# Effects of sampling and construction stress paths on stress-strain properties of a sand

B. K. MENZIES, H. SUTTON *

SUMMARY: On the basis of existing evidence a case in made for achieving similarity between the laboratory test model and the field prototype. The extent to which this similarity is both possible and necessary is explored in a series of tests on a normally consolidated coarse sand. The tests are carried out using an automatic programmable triaxial test system where a desktop computer is used to log and process test data and to control the test to allow the simultaneous application of varying axial and radial stresses to simulate a field loading construction stress path. The insitu soil is modelled by carrying out $K_o$ consolidation in the conventional triaxial cell. The effects of undrained total stress relief sampling disturbance is examined together with the effects of isotropic and anisotropic reconsolidation and the application of an idealised construction stress path measured at the site of an embankment dam.

## Introduction

In the prediction of ground movements induced by construction, deformation moduli are used as design parameters in an elastic analysis. These moduli may be measured in the triaxial compression test in order to provide data at the design stage. The laboratory test model, however, does not simulate closely the field prototype. For example, back-analysing the undrained Young's modulus from field observations of large scale tests and actual structures in London clay and correlating these values with those obtained from corresponding triaxial compression tests have shown that the laboratory measured moduli are significantly in error, the disparity being ascribed to the cumulative effects of scale, stress level, sampling disturbance, machine interference and an isotropic starting state of stress in the laboratory tests [MARSLAND, 1971; ATKINSON, 1974].

The advent of improved analytical methods such as finite element stress analysis incorporating anisotropy and non-homogeneity of soil parameters have increased greatly the degree of similitude between analytical models and the field prototype. The full exploitation of these powerful analytical techniques requires the prior provision of realistic field parameters and where such parameters are not available from back-analysis, parametric studies only may be carried out at the design stage. There is a clear need therefore to develop laboratory testing techniques which achieve comparable similarity between the test model and the field prototype as exists between the analytical model and the field prototype [MENZIES, 1976].

This paper seeks to explore the extent to which such similarity is both possible and necessary; and to demonstrate the capacity of equipment now in use to carry out accurate stress-path testing.

## The influence of stress history on laboratory measured soil properties

The stress history of an undisturbed (¹) test specimen of soil tested conventionally in the triaxial cell includes the stress changes in the parent soil due to the presence of the borehole changing the stresses locally within the soil mass together with any local residual stress changes caused by driving the hole and its casing, the complete removal of total stresses on extrusion and trimming in the laboratory, normally followed by an isotropic increment in total stress by applying cell pressure, normally followed by a monotonic increase in axial total stress only. The conventional triaxial test model is thus subjected to a loading sequence which does not occur in the soil in the field where vertical and horizontal construction stresses vary similtaneously and total stress removal occurs only adjacent to tunnels, cuts and excavations. Since the behaviour of soil under load is stress path dependant [WROTH, 1975], measurements of conventional triaxial test model performance are unlikely to produce data applicable directly to the field prototype.

While the physical disruption associated with sampling can be minimised by utilising good sampling techniques [SIMONS *et al.*, 1975; SIMONS, 1967; WARD *et al.*, 1959; SKEMPTON *et al.*,

---

* University of Surrey, England.

(¹) As pointed out by DAVIS and POULOS [1967], if it were not for established usage, undisturbed samples would be better termed constant-moisture-content samples.

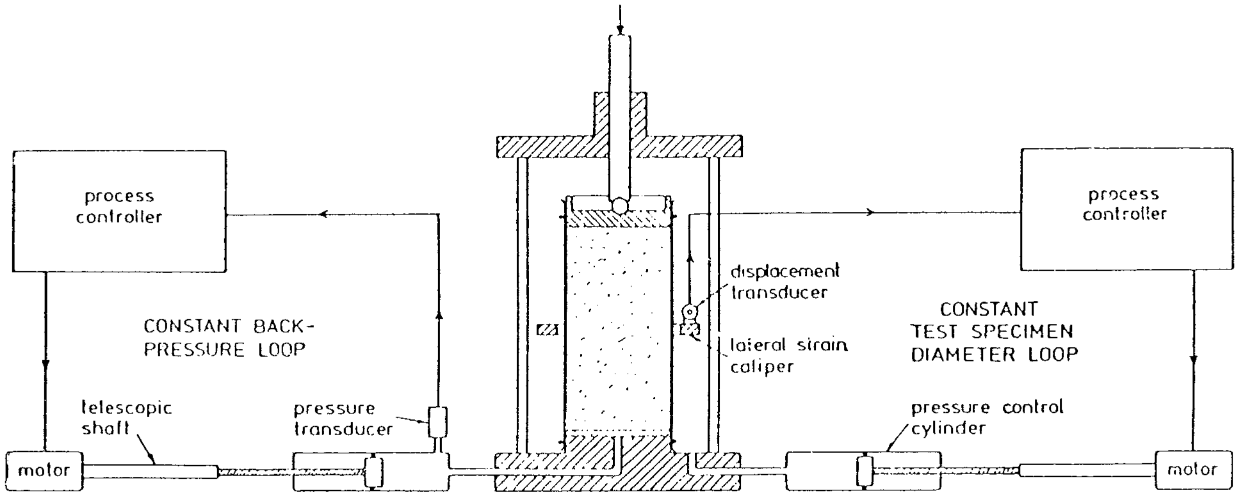

Fig. 1. - Control system to simulate $K_0$ consolidation and $K_0$ swelling in the triaxial cell [after MENZIES *et al.*, 1977].

