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Effects of Earthquake Induced Rates of Shearing on Residual Soil Strength

Paper No. 1.28

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SYNOPSIS The behaviour of soils when sheared at high rates of displacement, such as those which may be induced by earthquakes, has been investigated by means of the ring shear apparatus. Plastic and non-plastic soils were tested normally and over-consolidated, remoulded and dry, submerged and non-submerged in water, in order to assess the effect which the stress history and the presence of water in the matrix and the environment of the sample have on its response upon fast shearing. It was concluded that two types of behaviour exist which depend on the nature of each sample and the presence of water in its environment.

INTRODUCTION

The behaviour of soils when sheared at high rates of displacement under constant normal stress has been investigated by previous researchers (Lemos, 1986 and Tika, 1989). The complicated picture, associated with the aforementioned behaviour, which resulted from these investigations was attributed to limitations imposed by the ring shear apparatus. The sample loss through the gap of the confining rings forced the termination of fast shearing tests before the measured strength had stabilised. For the purposes of this investigation the ring shear apparatus was modified in order to enable prolonged stages of fast shearing which could result in the development of a "steady" measured strength.

SAMPLE PREPARATION AND TESTING PROCEDURE

The preparation techniques varied for the different soil types which were tested. The natural soils, i.e. brown London clay and Cowden till, were air-dried, mechanically crashed, sieved through the 425 μm sieve, remoulded to a water content around their plastic limit and left overnight to hydrate before they were placed into the confining rings. The commercially available soils, i.e. pure silica and artificial sandy-silt, were remoulded and left to hydrate. Additional information regarding the nature of the soils tested and the water contents of each sample, before and after testing, is provided in Table 1.

The standard testing procedure involved consolidating the sample at the desired normal stress level, shearing it at a "drained" rate of displacement (1.5×10^{-4} cm/sec) until its residual strength had been established, unloading it in the shear direction in order to engage the "fast" gear of the motor-drive and, consequently, shearing it at rates of displacement which varied between 0.1 and 10 cm/sec. Each fast shearing stage was terminated at a cumulative shear displacement of 4 to 5 m. The same sample was used for tests at higher normal stress levels.

ANALYSIS OF THE RATE OF DISPLACEMENT EFFECTS ON THE RESIDUAL SOIL STRENGTH

In analysing the behaviour of soils during prolonged fast shearing stages which result in large shear displacements, two types of residual strength must be defined: the "slow residual strength" which is associated with rates of displacement which allow drainage to occur ("drained" rates of displacement) and the "fast residual strength" which is the steady strength measured during prolonged fast shearing tests. Furthermore, two more strengths have been identified upon fast shearing, the "threshold strength" and the "post-threshold strength decrease". The first is associated with zero shear displacement and may be attributed to the restructuring of inter-particle bonding which takes place prior to the application of the fast rates of displacement. The second is defined as the decrease in measured strength below its threshold value, which is observed immediately after the latter has been achieved, and may be attributed to the dilation of the shearing matrix and/or the instantaneous increase in pore pressures.

The ultimate behaviour of soils during fast shearing is dictated by their nature, i.e. plasticity and slow residual strength, and by the presence of water in their environment and matrix. Two principal types of behaviour were identified from the results of this investigation (Fig. 1) and they were defined as positive (Type I) and negative (Type II) rate effects, depending on whether the fast residual strength stabilised above or below the slow residual strength, respectively.

The positive rate effect is associated with plastic soil samples which are not submerged in water, regardless of the shape of their shear zone, and with plastic soil samples which are submerged in water and have a nearly planar shear zone. In these cases, the fast residual strength stabilises above the slow residual strength, it increases with increasing rate of displacement and reaches its maximum value when the latter approaches 1.5 cm/sec. Above that level, any

