Granular Matter (2010) 12:87–95
DOI 10.1007/s10035-009-0164-0

# Some observations of the effects of pore fluids on the triaxial behaviour of a sand

**A. F. Çabalar · C. R. I. Clayton**

Received: 15 April 2009 / Published online: 6 February 2010


**Abstract** This paper describes unusual stress–strain behaviour, involving deviatoric stress, axial strain and pore pressure jumps, observed during undrained triaxial compression testing of Leighton Buzzard sand when using syrup and silicon oil pore fluids. The materials, pore fluids, specimen preparation and test methods are described, as are the results of a suite of triaxial tests in a temperature controlled cell in which deviatoric stress, pore pressure and local strain were measured. The results are compared with the some existing data showing similar effects, and possible causes of the strain jumps are postulated. The results suggest that specimen formation in the way used here, in a viscous fluid, could suppress dilatancy.

**Keywords** Triaxial compression tests · Leighton Buzzard Sand · Pore fluids

## 1 Introduction

The stress–strain behaviour of sand in the triaxial apparatus has been widely reported. Following the pioneering work of Casagrade [8] and Taylor [28] it seems accepted that it depends only on the type of sand, its initial void ratio and the effective stress level under which it is tested. Smooth relationships between stress, pore water pressure (or volume change) and strain are expected. However, the effects of different pore fluids on the stress–strain behaviour of sand in the triaxial apparatus have not been studied extensively.

A review of the literature enables one to identify some important characteristics of the behavior of geomaterials with different viscosity pore fluids. The authors note studies associated with centrifuge tests (e.g. [31]), soil dynamics [15] as well as basic soil behaviour (e.g. [26]). In centrifuge model tests, it is common to use pore fluids having high viscosity to unify time-scaling factors for dynamic and consolidation events. Zeng et al. [31] used viscous fluids such as silicone oil and glycerin–water mixtures as the pore fluids. For the tests with both glycerin–water mixture and silicon oil as pore fluids, coefficients of permeability are inversely proportional to the viscosity. However, using a glycerine–water mixture as the pore fluid has no significant effect on the strength and stress–strain relationship. It was also observed that the highly viscous fluids can lead the clogging of flow through the pores. Ratnaweera and Meegoda [26] have done a series of unconfined compression tests on fine-grained soils contaminated with varying amounts of chemicals. Their observations, which showed a decrease in shear strength and stress–strain behaviour due to the presence of the additives, were attributed to changes in dielectric constant and pore fluid viscosity caused by the additives. Pore fluid viscosity is also likely to make some contribution to the dynamic behaviour of sands, such as stiffness, damping, and liquefaction characteristics. As particles move with respect to each other, local viscous loss is likely to occur mainly close to the particle contacts [15].

This paper reports a series of triaxial loading tests that show large strain jumps, associated with changes in pore fluid. Triaxial testing on the specimens resulted in a sharp decrease followed by gradual increase in the deviatoric stress, stiffness, and a sharp increase followed by a gradual

A. F. Çabalar
University of Gaziantep, Gaziantep, Turkey

C. R. I. Clayton (✉)
School of Civil Engineering and the Environment, University of Southampton, Highfield, Southampton SO17 1BJ, UK
e-mail: c.clayton@soton.ac.uk

decrease in corresponding pore pressure (i.e., limited instability events). Specimens made with higher viscosity pore fluid exhibited more, as well as more significant, collapse events.

## 2 Materials

The materials used in the tests described in this paper were Leighton Buzzard sand, de-aired water, sugar-water solutions (syrup) at various concentrations, and silicon oil.

### 2.1 Leighton Buzzard sand

The material used was Leighton Buzzard quartz sand fraction B (BS 1881-131:1998) supplied by the David Ball Group, Cambridge, UK. Figure 1 shows that more than 90% falls between approximately 0.60 and 1.18 mm. $D_{10}$, $D_{30}$ and $D_{60}$ sizes are around 0.68, 0.78 and 0.92, respectively. Thus, the coefficient of uniformity ($C_u$) and the coefficient of curvature ($C_c$) have been calculated as 1.35 and 0.97. The scalene ellipsoid equivalent sphericity (SEES, an estimate of the minor to major grain dimension ratio, S/L (Clayton et al. [10]) is of the order of 0.55. The specific gravity of the grains was found to be 2.65.

Maximum and minimum dry densities were found to be 1.74 and 1.48 g/cm$^3$, respectively. The procedure defined by Cresswell et al. [11] was used to obtain the maximum dry density by pluviation and that of [4] was used to find the minimum dry density.

### 2.2 Syrup

Many specimens were tested with syrup, rather than tap water, as the selected pore fluid. The solutions employed during the experimental study were prepared using castor (also known as "superfine") sugar ($C_{12}H_{22}O_{11}$), a fine granulated sugar, which is freely available in the form of table sugar. The particle size distribution of the castor sugar varied between 0.1 and 0.5 mm (Fig. 1).

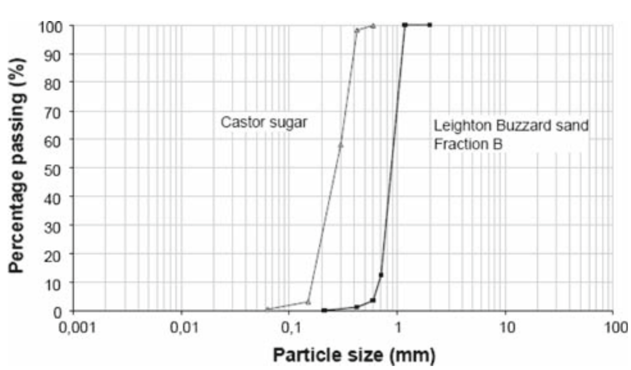


**Fig. 1** Particle size distributions for Castor sugar and Leighton Buzzard Sand

The solubility of sugar in water and the viscosity of the resulting syrup are dependent on temperature. For example, at 20°C 200 g of sucrose can be dissolved in 100 g of water, whilst at 40°C 235 g of sucrose can be dissolved in 100 g of water, and at 60°C 289 g can be dissolved in 100 g of water [3]. Depending on the concentration of sugar in the solution and the test temperature, sugar crystals may grow. Therefore the amount of sugar and the temperatures employed during testing were kept within limits, to avoid any crystal growth.

