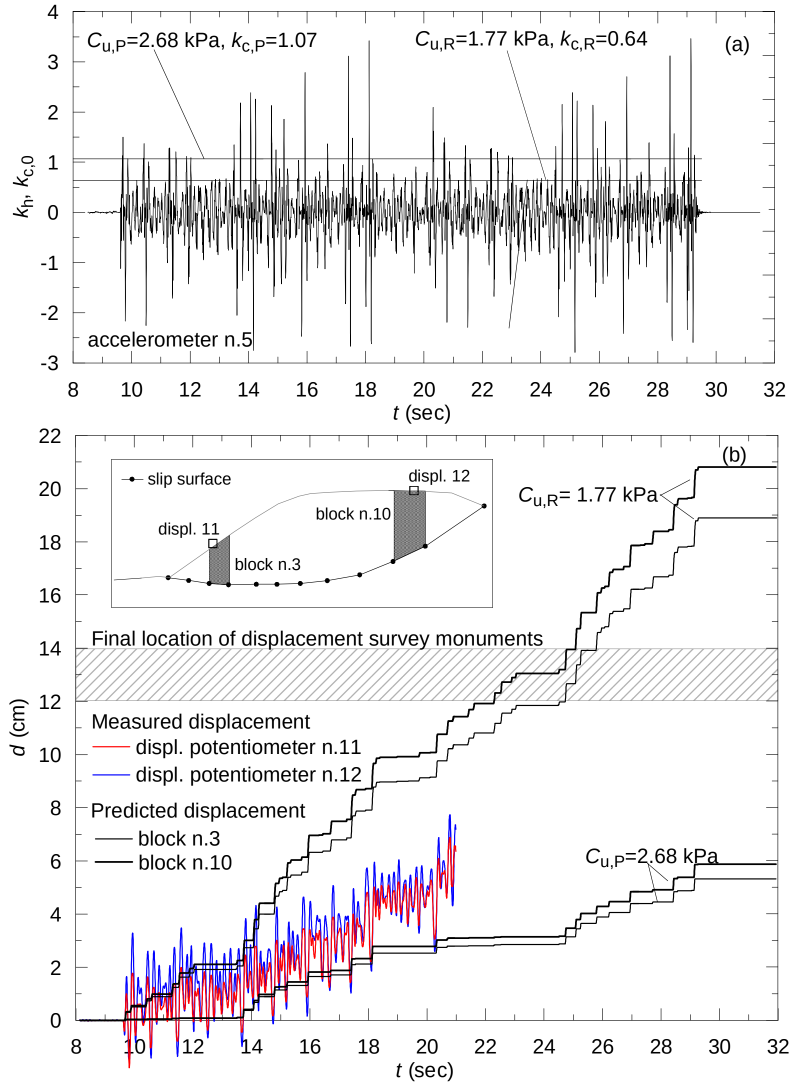

Figure 4. a) recorded base motion acceleration and calculated yield acceleration coefficients; b) measured and predicted displacements for peak and residual undrained shear strength.

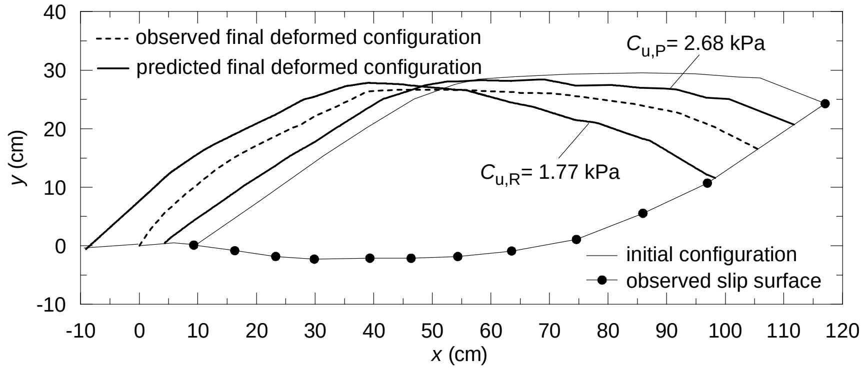

Figure 5. Observed and predicted slope configurations for peak and residual values of undrained shear strength.

