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Quality requirements for static liquefaction test of soil in triaxial apparatus

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Abstract: Since in the field of research concerning liquefaction phenomenon, the largest database exists for triaxial tests, this type of apparatus was selected as the most relevant. Available data concerning laboratory research on liquefaction tests for identification of undrained response of sand indicated that the results are very sensitive to even smallest incorrectness in the testing procedure. Besides, due to a complex nature of liquefaction phenomenon, it was considered prudent to undertake some efforts directed to increase the objectivity of tests. Therefore, before commencement of the actual test program for investigation of undrained response of soil, it is necessary to carry out some preparatory experimental work consisting of application of indispensable modification necessary for enhancement of a quality of a triaxial test. The paper presents the key issues pertaining to the implementation of the experiment. Significance of these modifications for desired characteristics is emphasized. Relevance of some upgrading of the equipment for liquefaction tests is exemplified.

Keywords: static liquefaction of soil; triaxial test procedure; quality requirements.

1 Introduction

Although catastrophic liquefaction failures are usually associated with cyclic loading released during earthquakes, there are also reported flow-slides for which no considerable source of cyclic loading has been detected. Terzaghi (1956) describes several cases of submarine flow-slides where no external trigger could be identified. He refers to this phenomenon of sudden liquefaction without presence of cyclic shear stresses as a spontaneous liquefaction. Such failures of natural or man-made slopes are believed to be initiated by minor stress changes such as ground water table fluctuation or toe erosion, hence essentially by static loading.

Depending on the initial state of soil, three kinds of material response can be distinguished: strain hardening (SH), limited strain softening (LSS), and fully softening behavior (SS). The last two are associated with liquefaction, and therefore, a key issue is to identify undrained response of the material to monotonic loading.

To evaluate either the response of existing structure or to design new structures on or with the soil that may liquefy, it is important to understand the soil behavior under appropriate loading conditions. Being aware of apparent advantages of field techniques of soil investigation in every day engineering practice, it should be realized that unknown boundary conditions with respect to stress, strains, and drainage conditions place these techniques in a secondary position when understanding of soil nature behavior is considered. Therefore, only high-quality laboratory tests that do not have the drawbacks of field techniques are appropriate for investigation of undrained response of soil.

Among various laboratory equipment, a triaxial apparatus seems to be most suitable for this purpose since it can be easily equipped with additional systems enhancing the accuracy of a test (like proximity transducers for precise void ratio control, shear wave velocity measurement for noninvasive state control, or fast data acquisition system).

The paper is concerned with a very specific subject, that is, accuracy requirements of laboratory procedure to carry out static liquefaction tests on various soils properly. The reason why the authors decided to raise this subject is the fact that many of this kind of tests reported in the literature are not accurate enough, and thus lead to incorrect hypothesis and conclusions. During static liquefaction test, soil changes one or twice the state of matter from solid to liquid and again to solid, which is

