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原論文

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THE SMALL STRAIN STIFFNESS OF A CARBONATE STIFF CLAY

CHARLES NG[i], MALCOLM BOLTON[ii] and GANESH DASARI[iii]

ABSTRACT

Knowledge of the small strain stiffness of the heavily overconsolidated Gault Clay, which has up to 30% calcium carbonate content, is rather limited. This has resulted in some difficulties in the analysis and design of structures constructed in the Gault. In this Technical note, the small strain stiffness of the Gault Clay is examined based on results from triaxial tests with internal small strain measurements, published geophysical data, and values deduced from the back-analysis of full-scale field observations of an excavation at Lion Yard Cambridge, U.K. Comparisons of stiffness values have also been made between the Gault Clay and the non-carbonate heavily overconsolidated London Clay. The results of these examinations have led to the conclusion that the stiffness-strain characteristic of Gault Clay is highly non-linear and exhibits first yield at a threshold shear strain of about 10^{-5}, beyond which the stiffness deteriorates dramatically from an initially very high value. After modest straining the stiffness reduces to values comparable to those for London Clay. The Gault Clay behaves like a low plasticity clay at small strains but as a high plasticity clay at medium to large strains. This behaviour is probably due to the breakdown of the weakly cemented bonding caused by the calcium carbonate content.

Key words: back-analysis, carbonate, field monitoring, Gault Clay, geophysical, overconsolidated, stiffness, triaxial (**IGC:** D6/E12)

INTRODUCTION

The knowledge of Gault Clay is limited, particularly related to small strain stiffness which is very important for understanding soil-structure interaction problems (Jardine et al., 1986; Ng et al., 1995). Over the last fifteen years, a number of field tests were carried out in the Gault Clay at Madingley in Cambridge. Abbiss (1981) reported some dynamic measurements of the shear moduli using shear wave refraction and Rayleigh methods. Powell and Uglow (1986) used a Marchetti flat dilatometer to measure in-situ soil parameters of the Gault. Powell and Butcher (1991) compared the in-situ measurements of shear stiffness obtained from self boring pressuremeter tests and geophysics measurements. The field measured soil stiffness at very small strains, however, shows substantial scatter depending on what type of in-situ test was used. An apparent factor of 4 can be found between the measured maximum and minimum soil stiffness at very small strains.

In contrast, few laboratory studies of the Gault Clay have been reported. Samuels (1975) reported the undrained shear strength, stress-strain characteristics, and consolidation and swelling characteristics of reconstituted and undisturbed samples obtained from the Ely-Ouse Essex water tunnel. Ng and Nash (1995) described the compressibility characteristics of Gault Clay from Lion Yard Cambridge. They concluded that the presence of high carbonate content in the Gault Clay does not affect its intrinsic and natural compressibility properties at medium to large strains. As far as the Authors are aware, no laboratory tests on small strain stiffness values for Gault Clay have yet been reported. This has resulted in some difficulties in the design and back-analysis of structures founded in the Gault, such as the multi-propped excavation at Lion Yard Cambridge (Lings et al., 1991; Ng, 1992).

During the back-analysis of the multi-propped excavation at Lion Yard Cambridge in 1991, the first author has conducted a series of finite element analyses using the non-linear Brick model (Simpson, 1992) to deduce the small strain stiffness operating in the field during the excavation. The use of the upper bound values of field-determined small strain stiffness data published by Powell and Butcher (1991) seemed to give convincing predictions which match well with nearly all aspects of the field obser-

[i] Assistant Professor, Department of Civil and Structural Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong, formerly Research Associate, Engineering Department, Cambridge University, Trumpington Street, Cambridge CB2 1PZ, UK.
[ii] Lecturer, Engineering Department, Cambridge University, Trumpington Street, Cambridge CB2 1PZ, UK.
[iii] Research student, ditto.

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vations. It has been difficult, however, to be absolutely confident regarding the small strain soil parameters selected for the finite element analysis (Ng, 1992).

Recently some laboratory tests on natural Gault Clay were conducted with internal small strain measurements. In this Technical note, the small strain stiffness of the Gault Clay is evaluated in light of these laboratory tests and published geophysical measurements, and the values deduced from the back-analysis of full-scale field observations of the excavation at Lion Yard. In addition, the deduced and measured small strain stiffness of Gault Clay is compared with some other published data for stiff London Clay. The Gault Clay shows a very high initial shear stiffness at very small strain. This is probably due to its calcium carbonate content.