### 2.3 Silicon oil

Another substitute pore fluid used in the study was the Dow Corning (200/50) type silicon fluid (Dow Corning Corporation, undated). Dow Corning 200 Fluids are polydimethysiloxanes, which are available in a wide range of viscosities. Polydimethysiloxanes are not soluble in water. The specific gravity of the oil was 0.96 (Dow Corning Product Information Ref. no. 22-0224J-01).

### 2.4 Water

The water used in the measurements was tap water, de-aired using a Walter Nold DeAerator.

## 3 Viscosity tube measurements

Measurements were carried out in a temperature controlled room at 23°C using a BS/U 1619/02 glass U-tube viscometer, with a rated range of 2–10 mm$^2$/s, manufactured by Poulten Selfe & Lee Ltd. The viscosity of the syrup was measured at the ratios of 0.5, 5, 25, 50, 100, 150 and 207 g sugar/100 g water. The measured viscosities of the fluids used in the study are given in Table 1.

**Table 1** Viscosity of the pore fluids used during the experimental study

| Fluid | Viscosity (mm$^2$/s) |
|---|---|
| Water (de-aired) | 0.942 |
| 25 g sugar /100 g water | 1.580 |
| 50 g sugar /100 g water | 2.897 |
| 100 g sugar /100 g water | 9.345 |
| 150 g sugar /100 g water | 37.120 |
| 207 g sugar /100 g water | 134.151 |
| Silicon oil (Dow Corning 200/50) | 50.983 |

*Note*: All tests were conducted at 23°C

## 4 Testing apparatus and experimental procedures apparatus

Tests were carried out in a 50 kN conventional (Wykeham Farrance) triaxial loading frame, using a 150 mm cell modified to include a temperature control system. The apparatus was equipped with a submersible 5 kN load cell, an external linear displacement sensor (LDS) with a range of 0–25 mm, two linear variable differential transformers (LVDTs) with a linear range of ±1 mm, and pressure transducers with a range of 0–1,000 kPa for the measurement of cell pressure and pore pressure. Temperature control was achieved by mounting a 10 mm o.d. copper coil in the cell, around the specimen, through which water could be circulated at various temperatures. Circulation of the water through the coil was regulated using a Watson Marlow peristaltic pump (model 603S-1). The recycled water could be supplied continuously using a chiller (Tricity 455 × 455 × 845) or a heater (Grant type, having $0 - 80^{\circ}$C temperature capacity). The temperatures in the specimen and in the cell were measured using two thermistors. The specimens were prepared in a 100 mm diameter 200 mm high split mould.

### 4.1 Specimen preparation

The specimens were approximately 100 mm in diameter by 200 mm height. A membrane was attached to the pedestal using o-rings and a three-part split mould was then placed around the pedestal. The membrane was stretched inside the mould and fixed at the top. For the initial sand/water specimen the required amount of Leighton Buzzard sand was weighed, mixed with de-aired water and then spooned, without vibration, into the mould. When the mould was completely filled, the membrane was stretched over the top platen, and attached with o-rings. A small suction (of the order of 20 kPa) was applied to the specimen, before stripping the specimen mould, installing the triaxial cell onto its base, and filling the cell with de-aired water. The vacuum applied to the specimen was then reduced while gradually increasing the confining cell pressure until the desired starting values of total and effective stress were achieved.

Sand/syrup specimens were prepared in a slightly different way from that followed for the specimen made with de-aired water, as the sugar particles needed to be dissolved in a given amount of water before starting the preparation of a specimen. The mix ratios of the sugar to water of 25/100, 100/100, 150/100, and 207/100 g/g were tested at room temperature. The sugar was mixed with water and stirred until it dissolved completely, the solution was poured in to the mould, and then the procedure described above for the sand/water tests was repeated.

In addition, a mix ratio of 287/100 g/g was also tested. As can be judged from the figures given above, syrup of this strength would be super-saturated at room temperature, and sugar precipitation and crystallization could be expected. To avoid this, the specimen preparation mould was covered with an electrical heater mat during specimen preparation, and was filled with the pre-heated syrup. Following the preparation of specimen, the heater coil was placed in the cell, and the triaxial cell was filled with pre-heated water at approximately 60°C.

A triaxial test was also conducted to measure the mechanical properties of Leighton Buzzard sand with silicon oil pore fluid. In these tests the procedure was the same as for the sand/water specimens, except that the silicon oil was poured in layers of 1/3 height of the mould, with thin layers of sand being spooned into the mould.

### 4.2 Test procedure

Specimens were isotropically consolidated to 100 kPa effective stress, with a back pressure of 300 kPa, before being sheared 'undrained' (i.e. without allowing pore fluid drainage from the specimen) with pore pressure measurement. A minimum B-value of 0.95 was obtained before shear. A standard machine rate of displacement, equivalent to 10% strain per day, was used throughout the testing. During shear, measurements of deviatoric load, external axial deformation, local strain, and base pore pressure were made at approximately 10 s intervals.

