TRIAXIAL TESTS ON WEAK COHESIVE SOILS – SOME PRACTICAL REMARKS (PART 2)

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Abstract
This paper is a continuation of the paper “Triaxial tests on weak cohesive soils – some practical remarks (part 1)” and concerns the problems related to the preparation of weak cohesive soils for triaxial testing. This part (2/2) presents detailed description and discussion of the issues related to installation of specimen in the apparatus and assembling various accessories before the main test. It is based on the Authors’ own experience and literature review. Some solutions, which make the work with weak soils easier and, at the same time, increase the reliability of the results, are suggested e.g.: the paraffin method or the use of a special frame enabling repositioning of local microdisplacement sensors during the triaxial test. The issues connected with soil sampling and forming of triaxial specimens have been included in part 1/2 of this article. In the Authors' opinion, the text (parts 1 and 2) may constitute an important hint for researchers completing a triaxial testing station intended for testing weak cohesive soils.

Słowa kluczowe: Local displacement transducers; Soft clays; Triaxial tests; Weak cohesive soils.

1. INTRODUCTION

The term “weak cohesive soil” concerns soils characterized by low shear strength and high deformability (refer to part 1 [1]).

This paper presents the most common difficulties concerning installation of weak cohesive soil specimens in a triaxial apparatus and equipping it with a membrane, filter paper strips, filter stones and local displacement sensors. Three types of transducers will be analyzed in terms of their application for soft clays. Attention will be also given to issues relating to the duration of triaxial tests. Alternating solutions are described. Among others, they are based on the Authors’ experience gained from the research on the determination of stress-strain characteristics of cyclically loaded specimens of kaolin from Tułowice [2-4] and on the estimation of the influence of loading history on the parame-
ters of soil constitutive models for normally consolidated Speswhite kaolin [5, 6].

2. SPECIMEN INSTALLATION

Installation a specimen of weak cohesive soil in the triaxial chamber and its preparation for further testing is not simple for several reasons. At this stage the chamber construction itself and also the particular parts of the triaxial apparatus equipment may cause difficulties. The influence of all the elements on testing quality and reliability of results depends on the type and consistency of the soil tested and on the procedure and purpose of the experiment (with or without consolidation, with or without saturation, drained or undrained shearing).

Most of the requirements amount to full control of the current specimen’s size and its variations during the experiment – from the prevention of sample disturbance during the installation in the apparatus, to the measurement of soil deformations not only during the main stage of the test, but also during the specimen preparation (e.g. flushing and back pressure application). This forces the use of an appropriate system of displacement measurement, which will be discussed further in this paper.

Transportation of the specimen from the place of its preparation to the apparatus and its set up should be done with the use of a special rigid bipartite mould (see Fig. 1(a)). It is usually designed to fit a specific triaxial chamber as they may have very different constructions. The main purpose of such a mould is to centre and orient the specimen by means of pins installed on the pedestal while limiting the necessity of touching the specimen by hand to a minimum. In case of a rigid connection of a top cap with piston the same mould has to be used also to install a membrane and O-rings on the specimen (Fig. 1(a)). Otherwise the membrane and O-rings are mounted by means of simpler tools (Fig. 1(b), Fig. 1(c)).

When very soft clays are tested in an apparatus with top cap non-integrated with piston, the mass of the top cap becomes important – it should be made from a lightweight material, e.g. acrylic or aluminium.

End friction, disturbing the homogeneity of stress and strain distribution in triaxial tests, is a very significant issue. Its impact is commonly reduced by maintaining an appropriate slenderness of the specimen.