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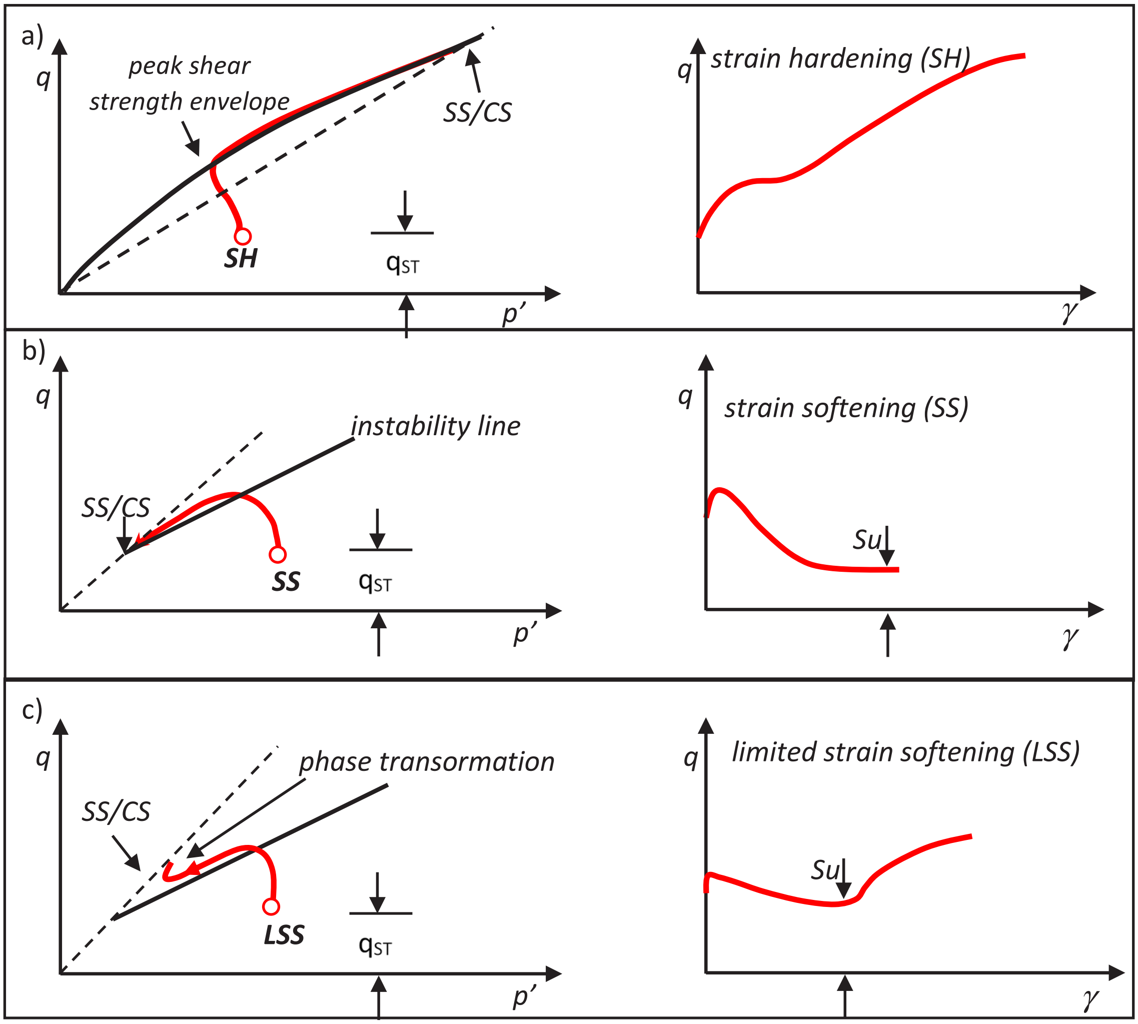

Figure 1: Types of undrained response of soil to monotonic loading: a) strain hardening (SH), b) strain softening (SS), c) limited strain softening (LSS).

not the case during conventional soil testing. Accuracy requirements in such tests are higher than in standard triaxial testing. The paper indicates and describes the most important issues contributing to the final results, that is, sample preparation method, void ration control, uniformity of stress and strains, and importance of fast data acquisition system. Importance of these issues was exemplified by own original test results.

The paper focuses on laboratory test procedure of static liquefaction test. The key issues which control accuracy of the test are discussed, since they subject quantitative analysis of the static liquefaction phenomenon.

2 Undrained response of soil to monotonic loading

Over the entire range of states that can be tested on a particular sand, the observed stress–strain behavior can be characterized by one of three response types, as illustrated in Fig. 1 (Robertson, 1993). Types strain softening (SS) and LSS are both SS responses which can lead to collapse liquefaction and partial or limited liquefaction, respectively. Sand which behaves in this manner is said to be contractive.