## 5 Results

Table 2 gives a summary of the specimens used in the eight tests reported here. The initial relative density of all specimens fell between 34.5 and 50.8%, with most specimens having a relative density in the region of 48–51%. Specimen SW1, with water pore fluid, had the lowest relative density. The specimens were loose to medium dense.

**Table 2** Summary of specimen data

| Specimen | Pore fluid | Test temperature (°C) | Dry density (Mg/m$^3$) | Relative density (%) |
|---|---|---|---|---|
| SW1 | Water | 23 | 1.560 | 34.5 |
| SS1 | 25/100 syrup | 23 | 1.577 | 41.4 |
| SS2 | 100/100 syrup | 23 | 1.581 | 43.0 |
| SS3 | 150/100 syrup | 23 | 1.595 | 48.4 |
| SS4 | 207/100 syrup | 23 | 1.595 | 48.5 |
| SS5 | 287/100 syrup | 60 | 1.598 | 49.2 |
| SO1 | 200/50 oil | 23 | 1.590 | 50.8 |

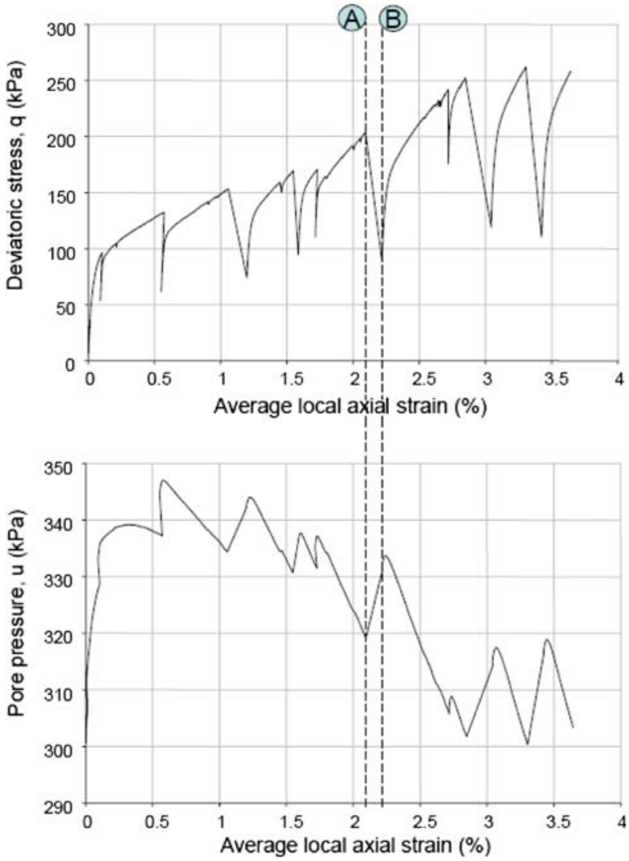


**Fig. 2** Deviatoric stress and pore-pressure as a function of local axial strain for Test SS3

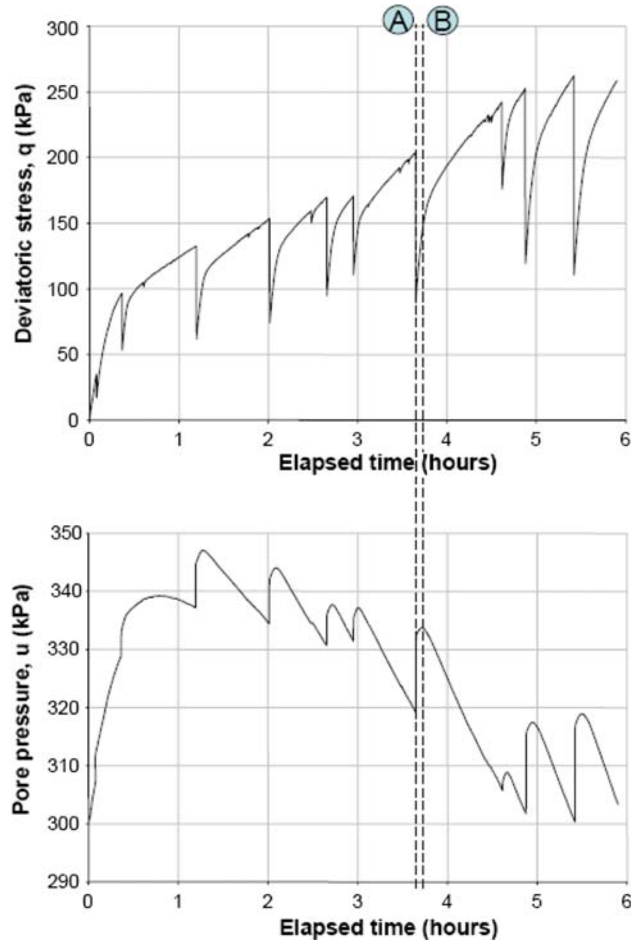


**Fig. 3** Deviatoric stress and pore-pressure as a function of the elapsed time since start of Test SS3

Figure 2 shows the variation of deviatoric stress and pore pressure as a function of average local axial strain for specimen SS3, which had a syrup pore fluid with a sugar content of 150/100 g. Large drops in deviatoric stress, accounting for about $^1/_3$rd to 1/2 of the prior deviatoric stress, can be seen once local strain levels exceed about 0.1%. These drops (for example from A to B in Fig. 2) are associated with significant *increases* in local axial strain (the so-called 'strain jumps' of [27]), and *increases* in measured pore pressure. It is therefore apparent that collapse is occurring within the sand structure.