1963] the sampling disturbance due to stress relief is unavoidable. Stress relief sampling disturbance has a marked influence on the undrained deformation moduli of soft clays, for example, but values close to the field parameters may be obtained provided the test specimens are reconsolidated to the insitu stresses [WROTH, 1975; LADD, 1964].

There is thus a good case, both intuitively and on the evidence, for mitigating the effects of sampling restoring the insitu stresses to the test specimen. Logically, if the stress state is restored to the beginning of the field construction stress path, this path should not then be abandoned by carrying out a conventional compression test. Furthermore, if the effects of the non-field stress path of sampling stress relief are detrimental and require remedial measures, it follows that the non-field stress path of the conventional compression test probably has a similarly detrimental effect also requiring remedial measures. Accordingly, having restored the insitu stresses, the degree of similitude achieved with the field condition should logically be sustained by then following the field construction stress path.

The way in which such a test procedure may be implemented and the degree of field simulation necessary for the laboratory test to adequately model the field prototype will now be considered.

## The influence of degree of field simulation in the triaxial test

The following describes the equipment used and the testing programme followed which allowed a study to be made of the influence of degree of field simulation on the stress-strain properties of a coarse sand tested in the conventional triaxial cell.

### *$K_0$ Consolidation and Swelling*

The system is shown diagrammatically in Fig. 1. Changes in test specimen diameter are detected by a lateral strain caliper [MENZIES, 1976] which is linked to a process controller which in turn operates a cell pressure servomechanism thus forming a control loop. The servomechanism consists of a pressure control cylinder driven through a telescopic shaft by an electric motor and a gearbox.

The process controller is an electronic device in which a reference signal may be set. This reference signal is compared with a feedback signal and the difference or error is found. The process controller is sensitive to the magnitude of the error and to its polarity. If the error exceeds a pre-set level the system is driven until the error is eliminated, this null position being attained without overshoot.

The process controller may be operated by a feedback signal from any electrical transducer monitoring the quantity to be controlled. It may be used to link a pressure transducer to the cell-pressure or back-pressure servomechanism enabling the arrangement to function as a constant pressure system. In the tests described in this paper a back pressure system of this type was used (Fig. 1) having an accuracy of within 0.1% of the full pressure range of 1000 kPa. Using the process controller to link an axial load cell to the motorized triaxial laoding frame enables this arrangement to operate as a constant axial load system. The process controller is set to local mode for these operations and the required constant pressure or constant load may be directly dialled in appropriate units on a for figure digital switch scales the reference signal. Switching the process controller to remote mode passes the control of cell pressure, back pressure and axial load to an external reference source such as a desktop computer.

When automatically simulating $K_0$ consolidation or $K_0$ swelling in the conventional triaxial cell the feedback signal to the process controller operating the cell pressure servomechanism is the output of a displacement transducer bridging the opening of a lateral strain caliper. The reference signal is set as the transducer output prior to the axial loading change. When the axial loading changes, the diameter of the test specimen changes. This change is detected by the lateral strain caliper giving a feedback signal above or below the reference value whereupon the process controller drives the cell pressure servomechanism. As the cell pressure changes, the diameter of the test specimen is corrected until the error signal is eliminated. In this way the test specimen diameter is kept within a set tolerance. On maximum sensitivity the system limits changes in test specimen diameter to less than ± μ [MENZIES *et al.*, 1977].

### *Programming Generalised Stress Paths*

The Automatic Programmable Triaxial Test (APTT) has been developed in order that any stress path theoretically possible in the triaxial cell may be achieved in testing practice. Thus quite complex stress paths may be followed. The stress paths may simulate construction stresses or may be generalised to explore fundamental soil behaviour. This has been made possible in the APTT system by controlling the test servomechanism from a desktop computer via process controllers. The computer also monitors the test specimen stresses and deformations. The system is automatic as well as programmable, the process controllers enabling automatic control of cell pressure, back-pressure and axial load independently of the desktop computer and ancillary instruments.