Type SS response exhibits a marked SS behavior, that is, after the peak is reached in the stress–strain diagram, which occurs at a small strain, there is a marked reduction in resistance until stress stabilizes at an ultimate or residual strength (Alarcon-Guzman et al., 1988). The reduction in

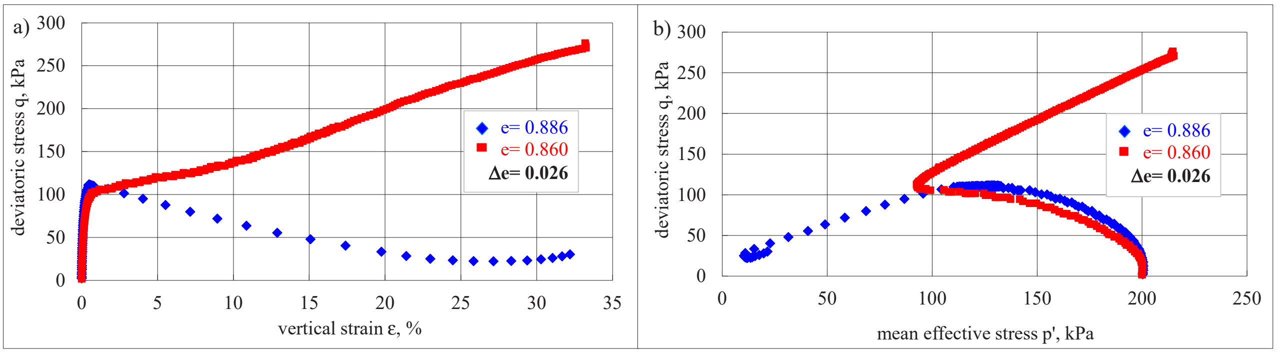

Figure 2: Sensitivity of undrained response of coarse sand to change of void ratio value: a) stress–strain characteristics, b) effective stress paths.

strength is usually termed "flow deformation" and the residual strength as "steady-state strength."

Type LSS response represents a transition stage in which the strength of the specimen decreases to a residual value and then gains strength (strain hardens). SH coincides with the onset of dilation and, as a consequence, reduction in pore water pressure (Vaid and Chern, 1985). Also characteristic to LSS type response is an "elbow" in the stress path, which separates SS from SH and corresponds to the minimum deviatoric stress. This state of minimum shear stress is called the state of phase transformation (Ishihara et al., 1975). The temporary stage of SS can be referred to as partial or limited liquefaction.

Type SH response represents a path in stress space in which the sand will exhibit SH behavior. Sand which behaves in this manner, under undrained loading, is called highly dilative. If the sand is mildly dilative, the effective stress path may show a recognizable turnaround in the stress path, similar to the case of limited liquefaction.

Type of response of cohesionless soil to monotonic loading depends to the largest extent on the void ratio value. Void ratio has been long recognized as an important parameter controlling undrained response of sand. All parameters developed for scaling the state of sand are based on void ratio (e.g., relative density D_r, state parameter ψ as defined by Been and Jefferies, 1985, state index I_s proposed by Ishihara, 1993 after Verdugo's 1989 work). Engineers intuitively know that if sand has a value of relative density corresponding to medium-dense state (say, lower than 50%), it might be prone to liquefaction when subjected to undrained cyclic loading. However, in an analysis of factors pertaining to undrained behavior of sand, it is vital to try to separate void ratio contribution to overall behavior. As an illustration of its importance, in Fig. 2, an example is given in which comparison of shearing characteristics of two triaxial tests is shown. Two specimens of coarse sand (d_{50} = 0.55 mm) prepared by moist tamping and consolidated isotropically to the same effective stress 200 kPa are compared. The only parameter which differed in these two specimens was the void ratio value. However, the difference in *e* between two tests at the end of consolidation determined on the basis of internal measurements of soil deformation was 0.026 (*sic!*) (Lipiński et al., 2020). Results on the characteristics shown in Fig. 2 reveal that this small difference was sufficient enough to entirely change the response of soil from dilative to contractive. In terms of shear stresses at 30% of vertical strain, it means 10 times decreased value of shear strength from 130 to 13 kPa. Pore pressure changes in both specimens were substantially the same until a vertical strain of around 1.5%. Having achieved a certain value of around 130 kPa in the contractive specimen, it continued increasing, while in the dilative specimen, it started to decrease. This phenomenon is reflected very well in effective stress paths, which until a certain point are very similar, but when denser specimen achieves phase transformation, both go in the opposite direction.

