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XIII ICSMFE, 1994, New Delhi, India / XIII CIMSTF, 1994, New Delhi, Inde

DISPLACEMENTS OF COHESIVE SLOPES INDUCED BY EARTHQUAKE LOADING
DEPLACEMENTS DE TALUS COHERENTS PROVOQUES PAR ACTIONS SISMIQUES

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SYNOPSIS: The post-rupture displacements and rates of displacement of slopes on pre-existing shear surfaces in coesive soils are influenced by the behaviour of soil under earthquake loading conditions. Pre-existing shear surfaces at or close to residual strength are frequently present in slopes of coesive soils and weak mudstone, due to previous slope movement or tectonic disturbance. A knowledge of the strength of such surfaces under rapid loading is necessary if stability during and after an earthquake is to be examined. To obtain such data, high speed displacement controlled ring shear tests have been performed, on samples after being pre-sheared to residual conditions. With the results from those tests, suitable constitutive laws were developed and analysis were made of old landslides submited to earthquake loading. Newmark's sliding block was used, sliding on a curved surface. The strength of such surfaces depends on the displacement and rate of shearing. The analysis shows that the displacement induced by earthquake loading is influenced significantly by the behaviour of soil under earthquake loading conditions.

INTRODUCTION

Pre-existing shear surfaces are frequently present in cohesive soils due to previous shearing due to previous slope movement or tectonic forces. The prediction of the displacement of a soil mass sliding on a pre-existing shear surface and subjected to earthquake shaking is of importance to the design of structures.

The sliding block model developed by Newmark (1965), was used. The slope angle was varied in order to simulate a circular slope, Lemos et al (1991). In this method, it is assumed that slope failure would be initiated and movements would begin to develop if the seismic forces, induced by the ground acceleration time history, on a potential slide mass were large enough to overcome the yield resistance and the movements would stop when the seismic forces were removed or reversed. Thus, by computing the acceleration at which yielding begins and summing up the displacements during the periods of instability, the final cumulative displacement of the slide mass can be evaluated.

A program of testing on the ring shear apparatus was carried out on various soils to investigate the influence of the rate of displacement on residual strength, Lemos et al (1985), Lemos (1986), Tika (1989) and Lemos (1991). Rates of displacement ranging from 0.001 to 6000 mm/min were used. Residual conditions, for a given normal stress were established at a nominal displacement rate, which is calculated in order to ensure 90% dissipation of the pore water pressures in 1 to 2 mm of displacement. After the residual conditions were achived, fast rates were applied followed by slow probes at the nominal rate. In the fast rates it was measured:

i) the immediate (viscous) increase in strength,
ii) the maximum shear resistance, and
iii) the minimum shear resistance (fast residual).

In the drained slow probes, that followed the fast rates with enouth time allowed for consolidation, it was measured the disturbance of the shear zone induced by fast shearing, which was given by the difference between the new peak and the slow residual strength.

In fast shearing three types of behaviour were identified, concerning the value of the fast "residual" strength, Lemos et al (1985), Lemos (1986), Lemos (1991):

i) positive rate effect (clay fractions higher than 50%). The fast residual is higher than the slow residual;
ii) neutral rate effect (soils predominantly composed by massive particles, with a very small percentage of clay particles %$<$ 2μm $<$ 3 to 5%). The influence of the fast rate on shear resistance is negligible;
iii) negative rate effect (clay fractions between 5 to 40%). The fast residual is lower than the slow residual.

Lemos et al (1991) presented analysis where the displacements under seismic loading were calculated considering soils with a positive rate effect. They concluded that the displacements calculated with rate effects were 10 times smaller than the ones calculated without rate effects. The maximum displacements obtained were of the order of 10 cm.

Failures of slopes on low plasticity clays, showing negative rate effects, have high losses of strength in fast shearing, and the slopes have a potencial for catastrophically fast movement. The consideration of this influence to the evaluation of the displacement of the sliding block model subjected to an earthquake is the subject of this paper.