The equipment is arranged in a control loop as in Fig. 2. Test output parameters are measured by transducers monitoring axial load, cell pressure, back-pressure, axial deformation, radial deformation and test specimen volume

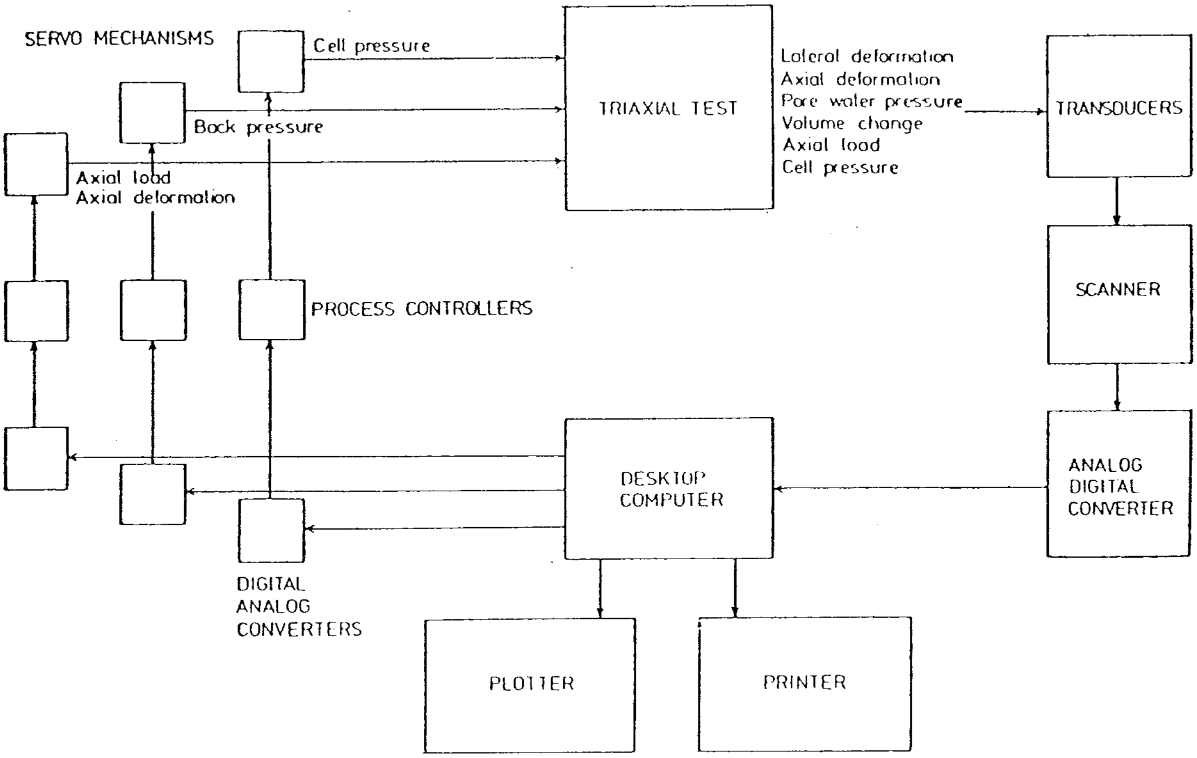

Fig. 2. - Automatic Programmable Triaxial Test (APTT) system control loop [after MENZIES *et al.*, 1979].

change. These analogue outputs are periodically switched in turn to an analogue-digital converter by a scanner controlled by the computer. The resulting digital information is passed into the computer along the interface bus which links the computer with all the pepherical instruments. On the basis of the updated information the computer outputs digital instructions to the digital-analogue converters which output corresponding latched analogue signals to the process controllers controlling cell pressure and axial load. These analogue reference signals are scaled to correspond to an appropriate point on the programmed stress path. Accordingly, the servomechanisms generating cell pressure, back-pressure and axial load are automatically driven to give measured feedback signals which correspond to the applied reference signals. In this way the applied stress path is constrained to coincide with the programmed stress path to a high degree of precision [MENZIES *et al.*, 1979]

### *The Testing Program*

The testing program is summarised schematically by the chart given in Fig. 3 and consists of a series of triaxial tests on normally consolidated sand. The tests were carried out on 100 mm. diameter by 200 mm high test specimens of saturated coarse Ripley sand, a rounded alluvial sand from the river terrace of the River Wey at Ripley in Surrey. The test specimens were prepared in a loose state by depositing the sand through water [BISHOP *et al.*, 1962] giving an initial porosity of approximately 40%. After preparation, the test specimen was subjected to an isotropic effective stress of 20 kPa.

It may be seen from Fig. 3 that the essential preliminary to all tests was a $K_0$ consolidation stage under conditions of zero radial strain whereby the insitu soil was modelled and the value of $K_0$, the ratio of the horizontal effective stress to the vertical effective stress, was established.

With the exception of the modelled field loaded insitu soil (test type 1), the next stage in the procedure was undrained perfect sampling by stress relief to zero total stresses. This was followed by either isotropic or anisotropic reconsolidation. Volume change was measured by an electronic volume change device [MENZIES, 1975].