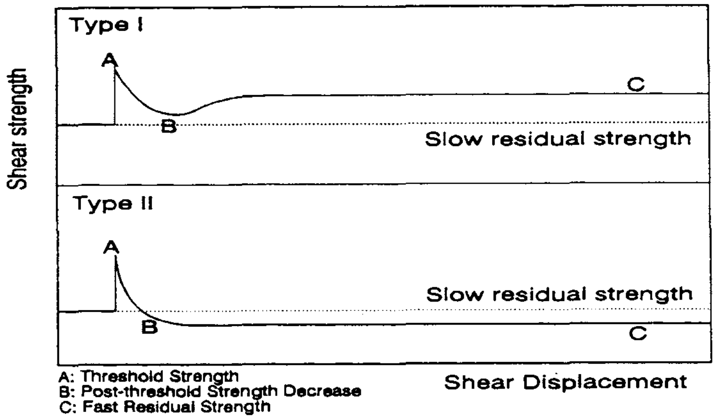

Fig 1 Types of soil behaviour and strengths identified during fast shearing

increase in the rate of displacement does not influence the fast residual strength. Furthermore, the fast residual strength of plastic soil samples which exhibit a positive rate effect decreases with increasing normal stress (Fig. 2-5).

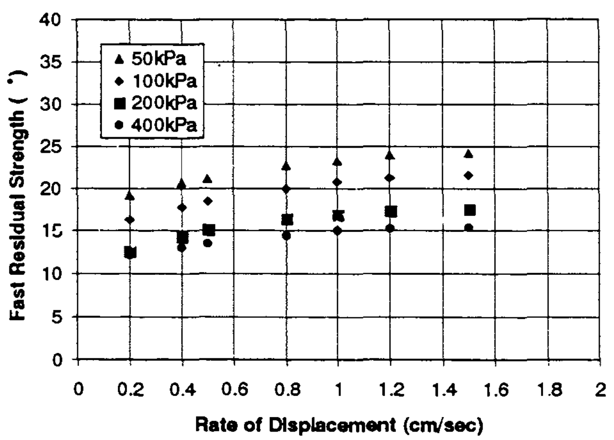

Fig 2 Rate of displacement and normal stress effects on normally consolidated, non-submerged brown London clay

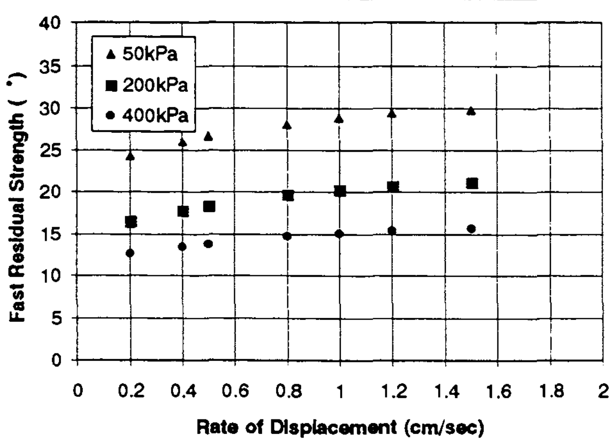

Fig 3 Rate of displacement and normal stress effects on normally consolidated, submerged brown London clay

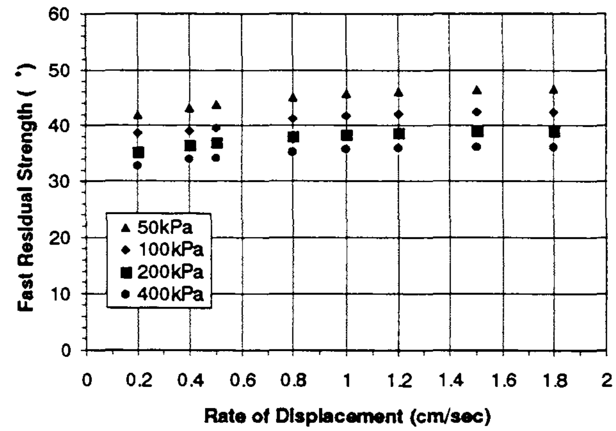

Fig 4 Rate of displacement and normal stress effects on normally consolidated, non submerged Cowden till

