Archives of Hydro-Engineering and Environmental Mechanics
Vol. 49 (2002), No. 1, pp. 23–41

On the Measurement of Strains in the Triaxial Test

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(Received October 30, 2001; revised February 28, 2002)

Abstract

In the paper, various methods of measuring a sample strains in a triaxial test are analysed. Accurate determination of the deformation of a specimen in a triaxial compression test is of great importance for correct evaluation of soil strain-stress characteristics, particularly in the pre-failure stress state in the range of small strains. In the paper, three different methods of measuring axial strains are analysed and discussed. Two consider the measurement of relative movement between top cap and base pedestal of the triaxial cell, the third being based on the direct measurement of local axial deformation of the sample tested. The measurement of radial strains is also discussed in respect of the corrections introduced for the specimen's bulging. To analyse various methods of strains measurements tests on diverse materials such as sand, steel and rubber were carried out, enabling the evaluation of the efficiency and accuracy of the measurement methods applied.

1. Introduction

Conventional triaxial tests on soils usually serve to determine the strength characteristics of the material tested. Strength parameters are normally evaluated from the analysis of stress paths in stress space and the response of the material in the form of corresponding strains is not so significant. However, accurate determination of the strains' value becomes important for modelling of the soil's behaviour in the pre-failure stress state, or for the accurate determination of soil stiffness, which is difficult to achieve in routine laboratory testing. Additionally, for "soft" soils (loose sands or soft clays) in which the shearing phenomenon is not so noticeable, strains can be used as an indicator of the material's yielding level. Thus, accurate determination of strains developing within the sample when subjected to various stress paths, becomes very important, in some cases.

Conventionally, the measurement of vertical strains is based on external measurements of displacement of either the piston or pedestal of the triaxial apparatus, depending on the type of device used. However, such measurement may differ significantly from true soil response, due to a number of extraneous movements. The

source of these movements can be divided into two main groups (Jardine et al., 1984). The first is related to the compliance of loading and load measuring systems. The second group concerns errors arising from the proper preparation of a sample and its subsequent loading. The latter are usually included in the term known as sample bedding effects.

Taking into account the fact that external measurement of vertical strains includes some movements which do not correspond to true shortening or elongating of the sample determined in this way, the stress-strain characteristic does not correspond to the field behaviour of the material tested. This is particularly visible and important in the range of small strains of the order of 10^{-3} and less.

The problem of accurate measurements of axial displacement of the sample in the triaxial test has long been recognised and many experimental researchers have tried to solve it by diverse techniques, in order to improve the accuracy of strain measurements. One of the most popular and widely developing techniques relies generally on the measurement of relative displacement between two reference footings over the central length of a sample. The difference between the particular techniques is related to the diverse gauges used for this measurement (e.g. Costa Filho 1980; Jardine et al. 1984; Clayton and Khatrush 1986; Tatsuoka and Kohata 1995; Geoteko 2000). Most poplar now are the so-called LDTs (local deformation transducers) – (University of Tokyo, Japan), LVDTs (linear voltage digital transducers) – (Politecnico di Torino, Italy), proximity transducers (Ecole Nationale des Travaux Public de l'Etat, France, Geoteko, Poland) or Hall Effect gauges (GDS Instruments Ltd.), see Tatsuoka et al. (1999); Clayton and Khatrush (1986); Geoteko (2000). Detailed descriptions of all the gauges mentioned is beyond the scope of the subject of this paper and will thus not be discussed, here. Attention will be only focused on the Hall Effect gauge used in experiments described in subsequent Sections of the paper.

It should be noted that, although the new measurement techniques afford improvements and important results, they nevertheless have certain limitations such as small testing range or even damage, at larger strains, difficult systems of installation on samples, special installation techniques in the case of loose sands, very high costs, etc. This type of strains measurement is thus still unavailable for standard geotechnical laboratories.

The problem is similar in the case of the accurate determination of lateral strains. It becomes much more significant in the case of formulating general stress-strain relations, where knowledge of all strain tensor components' values is indispensable.

Lateral strains are usually evaluated either by measuring the change in the diameter of a sample directly or by calculating from externally or locally measured axial strains and volume changes obtained from the amount of water expelled from or sucked into a water saturated specimen. Direct measurement is normally

performed by using the same gauges which serve to measure axial deformation of a specimen.

The problem of accurate determination of a specimen's deformations has also been faced in the geomechanical laboratory of the Institute of Hydroengineering during triaxial testing of various types of sands. The tests were carried out within the framework of a comprehensive experimental programme realised in the Institute in 2000–2001, concerning the experimental identification of plastic strains tensor of non-cohesive soils from the triaxial test. The experiments were made using a computer controlled hydraulic triaxial testing system from GDS Instruments Ltd. (UK), with triaxial cell based on Bishop & Wesley design.

To evaluate efficiency and reliability of measurements of a specimen's strains by various methods, a special testing programme has been carried out. The tests were made on steel, rubber and sandy samples, the latter – both dry and fully saturated. The results of tests enabled the assessment of the influence of various factors such as compliance of the testing system used and bedding errors affecting the values of strains measured, as well as the determination of correction coefficients for external measurement of axial strain. The efficiency of the measurement of lateral strains by local gauge installed in the middle of the sample's height has been verified by comparing the value measured with that obtained from pore water volume change. Some correction coefficients correcting "barrel" deformation of a specimen into equivalent "cylinder" deformation were also analysed and determined. The aim was the elaboration of a proper testing technique and reliable system of measuring of strains in the triaxial test.

2. Brief Description of the Triaxial System and External Measurement of Vertical Deformation

A detailed description of a computer controlled hydraulic triaxial testing system from GDS Instruments Ltd. can be found elsewhere (Menzies 1988; Świdziński 2000a). In the paper the description has been limited to the basic elements of the system and some construction details directly related to the measurement of axial and radial strains.