In eq. (1) G_1 and G_N denote the secant shear modulus in the first and *N*th cycles, respectively, $\tau_{c,1}$ and $\tau_{c,N}$ denote the amplitude of shear stress in the first and *N*th cycles, and finally, γ_c is the constant amplitude of the imposed shear strain. The degradation parameter *t* was introduced to take into account the rate of degradation:

$$t = -\frac{\log \delta}{\log N} \quad \text{or} \quad \delta = N^{-t} \tag{2}$$

The definition of *t* is based on the observation that the slope of the $\log \delta$–$\log N$ relationship is approximately constant (Idriss *et al.*, 1978). The degradation parameter *t* depends on many factors among which, the amplitude of the shear strain γ_c, the plasticity index *PI* and the overconsolidation ratio *OCR* are the more relevant.
Assuming that the cyclic loading path imposed to the model slope by the applied shaking can be described as a strain-controlled phenomenon and using eqs. (1) and (2), the soil shear strength $C_{u,N}$ available after *N* loading cycles can be evaluated as:

$$C_{u,N} = C_{u,0} \cdot N^{-t} \tag{3}$$

where $C_{u,0}$ is the initial static value of the undrained shear strength available at the depth of the failure surface. In the analyses described hereafter $C_{u,0} = C_{u,P}$ was assumed.

If the variation of *t* can be determined, the time-history of the undrained shear strength of the soil can be computed; then the current value of the yield acceleration coefficient can be evaluated applying the *GLE* method for each time step of the input accelerogram.
The time-history of the undrained shear strength in the multi-block displacement analysis is evaluated through a simplified procedure that is synthetically outlined in the following and is shown in Figure 6.
The time-history $\gamma_c(t)$ of the shear strain induced at the base of a generic slice of the slope is computed solving iteratively the following equation:

$$\gamma_{c,i}(t) = \frac{\Delta\tau_i(t)/G_{0,i}}{G_i(\gamma)/G_{0,i}} \tag{4}$$

where $\Delta\tau_i(t)$ and $G_{0,i}$ represent the pseudo-static increment of the shear stress with respect to the static condition and the small strain shear modulus at the base of the ith slice, respectively, while $G_i(\gamma)/G_{0,i}$ represents the modulus reduction curve. In the analysis the modulus reduction curve is evaluated using the expression proposed by Yokota *et al.* (1981):

$$\frac{G_i(\gamma)}{G_{0,i}} = \frac{1}{1 + \alpha \cdot \gamma(t)^{\beta}} \tag{5}$$

where α and β are material constants related to the plasticity index *PI.* Using equations proposed by Bandini (2008), best-fitting the experimental data provided by Vucetic & Dobry (1991), for $PI = 106\%$ values of $\alpha = 1.54$ and $\beta = 0.93$ were obtained. The modulus $G_{0,i}$ was computed as a function of the plasticity index and of the mean effective pressure at the base of the ith slice using the relationship proposed by Rampello *et al.* (1994) and assuming that the soil is normally consolidated.

For the slice located in an intermediate position in the slope, at a distance of about 50 cm from the toe of the slope, the computed time-history of the shear strain is shown in Figure 6a; as expected, it is similar to the time-history of the input motion (accelerometer n.5) and the maximum values of the shear strain amplitude vary within the range ±3%. Figure 6b shows the time-history of the mean shear strain $\gamma_{mean}(t)$, defined as the mean value between the positive and negative peaks in each straining cycle; in the figure the volumetric threshold shear strain $\gamma_v = 0.16\%$, evaluated as a function of plasticity index as proposed by Vucetic *et al*. (1994), is also indicated. The number *N* of significant imposed straining cycles exceeding the volumetric threshold shear strain γ_v is plotted in Figure 6c, summing up to 194 at the end of shaking.