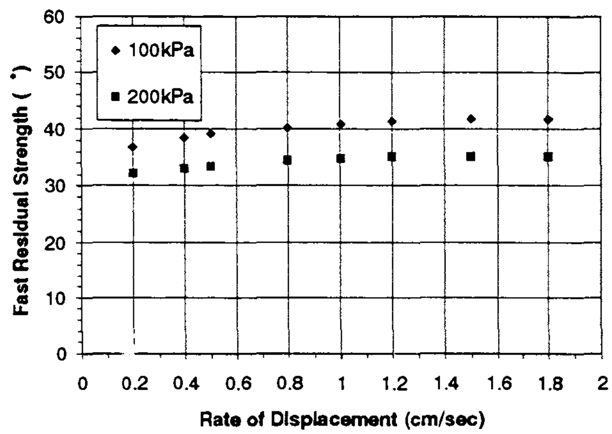

Fig 5 Rate of displacement and normal stress effects on over-consolidated, submerged Cowden till

The negative rate effect is associated with non-plastic soil samples which have a high slow residual strength, regardless of the environment (submerged, or not, in water) and shape of their shear zone, with plastic soil samples which are submerged in water and have an oscillating or highly non-planar shear zone and with completely dry, plastic soil samples.

In the cases of non-plastic and completely dry, plastic soils, the negative rate effect is attributed to an increase in the porosity of the shearing matrix resulting from the inter-particle movements upon the application of the fast rates of displacement. Furthermore, this effect is associated with the development of a "flow structure" involving continuous movement of the shearing particles and resulting in a decrease in shear strength. The results from this investigation indicate that the fast residual strength of non-plastic and, completely dry, plastic soils may be 4 to 12 % lower than their slow residual strength, it is not rate dependent and it does not appear to be influenced by any increase in normal stress.

In the case of plastic soils, the negative rate effect is attributed to the development of pore pressures which in turn are induced by the mechanism of shearing involving an oscillating shear zone (Fig. 6). The evidence suggest that in this case the oscillating shape of the shear zone induces a "pumping" action which causes the pore pressures within the shearing matrix to increase and sustains them at high levels as long as it persists. It has been shown that, when the rate of displacement was decreased to a level which would allow for the dissipation of pore pressures, immediately after the termination of a fast shearing stage during which a negative rate effect on a remoulded plastic soil sample had been established, the shear strength of the sample increased gradually and returned to its slow residual level. Moreover, in cases were the amplitude of the oscillating shear zone decreased during shearing, the shear strength gradually increased. This indicates that the pore pressures which were increased and sustained at high levels by means of the "pumping" action caused by the oscillating shear zone, were allowed to dissipate and the measured strength increased. The soft texture of the material within the shear zone of these samples and the increased water content within this zone which approached the liquid limit, indicated the existence of a liquefied structure.

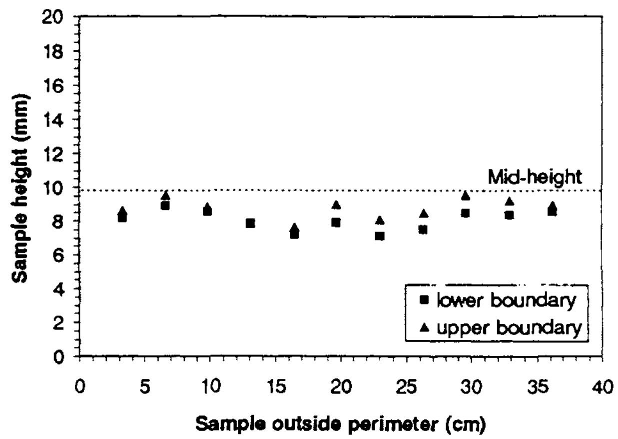

Fig 6 Shape and position of shear zone from sample exhibiting negative rate effect