In terms of large strain behavior, it is worth noticing that the contractive specimen achieved quasi-steady state at 25% of vertical strain, while for slightly denser specimen, 33% was not enough to reach a steady state.

It should be emphasized that undrained response assumes full saturation of soil at which the pore pressure reaction converts immediately to change in effective stress. Partial saturation conditions, although sometimes considered in the context of liquefaction phenomenon (e.g., Mele et al. 2019, Świdziński & Smyczyński 2022), introduce additional variables which significantly complicate quantitative analysis of the phenomenon.

3 Preparation of representative sample for triaxial test

It is quite obvious that the material tested in triaxial apparatus must be representative for the problem considered. In case of cohesive soils, the vast majority of tests are carried out on undisturbed samples. This is not the case in static liquefaction test. Although there is some possibility to get so-called undisturbed coarse material like gravel by freezing technique or using Gel-Push sampler for other cohesionless soils, it always poses a question of sample disturbance. Therefore, in liquefaction test, soil samples are usually reconstituted in the laboratory by various methods (see Fig. 3). There are three major methods used for sample preparation for liquefaction test, which are as follows:

1) moist tamping by undercompaction,
2) dry deposition, and
3) water sedimentation.

In the later part of this section, they will be briefly characterized. There are two major requirements for these methods. The first one concerns homogeneity of prepared sample. It should be noted that certain amount of fine content in reconstituted sand considerably complicates the fulfillment of this condition. The second requirement concerns possibility of preparation of a soil sample to predetermined void ratio. Therefore, the range of achievable density is a crucial criterion in the selection of specimen preparation method.

Before installation of devices for specimen preparation, the upper part of a triaxial cell connected to internal linking bars should be disassembled. In all methods, the cylindrical specimens are reconstituted by mean of a split mold, whose internal dimensions are those of the sample to be tested, placed at the bottom of the triaxial cell and equipped with a rubber membrane, which isolates the specimen from the cell fluid. The membrane is stretched out to the inside face of the mold and kept in contact with it by applying vacuum. In a triaxial cell prepared in such a way, the soil specimen can be reconstituted by one of the methods shown schematically in Fig. 3.

Ad 1) Moist tamping by undercompaction (Fig. 3a)

This technique (as described by Ladd, 1978) is superior to others as far as achievement of predetermined void ratio value is concerned. By this technique, very dense and very loose specimens can be prepared. Specimen prepared with very high value of void ratio, which is not encountered in natural field conditions, is easy achievable with this method, which is suitable for the study of collapse behavior caused by liquefaction phenomenon.

Dry mass of soil corresponding to predetermined void ratio is prepared and put in a few plastic bags (five or seven), depending on the volume of a soil specimen. The specimen in this method is prepared in layers of the same mass but different heights. Tamping is applied lightly with a small, flat-bottomed tamper. Undercompaction effect is regulated by the thickness of each layer. Fig. 3a shows the stage of tamping a particular layer and the reconstituted specimen.

Ad 2) Dry deposition (Fig. 3b)

In dry deposition method, two techniques can be distinguished – air pluviation and direct dry placement. In case of air pluviation, much more uniform specimen can be reconstituted than in placement method.

This method can be realized by sand spreader in a plexiglass column under application of vacuum, which, to some extent, prevents segregations of fines. The second version of air pluviation method is the Miura Toki apparatus, known as a screen column called “Multiple Sieving Pluviation (MSP)” method, which allows grains to scatter randomly while pouring media into a column, preventing particle segregation (Fig. 3b). With this technique, very uniform sample can be obtained, provided the pluviated materials do not contain fines. Dry placement realized with the use of funnel (Fig. 3b) does not guarantee such homogeneity, but is less time-consuming than air pluviation methods. The drawback of this method is that it does not allow to prepare sample of high value of void ratio when contractive behavior is expected. In air pluviation method, regulation of desired density can be done by adjustment of diameter of the nozzle. In dry placement with funnel, this regulation is very limited, especially with respect to loose state.