MODEL OF SOIL BEHAVIOUR

The soil models for fast shearing used in the analysis have been presented with same detail in Lemos et al (1991). Lemos (1991) show that if a shear surface or zone is formed at residual strength by slow drained shear, and then subjected to more rapid displacements rates, the following features were normally observed:

i) an immediate increase in strength (threshold) without displacement. This value seems to increase with displacement rate and can be formulated with the following expression:

$$\frac{\mu_T - \mu}{\mu} = a\, d^b$$

Where:
μ_T - represents the threshold shear resistance at a displacement rate of d
μ - represents the static resistance at the nominal displacement rate.

The value of the constants a and b used in the analysis were respectively equal to 0.435 and 0.230 . This values were obtained from ring shear test results on samples of low plasticity clays showing negative rate effects, as is demonstrated in figure 1. The viscous shear resistance is dependent on the rate of shear strain and so on the thickness of the shear zone. The thickness of the shear zone differs in the laboratory and in the field and so the constants derived from the laboratory tests may be different from those in the field. Lemos et al (1991) demonstrated that the constant a for thicker field shear zones should be multiplied by the ratio of the thichness of the laboratory and field shear zones to the power b. It was considered, in the analysis, that the shear zone in the field was 10 times thicher than the one observed in laboratory.

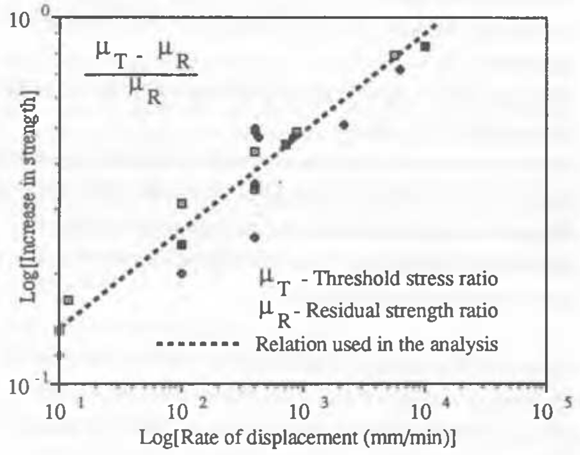


Figure 1. Immediate increase in resistance in relation to the residual strength plotted against rate of displacement.

ii) When a slow probe was applied after a fast rate of displacement a peak strength was observed which reduced to residual conditions with relative small further displacements (typically 2 to 3 cm). The peak shear ratio refered to above increases with the increase of the displacemente rate of the previous fast shearing stage. This peak is a measurement of the disturbance of the shear zone. The ring shear results have been presented by Lemos (1991) and can be with a good approximation modelled with a sectioned linear approach showed on figure 2. The values (1-R) represented in figure 2 represent the increase in static strength, that would be observed in a slow pobe on a surface over which large displacements had taken place at a fast rate. The increase or decrease in strength, depending on the current static strength and rate of displacement, was modelled using an exponential function, as ilustrated on figures 3 and 4.

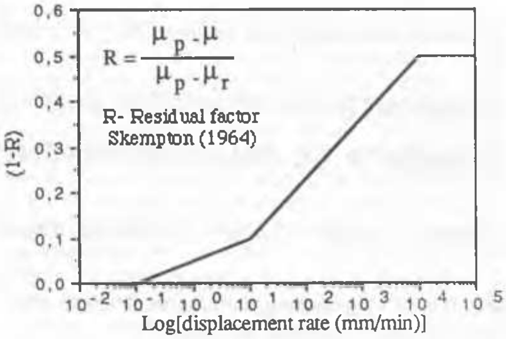
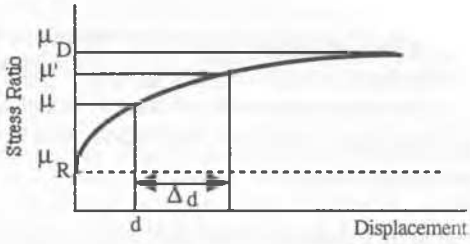


Figure 2. Model for the disturbance of the shear zone as a function of the displacement rate.



$$\mu' = \mu_D - (\mu_D - \mu_R)\, e^{-a(d+\Delta d)}$$

Where:
$d = -(1/a) \ln [\, (\mu_D - \mu) / (\mu_D - \mu_R)\,]$ displacement corresponding to the stress ratio for a given displacement.
Δd displacement increment.
μ_D static strength which depends on the rate of displacement, if enough displacement was allowed for it to develop fully.
μ_R stress ratio value for the residual strength.
μ and μ' stress ratio at displacement d and $d+\Delta d$.