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Figure 1.
Tools used to set up a specimen: a) orienting and membrane fitting mould, b) O-ring and c) membrane fitting tool (photograph: M. Kowalska)
(height/diameter ≥ 2), by the use of smooth end platens and by replacing the external strain measurement sensors with internal ones. Research conducted e.g. at the Norwegian Geotechnical Institute (NGI) [7, 8] proved that in case of very weak soft clays the influence of end friction can be neglected. Germaine and Ladd [9] also claim that in case of soft cohesive soils the stiffening of a specimen caused by friction ends is relatively small. However, if external vertical displacement sensors are used, at larger strains a proper correction of the current specimen area A needs to be applied. For barrel-like deformation of specimens in undrained test they suggested a correction:

\[
A = A_0 \left[ 1 + \frac{\sqrt{25 - 20\varepsilon_a - 2.5\varepsilon_a^2}}{4(1 - \varepsilon_a)} \right]^2
\]

where:

- \(A_0\) – initial specimen area,
- \(\varepsilon_a\) – axial strain.

According to Sheng et al. [10], based on numerical analysis simulating slightly overconsolidated Swedish clay, in case of rough contact ends, a good representation of true stress path and stress-strain curve can be achieved when the global axial stress is calculated based on the cross-section area at the 1/10 or 9/10 height.

When reduction of end friction is necessary (e.g. when reliable data at large strains are required) there are two options to achieve this: either the porous filter stones are built into the pedestal and the top cap and the rest of the surface is smooth and/or lubricated or the whole surfaces of the pedestal and the top cap are frictionless and the drainage gets limited to filter paper strips attached to the sides of the specimen (see e.g. [7], [9], [11]). In both cases the end platens must be larger than the diameter of the specimen. Apart from technical difficulties, the greatest disadvantage of such a solution is much longer time of consolidation (see sec. 4) and inhomogeneity of pore pressure distribution within the specimen volume.

3. MEMBRANE AND FILTER-PAPERS

Another problem when soft cohesive soils are tested is the presence of a membrane, used as a barrier between the pore water and the triaxial cell medium. Its stiffness is often high, in comparison to the soft and very deformable soil, and due to that it transfers part of the specimen load [12]. Determination of the real stress in soil requires thus the implementation of some corrections depending on, mainly, parameters of the membrane: its thickness, Young modulus and the specimen deformations (e.g. [13-18]). The correction may account for even more than 10% of the measured shear stress [7] at high strains – characteristic for the weak cohesive soils. That is why it is essential to use the thinnest membranes available. In many research laboratories, unless specimens with a diameter greater than about 38 mm are tested, commonly available condoms are used instead of the regular rubber membranes. Their tightness is guaranteed and their thickness is often not greater than 0.04 mm.

According to Olson and Kiefer [19] the consolidation time of clays may be even ten times smaller if filter-paper drains are used. They also improve equalization of pore pressures during shearing. That is why lateral filter-paper drains are so often used in triaxial testing. Unfortunately, similarly to the membrane, they influence the measured shearing characteristics of weak soils. Olson and Kiefer [19] established that at low consolidation pressures, stronger filter drains (Whatman No. 50) may reduce shearing strength due to buckling into the soil and inducing premature failure. Softer filter drains on the other hand usually increase the apparent shearing strength at all consolidation pressures. Leroueil et al. [20] observed however that the effect of consolidation time reduction is distinct only for overconsolidated clays and in case of normally consolidated cohesive soils it is substantially smaller – the consolidation time can be reduced by not more than 2.5 times. The reason for that is probably a clogging phenomenon. Ipso facto these researchers question the efficiency of using filter-paper drains at all.

An alternative solution providing a negligible restraint in case of soft soils may be the use of filter paper strips placed in spirals with inclination (vertical: horizontal) 1 : 1.3 for compression and 1 : 1.5 for extension tests, as recommended by NGI [7]. Probably based on these experiments in ISO instruction [18] the inclination of 1 : \(\sqrt{2}\) has been suggested as well.

The membrane and filter-paper corrections have a special meaning during the triaxial tests, where the stress path is controlled to simulate a particular load history. They must be taken into account already at the planning stage of the experiment; otherwise they will influence not only the measured soil response in terms of strain and shear strength but will also distort
the controlled stress path. An example from the abovementioned experiments on Speswhite kaolin [5, 6] is given below.