Various test programs were implemented as follows (Fig. 3):

### Test Type I

Here the construction laoded insitu soil was modelled by applying the field total stress path to the $K_0$ consolidated test specimen to give a

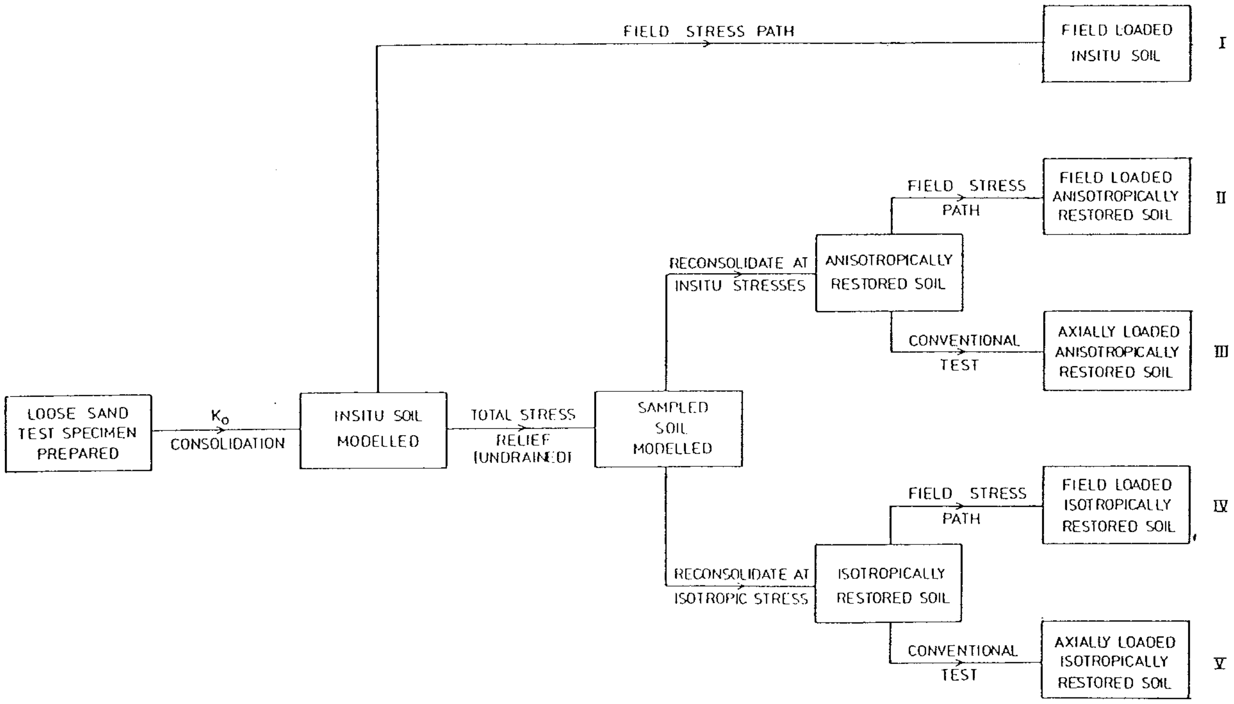

Fig. 3. - Testing programme chart.

continuous path. This test provided the basis of comparison with the other test types. The full stress path is plotted in Fig. 4. The construction total stress path simulated in the tests described in this paper was that measured at the Balderhead Dam [VAUGHAN, 1972]. The computer was programmed with an idealised linear stress path which omitted the discontinuity due to the winter shut-down period.

### Test Type II

Here the insitu soil was perfectly sampled by total stress relief under undrained conditions. After a brief period of aging, the previous insitu total stresses were reimposed to anisotropically restore the stress state and the pore water duct opened to the back-pressure applied during K₀ consolidation. The field total stress path was then applied in both the undrained and the drained modes. The path is plotted in Fig. 5.

### Test Type III

Here the anisotropically reconsolidated test specimen was subjected to a conventional triaxial compression test where the axial total stress only was monotonically increased in both the undrained or drained modes. The path is plotted in Fig. 5.

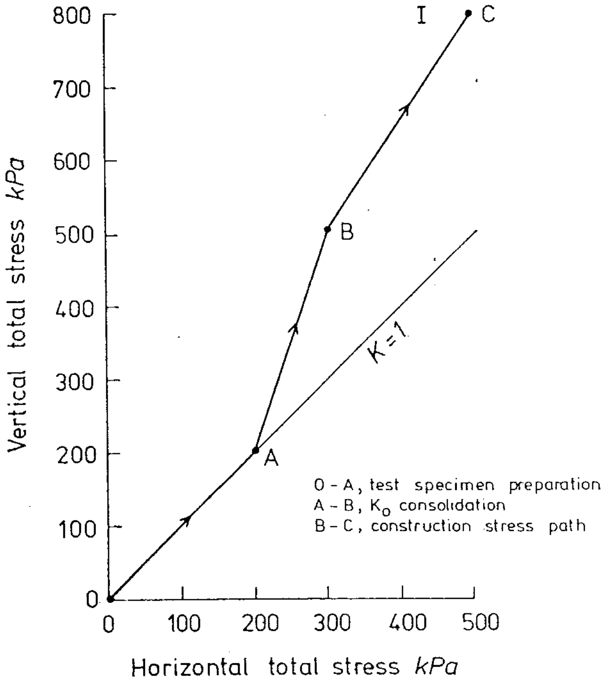

Fig. 4. - Stress paht for test type I, modelling insitu soil.

### Test Type IV

Here the perfectly sampled soil was reconsolidated by applying an isotropic increment in total stress by increasing the cell pressure to two-thirds the previous vertical total stress. The field total stress path was the applied in both the undrained or drained modes. The path is plotted in Fig. 6.