Ad 3) Water sedimentation (Fig. 3c)

Water sedimentation technique is representative for a material which is deposited in a liquid state, like the tailings material. Sand is mixed with de-aired water and poured gently into mold filled with water, as shown in Figure 3c. The whole volume of material should be divided in a few portions to ensure homogeneity. The more the amount of fines, the more stages of preparation (portions) are required. After each stage of deposition, some time must elapse before the next deposition. This kind of technique does not give any freedom in void ratio regulation; however, it simulates very well the conditions of wet placement.

This kind of material preparation can be done in a separate container of volume big enough to extrude from the prepared material a few samples for the triaxial test.

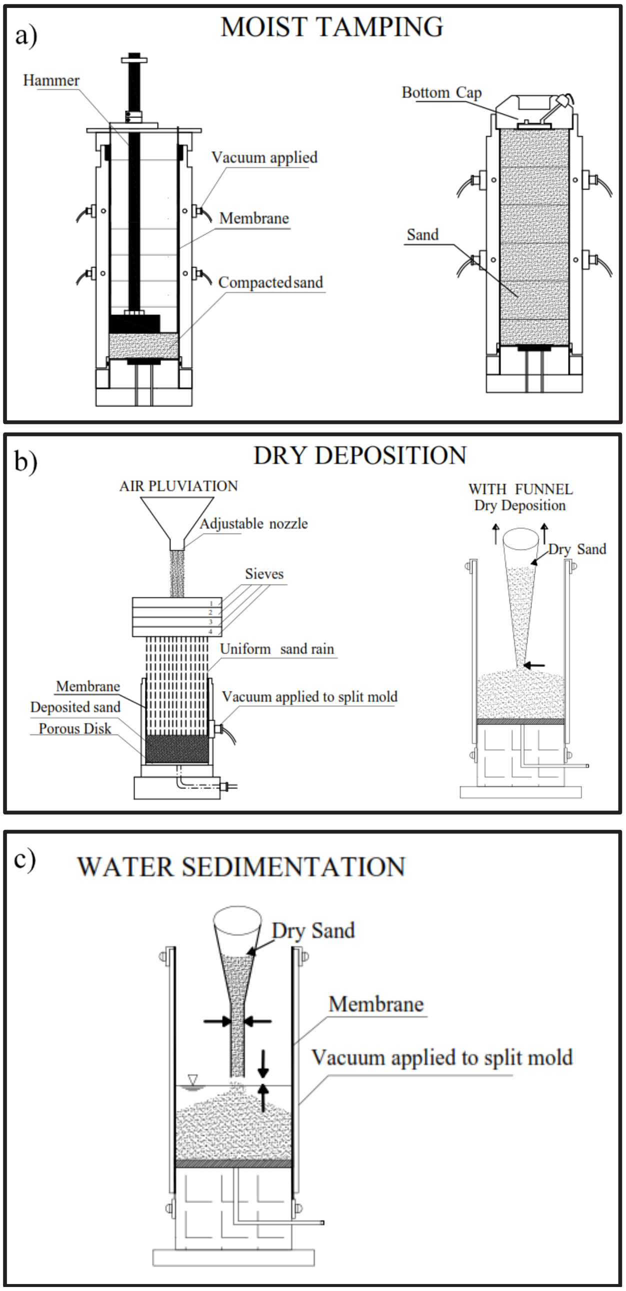

Figure 3: Specimen preparation procedure for reconstitution of soil specimen for liquefaction test in a triaxial apparatus: a) moist tamping, b) dry deposition, c) water sedimentation.