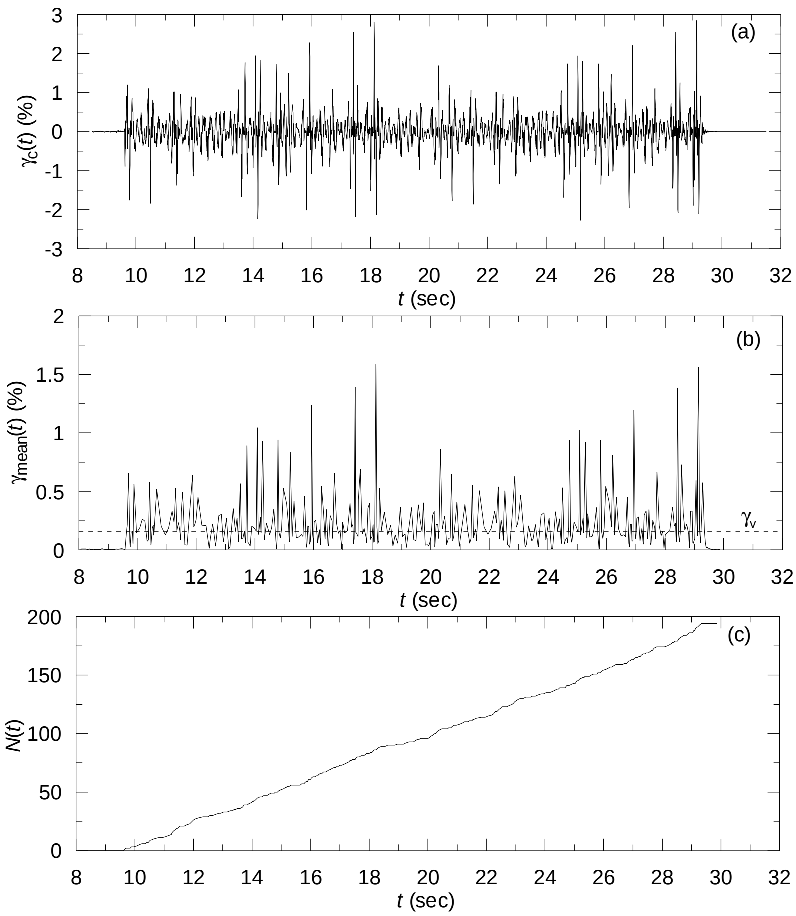

Figure 6. Time histories of a) shear strain; b) mean shear strain; c) number of significant cycles.

Using the computed time history of the significant number of cycles *N* and of the degradation parameter *t*, the time-history of the undrained shear strength $C_{u,N}$ was computed by means of eq. (3) (Fig. 7a); the predicted time-history of the yield acceleration coefficient $k_{c,N}$, evaluated applying the General Limit Equilibrium Method, is shown in Figure 7b.
The results of the multi-block analysis carried out accounting for the reduction of the yield acceleration coefficient due to the variation with time of the undrained shear strength are shown in Figures 8 and 9.