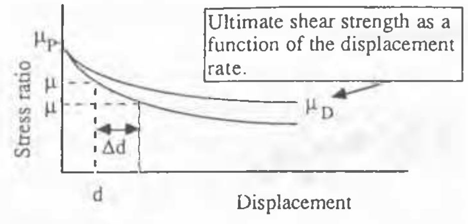
The value of the constant "a" used in the analysis was 0.4 .

Figure 3. Model representing the increase in static shear strength with displacement.

iii) the stages obtained from fast ring shear tests which are presented on figure 5 a) and b), it is observed that:

1 - there is a threshold displacement rate, above which the minimum fast shear resistance drops to values below the slow residual;

2 - the minimum fast shear strength attains the minimum value for displacements rates of the order of 1000 mm/min, being then constant for higher rates;



$$\mu' = \mu_D - (\mu_P - \mu_D)\, e^{-b(d+\Delta d)}$$

Where $d=-(1/b)\ \ln[(\mu-\mu_D)\div(\mu_P-\mu_D)$ displacement correspondly to the strength ratio μ, at a given time.

Δd displacement increment

μ_P Peak shear strength

μ_D ultimate (residual) strength for a given rate of displacement

μ e μ' static strength of the soil before and after the displacement increnent

The value of the constant "b" used in the analysis was equal to 0.3.

Figure 4 Model for the decrease in the static shear strength with displacement from peak (μ_P) to residual (μ_D) function of the displacement rate and degree of particle orientation.

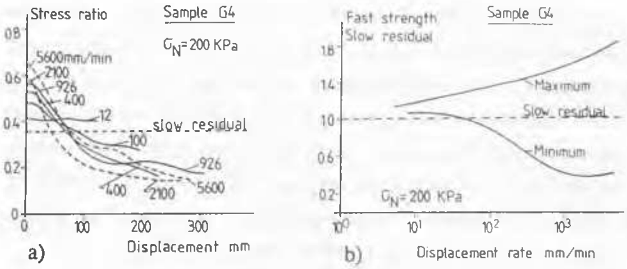


Figure 5. Test results of fast ring shear tests.(a) and (b) negative rate effect.

3 - the minimum fast value is obtained within displacements of the order of 200 mm. After this minimum is obtained it remains constant during prolonged fast shear and even when the displacement rate is immediatly reduced to values lower than 10 mm/min (without consolidation), Lemos (1986), Lemos (1991). The causes for this behaviour have been fully discussed in Lemos (1991).

Thus, this behaviour can be modeled as shown on figure 6. The values given on figure 6 were taken as the avarage of the samples that did show this type of behaviour.

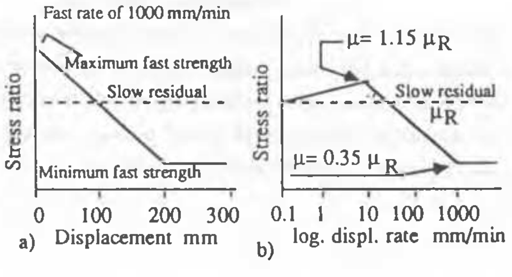


Figure 6.a) Variation of the stress ratio in fast shear with displacement b) Variation of the fast residual strength with displacement ratio.

ANALYSIS AND RESULTS

A sliding block moving on a curved surface, with initial sloping angles between 18 and 10 degrees and with the shear resistance at residual (μ=0.36) , which gave critical acceleration k_cg between 0.031g and 0.173. The critical acceleration k_cg is a function of the geometry and the soil parameters of the sliding mass corresponding to factor of safety of one and it is a measure of the resistance to sliding of a soil mass subjected to an earthquake. In the analysis were used 54 earthquake records with values of the maximum ground acceleration k_mg varying from 0.05g to 1.83g.