It is worth noticing that sample preparation method is reflected in the response of material during undrained loading. The same material prepared to the same void ratio by three techniques described above would have different fabrics. This difference is even better observed when compressibility characteristics are compared (Fig. 4), which have decisive influence on undrained response of material because their locations in relation to steady-state line determines the state of sand. As shown in Fig. 4, the

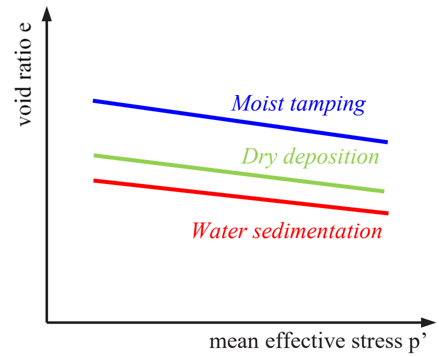

Figure 4: Position of compressibility curves of materials prepared by various specimen preparation methods.

samples prepared by moist tamping by undercompaction are located above the others. Samples which are prepared by dry deposition and especially by water sedimentation, are not prone to contractive behavior, even without additional tapping on mold after deposition.

4 Upgrading of the equipment for liquefaction test

In a physical experiment, accuracy is a key issue for achievement of required reliability. The meaning of this sentence is magnified in case of static liquefaction test. This can be easily imagined when one realizes that in case of contractive behavior, a material from solid state converts to the liquid state and then again becomes solid. Also, this doubled change of state of matter must be registered quantitatively. Apart from the routine experimental work and standard procedures for undrained triaxial test, there are necessary modifications of equipment and indispensable calibration for enhancing scientific insight into the experiment. Identification of items considered during modification of triaxial apparatus is presented in Fig. 5.

The paper is not on static liquefaction test results for particular soil; it is concerned with a much more universal issue. It shows what should be done during testing various soils to take into account important phenomena which influence accuracy of the test, such as capillary tension during flushing or shear stress reduction on the top and bottom of triaxial cell.

As shown in the schematic diagram, three main subjects can be distinguished:

– void ratio control,
– uniformity of stress and strain distribution, and
– adjustment of data acquisition system during load controlled tests.

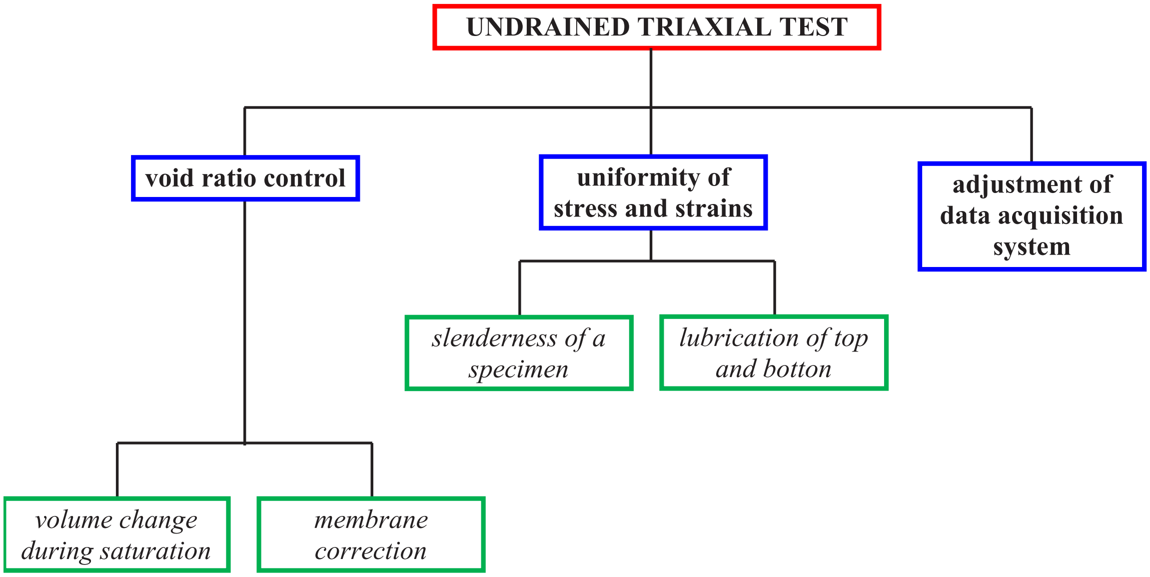

Figure 5: Necessary quality enhancement of test procedure for static liquefaction test.