The most important part of the system is Bishop and Wesley's triaxial cell for controlled stress path testing, linked to a desktop computer via three microprocessor controlled hydraulic actuators called "digital pressure controllers". As shown in the schematic diagram in Fig. 1 the triaxial cell consists of a main cell for sample installation, loading cell fixed to the top of the cell during every test and integral lower pressure chamber. The axial force is exerted on the test specimen by the piston actuated hydraulically from an integral lower chamber in the base of the cell, which contains deaerated water. Axial force is measured by loading cell fixed to the top of the triaxial cell. Such a system of loading means that the

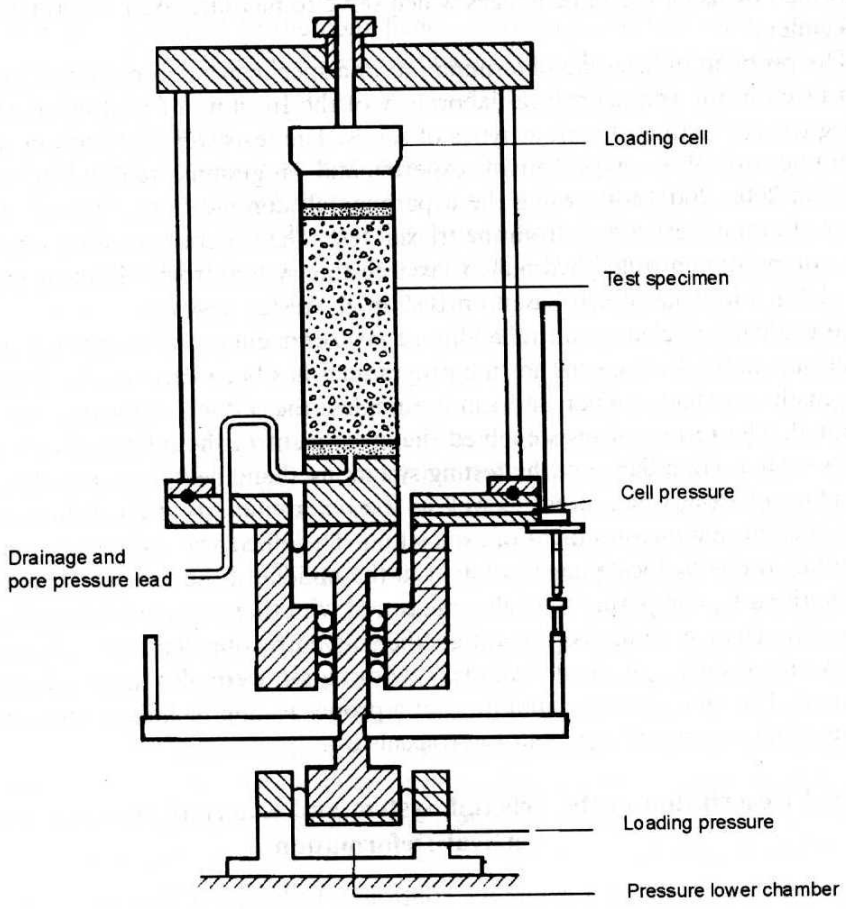


Fig. 1. Schematic diagram of the Bishop and Wesley's triaxial cell

specimen is not subjected to any vibrations which sometimes arise in the case of conventional loading frames.

The controllers regulate pressure and volume change of deaerated water supplied to the cell to control axial load or axial deformation, cell pressure, and back pressure with precision. The system is supplemented by a data acquisition system for collecting and transmitting all data to the computer with special software which enables automatic control of all operations made during the test.

The system of hydraulic forcing the piston movement vertically by digital pressure controller has been used for indirect measurement of vertical deformation. This method does not require any additional equipment, but however, has a significant disadvantage.

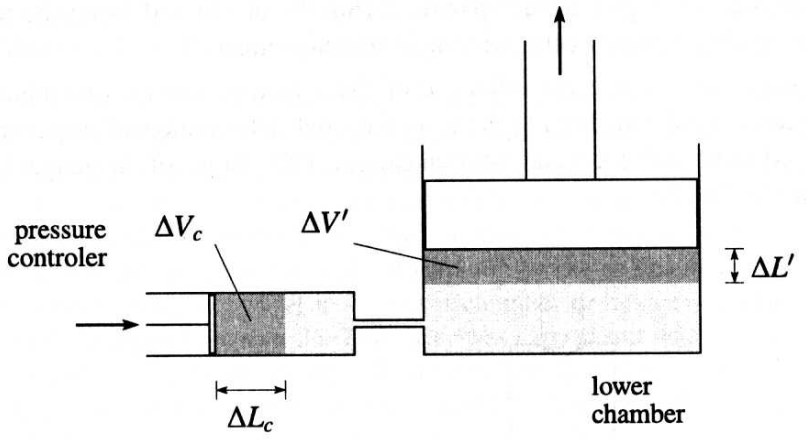


Fig. 2. Schematic view of the axial strain measurement in terms of volume change in the lower chamber

The principle of the axial strain measurement is schematically shown in Fig. 2. The pressure of liquid (p_d) in the lower chamber is controlled by a pressure controller in such a way as to achieve specific vertical stress acting on the sample. A microprocessor in the pressure controller can precisely measure the movement of the piston (ΔL_c) in the controller corresponding to the change of liquid volume $\Delta V_c = \Delta L_c \times A_k$, where A_k is the cross-section area of the controller cylinder (see Fig. 2). In this method it is assumed that if the liquid volume in the controller decreases by the amount ΔV_c, the same amount increases the volume in the lower chamber.

This measurement is based on the assumption of perfectly incompressible liquid in the lower chamber. According to this assumption, any change of volume that is accurately monitored by digital pressure controller should correspond to the change of height of the sample tested ($\Delta L' = \Delta L_c(A_k/A_T)$, where A_T is the cross-section of lower chamber). However, in practice, even very well deaerated water is not perfectly incompressible. It causes the volume change in the lower chamber to be higher than that corresponding to the vertical deformation of the sample. Thus, this is one of the sources of errors of such measurement technique.

Let us imagine that the sample subjected to vertical stress is perfectly rigid. In order to increase the pressure of water in the lower chamber the pressure controller piston moves to the right and the corresponding change of water volume is monitored. However, the piston in the lower chamber does not change its position, hence the monitored change of volume in the pressure controller will not correspond to the axial strain.

In addition, such external measurement of the axial strain of the sample may be influenced by deflection of the load cell, stretching of the triaxial cell due to

cell pressure, some play in the system moving the piston and fixing the load cell to the top of the triaxial cell and sample bedding effects.