Specimens of reconstituted soil were tested drained in an apparatus with automatic stress path control. The loading of the soil simulated theoretical stress paths (mean effective stress $p'$ – stress intensity $q$) determined with the use of finite element method and Modified Cam Clay model at some selected points of a homogeneous subsoil. The loading history consisted in “geological” uniformly distributed loading and unloading on the terrain surface (“preloading”) to obtain a required OCR, excavation, construction of a simple footing and its loading. Fig. 2 presents the numerical model and a (grey) theoretical stress path 0123 representing point E under an edge of the foundation. This stress path was programmed in the computer controlling the test and realized on one of the kaolin specimens. Afterwards, it has turned out that corrections due to the use of a rubber membrane 0.64 mm thick (based on the method by Kuerbis and Vaid [14]) and vertical filter-paper strips (according to [21]), applied after the test (and not before – as recommended) shifted the experimental stress path from the theoretical position 0123 (grey) to position 01’2’3’ (black). The values of stress invariants at the last point of the stress path, planned as $[p', q] = [178 \text{kPa}, 133 \text{kPa}]$ turned out to be equal to $[171 \text{kPa}, 119 \text{kPa}]$ at the axial strain $\varepsilon_a \approx 20\%$ and volumetric strain $\varepsilon_{vol} \approx 10\%$. So the mean stress $p'$ decreased due to the use of the membrane by 4%. The stress intensity $q$ decreased by more than 10%, out of which 8% was due to the membrane and 2% – due to the filter-paper drains. Eventually, this long-lasting test must have been treated as unsuccessful, because the stress path applied to the kaolin specimen did not satisfy the required precision for loading history simulation ($\pm 2 \text{kPa}$).

The use of a rubber membrane in a triaxial test is also connected with an increased probability of disturbing the weak specimen during the operation of putting it on the specimen and installation of the O-rings. To avoid that the tools, described before (Fig. 1) are indispensable.

The problems caused by the use of the membrane will obviously not occur if the triaxial test is carried out non-standardly without the membrane, but with the use of a so called “paraffin method”. This technique has been described by Iversen and Moum [22] and is still used in the laboratories of NGI when very soft sensitive clays are tested [7, 8]. It simply consists in installing a specimen with no membrane in a triaxial cell filled with liquid paraffin instead of water. The interfacial tension between the paraffin and pore water prevents the paraffin from entering into the specimen. It has been calculated that the interface between a clay sample, with a maximum pore diameter below 1 µm, and the paraffin could sustain pressures in the range of 1-10 atmospheres. Berre [7] and Lacasse and Berre [8] admitted however that this method is useful only for effective horizontal stresses up to 100 kPa, which constitutes a huge limitation. Another advantage of the paraffin method is the pos-

![Figure 2. Influence of the membrane (0.64 mm thick) and vertical filter-paper drains on the shape of controlled stress path in a triaxial test on Speswhite kaolin: a) numerical model, b) stress path at the element E: theoretical path 0-1-2-3 and experimental (corrected) path 01’2’3’; 0-1-2 corresponds to ‘preloading’ and 2-3 – excavation, construction and loading of the foundation](image-url)
sibility to observe the specimen deformations directly through the perspex cylinder and that is particularly valuable when a well-defined failure surface is formed. The problem of water leakage through the membrane is eliminated then as well. It should be remembered though that the use of paraffin as the cell fluid excludes the simultaneous use of a membrane, because a rubber membrane would swell, crease and become very brittle when in contact with paraffin oil [20].

4. SELECTION AND ASSEMBLY OF STRAIN MEASUREMENT DEVICES

To assess the small strain behaviour of soil in a reliable way, internal strain measuring devices are indispensable [23-25]. Additionally, they allow controlling strain of soil from the very beginning of the triaxial test, even during flushing and back pressure application when external measurement of displacements is usually encumbered with errors.