The collapse highlighted in Fig. 2 between A and B on the deviatoric stress v. local axial strain curve starts at the same point on the pore pressure strain curve below, but finishes later, perhaps as a result of the time required for pore pressure equalisation between the position of the collapse and the base pedestal, or perhaps because of the increase in deviatoric stress occurring immediately post collapse. Figure 3 shows the same data as a function of elapsed time since the start of testing. The rapid rise in deviatoric stress immediately post collapse is more obvious here. These collapse events occurred almost without exception within the 10 s data logging interval, and were accompanied in many cases by an audible "cracking" noise.

Figure 4 shows secant modulus v. the logarithm of local axial strain (top) and stress path (bottom) plots. The secant modulus plot shows clearly that although collapses generally occur at larger strains, the earliest occurs at about 0.01% axial strain. The stress paths (in MIT t-s' stress space) show that each collapse is associated with a reduction in stress obliquity ($\sigma_1'/\sigma_3'$), with the specimen moving along an approximately drained unloading path. This presumably occurs because although the specimen is globally undrained, drainage from one part of the specimen to another cannot be prevented.

Figure 5 shows the details of displacements (interpreted as strains) measured at different locations (on the triaxial cell ram, and the two local LVDTs), which are compared with the applied machine deformation. The differences between the applied and the externally-measured strains are too small to see on this scale. However, it is evident that in most cases the collapse events are associated with positive (compressive) strains at both (diametrically opposed) local strain gauge positions (for examples, see points marked A). However in other instances (such as at B) the event is associated with a reduction in strain, presumably because of load redistribu-

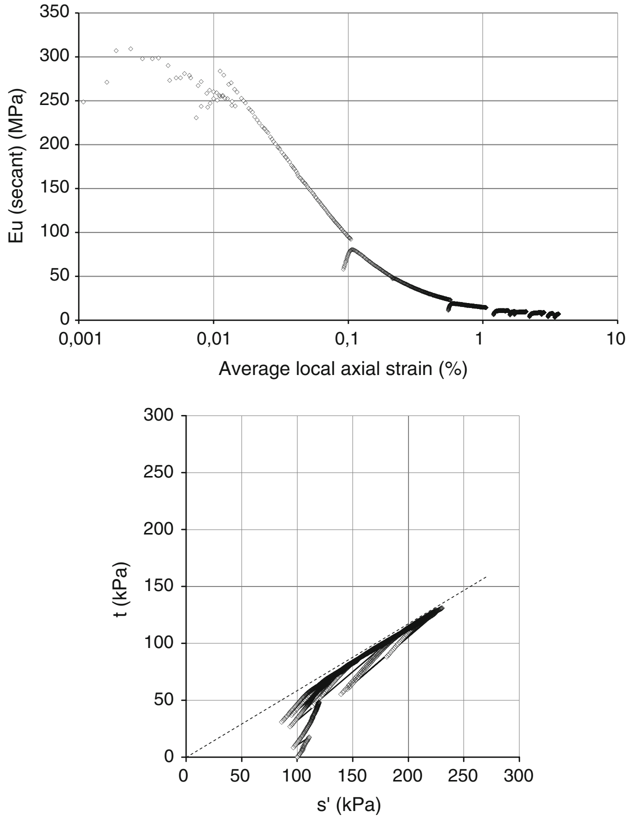


**Fig. 4** Secant modulus—local axial strain (top) and stress path (bottom) for Test SS3

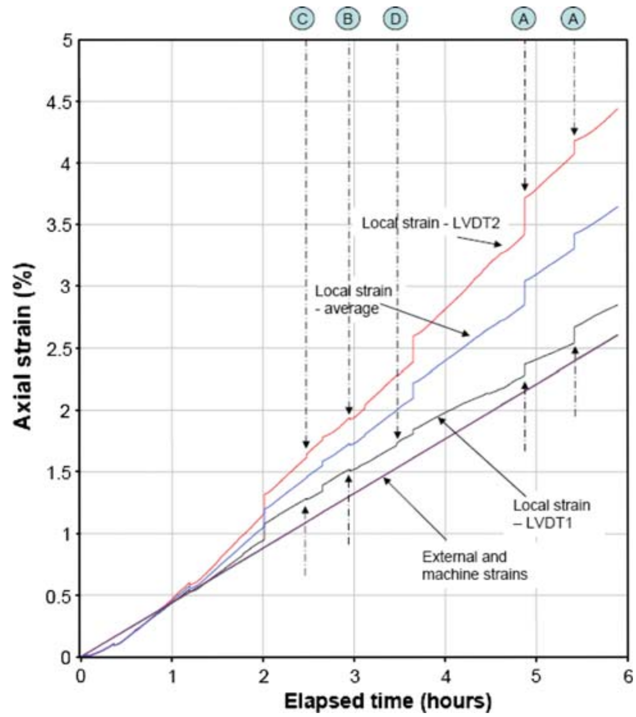


**Fig. 5** Axial strains as a function of time for Test SS3

tion, and during other events (such as C) one gauge shows positive movement and the other negative. Events where one gauge moves but the other apparently does not (D) are also seen. These features suggest that the collapses are spatially distributed within the specimen, perhaps as a result of heterogeneous structure created during specimen formation.

Figure 6 shows the difference between axial external strain and the theoretically imposed machine rate of strain. Negative values indicate that the measured external displacement is less than the assumed (but actually unknown) rate of displacement applied by the triaxial loading frame, i.e. that energy is being stored in the loading system. Upward jumps such as those labelled A to I in Fig. 6 show where collapses are occurring and stored energy is being recovered.