In order to evaluate the influence of these factors, several preliminary tests have been carried out. During the tests the axial deformation of a specimen was measured using both local and external gauges. The scheme of the gauges installed is shown in Fig. 3.

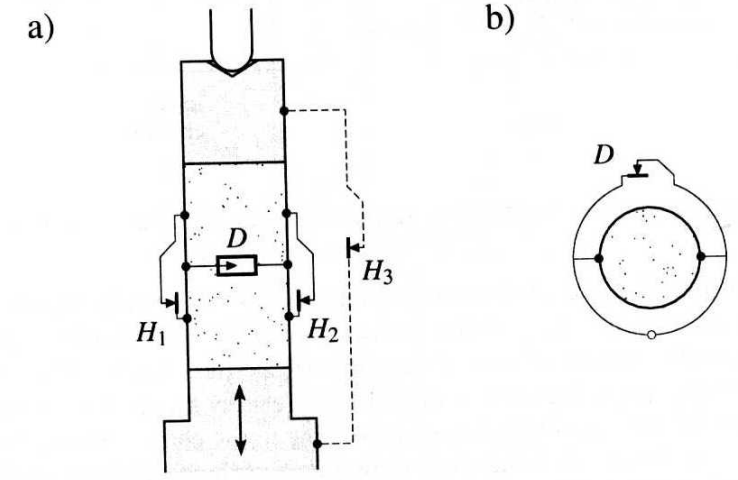


Fig. 3. Schematic view of the system of gauges installed on a sample for the measurement of its axial and radial deformation

The measurement of local axial deformation was taken in terms of special gauges equipped with semiconductors which make use of the Hall Effect. The gauge consists of two independent pads which are fixed to the specimen at an even distance from the middle of the sample height, either by pins or bonded to the membrane by adhesive. In the experiments performed, the second fixing method was used. In our case the distance between the centre points of pads was as high as 50 mm (for 80 mm high samples). The upper pad serves to hold the magnet assembly suspended from it whereas the lower one holds the linear output Hall Effect semiconductor. Axial deformation of a sample causes relative movement of the magnet along the semiconductor, which is recorded in terms of a data acquisition system and stored in the computer memory. Practical resolution of the semiconductor amounts to 1 μm what for a sample 80 mm high and with an average diameter of 38 mm, corresponds to a change of strain of the order of 10^{-4}.

3. Determination of Correction Coefficients for the Axial Strains Measured by Volume Change of Water in the Lower Chamber

The first series of the experiments aimed at the analysis of the influence of the compressibility of liquid in the lower chamber and compliance of the loading system and load measuring system (stretching of the triaxial cell, deflection of the loading cell, friction of bearings between lower chamber and triaxial cell, etc.).

In order to evaluate this influence, various tests on different materials have been carried out. In the tests, vertical deformation of the samples was measured either by volume changes of water in the lower chamber or by direct measurement of the height changes of the sample. The latter was carried out using a Hall Effect gauge adapted for the measurement of changes between the top cap and base pedestal (H_3 gauge in Fig. 3). Such a measurement technique does not, of course, eliminate bedding errors. However, the main goal of this series of tests was to isolate the first group of potential errors and to verify the efficiency and reliability of the axial measurement by volume change, only.

Let us denote the height changes of the sample measured by the Hall Effect gauge H_3 as ΔH. The difference between axial deformation measured by volume changes of water in the lower chamber and the changes of the sample height can be calculated as:

$$\delta H = \Delta V_c / A_T - \Delta H, \tag{1}$$

where A_T is the cross-section area of the lower chamber (see Fig. 2). It has been assumed that the difference described by Eq. (1) is mostly caused by two factors, namely: the compressibility of water in the lower chamber and pressure controller, and deflexion of load cell. The first factor is mainly induced by pressure changes Δp within the triaxial cell, whereas the second by changes of the axial force ΔF_z acting on the sample. The other factors such as stretching of the triaxial cell and friction are of less importance, but are also included in these coefficients. The above-mentioned relations can be summarised by the following formula:

$$\delta H = a \Delta p + b \Delta F_z, \tag{2}$$

where a and b are coefficients which have to be determined experimentally. For the sake of convenience the following units have been assumed: for pressures in kN/m^2 and force in kN. In order to have the unit of δH in μm, the respective units for coefficients a and b are m^3/kN $\times 10^{-6}$ and m/kN $\times 10^{-6}$.

For the determination of the coefficients from Eq. (2) in all tests, a dual system of vertical deformation measurement has been used.

The best way to determine coefficient a are tests with isotropic loading and zero axial load and for coefficient b, tests in which deviatoric loading predominates at zero changes of cell pressure. During isotropic compression, the mean stress $p = (\sigma_1 + 2\sigma_3)/3$ increases, whilst deviatoric stress $q = \sigma_1 - \sigma_3$ is equal to zero. σ_1 and σ_3 denote axial and radial stresses, respectively.

The coefficients a and b have been determined from the tests performed on a sample made of steel, which is assumed to be perfectly rigid material and does not undergo any deformation under the load applied. The sample of the dimensions 80 × 40 mm (the height and the diameter, respectively) was subjected to two stress paths. In the first case the sample was isotropically compressed to the pressure of 400 kPa and in the second only axial load was applied. The results of the typical test have been shown in Fig. 4. As can be seen, in both cases the experimental data have a linear form where the inclinations of approximating lines, determined by least square method, correspond to the value of coefficients a (isotropic compression – Fig. 4a) and b (shearing – Fig. 4b).

The same tests have been repeated for a sample of "Lubiatowo" dry sand, composed of fine, medium sub-rounded grains. The characteristics of this sand are summarised as follows: mean diameter $D_{50} = 0.25$, minimum void ratio $e_{\min} = 0.56$, maximum void ratio $e_{\max} = 0.83$, coefficient of uniformity $c_u = 1.5$, specific gravity $G_s = 2.65$. The initial density index of the sample was $I_D = 0.76$.

The average values of coefficients a and b for both materials tested are collated in Table 1.