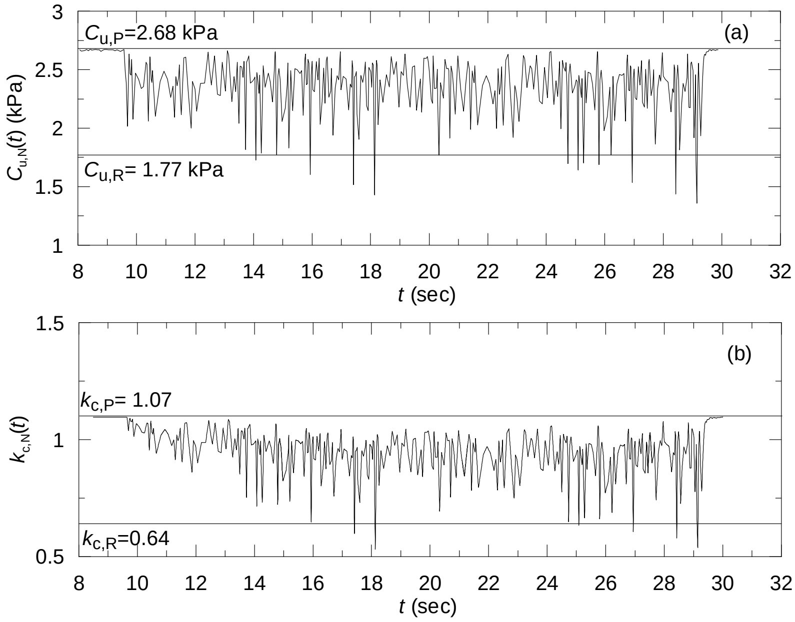

Figure 7. Time-histories of a) undrained shear strength and b) yield acceleration coefficient.

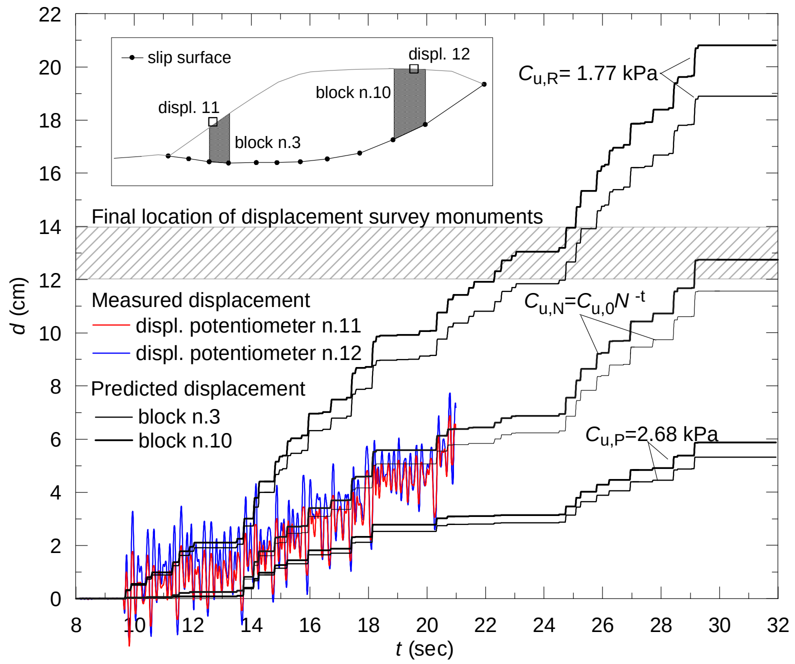

Figure 8. Measured and predicted displacements accounting for shear strength degradation.

Computed displacements of blocks n.3 and n.10 match very well the displacements measured by potentiometers n.11 and n.12 in their recording range (about 21 s) (Fig. 8); the final displacements computed in the analysis are also within the dashed area of the displacements measured by survey monuments.

Figure 9 shows the comparison between predicted and observed slope configuration at the end of shaking. It is apparent that in the analysis accounting for soil shear strength degradation the final slope configuration is predicted with good accuracy.

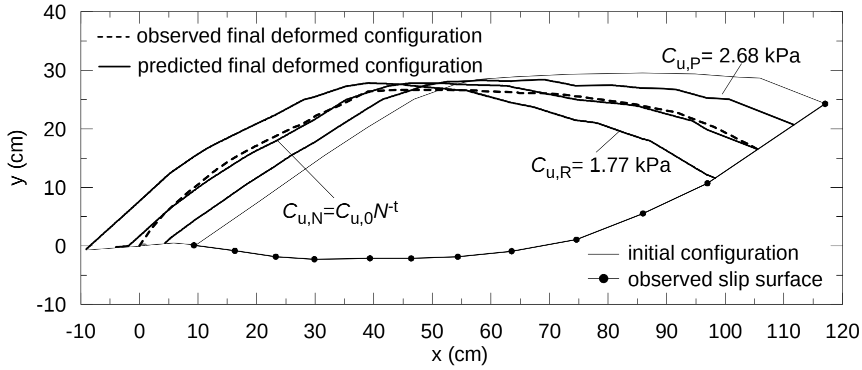

Figure 9. Observed and predicted slope configuration accounting for shear strength degradation.