The effect of changing the sugar content of the pore fluid can be seen in Fig. 7, in terms of the stress–strain and pore pressure strain behaviour. The effect of introducing sugar into the pore water is threefold;

1. The number of jumps in deviatoric stress and pore pressure is increased;
2. The magnitude of jumps, in terms of the percentage reduction indeviatoric stress, increases;

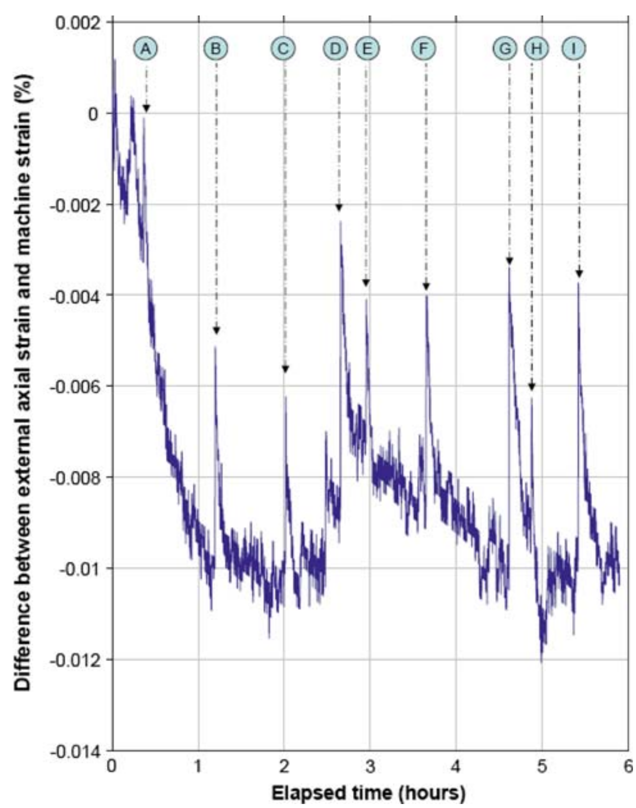


**Fig. 6** Difference between external axial strain and machine strain (Test SS3)

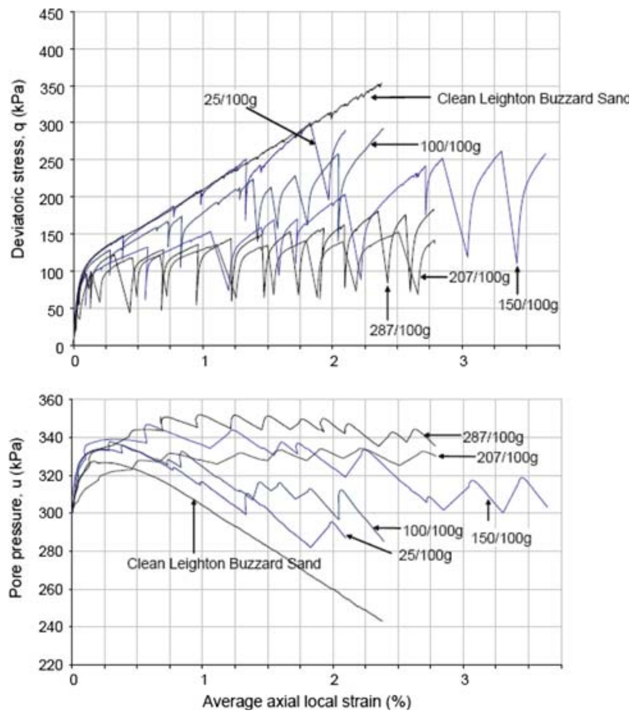


**Fig. 7** Effect of sugar content of pore fluid on deviatoric stress and pore pressure strain relationships

3. Dilation, clearly seen by the reduction in pore pressure with strain (at strain levels greater than about 0.1%) is suppressed.

The effect of changing the sugar content of the pore fluid on stress path can be seen in Fig. 8. In conventional undrained triaxial tests on water-saturated medium dense or dense rotund sand, dilation occurs after an initial minor contraction and increase in pore pressure, and pore pressures fall until cavitation occurs, typically (for deaired pore water) at about −70 to −90 kPa. Maximum effective principal stress ratio occurs early in the test, and the final strength of the specimen is an artefact of the test, being a function of the cell pressure (in this case 400 kPa) and the pressure at which cavitation occurs. Figure 7 shows that dilatancy appears completely suppressed for sugar contents greater than 200 g/100 g of water, and Fig. 8 shows the material to be at failure during these stress jumps.

It was postulated that the observed effects might be due to an increase in viscosity. Therefore in Test SO1 silicon oil (with a viscosity of 51 $mm^2/s$—see Table 1) was used as a pore fluid. Figure 9 compares (top) the deviatoric stress v. average local axial strain relationships and (bottom) the pore pressure v. average local axial strain relationships for Leighton Buzzard sand with deaired water and silicon oil as pore fluids. Figure 10 compares the stress paths for the tests with the two different pore fluids.