Regarding void ratio control, two major factors contributing to a measured value of void ratio can be identified: a membrane correction and volume change during saturation. In geotechnical literature, much attention has been given to a membrane correction. Since Newland and Allely (1957), who were the first to report corrections for membrane misfit, many investigations have been reported. Later, Miura and Kawamura (1996) tried to systematize around 40 works collected from the geotechnical literature into four categories. They distinguished works focused on the following subjects:

– direct evaluation of volume resulting from membrane penetration,
– methods for minimization and corrections of membrane penetration during undrained loading,
– theoretical analyses of membrane penetration effects, and
– influence of membrane penetration and bedding errors on undrained behavior of soil tested in triaxial apparatus.

Although these 40 papers do not fulfill the whole list of works dealing with membrane penetration corrections (e.g., Kuerbis and Vaid, 1990), it is very valuable contribution to systematization of knowledge accumulated during years. In the authors' opinion, the first and the last groups are most relevant subjects for quantitative evaluation of undrained response of sand. Major volume change due to membrane penetration comes from radial confining stress. This is especially true for gravel. To illustrate the significance of this correction in such material, influence of membrane penetration on a position of quasi-steady-state line of coarse sand (d_{50} = 0.55 mm) is shown in Fig. 6. As shown in the figure, the size of a specimen is an important factor influencing the position of quasi-steady-state line even in medium coarse sand. The procedure for determination of volume correction was described by Lipiński (2000).

Another aspect of void ratio control concerns the method of specimen volume change measurement at an early stage of the triaxial test. In fully saturated soils, this does not create any problem, since it is precisely determined on the basis of volume of water expelled from a specimen. However, at the primary stage of saturation, when soil is a three-phase medium (skeleton, water, and gas), measurement of volume of water is not representative. Especially that after reconstruction of a soil specimen it is saturated with carbon dioxide which easier dissolves in water than air. Next, in the stage of flushing with water, due to a capillary tension, a specimen experiences some deformation, which cannot be detected by conventional system. At this stage, it is necessary to measure the volume of a specimen inside a triaxial cell. The most convenient is a system of proximity transducers, which are characterized by high accuracy and resolution. Such a system working on eddy currents principle and used for soil stiffness measurement has been described by Lipinski et al. (2020). Measurement of specimen volume change with such a system enables full control of void ratio at each stage of preceded saturation of soil with a back pressure. Four stages can be distinguished here:

- filling cell with water,
- substituting vacuum with cell pressure,
- flushing with carbon dioxide, and
- flushing with de-aired water.

It is expected that the contribution of volume change at any of the above stages would depend on the kind of soil. To illustrate this, in Fig. 7, histograms of volume change during these stages for four different materials are shown. There are two coarse and fine sands with no fines and two tailings batches with 10% and 36% of fines, respectively.

The results presented in Fig. 7 clearly show that the higher the fines content, the greater the possibility of making an error. When considering the impact of the fine fraction content on change in volume due to flushing with water, it turns out that the most susceptible to it are not clean sands or tailings with small amount of fines, but those materials containing from 30% to 40% of fines. This is due to the capillary infiltration, which depends on the size of grains and pores. The shape of the water meniscus forming the wetting front, resulting from capillary infiltration, causes negative water pressure in the pores, which, according to Terzaghi's principle, is the cause of the increase in effective stresses and, consequently, the decrease in volume due to compressibility. Naturally, the greater the change in the void ratio, the greater is the initial porosity of the soil, as can be clearly seen in the example shown in Fig. 8 for tailings material with 10% of fines.

The second important subject, identified in Fig. 5, concerns the uniformity of stress and strain distribution in a specimen. Two major issues can be distinguished here:

- slenderness of a specimen and
- decrease in friction on the top and bottom of a specimen.