Table 1. Average values of correction coefficients determined for two different materials

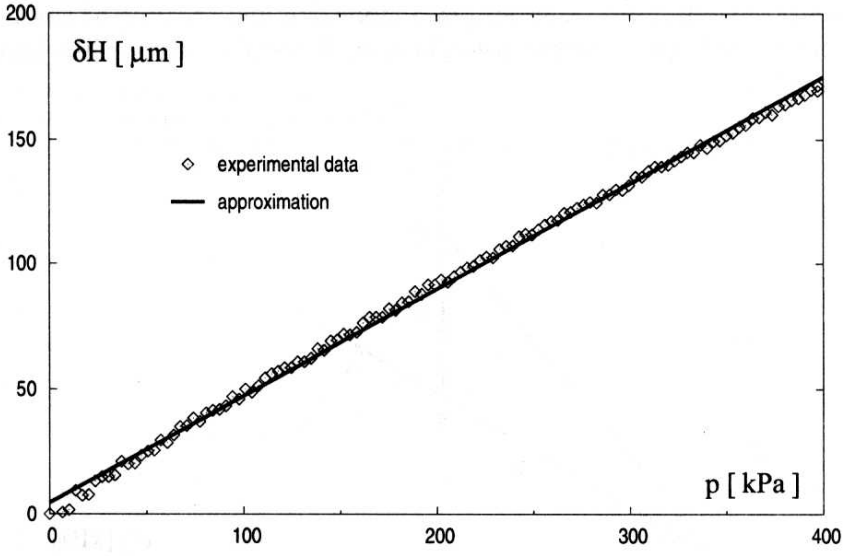
Material	a [10^{-6} m^3/kN]	b [10^{-6} m/kN]
Sand	0.385	160
Steel	0.45	164

Having determined the error δH of the external measurement by volume change, we can easily calculate true sample height changes using Eq. (1). However, one has to remember that it is still only an approximation.

4. Evaluation of the Influence of Bedding Errors on the Measurement of Axial Strain

In the tests discussed in the previous Section the measurement of axial deformation was restricted to that of the movement between the top cap and the base pedestal of a triaxial apparatus. Such measurement is, however, significantly affected by errors arising from the difficulty of providing perfectly plane, parallel and smooth ends on the test specimen, which are designated as bedding errors. In order to quantitatively evaluate its influence, the series of tests performed on sand were made. In the tests, axial deformation was measured by three independent gauges which are schematically shown in Fig. 3. Two of them were installed locally (gauges H_1 and H_2) and one (H_3) in the same way as in previous tests i.e. between the top cap and base pedestal. In all gauges the Hall Effect semiconductor was used. In addition, the external measurement by volume change in the lower chamber of the triaxial apparatus was also taken.

a)



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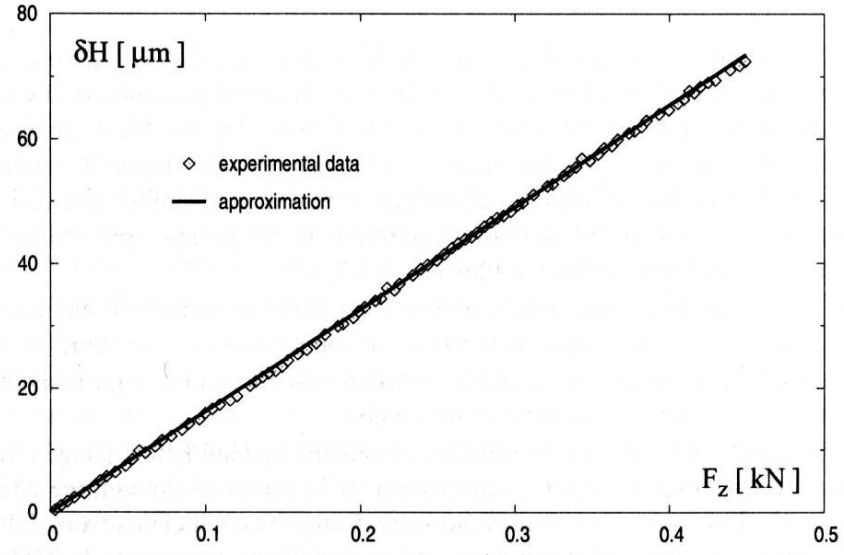

Fig. 4. The results of tests made on steel sample
(a) – isotropic compression, (b) – shearing at zero cell pressure

In order to evaluate the influence of bedding errors in various loading conditions the samples in this experimental series were subjected to diverse stress paths i.e. isotropic compression, anisotropic compression and shearing at constant cell pressure preceded by isotropic consolidation. Respective stress paths have been shown in Fig. 5.

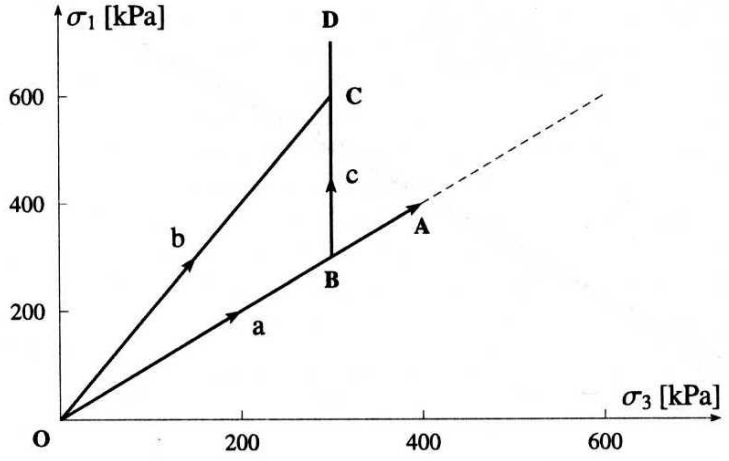

Fig. 5. Stress paths

All tests have been carried out on samples built of dense dry "Lubiatowo" sand with typical dimensions of 80 × 38 mm. In order to avoid preliminary disturbance of a specimen which might occur during installation of the local gauges, small negative pressure of 15 kPa was applied to the sample. This made it rigid enough to glue the pads to the rubber membrane freely and assemble the rest of the gauges. Such technique of sample preparation is of extreme importance in the case of loose and very loose samples ($I_D < 0.2$).

In Fig. 6 are shown the results of a test in which the sample of medium dense "Lubiatowo" sand was subjected to isotropic compression to the value of 400 kPa (path OA in Fig. 5). In the analysis standard soil mechanics sign convention is adopted where sign "+" denotes compression.