Based on experiments on four different soils with varying amounts of fines Lipiński et al. [26] have proved that the volumetric strain during all the preparatory processes: filling the chamber with water, transition from suction to pressure, CO₂ flushing and saturation is not negligible. The volumetric strain during the saturation process is the bigger, the finer the soil is. This phenomenon may be explained by capillary suction, which is related to the size of grains and pores in the soil skeleton. The change of the void ratio value is the larger the greater the initial void ratio is, no matter whether the soil is cohesive or noncohesive. Fig. 3 presents the boundary values of the void ratio, depending on fines content, below which during flushing no uncontrolled soil volume changes due to capillary rise should be observed. And so all the weak cohesive soils with fines content of about 55-60% tested by Jastrzębska [4, 27] having void ratio values from \( e = 0.802 \) to \( e = 1.057 \) (much more than the \( e_{\text{bound}} = 0.65 \) – according to Fig. 3), showed volume changes during flushing. The mean increase of void ratio equalled about 5% (Fig. 4).

According to Scholey et al. [24] the internal strain measuring systems may be divided into whole body (imaging) and local (electrical) techniques.

The first type is based on sectional X-ray radiography or video recording of the strain with the use of a set of cameras. The indubitable advantage of these methods is the fact that the specimen’s surface does not have to be disturbed in any way. These techniques nowadays offer similar precision and frequency of measurements as the electrical systems. There are however some shortcomings referring to these methods. The X-ray radiography e.g. needs expanded laboratory stations available only in selected research centres (like e.g. European Synchrotron Radiation Facility in Grenoble or Tomotriax in Lab 3S-R in Grenoble) [28-31]. So far due to the complicated nature of the tests and difficulties in interpretation of the results (too low resolution), the X-ray technique is used mainly for coarse grained soils in order to observe strain localization, void ratio evolution or fluid flow within soil pores [32-34]. The advanced imaging techniques have their own limitations and requirements. One of the problems in case of the optical measurement of strains (video recording) is the distortion of the recorded image caused by the liquid filling the triaxial cell (usually water or oil), curvature of the chamber wall or possible inhomogeneity of the wall material (e.g. perspex).
Important in the analysis turns out to be also a proper lighting. To avoid or diminish such problems modified triaxial chamber is necessary (including e.g. direct inlets for cameras and change of wall shape from cylindrical to cuboidal). More about such modernizations can be found in [35-37]. According to the Authors’ knowledge and based on some trial experiments conducted with the help of the representative of DantecDynamics company, the optical measurement system seems to be very promising in case of weak cohesive specimens, provided that in the near future the technical problems get solved.

In the second group of displacement measurement systems, being the most often used, the sensors are installed inside the triaxial cell. The measurement is done on the basis of a relative displacement of two points located at some specific distance in the central one third of the specimen, which enables eliminating the influence of end friction. Variations of the specimen diameter are measured at the mid-height of the specimen. In the period of the last thirty years, since the inaccuracy of external strain measurement was defined, many local systems have been developed [24, 38]. Apart from the technology, measuring range and resolution, they differ in the methods of their assembly on the soil specimen, which, together with the dimensions and mass of the transducers, often decide about their limitations, especially when soft soils are tested. The initial stiffness of the triaxial specimen at the beginning of the test is sometimes so low that the use of a system that requires assembly of heavy sensors directly on the specimen turns out to be infeasible. Very often also the range of sensors is too small to obtain a whole curvilinear characteristic of soil stiffness, particularly in the case of cyclic loading.