GAULT CLAY AT CAMBRIDGE, U.K.

Gault Clay was laid down in south-east England as a result of a widespread marine incursion that spanned the Middle and Upper Albian stages. Following the deposition of the Gault, the Chalk was laid down as the sea water cleared and the land areas dwindled so that less and less terrigenous sediment became available. During the Tertiary and Quaternary epochs, uplift and extensive erosion took place and eventually produced the present landscape. An estimated 200 m to 400 m of Chalk had been eroded (Lings et al., 1991). In the Cambridge area, the thickness of Gault varies between 27 m and 42 m.

The Gault in its natural state is heavily overconsolidated, having natural water contents close to the plastic limit. It consists of stiff to hard silty grey clay with high plasticity (about 50%) and it contains closely spaced fissures and joints. The top few meters of clay show signs of weathering, such as cryoturbation. Hard nodules of phosphatized marl are scattered throughout the clay. The Gault Clay in the Cambridge area has been reported by Worssam and Taylor (1975) to contain calcium carbonate up to 30% by weight. Similar results have also been found in the Gault Clay samples obtained from Essex (Samuels, 1975). Acid-base titration tests were also carried out on three samples from Lion Yard and showed that 27.5% ± 0.2% by weight of calcium carbonate was present in the clay (Ng, 1992).

DEDUCTION OF SMALL STRAIN STIFFNESS FROM FIELD MONITORING

For numerical analysis of the multi-propped excavation in Gault Clay at Lion Yard using the non-linear Brick model (Ng, 1992), an "S-shaped" curve which defines the way that shear stiffness varies with shear strain was required for an assumed isotropic soil. To obtain the maximum shear stiffness value $G_{\max}$, a constant mean effective stress p' test with a 180° of rotation of stress path was used (Simpson, 1992). Since no laboratory measurements of soil stiffness at small strains of Gault Clay were available at that time, the geophysical measurements of soil stiffness at very small strains on Gault Clay at Madingley (Powell and Butcher, 1991) were used to derive appropriate "S-shaped" curves.

Geophysical Measurements of Shear Stiffness

The magnitude of elastic small strain stiffness depends not only on the current value of void ratio but also on stress level and soil structure which includes the effects of depositional environment and post-depositional processes such as aging and cementation (Jamiolkowski et al., 1994). Geophysical techniques have been adopted to determine small strain soil stiffness both in the laboratory (Lo Presti and O'Neill, 1991; Stokoe et al., 1991; Jamiolkowski et al., 1994) and in the field (Powell and Butcher, 1991; Butcher and Powell, 1995).

Powell and Butcher (1991) reported a large amount of geophysics data for shear stiffness from various site locations. Some of their data which are relevant to the present study are reproduced in Fig. 2. It can be seen that the measured shear stiffness of the two stiff clays (Gault Clay and London Clay) using the Refraction method is considerably higher than the measurements made using the Rayleigh method. Both the geophysical methods gave consistent measurements for the Bothkennar Clay which is a normally consolidated soft clay.

An attempt can be made to account for differences in the apparent shear stiffness by considering differences in the mode of wave propagation. In Refraction measurements, a source rich in shear waves is used to generate seismic pulses travelling through the ground. These seismic pulses are described by Abbiss (1981) as to approximate the horizontal propagation of horizontally polarised shear waves, which could be governed mostly by the shear stiffness in the horizontal plane (G_{hh}). For the Rayleigh method, continuous surface waves generated by a vibrator have elliptical particle motion in the vertical plane containing the direction of propagation. The velocity of the waves travelling through the plane is mainly controlled by the shear modulus (G_{vh}) in the vertical plane. These two geophysical methods, therefore, measure shear stiffness in different planes. The observed differences in shear stiffness for these two heavily overconsolidated clays may therefore be attributed mainly to anisotropy. More recent field work by Butcher and Powell (1995) demonstrates the strong influence of soil anisotropy on shear wave velocity (i.e. small strain stiffness) in various clay deposits such as Gault Clay in the U.K. Although the combined effect of pulse broadening and anisotropy on the velocity of wave propagation could result in pulses travelling up to 1.7 times faster than the continuous Rayleigh shear waves (Abbiss, 1981), it remains difficult to fully reconcile these diverse in-situ measurements.