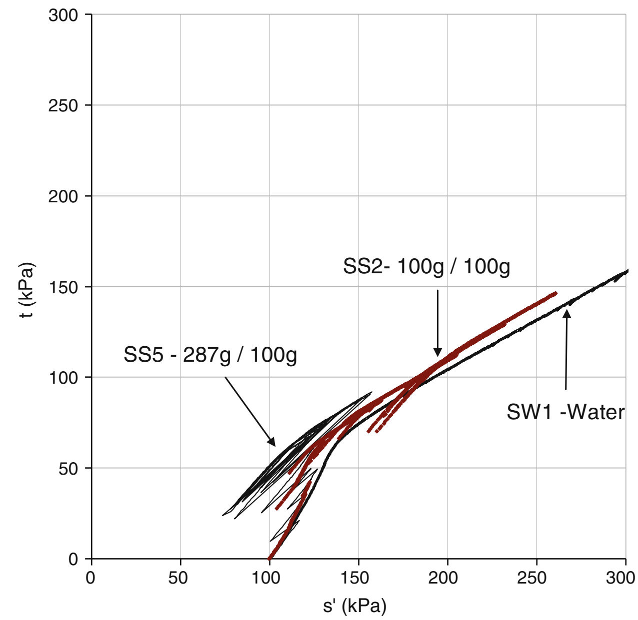


**Fig. 8** Effect of sugar content of pore fluid on stress paths

## 6 Discussion

This study describes unusual stress–strain behaviour, involving deviatoric stress, axial strain and pore pressure jumps, observed during undrained triaxial compression testing of Leighton Buzzard sand when using silicon oil and syrup pore fluids. The fact is that observations of limited instability in triaxial tests are not new. For example, Lindenberg and Koning [22] observed of the behaviour of sand in drained stress controlled triaxial tests that *"In some cases, limited failure occurs, which manifests itself in a sudden, but limited, increase in pore water pressure and in a sudden vertical deformation. The sample recovers, and the stress path, from a certain point onwards, is characterized by increasing values of q. This type of behaviour was called limited liquefaction by [9]. The phenomenon of limited failure occurs regularly in a transitional region between liquefied and nonliquefied samples.."*. Liquefaction under undrained conditions has been commonly reported in the literature, as have the factors affecting the phenomenon (for examples see [9,20,30,7,13]).The data in Fig. 3 show a typical event observed in our tests, with load being transferred from the soil skeleton to the pore water as collapse occurs, over a period of less than the reading interval of 10 s. At point A, for example, there is a 13 kPa increase in pore pressure as a result of a 110 kPa decrease in deviatoric stress. Collapse events occur over a wide range of strains, although the majority are at higher strain levels. With high viscosity pore fluid the collapse events are more frequent, the deviatoric stress reduction is proportionately greater, and at the highest viscosities

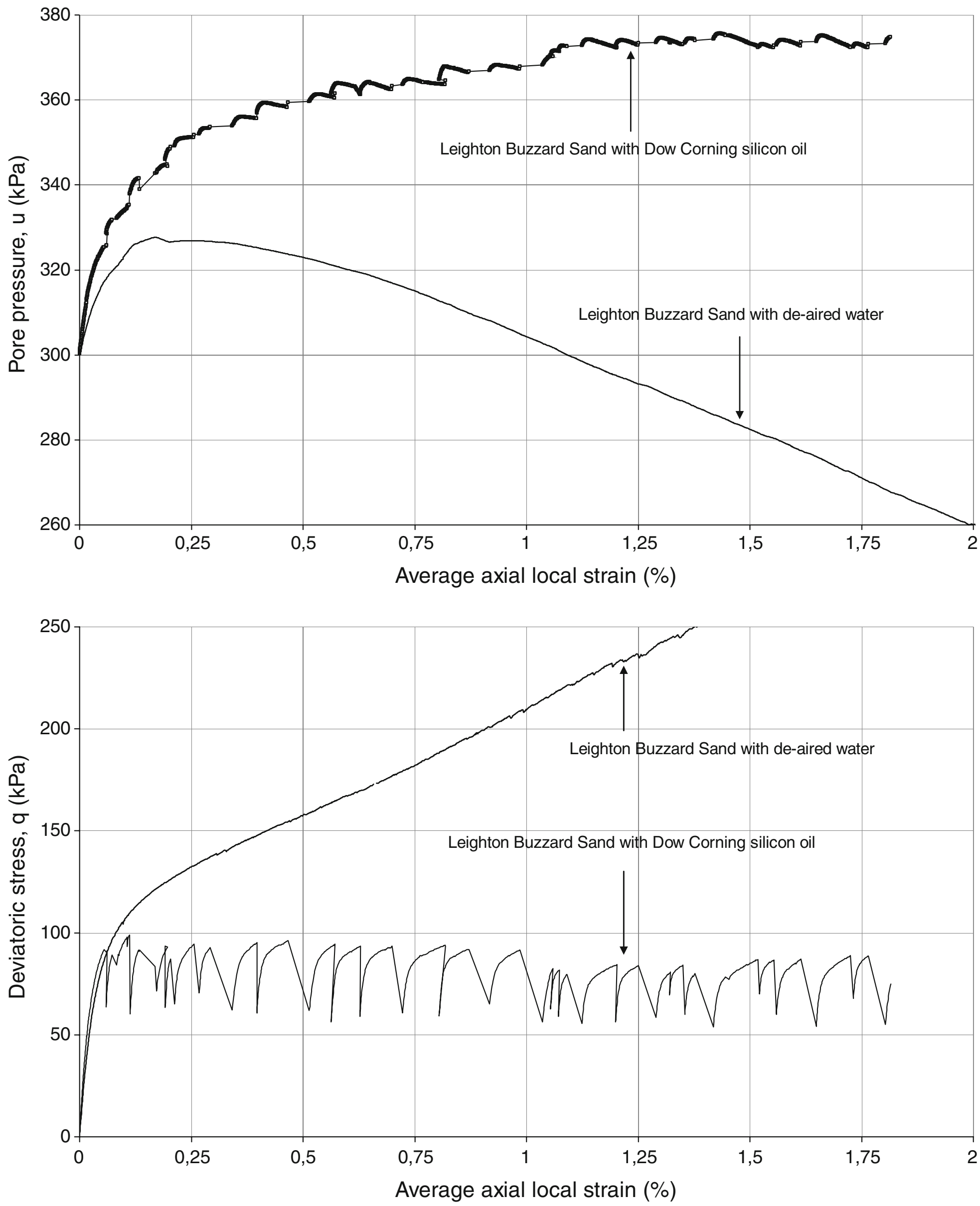


**Fig. 9** Effect of silicon oil on deviatoric stress and pore pressure strain relationships

dilation appear to be suppressed, as shown by the pore pressure curves for 207/100 and 287/100 g syrup in Fig. 7.