In the following subchapters, the applicability of selected local strain measuring systems (linear variable differential transformers LVDT, Hall effect gauges and non-contacting proximity transducers PT) will be discussed in terms of their use in triaxial tests on soft and very soft clays. The comments will be based on the examples presented in the literature, but also on the Authors’ own experience with the usage of the abovementioned sensors during triaxial tests carried out in the laboratories of the Department of Geotechnics at the Silesian University of Technology (SUT, Poland) and Department of Civil Engineering at the University of Bristol (UBr, UK). Some of the material presented in this chapter is abstracted from [39].

### 4.1. LVDT system

Local strain devices employing Linear Variable Differential Transformers (LVDT) belong to the first systems used for internal measurement of displacements in geomechanics [40-42].

The measuring range of the LVDT sensors depends primarily on their size. Usually in triaxial testing the transducers with the range of up to 10 mm are used. The length of their bodies is equal to about 50 mm and diameter – about 9 mm.

The complete system consists of three sensors (two – to measure the vertical strain and one – to measure variability of the specimen diameter) and fittings – to attach them directly to the soil specimen. The mounting devices are usually glued to the membrane and sometimes additionally pinned. The puncture in the membrane should always be protected with a layer of silicone resistant to high pressures. There are at least two options of connecting the sensor body with an electrical cable: perpendicularly – then the bobbin bore goes through the whole length of the transducer body, or in parallel – the cable exits the sensor body from the side opposite to the core, sometimes closing the opening. Systems used e.g. at the City University in London [41] or at the University of Bristol [5, 43] are representative of the first case. They are presented in Fig. 5. The vertical sensor there is mounted in the upper part of the specimen (two thirds) and the core rests freely on a base attached at the one third of the specimen height, thanks to which the vertical soil deformation is not restricted (e.g. by the barrel shape or formation of a distinct failure plane). The second example of the cable connection can be found e.g. in the system owned by the Silesian University of Technology in Gliwice. The sensor there is mounted in the lower part of the specimen and the core is attached above with the use of a special holder (Fig. 6). In this case a substantial vertical strain and change of the specimen shape may result in blocking the core and force further deformations. Similar effects may be observed when the sensors are installed according to the method proposed by Costa-Filho [44], where the transducer bodies are mounted on a separate independent frame and only the cores are attached to the specimen. Measurement of vertical strain on the opposite sides of the specimen then requires a set of four instead of just two LVDT sensors.

The sensor used for measuring variations of the specimen diameter is mounted on a split collar, which is attached to the opposite sides of the specimen at its mid-height. In this solution the core ending is always...
attached to the collar. Unless there is an appropriate gap between the specimen and the inner edge of the radial belt, a substantial increase of the specimen diameter, which is not rare at failure when it comes to soft clays, may cause the collar to cut into the soil – see (Fig. 7). Sometimes, instead of fixing the collar by gluing and, optionally, pinning it, the split collar is equipped with a spring (like in Fig. 6), which keeps the device in place without any other help. Unfortunately stiffness of the spring in case of weak cohesive soils, especially at initially low stresses, may restrict lateral soil deformations.

Installation of the LVDT system on stiff and low deformable specimens is quite easy and does not cause many problems, like e.g. in the tests carried out by Cuccovilo and Coop [41] on a kaolin with OCR = 4 and a granular soft rock from the Lower Greensand. It is different when soft and very soft soil is tested. The biggest difficulty is caused by the stiffness of the cables connecting the sensors with demodulators, which is characteristic for water submersible versions. Particularly in the case of a perpendicular connection of the cable with the transducer’s body (see Fig. 5), each cable must be bent in such a way to not touch the cell wall, otherwise some false readings, caused by movement of the loading piston, might occur. This problem may be reduced if an appropriately long fragment of the cable between the sensor and a port in the chamber base is provided. It is feasible if the port is located opposite to the sensor and the cable is twisted along at least a half of the specimen’s circumference and does not touch the chamber wall. Another solution, used e.g. by Sukobrat [43] for tests on soft Bothkennar clay, is changing the cable to a slightly more elastic one based on a technique suggested by Rolo [45]. Both the solutions however do not eliminate the problem completely. If the LVDT sensor is mounted in the bottom part of the specimen (like in the case of a parallel connection of the cable with the transducer’s body – see Fig. 6) the stiffness of the cable is of much less importance. Nevertheless, in both examples, often just the weight of the transducer’s body (about 24 g) and all the mounting devices cause tilting of the sensors on the weak soil specimen, even during the transducer installation, when the buoyant force is not acting yet.

