

DISCUSSION

Cracks, bifurcation and shear bands propagation in saturated clays

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The experimental results presented in the Paper represent a significant step in the process of understanding the complex phenomena of strain localization and shear banding in saturated clayey soils. However, although the measurements and observations on reconstituted clays described are undoubtedly needed 'to test the validity of the various models that have been or will be proposed' for strain localization in clays, we do not agree they are all 'what is needed'. Besides the well-known differences between the mechanical behaviour of natural clays and that of reconstituted clays, our experience with natural clays indicates that local measurements of both pore pressures and deformations are also needed to evaluate strain localization in saturated clays.

In the Authors' experiments, pore water pressures are measured at the ends of the sample. Various experimental results on natural stiff overconsolidated clays have been recently presented which show that different excess pore water pressures can develop close to the zone of localization. Either in triaxial compression (Rampello 1989, 1991; Viggiani, Rampello & Georgiannou, 1993a) or in plane strain compression (Viggiani, Finno & Harris, 1993b) these non-uniformities and the development of localized zones of deformation were recognized to be interacting phenomena. All test results are discussed by Viggiani (1994). To illustrate this point, the pore water pressure response measured during undrained plane strain and triaxial compression of two stiff overconsolidated clays is examined here.

In plane strain compression of Vallericca clay two miniature pore pressure transducers were mounted on the sides of the specimen subjected to confining pressure, at mid-height. Fig. 33 shows the difference between the excess pore water pressures measured by two probes. In this test, the shear band intersected the boundary of the specimen just below pore pressure probe 1. The probes measured essentially the same positive excess pore water pressure until point O; the pore pressure then began to increase at probe 1

(i.e. the future location of the band) relative to that measured by probe 2. Just after the peak load was attained (point P) the difference in pore pressure reduced rapidly, i.e. the pore water pressure at probe 1 decreased to a value lower than the prevailing conditions away from the band (probe 2). This maximum difference corresponded to about 11% of the current excess pore water pressure at probe 2. Possible explanations for the subsequent rapid equilization (after point S) include details of the band location as it came out from the specimen relative to the probe (see Viggiani *et al.*, 1993b) or an increase of permeability along the band, when it is completely formed.

Similarly, in triaxial compression tests on Todi clay a difference was observed between pore water pressures measured at the base and at the

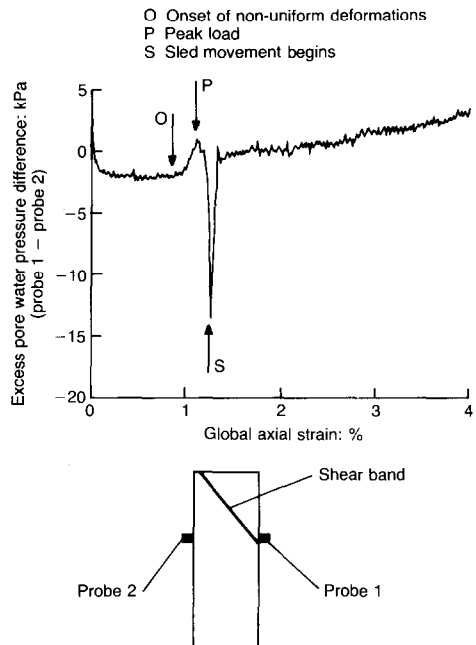


Fig. 33. Pore water pressures difference in undrained plane strain compression of Vallericca clay (after Viggiani *et al.*, 1993b)

mid-height of the specimen, with a miniature pore pressure transducer located within millimetres of the shear band. Fig. 34 shows the difference between the excess pore water pressures measured at the probe and at the base. The pore pressure decreased at the mid-height relative to that measured at the base. The maximum (negative) difference was attained at the maximum stress ratio  $q/p'$  (point O) and corresponded to about 16% of the current value of  $p'$  at the base. Pore pressure difference then gently decreases during the progressive development of strain localization, and abruptly reduces to about zero when the failure surface intersects the sample boundaries and the deformation consists in the near-rigid body sliding on this surface (Viggiani *et al.*, 1993a).

In both cases the additional local measurements of pore water pressure greatly enhanced the ability to capture the onset of strain localization during the tests. More important, results such as those described emphasize the importance of considering pore pressure; the effective stress and pore water response must be coupled in any model to understand strain localization phenomena in saturated clays. For a coupled model to be meaningful, it is essential to obtain measurements of pore pressure close to the band from the experiments.