Anisotropic stiffness of natural carbonate clays at small strains nevertheless has been reported in laboratory tests by Jamiolkowski et al. (1994). Based on test results from a specially instrumented square oedometer cell, they showed that the ratio of G_{hh}/G_{vh} was a function of coefficient of earth pressure at rest K_0. For instance, G_{hh}/G_{vh} was found to be 1.4 times $(K_0)^{0.22}$ for estuarine Pisa

Clay, which has up to 12% calcium carbonate content. Similar results were also obtained for marine Panigalia Clay containing 12% calcium carbonate. These results seem to suggest that for highly overconsolidated clays such as Gault Clay and London Clay which have high K_0, strong stiffness anisotropy would be expected at small strains.

Selection of an Equivalent Gmax Value for Numerical Analysis

For selecting an appropriate G_{max} value in conjunction with laboratory measurements of shear stiffness at medium strains to model the excavation in Gault Clay, parametric studies were carried out by varying the G_{max} value within the measured upper and lower bounds (*see* Fig. 1). The computed results were then compared with the field observations at Lion Yard.

For a chosen G_{max} value, a best fit "S-shaped" curve was drawn through the G_{max} value and the laboratory measured tangent shear stiffness (G_t) of reconsolidated natural Gault Clay specimens at constant mean effective stress p' (Ng, 1992). The area under the curve has been shown to be $\sin\phi'$ (Simpson, 1992), where ϕ' is the angle of shearing resistance. This result is used as an additional criterion to deduce the curves. The derived upper and lower bound "S-shaped" curves for the parametric studies are shown in Fig. 1.