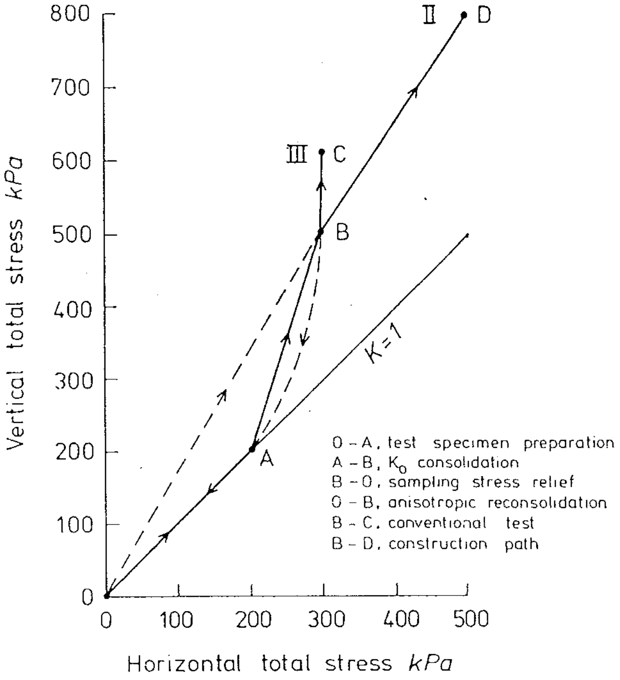

Fig. 5. - Stress paths for types II and III.

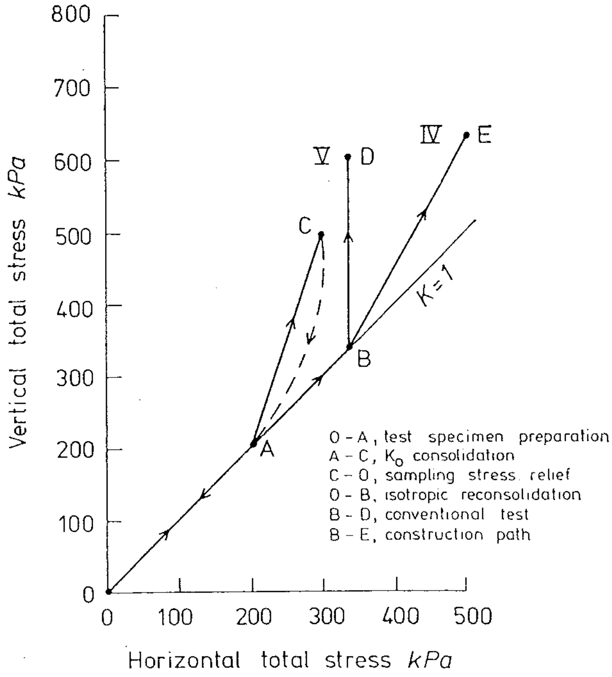

Fig. 6. - Stress paths for test types IV and. V.

Test Type V

Here the isotropically reconsolidated test specimen was subjected to a conventional triaxial compression test in both the undrained or drained modes. This test type simulated the stress history of test specimens sampled and tested in the usual way. The path is plotted in Fig. 6.

### *The Results*

The results are given in Figs. 7, 8 and 9 and in Table 1 and correspond to the final portion of each of the five types of test stress path i.e. starting from point « B » in Figs. 4, 5, and 6.

### *Undrained Behaviour*

It may be seen from Fig. 7 that the stress-strain relationships approaching most closely to the modelled insitu undrained behaviour (test type I) are those for the tests where the soil was anisotropically reconsolidated to the modelled insitu stresses (test types II and III). The stress strain relationships for the tests where the soil was isotropically reconsolidated (test types IV and V) show the greatest divergence from the modelled insitu behaviour. The

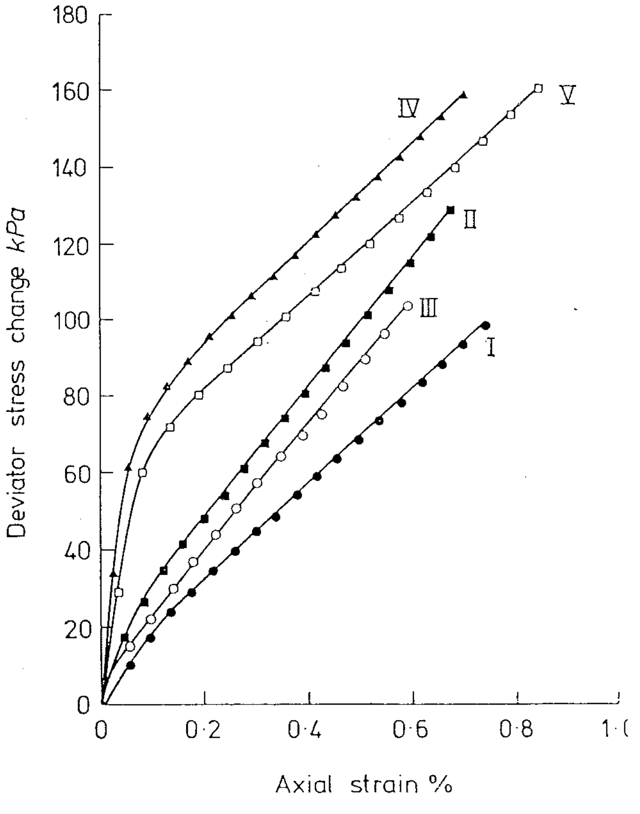

Fig. 7. - Undrained deviator stress change from point B (Figs 4, 5, 6) versus axial strain curves for the types I, II, III, IV and V.