In the Authors' experiments, global measurements of deformations and visual examination of the photographs are used to interpret the results. In our experience, local measurements of axial

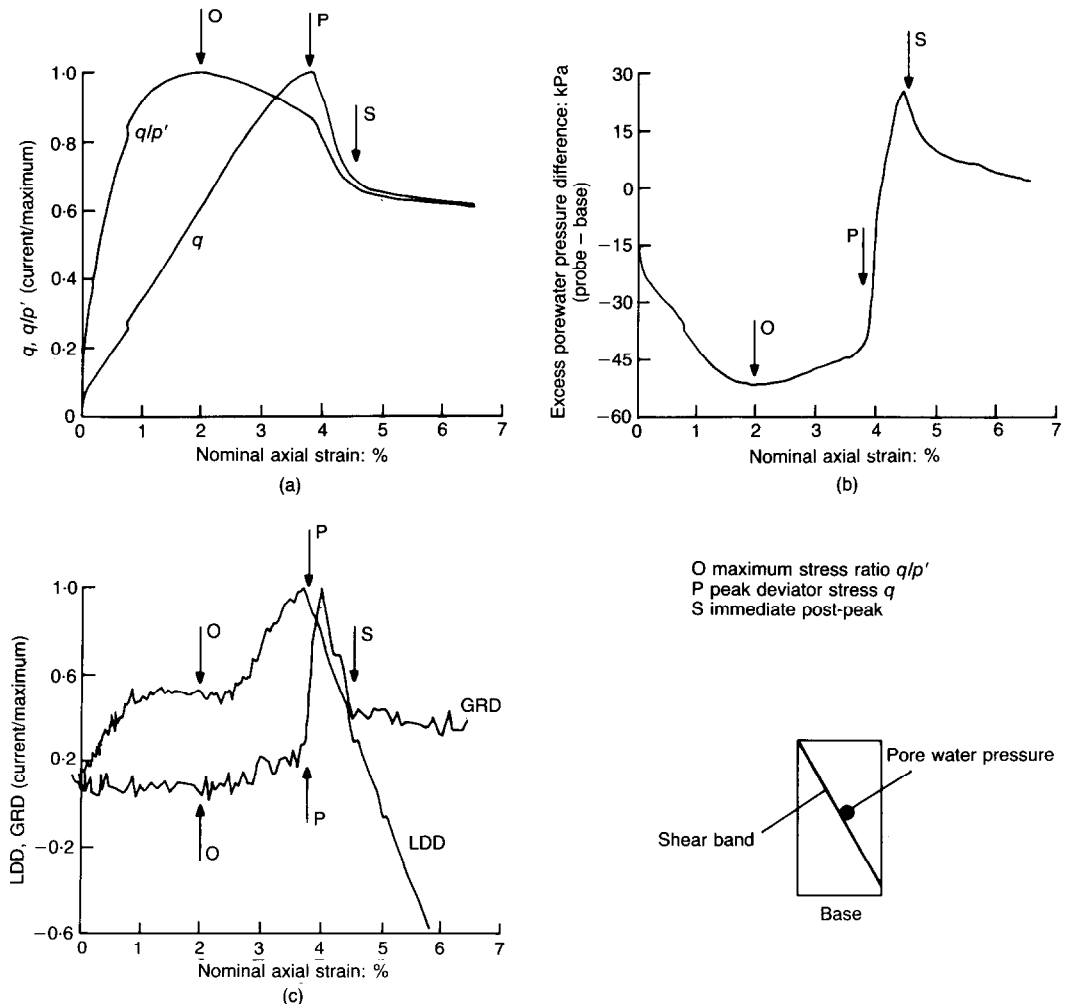


Fig. 34. Undrained triaxial compression of Todi clay: stress-strain response, pore water pressure difference and strain homogeneity indexes (after Viggiani *et al.*, 1993a)

displacements (in the triaxial cell) and of horizontal displacements (in the biaxial device) showed that the band completely forms and comes out from the boundaries of the specimen well after the onset of localization. In the latter case, this was also confirmed by means of stereophotogrammetry (Finno, Harris & Viggiani, 1994). Globally-measured displacements did not yield the same information. Results on stiff clays (Viggiani, 1994) and on a normally consolidated clay (Finno & Rhee, 1993) both indicated that the localization of strain is a progressive phenomenon, leading eventually to the formation of a shear band. This is shown by Figs 34–36. Fig. 34 refers to a triaxial compression test on stiff Todi clay; Figs 35 and 36 refer to plane strain compression tests on stiff Vallericca clay and soft Chicago clay, respectively.