Figure 7 shows the maximum relative displacements predicted using the model of soil behaviour described previously. Figure 8 shows the maximum relative displacements predicted using the model developed by Lemos et al (1991) for soils showing positive rate effects on the same figure it is shown results using rigid-plastic behaviour of soils in which the critical acceleration, k_cg, remains constant irrespective of the displacement.

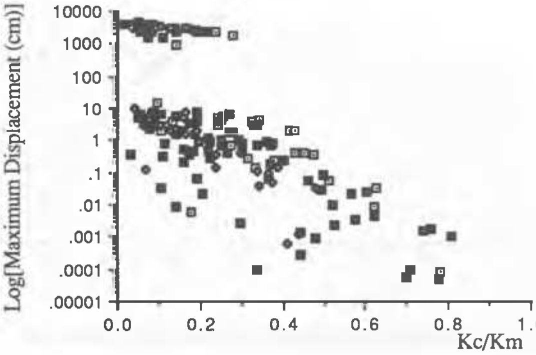


Figure 7. Maximum displacements induced by earthquake ground motions for soils showing a negative rate effect behaviour.

DISCUSSION

The results given on figure 7 and 8 shows that the final displacements with rate effects were 10 times smaller (one log cicle) than the ones predicted with the rigid plastic soil model, for values of (kc/km) smaller than 0.5. This difference seems to decrease then with the increase of that ratio, Lemos et al (1991). This prediction is consistent with the observations of earthquake induced displacements of pre-existing shear surfaces in plastic clays.

For soils with negative rate effects, where the loss of strength was induced during the earthquake, due to the large rates of displacement with accumulated displacements over 15 cm, lead to run away failures. The models developed from the ring shear data show that, for rates above 0.17 cm/sec and cumulative displacements above 10 cm the fast residual shear strength drops to values below the slow residual. Then the value of 15 cm given above and obtained in the predictions is strongly dependent on the values given above. The analysis consider a block sliding on a curved surface, where the angle β decreases at a rate of

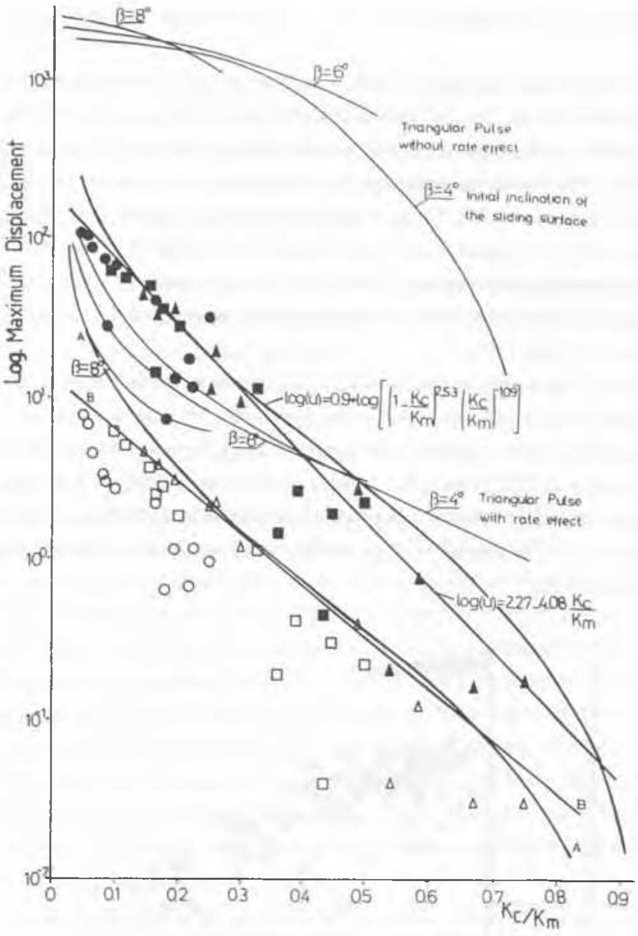


Figura 8. Maximum displacements induced by earthquake ground motions and triangular pulses with constante area, for soils showing a positive rate effect behaviour, Lemos et al (1991).

