Earthquake loading of shear surfaces in slopes

Chargement sismique des surfaces de cisaillement dans les pentes

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SYNOPSIS Slopes of stiff clay and weak mudstone often contain shear surfaces at residual strength. The effect of fast shearing on residual strength thus influences prediction of displacement during earthquake. Tests in the ring shear apparatus which examine this effect are presented here. Generally there is substantial gain in strength during fast shear. Predictions of displacement during earthquake are substantially reduced if this effect is included. In one soil tested, the strength during fast shear dropped to less than the static residual strength. This drop was not due to generation of excess pore pressure. If occurring in the field, this drop in strength could lead to large displacements during an earthquake and to these movements continuing post earthquake at quite high speed.

INTRODUCTION

Pre-existing shear surfaces at or close to residual strength are frequently present in slopes of clay, clay-shale and weak mudstone, due to previous slope movement or to tectonic disturbance (Skempton and Petley, 1967). The estimation of the stability of such slopes during earthquake requires consideration of the strength of shear surfaces during fast displacement, and of static strength post-earthquake. Rate effects during residual shear also control the rate at which landslides move under gravitational loading, and affect other phenomena such as the strength of shear zones on the sides of piles which are formed by pile driving (Martins and Potts, 1985).

This paper describes tests performed in the ring shear apparatus (Bishop et al, 1971) to investigate the strength of preformed residual shear surfaces in various clays during and after they have been sheared at rates approaching those which might occur during earthquake shaking. Such shaking will result in intermittent rather than continuous shear displacement. Tests have indicated that shear stress/displacement curves are similar for intermittent and continuous displacements at the same rate, and the later type of curve is presented here. Excess pore pressures may be generated within the mass of the slope by earthquake shaking, and these might cause post-earthquake failure on a shear surface. This problem is not considered here.

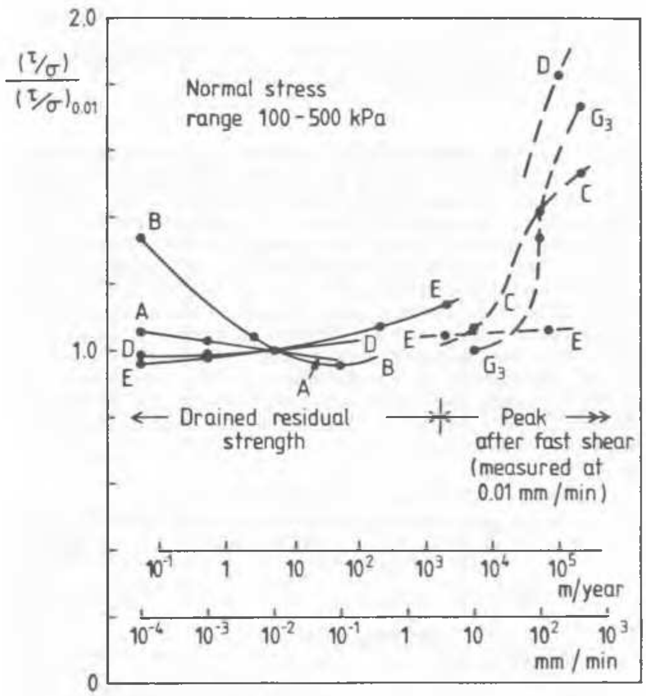

Fig. 1 Effects of actual and previous displacement rate on drained strength

RATE EFFECTS DURING CONTINUOUS DRAINED SHEAR

Such rate effects have been recognised previously (Skempton, 1965). More recent observations using the ring shear apparatus are shown on Fig. 1. Soil properties are summarized in Table 1. Changes in residual shearing mechanism have been described by Lupini et al, (1981). They identify two limiting mechanism: turbulent shear at low clay contents, occurring without orientation of platey clay particles, and sliding shear at high clay contents, with shear displacement by sliding within thin zones of highly orientated clay. Transitional behaviour occurs at intermediate clay contents.