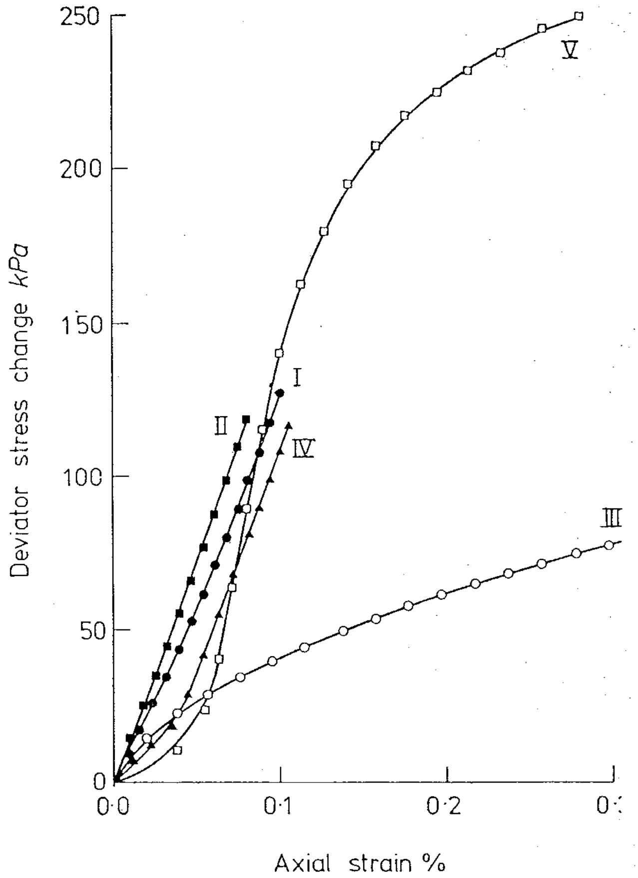

Fig. 8. - Drained deviator stress change from point B (Figs. 4, 5, 6) versus axial strain curves for test types I, II, III, IV and V.

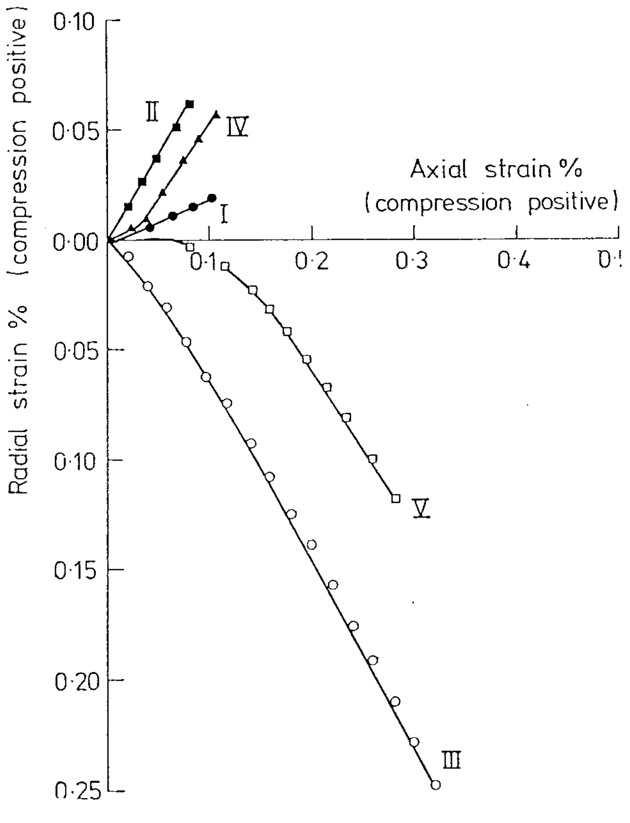

Fig. 9. - Strain paths from point B (Figs. 4, 5, 6) for test types I, II, III, IV and V.

computed deformation moduli given in Table 1 confirm this. Following the construction stress path, however, has little effect, the undrained soil behaviour being dominated by the type of reconsolidation.

### *Drained Behaviour*

It may be seen from Fig. 8 that the stress-strain relationships approaching most closely to the modelled insitu drained behaviour (test type I) are those for the tests where the construction stress path is followed (test types II and IV) irrespective of wheter the soil was isotropically or anisotropically reconsolidated.