For the analysis of strain localization in triaxial compression of Todi clay two indexes of the strain homogeneity were defined, based on the

local measurement of axial deformation (LDD and GRD in Fig. 34(c)). Zero slopes of both the indexes indicate that deformation is homogeneous within the specimen. Changes of the slopes of the indexes are related to changes of the mechanism of deformation (see Viggiani *et al.*, 1993a). The quantities on the  $y$  axis of Figs 34(a) and 34(c) are normalized by their maximum value. Localization is initiated at the maximum stress ratio  $q/p'$  (point O), occurring before and developing up to the peak strength (point P). The post-peak knee (point S) of the curve of the deviator stress  $q$  versus global axial strain is interpreted to correspond to the point when the failure surface is exposed to the boundaries of the specimen.

Plane strain compression tests were performed in a device with a low friction bottom sled which allows the kinematically unconstrained development of shear bands. The onset of localization (point O) can either precede (in Vallericca clay) or

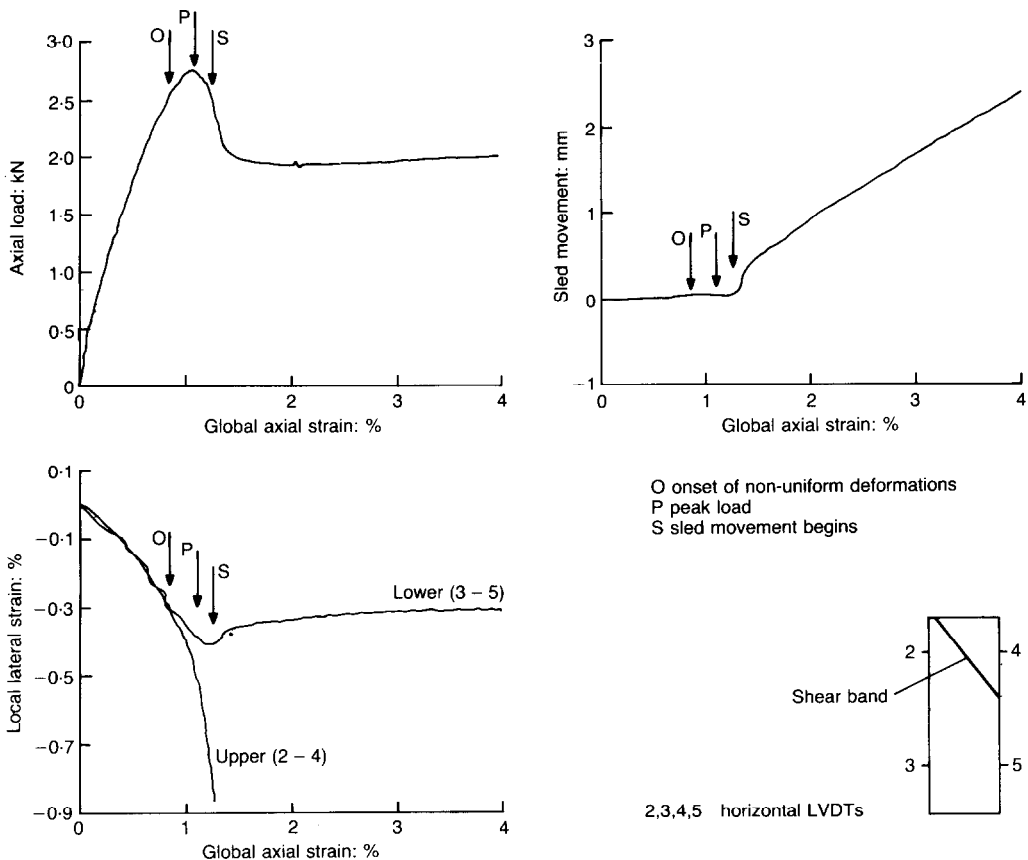


Fig. 35. Undrained plane strain compression of Vallericca clay: load–displacement curve and uniformity of deformations (after Viggiani *et al.*, 1993b)

be subsequent (Chicago clay) to the peak load (point P). In any event, the onset of localization does not coincide with the appearance (full formation) of the band. Here the first movement of the sled (point S) is interpreted to correspond to the moment when the band is completely formed and comes out from the boundaries of the specimen. Thereafter, the deformation consists in a near-rigid body sliding on the shear zone.