Figure 3 shows the comparison between the computed

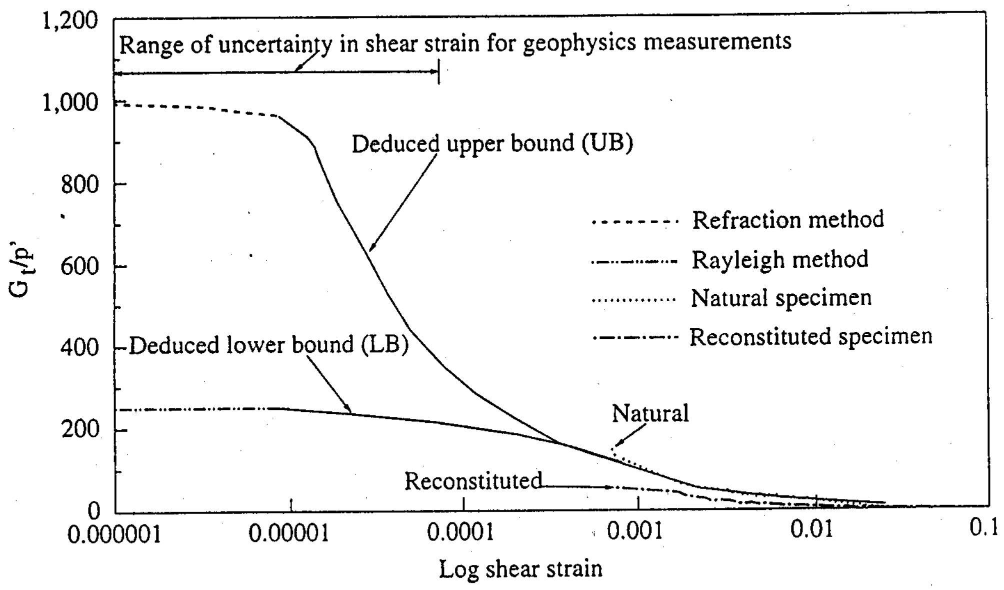

Fig. 1. Deduced normalised stiffness-strain relationship for Gault Clay

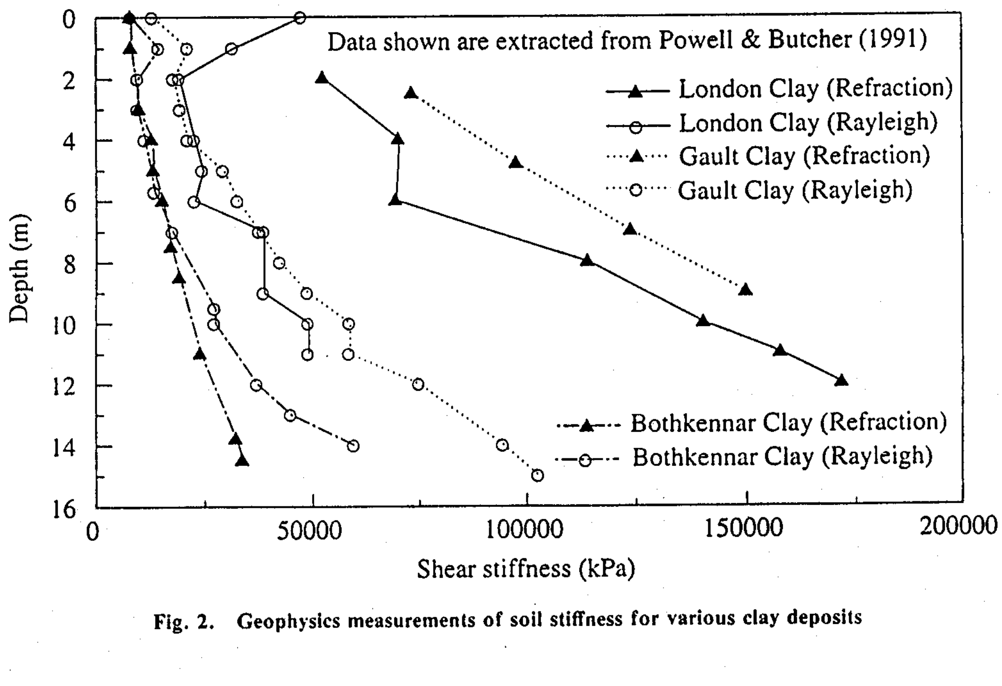

Fig. 2. Geophysics measurements of soil stiffness for various clay deposits

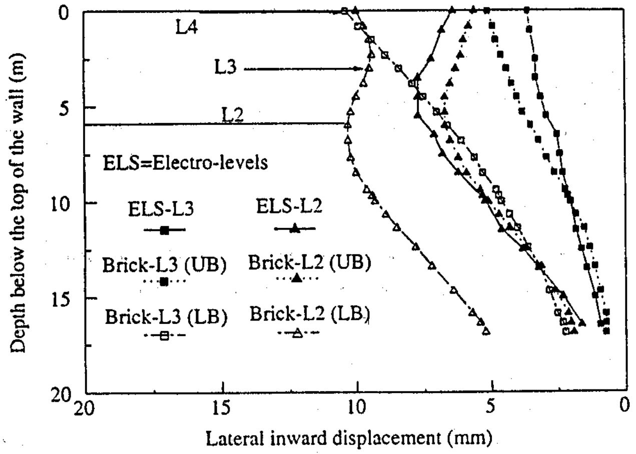

Fig. 3. Sensitivity of wall deformation due to soil stiffness

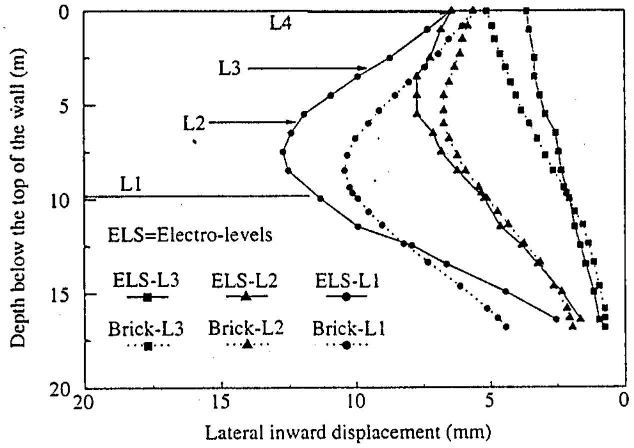

Fig. 4. Comparison of measured and computed displacements of the wall during excavation

and measured wall displacements during the first and second stages of excavation, in which the values of small strain shear stiffness were considered relevant. The results of these parametric studies suggested that analysis with the lower bound "S-shaped" curve substantially overestimated the measured wall deformation by a factor of about 3 and 1.5 at the end of the first and the second stages of excavation respectively. This substantial overestimate of lateral wall displacements was attributed to the low initial stiffness specified. Details of the parametric studies are described by Ng (1992). In contrast, analysis with the upper bound "S-shaped" curve predicted wall displacements which were in reasonably good agreement with field observations at all three stages of the excavation (*see* Fig. 4). This led to the suggestion that the Gault Clay operated at high stiffness at very small strains during the first two stages of excavation.