In practice, the mass of the LVDT system elements requires using pins to attach them to the specimen, which greatly increases the risk of leaks through the membrane during the triaxial test. Attaching the mounts only with the use of rubber bands – as suggested e.g. by the manufacturer of the Wykeham Farrance strain measuring system, may result in tilting of the sensors and, taking into account their heaviness and stiff cables, even deforming the soil specimen. An example of installation of LVDT transducers on soft silty clay specimen according to these
An interesting solution for axial strain measurement with the use of miniature LVDT sensors from the XS-B series manufactured by Schaevitz Sensors, used at the Massachusetts Institute of Technology, was presented by Da Re et al. [42] (Fig. 9). The transducers were set on two hinged lightweight (made of Lucite and weighting only about 12 g) yokes with springs, which were clamped onto the specimen at three points placed at equal distance from each other on the circumference. Gluing and insertion of pins through the membrane was thus avoided. The problem of specimen barrelling at large strains and blocking the core was eliminated thanks to a specific method of attaching the sensors to the yokes. The LVDT transducer’s body was held by the lower yoke and the core (extended) was suspended from the upper yoke on a Kevlar thread. To enforce verticality of the sensor’s body a small weight (6–10 g) was attached to the free end of the core with another small length of a Kevlar thread. The LVDT transducers were only 22.4 mm long, 4.7 mm in diameter and weighted only 4 g. The system acted very well in triaxial shearing tests on a Boston Blue Clay (K0 – reconsolidated to about 170 kPa) and a frozen Manchester Fine Sand (consolidated isotropically) and was capable of capturing the initial linear soil behaviour. The measuring range was yet very small: ±0.254 cm, so the initial setting of the core must had been determined extremely precisely allowing for the strains that were supposed to be reached at the end of consolidation stage, before shearing.

The limited transducer range, with no possibility of repositioning the sensor during the triaxial test, in practice limits the application of the LVDT systems in triaxial testing of soft and very soft clays, to monotonic loading.

4.2. Hall effect gauges

The Hall effect gauge was developed by the Clayton research group at the University of Surrey in UK [46]. The device measuring axial strain consists of two elements (see Fig. 10): the first one is the actual sensor (semiconductor) placed in a special fixing pad (with limiters of horizontal movement), located at the lower part of the specimen; the second one is a magnet, moving along the sensor (within the limiters), attached to a pendulum – an aluminium elongated
element mounted with a hinge in the upper part of the specimen. The transducer measuring lateral displacement is placed horizontally inside limiters on one end of a split radial belt mounted to the specimen at its mid-height — similarly like in case of LVDTs. The magnet is attached to the other end of the belt. All the holders are glued and/or (optionally) pinned to the specimen. They are made from aluminium, thanks to which their weight is very low. The magnet and the sensor, equipped with very thin and elastic cables, are of small dimensions as well. Thanks to all the parameters, installation of the Hall effect sensors, even on very soft specimens, does not cause much difficulties. The only complications may be: breaking the leak-tightness of the membrane as a consequence of the use of pins, stiffness of the spring keeping the two parts of the radial belt together or the radial belt cutting into the soil at large strains — all like in the case of LVDTs. Similarly to the local strain measuring system discussed earlier, the Hall effect sensors cannot be repositioned during the triaxial test, so their positioning before the actual testing of soft cohesive soils must take into account the, possibly significant, initial strains after saturation and reconsolidation. The use of these gauges is limited also in the case of planned cyclic loading that is to be started at the level of strains greater than the ones corresponding to the measurement range, which is not large and usually ranges from 2.5 to 8 mm.