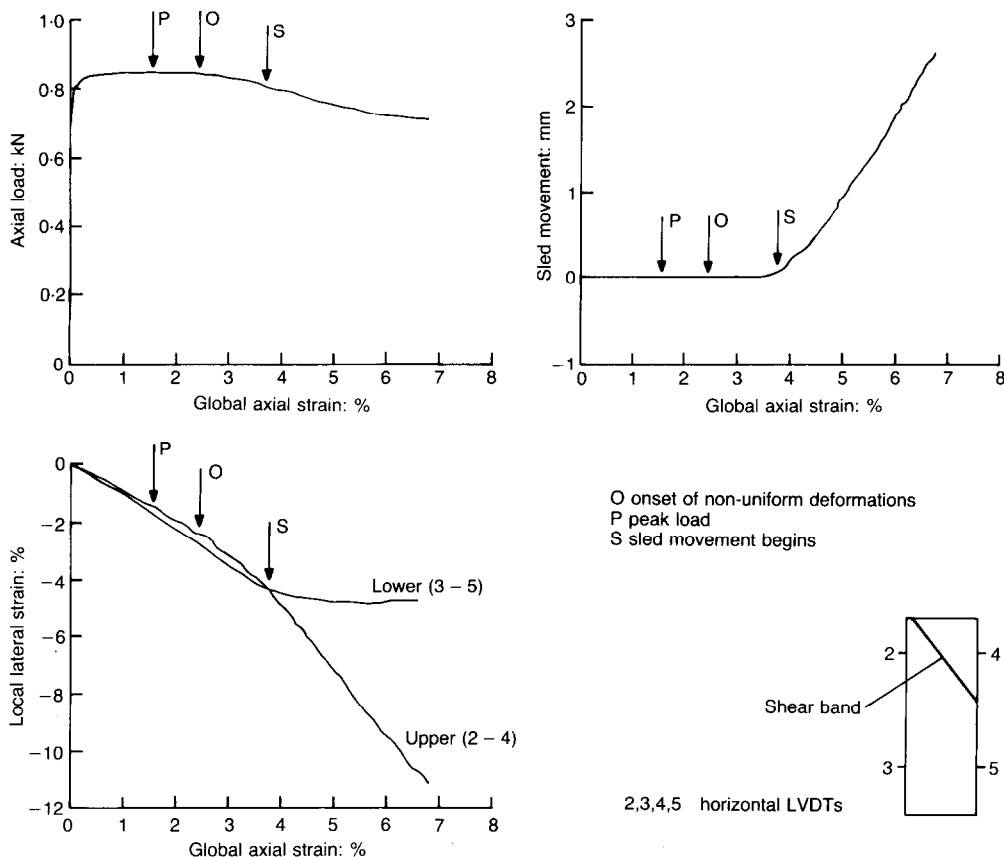
The use of local measurements is becoming the norm in the study of strain localization in soils and rocks; in addition to the studies on clay already mentioned, examples exist for plane strain experiments on sandstones (Ord, Vardoulakis & Kajewski, 1991), sands (Mokni, 1992; Harris, 1994) and marls (Tillard-Ngan, Desrues, Raynaud & Mazerolle, 1993).

**Authors' reply**

Dr Viggiani *et al.* draw attention to recent information about localization and bifurcation in

clays. The references they cite are welcome additions to the literature. They emphasize the use of local measurements, which is the ideal way to proceed, provided the measuring unit does not itself trigger the phenomenon it is supposed to detect; the presence of a pore pressure measuring probe embedded in a clay specimen would do just that. The best that such a measuring device can do is to alert the operator to the fact that something is happening in its vicinity. If the localization is a tendency for expansion the measurement will indicate a drop in the pore water pressure, and vice versa. Only methods that do not involve solid physical contact can be expected to give reliable measurements of point variable pore water pressures and the onsets of localization that cause them. Also the pore water pressure measured in the vicinity of a shear band can be very different from that on the surface of the band.

The observations and measurements obtained in a Vardoulakis apparatus can be very different from those obtained in a hollow cylinder in the



**Fig. 36. Undrained plane strain compression of Chicago clay: load–displacement curve and uniformity of deformations (after Finno & Rhee, 1993)**

walls of which an inclusion is placed. Here localization is induced and we were able to observe the initiation and measure the propagation of the shear bands in relation to stress and time. The presence of the grid allowed us to observe, photograph and measure the relative displacements locally; they vary from region to region and often deviate substantially from the averages obtained from end measurements.

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