The results of local and external measurement by Hall Effect gauges was supplemented by corrected external measurement in terms of the volume change of water in the lower chamber (thin solid line), using the coefficients from Table 1. It can be seen that the axial strain measured externally is approximately 25% higher than the corresponding local vertical deformation of the sample. This difference is caused by bedding errors. It should also be noted that the difference between pure (thin dashed line) and corrected external measurements by volume change in the lower chamber is very high, in this case. However, the correction made

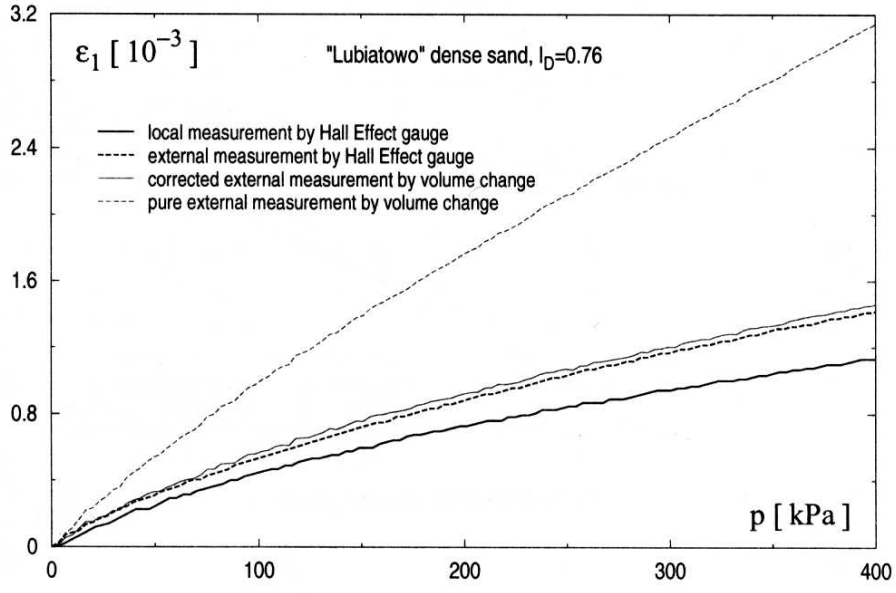

Fig. 6. The results of an isotropic compression test of a sandy sample with various axial strain measurement techniques

is very effective and the difference between two external measurements is rather small.

Changes of axial strains versus stress deviator q in anisotropic compression test are shown in Fig. 7. The stress path in this case approximately followed the K_0 line in the stress space (OC path in Fig. 5). The difference between the local and both external measurements of axial strain is relatively not so high as in the case of isotropic loading (9% approximately). Please note that the range of strains here is almost four times higher than in the previous case, which means that for larger strains the influence of bedding errors may not be so high.

Finally, Fig. 8 presents the results of a test in which a sandy sample was hydrostatically pre-loaded to the value of 300 kPa, sheared to the value of 700 kPa of axial stress at constant cell pressure (path OBD in Fig. 5) and then unloaded following the same stress path. The axial strains were presented in a function of stress deviator q. The influence of bedding errors is somewhat higher than in the former case, but lower than in the case of isotropic compression. It is clearly seen that the bedding errors affect the measurement of axial strains much more for small strain range and decrease for larger strains. However, the absolute values of bedding errors are very similar to each other for the same difference of axial stress.

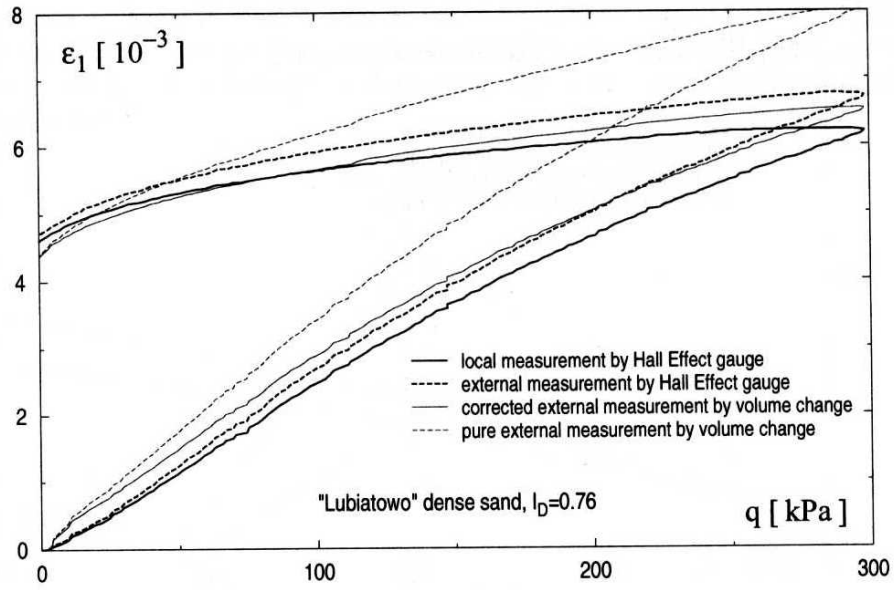

Fig. 7. The results of anisotropic compression of a sandy sample with various axial strain measurement techniques

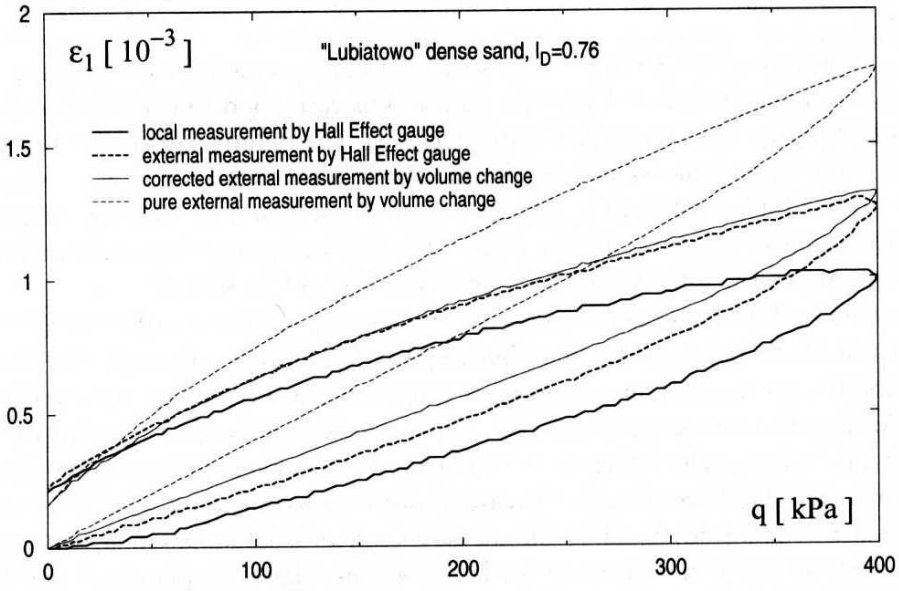

Fig. 8. The results of typical geotechnical shearing test in triaxial compression conditions