4.3. Proximity transducers PT

Proximity Transducers were used for the first time in soil mechanics in 1970s (e.g. [47, 48]). The sensors have flat heads, which must be situated in parallel to the surface of the element, the distance of which is being measured. The measuring range is small — usually not greater than 5 mm.

The great advantage of PT is the fact, that the displacement measurement is contactless. The sensors are placed not on the specimen but on some kind of special frame (or just bars) inside the triaxial chamber. Just thin targets (small plates) 1.5—2 times wider than the head of the sensor are then mounted on the specimen with the use of glue or silicone and pins. They are usually manufactured from a lightweight aluminium, which greatly reduces the risk of specimen disturbance during installation of the system and causes almost no additional load. The measurement of mean axial and lateral strains requires equipping the specimen with 6 sensors in the configuration presented in Fig. 11. In order to determine vertical displacement the targets are attached perpendicularly to the specimen at one and two thirds of its height. In case of lateral strains the mounting is even easier — the aluminium plates are simply glued to the membrane, e.g. with the use of silicone, at the mid-height of the specimen. Instead of measuring the change of the specimen’s circumference — which is the case when a split collar is used, here the increase or decrease of diameter is determined directly. Great attention must always be paid to maintain parallelism between the target and transducer [49], which means that much carefulness and dexterity is needed to attach them accordingly. In Fig. 12 a general view of a triaxial specimen equipped with a set of six proximity transducers for axial and lateral strain measurement is presented.
The standard range of the PT sensors is very small, that is why either special mounting appliances are needed to protect the transducers from damage (e.g. the solution proposed by Hird and Yung [48] with collapsible tubes) or to enable their repositioning without stopping the triaxial test. The latter can be achieved for instance when a special frame is installed inside the cell, with the mounting bars equipped with a system of gears and projecting from the top platen to enable rotating them from outside. Such a construction is used e.g. in the laboratory of SUT (Fig. 12) or in Warsaw University of Life Sciences. It required a complete modification of the triaxial chamber – consisting not only in building in a frame but also in separating the top platen from the chamber wall, which means adding tie bars inside the cell and a rigid connection of the top cap with piston. Thanks to this technical solution recording soil deformation with resolution and accuracy typical only for local strain measuring systems is possible even for relatively large relative displacements of the aluminium targets. It is thus possible to measure microdisplacements of soft clays loaded cyclically [50, 51].

5. SOFT CLAY TESTING IN TERMS OF TIME

Another factor influencing quality of triaxial testing of soft clays, especially in case of low-frequency high-cycle loading, and increasing the risk of unsuccessfulness is time.

The whole process of a triaxial specimen preparation: initial consolidation, saturation (flushing and back pressure), reconsolidation and then shearing in case of clays may take even 3–4 months (longer for drained shearing) [27]. Apart from the long wait time for the results and occupation of the testing station (which may generate costs), there is a much greater risk of leaks, e.g. due to aging of the rubber membrane, much greater when the membrane is punctured with pins attaching the local strain measuring sensors or when an opening was made to install a mid-height pore pressure transducer. There is also higher probability of an uncontrolled accidental energy supply failure or any other mechanical, electronic or electric equipment failure, which, in conformity with the Murphy’s law, would rather happen during the test than in the time when the apparatus is not used or used for a shorter experiment. A simple solution limiting the effects of energy supply failure is connecting all the electrical and electronic appliances to a substitute power supply (generator) or to, at least, an UPS (Uninterruptable Power System). Taking yet into account that usually the number of pieces of equipment used is high and that they often

![Figure 11. Basic configuration of six proximity transducers [27]](image1)

![Figure 12. A view of a triaxial specimen equipped with six proximity transducers (type: 2S1, prod. Kaman Precision Products; SUT) (after [39])](image2)
operate at high pressures, sometimes this solution is not so easily applicable. To decrease the possibility of leak occurrence, Leroueil et al. [20] suggested to use Ramses prophylactic membranes, like in the experiments described by Poulos [52], with silicone oil as the cell liquid. The latter solution however must be applied with care, as not every local strain measuring system can be used in oil.