The stress-strain relationships for the tests where the conventional triaxial compression stress path was followed (test types III and V) show the greatest divergence from the modelled insitu behaviour. This is perhaps most clearly shown in the strain path of Fig. 9. Here the conventional test leads to radial exstension as the test specimen bulges merkedly against a constant cell pressure. Conversely, the construction stress path tests give radial compression as the test specimen necks slightly under the monotonically increasing cell pressure.

The deformation moduli given in Table 1 confirm that the reconsolidation conditions have little effect, the drained soil behaviour being dominated by the type of stress path followed.

## Conclusions

The drained triaxial test may produce stress-strain relationships for coarse sand approaching closely the simulated field relationships under construction loading provided the construction stress path is applied in the test.

TABLE 1

DEFORMATION MODULI

| Test Type | Young's Modulus (MPa) | | Poisson's Ratio |
|---|---|---|---|
| | Undrained | Drained | |
| I | 13.5 | 214 | 0.23 |
| II | 19.6 | 283 | 0.175 |
| III | 17.6 | 25.3 | 0.434 |
| IV | 39.2 | 190 | 0.278 |
| V | 27.8 | 122 | 0.295 |

*Note*: Moduli computed as equivalent secant values for deviator stress change of 100 kPa.

The resulting stress-strain relationships are unaffected by whether or not the test specimen is isotropically or anisotropically reconsolidated prior to testing. POULOS [1978] found a similar sensitivity to reconsolidation conditions for drained moduli of Sydney Kaolin determined from the conventional triaxial test. In this respect therefore, Ripley sand models the drained behaviour of a clay.

The tests described in this paper were carried out on a normally consolidated coarse sand and the results and conclusion apply specifically to that soil.

The results show, however, that for the undrained triaxial test to produce stress-strain relationships for coarse sand approaching closely to the simulated field relationships under construction loading, the test specimen must be anisotropically reconsolidated to the modelled insitu stresses. In this respect, therefore, Ripley sand models the undrained behaviour of Boston Blue Clay [LADD, 1964] and Sydney Kaolin [DAVIES *et al.*, 1967].

A triaxial testing system has been developed which enables the application of any stress path possible in the triaxial cell including $K_o$ consolidation and $K_o$ swelling. The system in made up of commercially available devices which are arranged in a control loop with the conventional triaxial cell.

### ACKNOWLEDGEMENT

The authors are grateful for the support of the Science Research Council, and for the help and encouragement of Mr. R. E. Davies and Professor N. E. Simons.

### SOMMARIO

**Effetto della simulazione del campionamento e del percorso di sollecitazione sulle proprietà di una sabbia**

Come è noto, il modello sperimentale che generalmente viene adottato per la previsione delle deformazioni indotte nel sottosuolo da carichi esterni non riproduce perfettamente il comportamento del prototipo reale. Tale modello è basato sull'esecuzione di prove triassiali di tipo convenzionale (applicazione separata della componente sferica e della componente devatorica delle tensioni) che consente di determinare il valore del modulo di Young da introdurre nelle note espressioni fornite dalla teoria dell'elasticità.

Quanto tale procedimento risulti insoddisfacente viene mostrato dal confronto fra i valori del modulo di elasticità dedotti con tale procedura e quelli ricavati dai risultati di indagini su modelli in grande scala o su opere in vera grandezza; valgano in proposito i risultati delle esperienze effettuate circa i valori del modulo di elasticità non drenato dell'argilla di Londra. Le cause di tali divergenze vengono fatte risalire ad una serie di fattori connessi con il disturbo del campionamento ed alla particolare storia

tensionale subita dai privini che vengono sottoposti alle prove di laboratorio.

Con il diffondersi di modelli analitici sempre più sofisticati che, ad esempio, possono portare in conto la non linearità, l'anisotropia e la eterogeneità dei terreni, e permettono quindi di simulare in maniera sempre più soddisfacente l'effettivo comportamento delle opere, è cresciuto il bisogno di parametri più affidabili da ricavare con un'adeguata sperimentazione. In particolare, se l'uso di adatte tecniche di campionamento può minimizzare il disturbo connesso con tale operazione, è necessario che adeguate procedure sperimentali consentano una simulazione più aderente al vero dell'effettivo percorso di tensioni cui il terreno in sito è assoggettato a seguito dell'applicazione dei carichi.

Nel presente lavoro si illustra come tale problema possa essere affrontato; sulla base di una serie di risultati sperimentali viene inoltre discusso il grado di simulazione necessario affinché il modello sperimentale riproduca in maniera adeguata il comportamento del prototipo.

L'apparecchiatura adottata è completamente automatica e programmabile (Automatic Programmable Triaxial Test) e permette di eseguire prove triassiali secondo percorsi di sollecitazione qualsiasi.

Un piccolo calcolatore registra i valori delle varie grandezze in gioco (componente sferica e deviatorica delle tensioni, back pressure, deformazioni radiali ed assiali del provino) attraverso un controllore di processo collegato all'apparecchatura trassiale vera e propria mediante trasduttori. L'interazione con tale controllore di processo viene assicurata mediante uno scanner ed un convertitore analogico-digitale. Il calcolatore ha inoltre la possibilità di controllare ed eventualmente variare i percorsi di sollecitazione mediante servomeccanismi collegati al controllore di processo.