Based on the comparison of the results of finite element analysis and other field observation data (Ng, 1992), the upper bound "S-shaped" curve was considered to be the most appropriate one for the Gault Clay in Cambridge.

LABORATORY MEASUREMENTS OF SMALL STRAIN STIFFNESS

Recently natural Gault Clay samples obtained from Madingley were tested in a refurbished Bishop and Wesley type hydraulic triaxial stress path apparatus at Cambridge. Following the concept first developed by Goto et al. (1991), local deformation transducers (LDTs) were implemented with some modifications for the measurement of small strain stiffness. These modifications (Bolton et al., 1994) include:

1. the use of eight strain gauges instead of four to reduce heat generation during a long test,
2. the use of rounded reception corners (0.125 mm radius) in each hinge attachment for slow cyclic tests,
3. adoption of a 16-bit analog to digital data acquisition card instead of a standard 12-bit one.

The working principle of LDT essentially is very simple. Two thin strips of phosphor bronze are strain gauged and these strips are then attached directly to the member of a specimen on which two hinges are first fastened. On each strip, one full Wheatstone bridge circuit with eight strain gauges is mounted. As the soil sample deforms, the distance between the two hinges changes as does the curvature of the LDTs. The bending strains of the LDTs are then recorded. These bending strains can be converted to axial strains on the gauge length after the LDTs have been calibrated before and after the tests. Full details of the triaxial apparatus, the development and calibration of the LDTs at Cambridge, and the laboratory preparation and testing procedures are presented by Dasari et al. (1995).

Figure 5 shows the measured stress-strain curve for a typical heavily overconsolidated natural soil specimen (OCR=30-40) sheared at constant p'. The stress paths followed were (i) isotropic re-consolidation to $p'=200$ kPa (at A), (ii) isotropic unloading to $p'=100$ kPa at B, (iii) shearing during axial compression with the stress path having rotated 90° to reach $q=30$ kPa (at C), (iv) axial unloading leading to 180° rotation of stress path to reduce q to zero (at B). For this paper, the angle of rotation of stress path means the change of direction on a p'-q diagram between the penultimate and the final stress

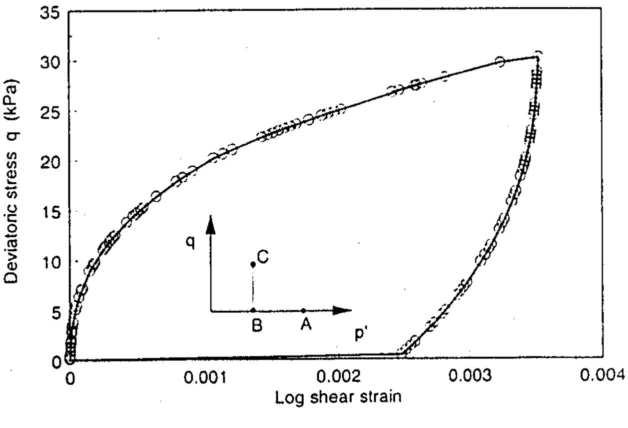

Fig. 5. Stress-strain curve for Gault Clay

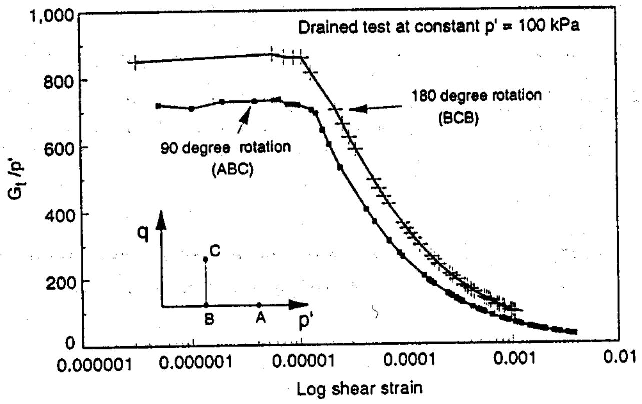

Fig. 6. Stiffness-strain curve for Gault Clay

paths. Figure 6 shows the variation of the normalized tangent shear modulus with logarithm of shear strain. As expected, a 180° of rotation of stress path gave a stiffer response than a 90° rotation.