6. SUMMARY

The paper, being a continuation of [1], extensively presents the problems relating to triaxial testing of weak cohesive soils.

The subject of this part of the article (2/2) were the procedures of installing the soil specimen in the triaxial chamber and mounting accessories, such as filter paper strips, membrane and local strain sensors. The problem of heterogeneity of stress and strain distribution has been discussed. It has been established that in case of soft clays the use of lubrication in order to reduce end friction can be waived provided that the ratio of the specimen height and diameter is equal to 2 or greater.

The aspects of the use of membranes and accessories accelerating pore water filtration were also commented on. It is recommended to choose prophylactic membranes due to their lower permeability (preferably together with silicone oil as the cell liquid) and the possibly thinnest and least stiff ones in order to reduce their influence on stress applied on the triaxial specimen. It is especially important in stress-path controlled tests and the experiments determining shear strength of soil. The solution eliminating all the problems connected with the use of membrane is the paraffin method. However its use is limited to experiments with low effective horizontal stresses. Installation of filter paper strips in case of weak, normally consolidated cohesive soils seems unjustified as the uncertainty of the measured stress and soil stiffness values outweighs their efficiency during consolidation.

Particular attention was given to the problems relating to the weight of the particular items of triaxial apparatus equipment that are in direct contact with the specimen: a top cap, mounts for local strain sensors and the sensors themselves. Three types of micro-displacement sensors were discussed and compared: LVDT, Hall effect transducers and proximeters. Apart from their weight, dimensions of the transducers, stiffness of the cables, measuring range and possibility of their repositioning during the test was considered. It seems that the best choice in case of weak cohesive soils are the contactless proximity transducers or, optionally, LVDTs mounted on a special frame inside the triaxial chamber, however it is necessary to be able to reposition them during the test.

Finally, the duration of a triaxial test on soft clays was referred to. It is much longer than in case of non-cohesive soils or other cohesive soils with lower water content. Aside from the higher cost of such an experiment, a longer time means a higher risk of accidents and a probability of unsuccessfulness.

Triaxial apparatus is rarely bought from a manufacturer as a set ready to be used at once. Usually the testing stand must be adapted to fit the available technical environment and to adjust it to the research program. The Authors hope that this article will facilitate making a decision about the equipment, which needs to be purchased or produced if weak cohesive soils are to be the tested material.

REFERENCES


[27] Jastrzębska M.; Kalibrowanie i weryfikacja jednopowierzchniowego sprężysto-plastycznego modelu gruntu o silnie nieliniowym wzmożeniu anizotropowym (Calibration and verification of a single surface elasto-plastic model for soil with strongly non-linear anisotropic hardening law), PhD thesis, Department of Geotechnics, Silesian University of Technology, Gliwice, 2002 (in Polish)


[36] Messerklinger S.; Non-linearity and small strain behaviour in lacustrine Clay, PhD, Swiss Federal Institute of Technology, ETH, Zurich, 2006

[37] Jastrzębska M., Pasieka M.; Wybrane metodybadawcze we współczesnym laboratorium geotechnicznym: od podłoża do parametrów gruntowych (Selected research methods in modern geotechnical laboratory. From the subsoil to the soil parameters). Silesian University of Technology Publishers, 2015; p.313 (in Polish)


[43] Sukobrat J.; Structure and destructuration of Bothkennar clay, PhD thesis, Department of Civil Engineering, University of Bristol, Bristol, 2007


[52] Poulos S.J.; Control of leakage in the triaxial test. Research report., Harvard University, 1964; p.230