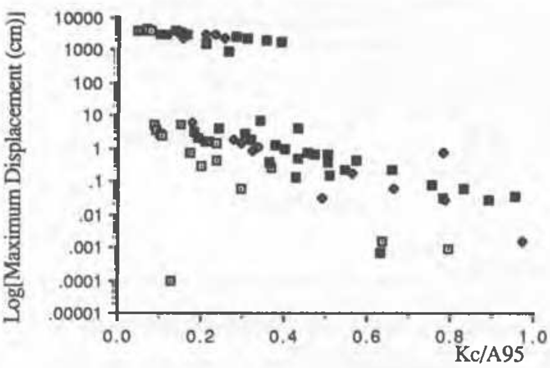


Figure 9. Maximum displacements induced by earthquake ground motions for soils showing a negative rate effect behaviour.

0.0001 with displacement. This simulates a circular slope with a radius of 100 metres, the maximum displacements in run away failures were of the order of 3500 cm, which is dependent on the value of the radius chosen. However, a mechanism of run away failure with earthquake-induced large displacements, may be associated with soils showing a negative rate effect. In the predictions of earthquake induced displacements given on figure 7 it was not found a threshold value of K_c/K_m, below which, the only mechanism present was the run away failure. This strongly suggests, that besides the maximum acceleration (K_m.g), the energy density (E_x) above a given level of acceleration K_c.g should be an important parameter, since it is related with the magnitude M of the earthquake and the focal distance R , Sarma et al (1987). Sarma et al (1987) found a parameter A_{95} which describes mathematically the relationship between the normalized enegy quantity of E_x/E_s and the normalized acceleration values of A/A_{95}. The acceleration parameter A_{95} is based on the Arias Intensity which is ralated to the seismic destructiveness. On figure 9 it is shown the relationship between the maximum displacement and the parameter A/A_{95}, and as well, it is not detected a threshold value below which there was only run away failures. Earthquakes with maximum acceleration above 0.5 g, and Kc/Km values below 0.3, acting on slides formed by soils which show a negative rate effect, the possibility of a run away failure should be investigated.

The residual shear condition is characterised by a shear zone formed by the clay particles orientated parallel to the direction of shear. The degree of orientation decreases with the increase of the rate of displacement. The earthquake induced displacement rates are high, disturbing the clay particles alighnement and consequently increasing the residual shear resistance towards the constant volume shear resistance. In the analysis it was predicted a decrease in the residual factor R from 100 to 60%, by the end of the earthquake. The residual factor R is equal to $[(\mu_P-\mu)/(\mu_P-\mu_R)]$ and measures the degree of particle orientation. Where:

μ_P - is the constant volume shear resistance, R=0%;
μ_R - is the residual shear strength, R=100%;
μ - is the current shear resistance, $0<R<100$.

CONCLUSIONS

It was presented the prediction of displacements on pre-existing shear surfaces in coesive soils induced by earthquake loading considering rate effects on the shear resistance. The results obtained show that the displacements calculated with rate effects were 10 times smaller than the ones predicted using a rigid-plastic model. This may explain why pre-existing slides in cohesive soils show small movements during earthquake shaking. However, in soils showing negative rate effect, if the enough displacement is accumulated under high rates of displacements which will induce a loss in shear strength during the earthquake shaking, then large movements may occur. The potential of a slide to run away failure can not be predicted by a single factor, such as K_c/K_m, but it depends on the type of the ground motion, that is level of energy density (E_x) above a given level of acceleration (K_c).

ACKNOWLEDGEMENTS

This work was carried out at the Department of Civil Engineering, Faculty of Science and Technology, University of Coimbra and was supported by the Junta Nacional de Investigação Científica (JNICT) under grant No. 87 260 Area C SISM.

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