5. Measurement of Radial Strains

The measurement of radial strains was taken by local gauge which is also based on the Hall Effect semiconductor. The semiconductor, together with two diametrically opposed pads creates a kind of calliper, mounted in the middle part of the sample by adhesive, bonding the device to the rubber membrane, so any radial change of a sample causes movement of the magnet against the semiconductor (gauge D in Fig. 3b).

However, the local measurement of radial strain has disadvantage due to the fact that the soil sample may deform as a barrel, which means that the radial deformation of a sample is highest just at its middle and decreases towards the ends.

In order to analyse this problem, some tests on a rubber sample were made. The rubber was chosen due to its high deformability at relatively low levels of axial force. The sample of the dimensions of 80 × 40 mm, equipped in local axial and radial gauges was subjected to axial compression at constant cell pressure equal to 200 kPa.

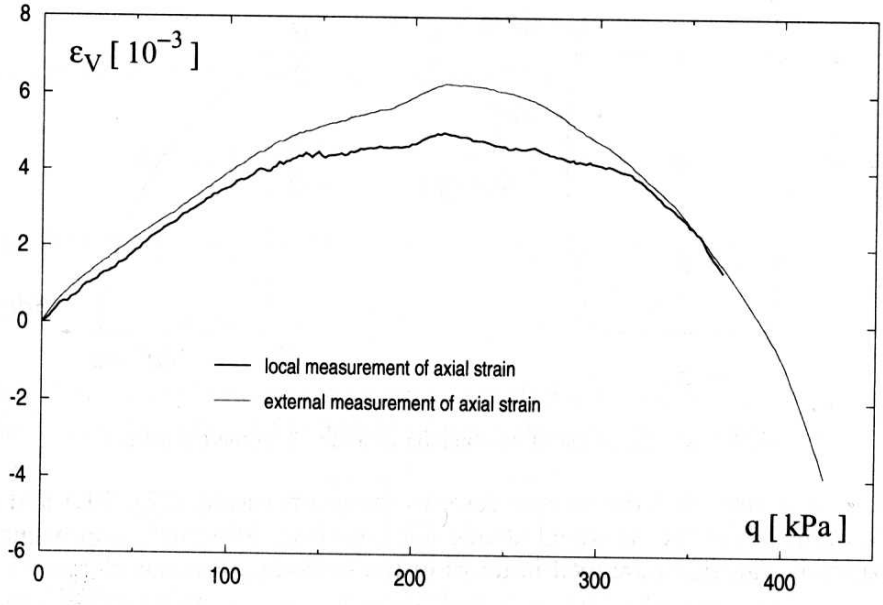

Fig. 9. Volume changes of a rubber sample subjected to axial load. The volume measured in terms of axial and radial deformations of the sample

The results of the test are shown in Fig. 9 where the volume change of the sample $\varepsilon_v = (\varepsilon_1 + 2\varepsilon_3)$ was plotted against stress deviator q (ε_1, ε_3 denote axial

and radial strains, respectively). In the test both local and external (by lower chamber volume change) measurements of axial deformation were taken.

It can be seen that the volume change calculated from the measurement of axial and radial strains cannot be accepted from the physical point of view. The permanent decrease of volume in this case rather should be expected, instead of the shape shown in Fig. 9. This decrease is visible for small deformations only and then the sample starts to increase in volume and at the maximum stress deviator the volume of the rubber sample is larger than the initial volume!

The main reason of such strange behaviour is related to the assumption that the sample deforms as a cylinder whereas it has a pronounced barrel shape. This means that the direct measurement of radial deformation taken by local gauge installed in the middle of a sample cannot be accepted without any corrections, especially for large strains. It should be noted that for a largest stress deviator both sample strains were of the order of 10^{-1}, in this case.

In order to analyse the problem of barrel deformation of a sample during its shearing in the triaxial test, let us the consider the schemes presented in Fig. 10.

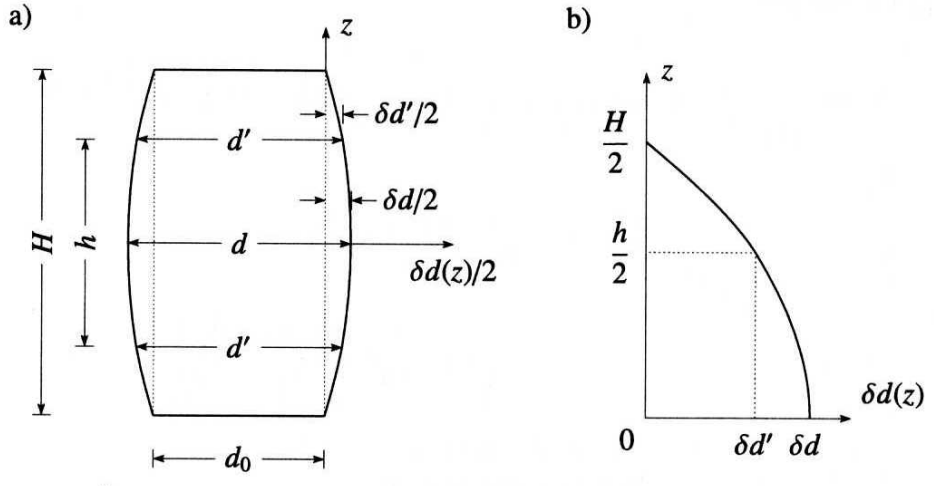

Fig. 10. Scheme of barrel deformation of a sample in the triaxial test

Let us assume that the sample deforms axi-symmetrically (Fig. 10a) and the shape of the half of the deformed sample side edge (Fig. 10b) can be approximated by parabolic function described in terms of the following formula:

$$\delta d(z) = \delta d \left[1 - \left(\frac{2z}{H} \right)^2 \right], \tag{3}$$

where z is an axis running along the non-deformable side edge of a sample, δd denotes the change in the diameter measured halfway along the sample height