The behaviour observed in our specimens could be controlled by two factors; (i) the heterogeneity and structure of the specimens, and (ii) the compliance of the apparatus. Recently, such behaviour has been observed in drained stress-controlled tests reported by Gajo et al. [18] and Gajo [17], and in tests on dense sand in undrained triaxial compression by Kuwano et al. [21]. In our tests the proportion of deviatoric stress lost during each event was almost certainly a function of the stiffness of the loading system, as suggested by Gajo [17] and in particular of the loading frame (see Fig. 6). A stiffer loading frame might, for example, be expected to show proportionately smaller losses of deviatoric stress, and could presumably produce smoother stress–strain curves, although with similar overall behaviour. It is beyond the scope of this study to provide a detailed discussion of apparatus compliance; however the authors would note that the same apparatus was used to best specimens with sucrose solutions and those with de-aired water. This study, therefore, specifically focus on the structural properties of the specimens tested, and the effects of viscosity. Gajo [17] has suggested that a fast rate of unloading may produce a good approximation to undrained behaviour, preventing migration of pore fluid (in a drained test) down drainage lines and (in an undrained test) within the specimen itself. This is particularly relevant here,

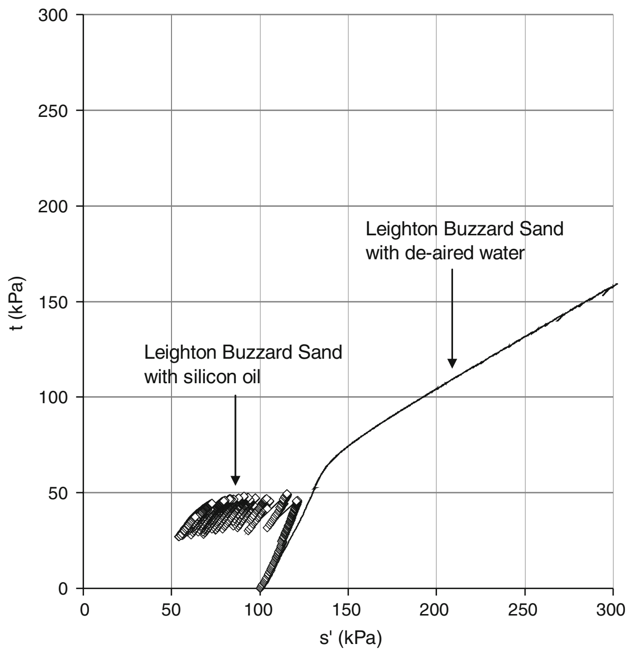


**Fig. 10** Effect of silicon oil on stress path

given the very different pore fluid viscosities in the various tests.

It is postulated that the mechanism observed in the specimens tested could be due to (i) the effects of spatial variations in the coordination number, (ii) the collapse of open fabric in some parts of the specimens, and (iii) stick-slip behaviour between the soil particles. The spatial and temporal distribution of strain jumps within our specimens (see for example Figs. 5, 6) could suggest that the observed limited instability might be associated with collapse of a honeycomb fabric [24] set up within the specimen during preparation, rather than some effect of viscosity or perhaps inter-particle friction occurring during shearing. The observed behaviour could not be explained by differences in the void ratios of the specimens since the specimens with more viscous pore fluid had higher relative densities. As has been noted, observed displacements occurred with different magnitudes, and sometimes with a different sense, at the three measurement positions. Furthermore, the successive formation (rises in deviatoric stress to a local maximum level and the sharp stress drop) observed in the Leighton Buzzard Sand with sucrose solutions at various concentrations and that with silicon oil might give a stick-slip behaviour nature to the fluctuations. Stick slip behaviour in granular materials has been investigated by many researchers in different disciplines, such as; [29,16,12,23], Nasuno et al. 1997, [1,6,19]. The deviatoric stress fluctuations could be attributed to the stick-slip mechanism between the sand grains as they form force chains to support the applied load. Jamming occurs because the sand particles form the chains (primarily) along the compressional direction. During the sticking, the sand grains are more closely packed and exhibit a gradual increase in deviatoric stress, however; when the force chain becomes relatively unstable, some grains slide out of the column resulting in the deviatoric stress to sharply drop. The deviatoric stress subsequently builds up (self organize) again to form a new chain of columns so as to support an applied stress. A similar behaviour was also noted by Alshibli and Roussel [2].

Use of a different, but also more viscous, pore fluid produced qualitatively similar results (Figs. 9, 10), although direct comparison on the basis of viscosity alone was not possible. Similar collapses have been observed in the tests using silicon oil as pore fluid. However, the amplitude of the deviatoric stress jumps and pore fluid pressure changes had slightly different characteristics. It is thought that this could be because of the differences between the chemistry of the sucrose solutions and that of the silicon oil.

## 7 Conclusions

The tests reported in this paper show three new facets of behaviour:

1. Limited instability events are shown to be associated with an increase in pore fluid viscosity. Specimens made with higher viscosity pore fluid exhibited more, as well as more significant, collapse events.
2. A spatial as well as temporal distribution of events within the sample was deduced from differences in displacement recorded by the three displacement sensors.
3. Tests showing limited instability events did not "recover", at least in the strain levels applied in these tests, in the sense described by Lindenberg and Koning [22].