TABLE 1

Soil Properties

Soil Type	W_L	I_P	% < 2 μ
A Happisburgh Till (TU)	22	10	14
B Cowden Till (TU/TR)	34	16	28
C Boniventre (Italy) (S)	53	26	39
D London Clay (S)	82	49	60
E Kaolin (S)	72	36	82
F Weathered Tuff (Panama) (S)	-	-	-
G1 Kalabagh (Pakistan) (S)	62	36	47
G2 " " (TR)	39	18	21
G3 " " (S)	45	22	40

Residual shear mechanism: TU = Turbulent; TR = Transitional; S = Sliding

Soils which show sliding shear show conventional rate effects, with strength increasing with increasing shear rate. Soils which show turbulent shear typically show a reversed rate effect over the slower range of shear rates investigated. The strength measured at the usual laboratory displacement rate of 0.01 mm/minute can only be slightly higher than the true static strength. Thus rate effects are quite small, but they may play a major part in preventing the rapid movement of landslides. For instance, a shear stress 10% greater than the true static strength may cause a displacement velocity of only 0.5 mm/minute.

OBSERVATIONS AT FAST RATES OF DISPLACEMENT

Times for 95% consolidation of natural clays in the ring shear apparatus are about 100 minutes. Thus results for fast rates of shear over displacements which are practical in the apparatus are essentially undrained. For the results quoted here, the samples were prepared at water contents such that both the undrained and peak drained strength of the soil on either side of the shear zone were considerably in excess of the shear stresses applied to the shear zone. Thus shear during fast displacement should have been restricted to the shear zone. However, some unequilibrated pore pressures might have been generated, and results for fast rates of displacement are presented in terms of total stress.

Typical results

Typical results from two soils are shown on Fig. 2. Five strengths can be recognised in each shear stage. The soil is first sheared slowly to establish the drained residual strength (a). It is then allowed to rest. Fast shearing is then performed with continuous monitoring of stress and displacement. Three strengths can then be identified; a threshold strength at which displacement on the shear surface recommences(b) a fast maximum strength (c), and a fast minimum strength (d). Shearing is then stopped and shear stress reduced immediately to prevent any displacement by creep. After a rest for consolidation, shearing is continued at the slow drained rate. A new slow peak strength (e) is generally observed, which is higher than the ultimate residual strength (a). This strength (a) is recovered after further displacement.

Peak strength after fast shearing (e)

It is convenient to consider this strength first. Typical values are shown on Fig. 1. Strengths (e) and (a) are usually the same in soils showing turbulent shear, in which residual strength does not depend on particle orientation. The increase can be very large in sliding shear, but it only occurs at fast rates of displacement. There is some slight indication that a limiting increase is reached.