Un programma di indagini sperimentali su provini (diametro 100 mm; altezza 200 mm) di sabbia grossa di origine fluviale ha permesso di controllare l'influenza sul comportamento di tali materiali della storia tensionale e dei percorsi di sollecitazione.

I provini di sabbia, dapprima consolidati isotropicamente ad una pressione di 20 KPa e successivamente consolidati in condizioni $K_o$ a valori più elevati della pressione, sono stati sottoposti a diversi percorsi di sollecitazione; ciò ha consentito di verificare, attraverso simulazione, l'influenza del camponamento e della storia tensionale successiva (che può essere diversa in funzione delle modalità di prova prescelte) sulla risposta di tali materiali.

Il programma sperimentale può essere così schematizzato (fig 3):

1. Riproduzione del percorso di sollecitazione relativo alla costruzione di un'ipotetica opera (si è fatto riferimento a quello msurato nel corso della realizzazione della diga di Balderhead); ciò ha consentito di effettuare confronti con i risultati delle prove simulanti il campionamento e le successive operazioni di laboratorio;

2. annullamento delle tensioni totali in condizioni non drenate (campionamento perfetto); riconsolidazione anisotropa e successivo percorso delle sollecitazioni analogo a quello dovuto alla costruzione;

3. Come il 2, ma con esecuzione di una prova triassiale di tipo convenzionale dopo la riconsolidazione anisotropa;

4 e 5. Come il 2 e 3, ma con consolidazione isotropa.

L'interpretazione dei risultati in termini di pressioni totali mostra come il comportamento dei terreni è in primo luogo influenzato dal tipo di consolidazione effettuata in laboratorio (molto più efficace quella anisotropa); il successivo percorso delle sollecitazioni ha invece scarsa influenza sui risultati finali; tutto ciò, in condizioni non drenate. Al contrario, in condizioni drenate il tipo di consolidazione non esercita una grande influenza; il comportamento della sabbia risulta invece governato essenzialmente dal percorso delle sollecitazioni.

## REFERENCE

Atkinson J. H. (1974) - *Discussion on Session 4: the interpretation of field observations.* Proc. B.G.S. Symp. Field Instrumentation in Geotech. Engng. Part. 2, 677-679, Butterworths, London.

Bishop A. W., Henkel D. H. (1962) - *The measurement of soil properties in the triaxial test.* Edward Arnold (Publishers) Ltd., London, 228p.

Davies E. H., Poulos H. G. (1967) - *Laboratory investigations of the effects of sampling.* Civil Engineering transactions. the Institution of Engineers, Australia, Vol. CE9, N. 1, 86-94.

Ladd C. C. (1964) - *Stress-strain modulus of clay in undrained shear.* Jnl. Soil Mech. & Foundn. Div., ASCE, Vol. 90, N. SM5, pp. 103-132.

Marsland A .(1971) - *Laboratory and insitu measurements of the deformation moduli of London clay.* Proc. Symp. Interaction of Structure and Fundn., Midland Soil Mech. and Foundn Engng. Soc., University of Birmingham, 7-17.

Menzies B. K. (1975) - *A device for measuring volume change.* Geotechnique *25*: 1, 1975, 133-134.

Menzies B. K. (1976) - *Discussion: Design manufacture and performance of a lateral strain device.* Geotechnique *26*: 3, 1976, 542-544.

Menzies B. K. (1976) - *Strenght, stability and similitude.* Ground Engng. *9*: 5, 32-36.

Menzies B. K., Sutton H., Davies R. E. (1979) - *A control stem for automatically simulating $K_o$ consolidation and $K_o$ swelling in the conventional triaxial cell.* Geotechnique *27*: 4, 1977, 593-596.

Menzies B. K. Sutton H., Dovies R. E. (1979) - *A control system for programming stress paths in the triaxial cell.* Ground Engineering (to be published).

Poulos H. G. (1978) - *Normalised deformation parameters for Kaolin.* Geotechnical Testing Journal, ASTM, *1*: 2, 102-106.

Simons N. E. (1967) - *Discussion: Proc. Geotech. Conf. Oslo Session 2.* Shear strenght of stiff clay, 159-160.

Simons N. E., Menziès B. K. (1975) - *A short course in foundation engineering.* Newnes-Butterworth, London, 159p.

Skempton A. W., Sowa V. A. (1963) - *The behaviour of saturated clays during sampling and testing.* Geotechnique *13*: 4, 269-290.

Vaughan P. R. (1972) - *Undrained failure of clay embankments Stress-strain behaviour of solis.* Proc. Roscoe Mem. Symp., Cambridge University, G. T. Foulis & Co. Ltd., Henley-on-Thames, pp. 683-691.

Ward W H., Samuels S. G., Butler M. E. (1959) - *Further studies of the properties of London Clay.* Geotechnique *9*: 1, 33-58.