This suggests that specimen formation in the way used here, in a viscous fluid, in the extreme could suppress dilatancy.

## References

1. Albert, I., Tegzes, P., Kahng, B., Albert, R., Sample, J.G., Pfeifer, M.: Jamming and fluctuations in granular drag. Phys. Rev. Lett. **84**(22), 5122–5125 (2000)
2. Alshibli, K.A., Roussel, L.E.: Experimental investigation of slip-stick behaviour in granular materials. Int. J. Numer. Anal. Meth. Geomech **30**, 1391–1407 (2006)
3. Bubnik, Z., Kadlec, P., Urban, D., Bruhns, M.: Sugar Technologists Manual. Verlag Bartens, Berlin, 417 pp (1995)
4. BS 1377; Part 4:1990. Methods of Test for Soils for Civil Engineering Purposes. British Standards Institution, London
5. BS 1881-131:1998. Testing Concrete. Methods for Testing Cement in a Reference Concrete. British Standards Institution, London

6. Cain, R.G., Page, N.W., Biggs, S.: Microscopic and macroscopic aspects of stick-slip motion in granular shear. Phys. Rev. E **64**, 016413 (2001)
7. Canou, J., Thorel, L., de Laure, E.: Influence of an initial stress deviator on the characteristics of undrained shear strength of sand. Proc. X ECSMFE, Florence, 1, 49–52 (1991)
8. Casagrande, A.: Characteristics of cohesionless soils affecting the stability of slopes and earth fills. J. Boston Soc. Civ. Eng. **23**(1), 13–32 (1936)
9. Castro, G.: Liquefaction of Sands. PhD Thesis. Harvard Soil Mechanics Series, 81, Harvard University, Cambridge (1969)
10. Clayton, C.R.I., Obula Reddy, C., Schiebal, R.: A method of estimating the form of coarse particulates. Geotechnique **59**(6), 493–501 (2009). doi:10.1680/geot.2007.00195
11. Cresswell, A., Barton, M.E., Brown, R.: Determining the maximum density of sands by pluviation. Geotech. Test. J. GTJODJ **22**(4), 324–328 (1999)
12. Demirel, A. L., Granick, S.: Friction fluctuations and friction memory in stick-slip motion. Phys. Rev. Lett. **77**(21), 4330–4333 (1996)
13. Doanh, T., Ibraim, E., Matiotti, R.: Undrained instability of very loose Hostun sand in triaxial compression and extension Part 1 experimental observations. Mech. Cohes. Friction Mater. **2**, 47–70 (1997)
14. Dow Corning Corporation (Undated) Product Information Ref. no. 22-0224J-01
15. Ellis, E.A., Soga, K., Bransby, M.F., Sato, M.: Resonant column testing of sands with different viscosity pore fluids. A.S.C.E. J. Geotech. Geoenviron. Eng. **126**(1), 10–17 (2000)
16. Feder, H.J., Feder, J.: Self-organized critically in a stick-slip process. Phys. Rev. Lett. **66**(20), 2669–2672 (1991)
17. Gajo, A.: The influence of system compliance on collapse of triaxial sand samples. Can. Geotech. J. **41**, 257–273 (2004)
18. Gajo, A., Piffer, L., Polo, F.de : Analysis of certain factors affecting the unstable behaviour of saturated loose sand. Mech. Cohes. Friction Mater. **5**, 215–237 (2000)
19. Gourdon, D., Israelachvili, J.N.: Transitions between smooth and complex stick-slip sliding of surfaces. Phys. Rev. E **68**, 021602 (2003)
20. Kramer, S.L., Seed, H.B.: Initiation of soil liquefaction under static loading conditions. J. Geotech. Eng. ASCE **114**(4), 412–431 (1988)
21. Kuwano, R., Hasbullah, N., Tatsuoka, F., Di Benedetto, H., Duttine, A., Oland, F. Unstable behaviour of dense sand upon a step increase in strain rate in undrained triaxial compression. Proc. Japanese National Conference on Geotechnical Engineering (2000) (In Japanese, courtesy Prof. F. Tasuoka)
22. Lindenberg and Koning: Critical density of sand, Geotechnique **31**: 723–764 (1981)
23. Miller, B., O'Hern, C., Behringer, R.P.: Stress fluctuations for continuously sheared granular materials. Phys. Rev. Lett. **77**(15), 3110–3113 (1996)
24. Mitchell, J., Soga, K.: Fundamentals of soil behaviour. Wiley, New York (2005)
25. Nasuno, S., Kudrolli, A., Bak, A., Gollub, J.P.: Time-resolved studies of stick-slip friction in sheared granular layers. Phys. Rev. E **58**(2), 2161–2171 (1998)
26. Ratnaweera, P., Meegoda, J.N.: Shear strength and stress–strain behaviour of contaminated soils. Geotech. Test. J. **29**(2), 133–140 (2006)
27. Skopek, P., Morgenstern, N.R., Robertson, P.K., Sego, D.C.: Collapse of dry sand. Can. Geotech. J. **31**, 1008–1014 (1994)
28. Taylor, D.W.: Fundamentals of soil mechanics. Wiley, New York, 700 pp (1948)
29. Thompson, P.A., Grest, G.S.: Granular flow: friction and dilatancy transition. Phys. Rev. Lett. **67**(13), 1751–1754 (1991)
30. Vaid, Y.P., Chung, E.F.K., Kuerbis, R.H.: Preshearing and undrained response of sand. Soils Found. **29**(4), 49–61 (1989)
31. Zeng, X., Wu, J., Young, B.A.: Influences of viscous fluids on properties of sand. Geotech. Test. J. GTJODJ **21**(1), 45–51 (1998)