($z = 0$) and H is the total initial height. It is also assumed that both ends of the rubber sample do not undergo any radial deformation. It directly follows from Eq. (3) that the diameter change $\delta d'$ at a point of the installation of axial strain gauges ($z = \pm h/2$) can be expressed as:

$$\delta d' = \delta d \left[1 - \left(\frac{h}{H} \right)^2 \right] = c \delta d. \tag{4}$$

Assuming that the ratio of h/H is constant during the test and equal to the ratio of initial heights ($H_0 = 80$ mm and $h_0 = 50$ mm) we have $c \cong 0.61$.

In order to relate the radial strain of the barrel halfway up its height with corresponding strain of equivalent cylinder let us consider the volumes of both solids. The volume of the parabolic barrel can be written in the following form:

$$V_b = \frac{\pi h}{60} \left(8d^2 + 4dd' + 3d'^2 \right)^2, \tag{5}$$

where d' is the diameter at level h (see Fig. 10a).

Let us find diameter d_c of the equivalent cylinder of the same volume and height. Thus, we have:

$$V_c = \frac{\pi h}{4} d_c^2 = V_b, \tag{6}$$

then for $d = d_0 + \delta d$ and $d' = d_0 + c\delta d$ we obtain:

$$d_c = d_0 \left(1 + \frac{2}{3} \frac{\delta d}{d_0} (c + 2) + \left(\frac{\delta d}{d_0} \right)^2 \frac{3c^2 + 4c + 8}{15} \right)^{1/2}. \tag{7}$$

If we then neglect the term $(\delta/d_0)^2$ and develop the root we have:

$$d_c = d_0 \left(1 + \frac{2}{3} \frac{\delta d}{d_0} (c + 2) \right)^{1/2} \cong d_0 + \delta d \frac{c + 2}{3}. \tag{8}$$

Thus, the relation between respective radial strains of barrel ε_{db} and equivalent cylinder ε_{dc} measured at the middle of a sample takes the following form:

$$\varepsilon_{dc} = \frac{\delta d}{d_0} \frac{(c + 2)}{3} = \varepsilon_{db} \frac{c + 2}{3} = \varepsilon_{db} f. \tag{9}$$

In our case, if we consider the whole sample height (external measurement of axial deformation, $c = 0$), the coefficient $f = 0.67$, whereas for deformations restricted to the height h (at local measurement of axial strains) $f = 0.87$. These values are lower-bound estimations due to the assumption that the ends do not undergo any radial deformation. If it is not true, the value of coefficient f will be larger (closer to unity) and both radial strains ε_{dc} and ε_{db} would not differ as much as follows from Eq. 9.

In Fig. 11 have been shown the corrected results from Fig. 10, applying the corrections given by Eq. (9). It can be seen that the volume change of the rubber sample due to shearing is now acceptable. However, this is considerable difference between the values obtained by two different methods of measurement of axial strains. It is most probably a consequence of the assumption of constant value of correction coefficient regarding the radial strains, see Eq. 9, which is too far going simplification.

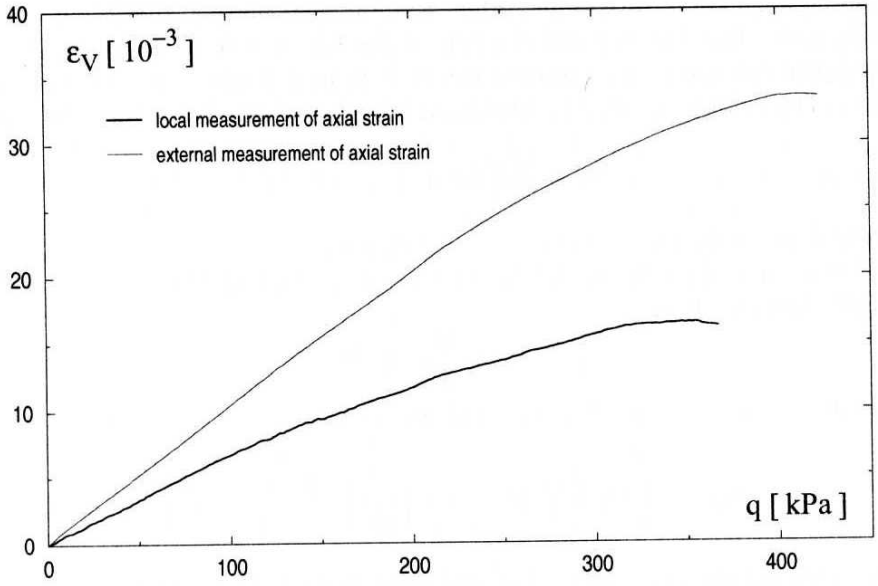

Fig. 11. Corrected volume changes of rubber sample

The results shown in Figs. 9 and 11 also show that for small strains (up to 10^{-2}) the correction due to barrel deformation of the sample is not significant and can be neglected.

The final series of experiments aimed at confrontation of volume changes calculated from measured local axial and radial strains with volume changes of water expelled from fully saturated sample subjected to two stress paths i.e. isotropic compression and shearing at constant cell pressure, both at constant pore pressure (u). The tests have been carried out on "Skarpa" medium sand, which has the following characteristics: $D_{50} = 0.42$, minimum void ratio $e_{\min} = 0.432$, maximum void ratio $e_{\max} = 0.677$, coefficient of uniformity $c_u = 2.5$, specific gravity $G_s = 2.65$.

In order to assure full saturation, the sample was first flushed by CO_2 which displaced the air from voids. After this process lasting around 1 hour, the satura-

tion was initiated with low saturation velocity, then the sample was left for several hours to enable the gas to dissolve in the water.