Figure 10 shows the magnitude of horizontal, vertical, and total predicted block displacements together with observed displacements, as measured at survey monuments fixed along the surface of the slope. Near the toe and the top of the slope, measured total displacements were essentially horizontal as evidenced by the similarity of the horizontal and total displacement magnitudes. Vertical displacements increase near the middle and back portions of the slope, but horizontal deformation continues to dominate also in this portion of the slope. The multi-block analysis predicts with a satisfactory approximation the measured final displacements of each survey monument. In particular the total displacement of each block follows the inclination of its own failure surface segment; the horizontal component of the displacement is constant for the compatibility of the failure mechanism; the vertical component is smaller than the horizontal one, is negative close to the toe and, as measured by the survey monuments, starts to increase from the middle to the back of the slope. Differences observed between measured and predicted displacements are related to the fact that the slope did not move as a perfectly rigid block during the test, but a limited amount of deviatoric straining may have occurred.

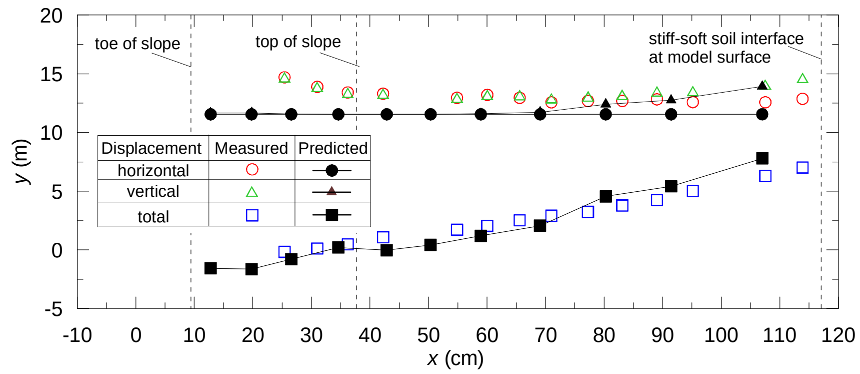

Figure 10. Horizontal, vertical, and total predicted block displacements and measured displacements of survey monuments fixed along the surface of the slope.

CONCLUSIONS

In common practice, earthquake-induced displacements are evaluated for translational or rotational sliding mechanisms. When the sliding surface is of general shape, permanent displacements can be evaluated describing the mixed roto-translational mechanism via a multi-block model. Based on previous works, Bandini *et al*. (2008, 2009) proposed a limit equilibrium multi-block model for the evaluation of seismic slope displacements occurring along slip surfaces of general shape. The proposed multi-block model accounts for the cyclic degradation of soil shear strength during the seismic motion and for the stabilizing effect due to geometric rearrangement of the soil mass during sliding.

To verify the accuracy of the model and its capability to reproduce typical mechanisms of seismically induced deformations of slopes, the proposed multi-block model was applied to a series of shaking table model experiments carried out by Wartman *et al.* (2005). In this paper the comparison between observed performance of one of the model tests and the slope behaviour predicted by the multi-block displacement analysis is presented.

According to the available data, total stress analyses were carried out using (i) peak and (ii) residual values of undrained shear strength and (iii) accounting for the cyclic reduction of undrained shear resistance using the degradation parameter approach. The multi-block analysis performed using a constant value of undrained shear strength, either peak or residual, is ineffective in reproducing the observed displacements, while the analyses provided an excellent match to the recorded data when a displacement-dependent degrading yield acceleration was used to model the soil's transition from peak-to-residual shear strength. The good agreement between observed and predicted slope behaviour was performed in terms of displacement time-histories, recorded at given locations in the slope, and in terms of final global configuration.

The results obtained in the analyses show that the multi-block model accounting for strength degradation and slope geometry rearrangement is capable to capture with good accuracy the pattern of behaviour of slopes subjected to seismic motions.

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