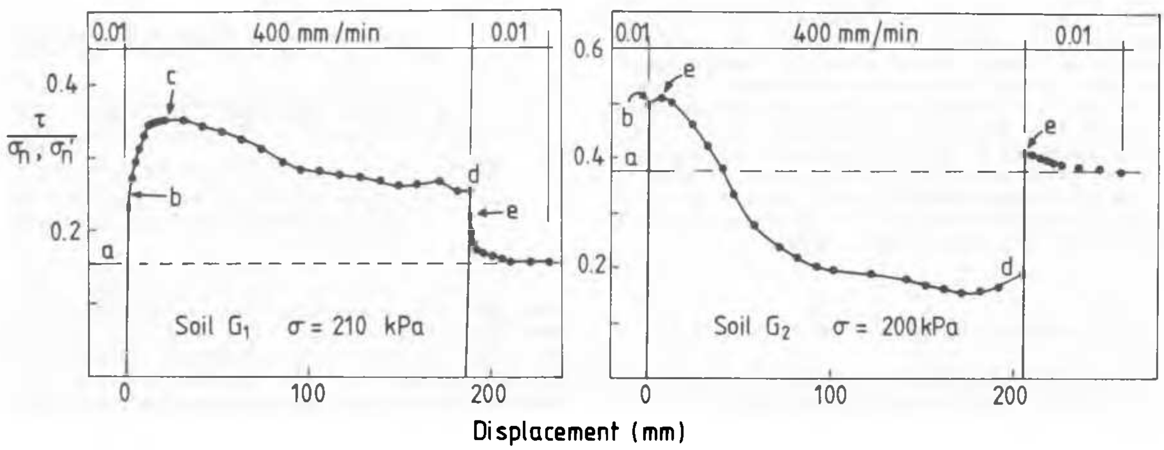

Fig. 2 Typical behaviour during fast shear stages

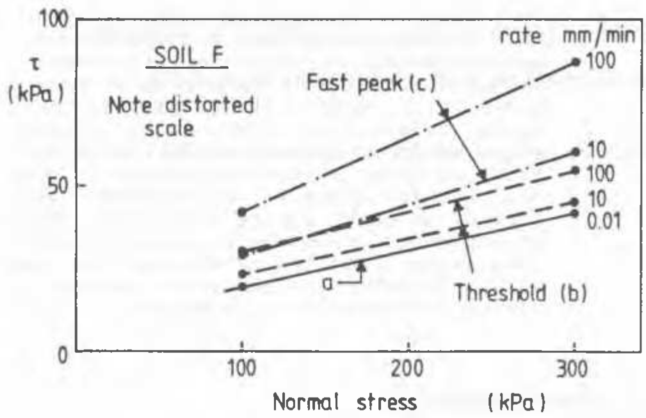

Fig. 3 Typical strength envelopes for threshold and fast peak strengths

The high consolidation rate for kaolin allows strength (e) to be measured after a fast drained shear stage (Fig. 1), and it is considerably lower than the strength (d) measured during this fast stage. Thus a viscous component of strength during fast drained shear is indicated that is independent of effective stress. It is reasonable to postulate that gain in strength is due to disordering of the oriented clay particles in the shear zone. The smallest effect is observed with kaolin, which is a pure clay, suggesting that disordering is facilitated by the presence of the rotund particles present in the other natural clays. The results indicate that, if a fast movement is arrested suddenly, the strength on the shear surface will have been increased. However, if deceleration is slow and occurs over displacements of about 50 mm, then the slow residual strength will be restored. The latter effect is more likely in slope failures loaded by gravity.

Threshold strength (b)

The loading time to reach the threshold strength is typically about 0.1 sec for a displacement rate of 100 mm/minute. This loading time is reasonable for an earthquake pulse. Other tests have shown that a comparable increase in strength is observed on fast loading of a shear surface which has not reached its ultimate slow residual strength.

Typical threshold strengths are shown on Fig. 3. The increase occurs mostly as an 'intercept' to the failure envelope rather than as an increase in angle of internal friction. It seems probable that movement on shear surfaces will only occur during an earthquake if shear stresses induced are greater than the threshold strength.

Peak strength (c)

Peak strengths (c) generally exceed threshold strengths (b) by a substantial amount for soils which show sliding shear, and they almost coincide with threshold strengths in soils which show turbulent shear. Typical values are shown on Fig. 3. The increase of peak strength (c) over threshold strength (b) approximates to the increase of post-shear peak strength (e) over slow residual strength (a). It is also generated over a displacement comparable to that required to reduce strength (e) to strength (a). Thus the increase from threshold (b) to peak (c) strength may well be due to the disordering effect postulated to occur for strength (e).

Ultimate fast strength (d)

As noted previously, results quoted are for specimens placed at low water contents, for which pore pressure increases in slow shear should be negligible, and so not cause a reduction in strength. All soils so far tested which