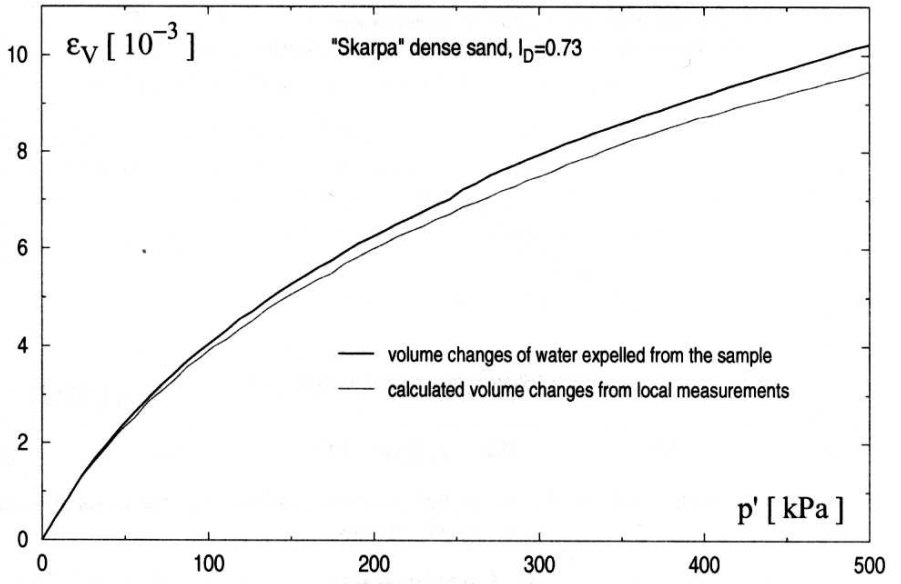

Fig. 12. Comparison of volume changes of a fully saturated sample subjected to isotropic compression

Fig. 12 shows volume changes obtained by various measuring methods in a function of cell pressure due to isotropic compression of the sample to the effective pressure of 500 kPa (u = const = 200 kPa). The sample was formed from dense "Skarpa" sand with $I_D = 0.73$. It follows from the results presented in Fig. 12 that both measurement methods afford similar values of volume changes. Small differences may result from the fact that the volume change of water concerns the whole sample whereas the calculated volume changes only part of it.

Similar agreement was obtained for the sample subjected to shearing at constant cell pressure σ_3 = 600 kPa (σ_3' = 500 kPa, u = 100 kPa), (Fig. 13). The difference between measured and calculated volume changes is negligible, in this case, especially when introducing the correction coefficient for barrel deformation in the radial direction, which in this case was f = 0.9.

The results presented in Figs. 12 and 13 confirm earlier conclusions that for small strain ranges only local measurement of strains corresponds to true soil response. In addition, it can be seen that for a small strain range local measurement of radial strain does not require any correction for barrel deformation of the sample.

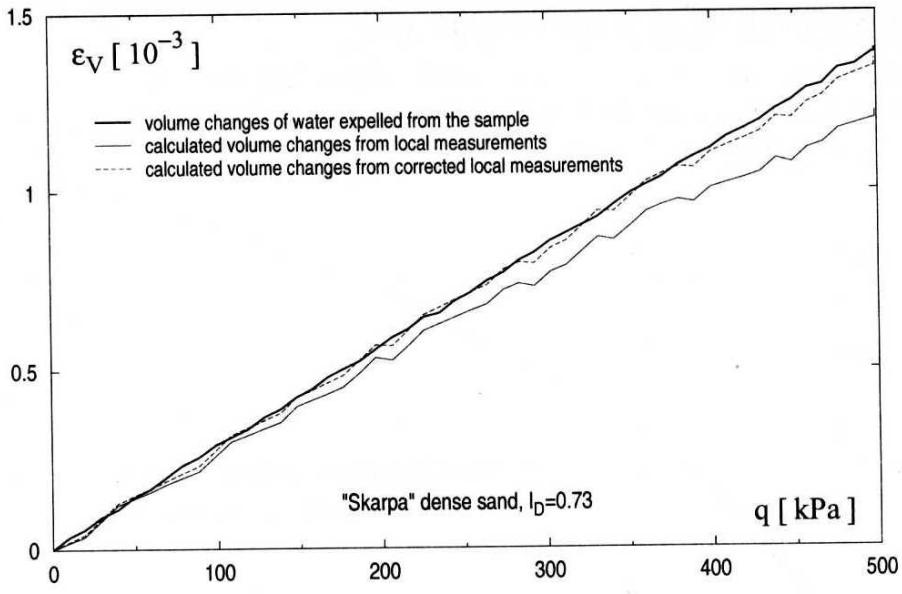

Fig. 13. Comparison of volume changes of fully saturated sample subjected to shearing at constant cell pressure

6. Conclusions

Basing on the experimental analysis of the measurement of strains in the traixial test presented in this paper gives rise to the following conclusions:

- the external measurement of axial strains in the triaxial test is influenced by various factors such as compliance of the loading and load measuring systems and bedding errors resulting from the preparation of the soil sample thus this type of measurement is not reliable, especially within the range of small strains up to the value of 10^{-2}. True soil axial response is lower than that measured by external gauges;
- the bedding errors may overestimate the axial deformation of sandy soil samples by even 25%. This value decreases for larger strains;
- when analysing soil response in the triaxial test for pre-failure strain ranges, only reliable measuring technique of axial deformation of the samples should be based on local axial gauges;
- the external measurement of axial strains based on volume changes of water in the lower chamber of the Bishop-Wesley triaxial cell is strongly influenced by compressibility of water and deflection of loading cell. This measurement technique may only be used after correcting the measured value in the manner described in the paper above;

- the analysis of the measurement of radial strains by local gauge installed at the middle of the sample shows the following:
  - for small stress range (10^{-2}) the local measurement of a sample corresponds to the radial deformation along the whole sample height,
  - for larger radial strains, due to barrel shape deformation, some decreasing coefficients for locally measured strains should be introduced. In our case the value $f = 0.87$ is a good approximation;
- comparison of volume changes of water sucked into or expelled from fully saturated samples with that calculated from measured local axial and radial strains shows no difference between these values, which confirms the efficiency and reliability of local measurement of sample deformation.

Acknowledgement

The research presented in this paper was supported by the Polish Committee for Scientific Research (KBN): Research Grant No. 9 T12 B02918.

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