In some of the tests the positive rate effect was reversed to negative, while they were in progress, because of an increase in the amplitude of the shear zone of the samples involved. This emphasises the effect which the development of an oscillating shear zone has on the results of fast ring-shear tests. This type of behaviour was recognised as a hybrid behaviour and was also attributed to the increase in pore pressures within the shearing matrix. The fast residual strength of remoulded plastic soil samples which exhibit a negative rate effect is not rate dependent and is not affected by any increase in normal stress. Furthermore, the drop in strength from slow to fast residual levels, in this case, appears to increase with increasing amplitude of the oscillating shear zone (Fig. 7) and may be as high as 78 %. It must be emphasized that, when the amplitude of the oscillating shear zone is less than 0.1 mm, no negative rate effect arises and, if the amplitude drops below that level within the duration of a fast test, the strength begins to increase. Therefore, it is suggested that the negative rate effect which is associated with increased pore pressures should not be considered as a "true-type" plastic soil behaviour during fast shearing but rather as a phenomenon resulting from the shearing mechanism and the increased pore pressures.

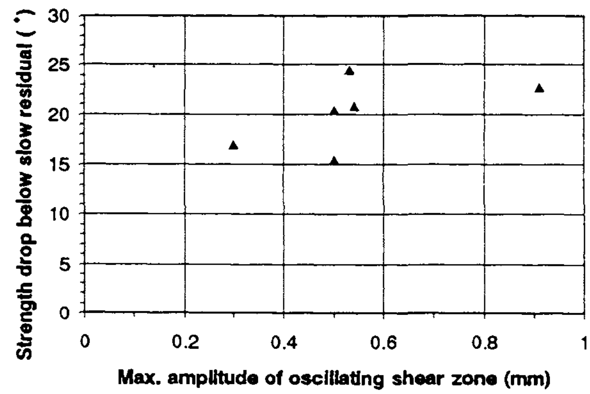

Fig 7 Effect of amplitude of oscillating shear zone on fast residual strength drop

CONCLUSIONS

From the results of this investigation it is concluded that the behaviour of soils during fast shearing does not only depend on their plasticity and the magnitude of their slow residual strength but also on the presence of water in their environment and matrix.

It is postulated that the non-plastic and completely dry, plastic soils exhibit negative rate effects. The remoulded plastic soils exhibit positive rate effects when they are not submerged in water, regardless of the shape of their shear zone. When they are submerged in water and their shear zone is nearly planar they also exhibit positive rate effects. The same type of soils exhibit negative rate effects when they are submerged in water and their shear zone is oscillating. The stress history of soils does not appear to influence their behaviour under fast shearing. The fast residual strength of samples which exhibit negative rate effects is independent of the rate of displacement and the normal stress level, while that of samples which exhibit positive rate effects decreases with increasing normal stress, increases with increasing rate of displacement and reaches its maximum value when the latter is around 1.5 cm/sec.

Soil Type	Atterber Limits (%)			Clay Fraction (%)	Sample Type[1]	Water Content (%)	
	PL	LL	PI			Before Testing	After Testing
brown London clay	28	69	41	64	NC N/S	36	31.2
					NC S	36.2	33.1
					OC S	35.9	32.6
					OC S	36	32.3
					OC S	35.3	31.8
					OC S	36.2	32.2
Cowden Till	15	28	13	29	NC N/S	21.8	14.7
					NC S	22	18.2
					OC S	21.5	16.5
					NC S	22	16.3
					NC S	21	17.7
					NC S	21.3	14.4
Artificial sandy silt	NP	-	NP	-	NC N/S	20	19.1
					NC S	20.2	19.3
					OC S	19.9	19.7
Pure Silica	NP	-	NP	-	NC N/S	20.4	18
					NC S	21	19.2
					OC S	21.2	23.8

1: N/S = non - submerged, S = submerged

Table 1 Soils used in the investigation

REFERENCES

Lemos, L. J. L. (1986), "The Effect of Rate on the Residual Strength of Soil", Ph.D. Thesis, University of London.

Tika, T. M. (1989), "The Effect of Rate of Shear on the Residual Strength of Soil", Ph. D. Thesis, University of London.