DISCUSSION

It is encouraging to see that G_t values determined from triaxial compression tests and the back-analysis of field displacements are very consistent, as shown in Fig. 7. Both of them illustrate the rapid loss of the initially high linear elastic stiffness when strain exceeds a threshold of about 10^{-5}. This sharp onset of first yielding was not observed in published test results on other UK stiff soils such as London Clay and glacial till (Powell and Butcher, 1991). The threshold shear strain of 10^{-5} is a factor of 10 smaller than the reported value for natural overconsolidated Todi Clay which has a carbonate content of about 27% and plasticity index of 28% (Georgiannou et al., 1991). It was reported that the value of threshold shear strain for clays increased with plasticity index.

In addition, some published data of London Clay are shown in Fig. 7. It can be seen that the measured shear modulus of Gault Clay at very small strains is considerably higher than London Clay. This may be attributed to the carbonate content of the Gault Clay. For medium to relatively large strains, both clays exhibited a similar magnitude of shear stiffness, as expected. This is reminiscent the observations of Atkinson et al. (1990) on artificially cemented sand which was four times stiffer than uncemented sand at small strains, but which reverted to the stiffness of uncemented sand after modest straining.

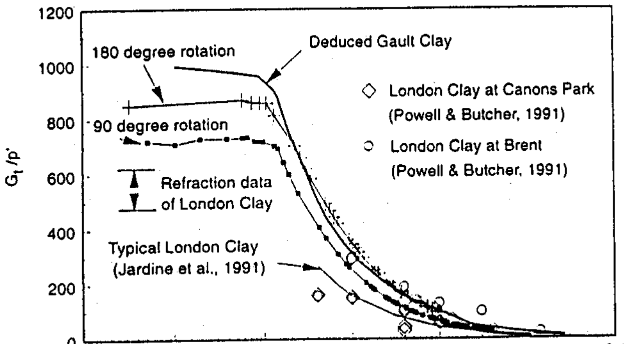

Fig. 7. Comparison of stiffness-strain relationship for Gault Clay and London Clay

Jardine et al. (1984) reported stiffness measurements at small strains for a range of soils. For Chalk and low plasticity clays, the measured normalized Young's modulus E_u over undrained shear strength c_u ratios are ranging from 2000 to 4500 at an axial strain of 10^{-5}. Assuming undrained and drained shear moduli are the same, one can express the observed stiffness of Gault Clay in terms of E_u/c_u. Following the assumption, the E_u/c_u ratio for Gault Clay at very small strain (less than the threshold value) can be found to be about 3000. This seems to suggest that calcium carbonate cementation of the Gault Clay causes it to behave like a low plasticity clay at very small strains, but that its stiffness reverts to that of a high plasticity clay at larger strains once the bonding has been broken.

CONCLUSIONS

The small strain stiffness of Gault Clay has been evaluated based on values deduced from geophysical measurements, from full scale field monitoring via finite element analysis, and from laboratory measurements. Shear stiffness determined from the seismic refraction method happened to correspond quite well with values deduced from field monitoring at very small strains, whereas Rayleigh wave determinations were much less stiff, possibly due to strong anisotropy of the clay. Triaxial tests on natural Gault Clay also corresponded well with the deduced values from field monitoring, and for the whole range of the "S-shaped" curve. In view of this evidence, it can be concluded that the stiffness-strain characteristic of Gault Clay is highly non-linear and exhibits first yield at a threshold shear strain of about 10^{-5}, beyond which the stiffness decreases drastically from an initially very high value. After modest straining the stiffness reduces to values comparable to those for London Clay. The Gault Clay behaves like a low plasticity clay at small strains but as a high plasticity clay at medium to large strains. It is proposed that this behaviour is due to the breakdown of the weakly cemented bonding caused by about 30% calcium carbonate content.

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