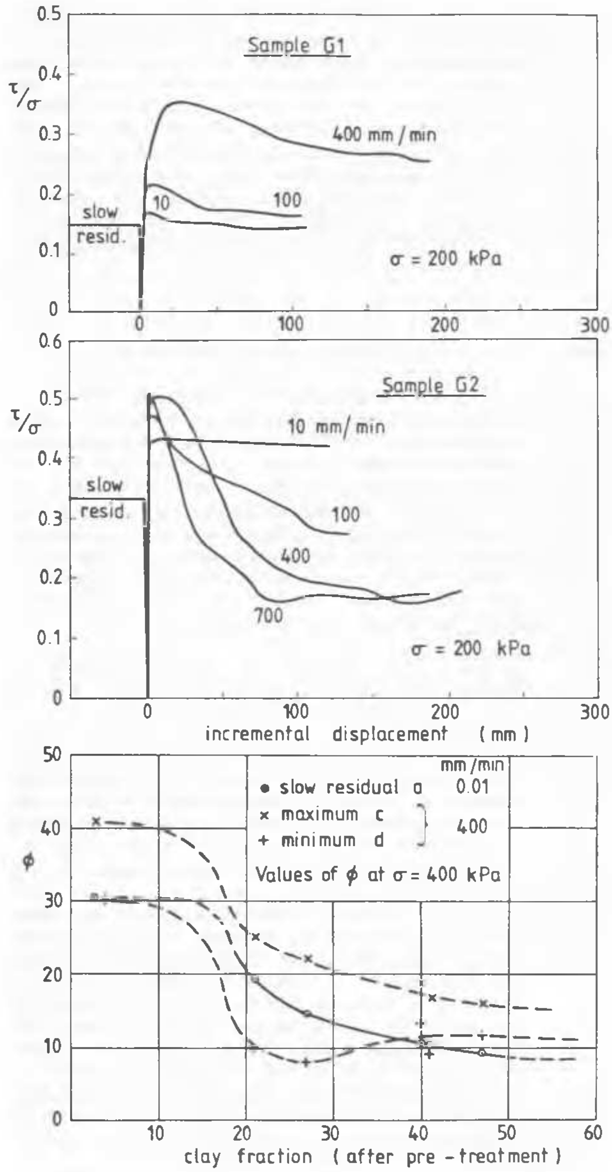

Fig. 4 Variation of fast strength with clay fraction for soil G.

show sliding residual behaviour also show minimum fast strengths (d) which are higher than their slow residual strengths (a). One soil (G2), which shows transitional behaviour in residual shear, showed a significant drop in resistance during fast shear to less than the slow strength (d). Results for this soil and others of different plasticity from within the same stratum are shown on Fig. 4.

This loss of strength has great potential significance; if the conditions leading to it are reached in the field, large fast movements may ensue even when loading is by gravity alone. Its cause and the types of soil in which it may occur is receiving further examination.

Pore pressure effects due to heating can be predicted theoretically (Voight and Faust, 1982). The theory indicates that these effects should be negligibly small in the test performed. It is impossible to instrument the ring shear samples internally to observe such effects. However, it is possible to shear the ring shear sample against an interface which can be instrumented. Preliminary observations at a rough glass interface show that the strength drop occurs without significant changes in temperature or pore pressure. Thus it cannot be explained conventionally in terms of effective stress.

PRACTICAL IMPLICATIONS AND CONCLUSIONS

The data obtained allows formulation of an approximate soil model linking strength on the shear surface to displacement and displacement rate. If the possibility that shaking may induce pore pressures within the body of a slope which may cause post-earthquake failure is neglected, then this model can be used to predict displacement during an earthquake. Simple predictions for a block sliding on a shear surface, initially just stable and then subject to earthquake loading, indicate that:

(i) There is a reserve of strength during fast loading to prevent sliding during an earthquake of modest severity.

(ii) If sliding does occur, shear rate effects will substantially reduce its magnitude compared to that predicted if rate effects are ignored. In soils showing sliding residual shear, this reduction may be by more than an order of magnitude.

(iii) In soils showing sliding residual shear, no test has shown a fast strength ever dropping below the slow drained strength. In these soils rapid movement followed by rapid deceleration may even result in a gain in strength on the shear surface. Thus there is no risk that movements will continue post-earthquake unless sufficient excess pore pressure has been induced in the mass of the slope.

(iv) In one soil tested, which showed transitional residual shear, fast displacement caused an eventual drop in strength to less than the slow drained value. If this strength loss were induced during an earthquake, it could lead to large, fast and potentially catastrophic movements which would continue post-earthquake. Where such behaviour is recognised it would be prudent to design to restrict movement during earthquake so that the ultimate state is not reached. This loss of strength during fast shear cannot be explained currently in terms of effective stress, and its nature and the types of soil in which it may occur are the subject of continuing research.

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