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Influence of displacement rate on residual shear strength of clays

Gianvito Scaringi*, Caterina Di Maio

University of Basilicata, via dell'Ateneo Lucano 10, Potenza, 85100, Italy

Abstract

This paper reports on the results of direct shear tests carried out under controlled displacement rate in the range of 10^{-4} - 10^{2} mm/min, under different normal stresses, with different shear devices. The tests were carried out on a kaolin, a bentonite, their mixtures with sand at various percentages, and the clayey soil of the *Costa della Gaveta* earthflow. The tests were performed on specimens reconstituted with distilled water as well as with NaCl solutions at various concentrations. Positive rate effects were exhibited by mixtures with c.f. higher than 50% and, consistently, by the natural clayey soil the c.f. of which is about 50%. The residual shear strength increases significantly for shear displacement rate higher than about 1 mm/min. The rate effect increases with the pore solution concentration. The residual shear strength independence of displacement rate has been confirmed in the range 10^{-6} - 10^{-1} mm/min by the results of shear tests performed under controlled shear stress, with varying chemical conditions of the pore fluid.

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Keywords: Residual shear strength; displacement rate; clay; mixtures; ring shear.

1. Introduction

The residual shear strength is the minimum strength that a soil can offer to shear displacements under given effective normal stresses. It is the available strength of landslides which underwent large displacements on regular slip surfaces. The residual shear strength parameters depend on the composition of both the solid skeleton and the pore fluid[1-5]. In addition, several results reported in the technical literature[1,6-12] also point out a dependence on the displacement rate, showing that the residual shear strength can increase, decrease or remain constant with the displacement rate increasing.

* Corresponding author. Tel.: +39-329-3094355.
E-mail address: gianvito.scaringi@unibas.it

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The rate effects are very important in the interpretation and in the forecasting of landslide behaviour. The temporal evolution of landslide displacements was attributed by Leroueil[13] also to the influence of the displacement rate on the residual shear strength. The Author highlighted that, for landslides in the reactivation stage, such influence can provide beneficial effect, preventing large movements. Similarly, Wang *et al.*[14], on the basis of laboratory test results, hypothesised that significant positive rate effect would have prevented catastrophic acceleration of a landslide system, experiencing repeated accelerating-decelerating cycles of movement, in Japan. Accounting for rate effects, Vuillet and Hutter[15] related the displacement rate of several landslides to the driving shear stresses.

The causes of rate effects were studied by several Authors. Lupini *et al.*[8] investigated the influence of clay type and grain size on the mode of shearing, identifying three mechanisms: turbulent, transitional and sliding, to which different energy dissipation corresponds. Tika *et al.*[11] showed that the shearing mode influences the rate effect. They observed three types of rate effect, corresponding to: fast residual strength higher than slow residual strength, fast residual strength lower than residual strength and constant residual strength, named positive, negative and neutral effect respectively. The relation between the types of displacement rate effect and the basic shearing modes of slow residual strength were considered, and the causes of the negative rate effect were investigated. Wang *et al.*[14], observed the shear zone of specimens of a Japanese landslide soil by means of laser microscope and scanning electron microscope. The examination of the shear-zone microstructure revealed that the change from sliding to turbulent shearing mode could have been the cause of the observed increase in shear strength. Furthermore, on different clayey soils, the Authors observed the same rate effect on both dry and water saturated specimens, thus excluding that excess pore water pressures played a significant role.

Tika *et al.*[11] also showed that rate effects depend on normal stress. Gratchev and Sassa[16] observed that negative rate effect decreases with normal stress increasing. Carrubba and Colonna[12] showed that even the type of effect (positive, neutral or negative) can depend on the normal stress.

Saito *et al.*[17] performed laboratory tests on sand, sand-illite mixtures and sand-montmorillonite mixtures with up to 20% c.f., by means of a ring shear apparatus[18] in undrained conditions and with pore pressure measurement. Their results show that the residual shear strength of their sand was independent of the displacement rate, consistently with the results reported by Tika *et al.*[11], while the residual shear strength of the mixtures was rate-dependent. For both c.f. = 10% and c.f. = 20%, a remarkable negative rate effect was evaluated for $v \geq 60$ mm/min. Although significant pore pressure variations were measured during the tests, the behaviour was also attributed, in part, to a decrease in the effective residual friction angle which, in turn, was considered the effect of the change in the shearing mode. Differently from Saito *et al.*[17], Li *et al.*[19] observed a positive rate effect on kaolin – glass beads mixtures with low clay content (c.f. ≤ 20%) and an opposite behaviour on mixtures with high clay content (c.f. ≥ 50%).

Thus, many experimental results show opposite, or at least inconsistent, behaviour for apparently similar conditions, suggesting the need of more systematic studies. In order to give a contribution in such direction, this paper shows the results of a large number of tests carried out on two different, almost pure, clays, on clay-sand mixtures at various percentages and on a natural clayey soil. The tests were performed under displacement rates varying in a wide range, and by means of different experimental devices.

2. Materials and methods

The laboratory tests were performed on reconstituted specimens of the *Costa della Gaveta* soil[20], a kaolin, a bentonite and mixtures of these two latter materials with a sand[21]. Some material properties and test conditions are summarised in Tab. 1, which shows that the *Costa della Gaveta* soil is characterised by high clay fraction. Its mineralogical analysis showed that illite-muscovite and kaolinite are the most abundant clay minerals[22]. However, relevant percentages of smectite are somewhere found[22]. The used kaolin is a practically pure kaolinite[23], and the tested bentonite is mainly composed of Na-montmorillonite[24].

The materials were reconstituted with distilled water, consolidated to given normal stresses and sheared in the range of displacement rates $0.00011 \leq v \leq 66.5$ mm/min. Some tests were carried out also on the soils reconstituted with – and submerged in – NaCl solutions at various concentrations. Most of the tests were carried out in the Bromhead ring shear apparatus. A number of tests was carried out by means of the Casagrande and the Bishop machines, thus the influence of the testing device on the results could also be investigated.