Regarding the slenderness of a specimen, various dimensions of specimens are usually used. Most often, the specimens are of 5, 7, and 10 cm in diameter. For practical reasons, for static liquefaction test, a specimen with 7 cm in diameter is acceptable. As far as slenderness of a specimen is concerned, two height to diameter (H/D) ratios are used: 1.5 and 2. Majority of the tests were carried out on specimens H/D = 1.5, because these dimensions ensure better identification of an arrival signal during shear wave velocity measurement. The second rationale for using the ratio H/D = 1.5 is an increase in uniformity of stress and strain distribution during development of large strains. This is particularly efficient when it is combined with application of lubrication to the top and bottom.

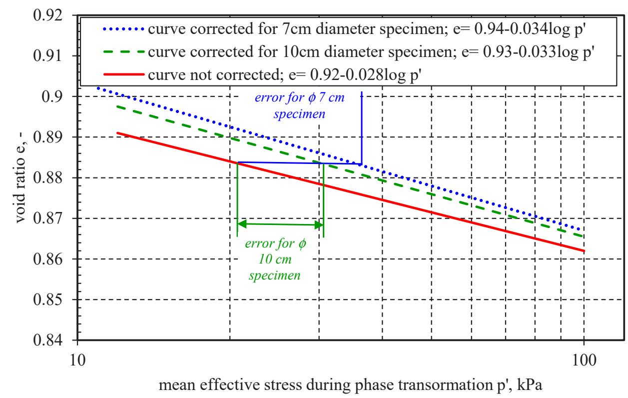

Figure 6: Influence of membrane penetration on a position of steady state of coarse sand (Lipiński, 2000).

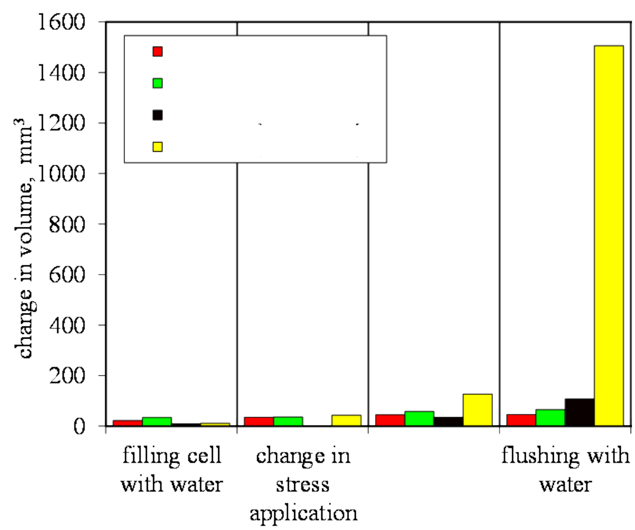

Figure 7: Specimen volume change during preparatory stages in triaxial apparatus for materials with various amount of fines (Lipiński, 2000).

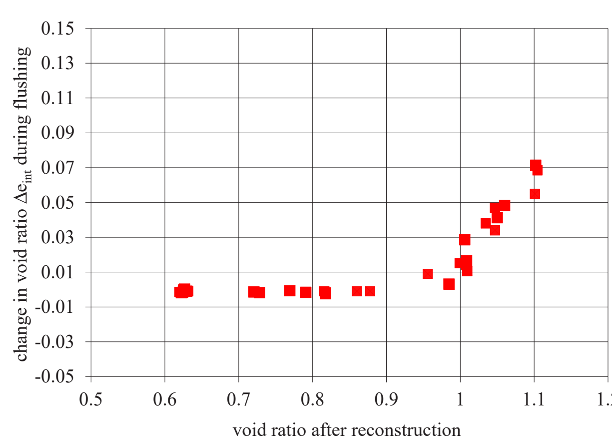

Figure 8: Change of void ratio during the first flushing with water against the initial value of the parameter (Lipinski,2000).

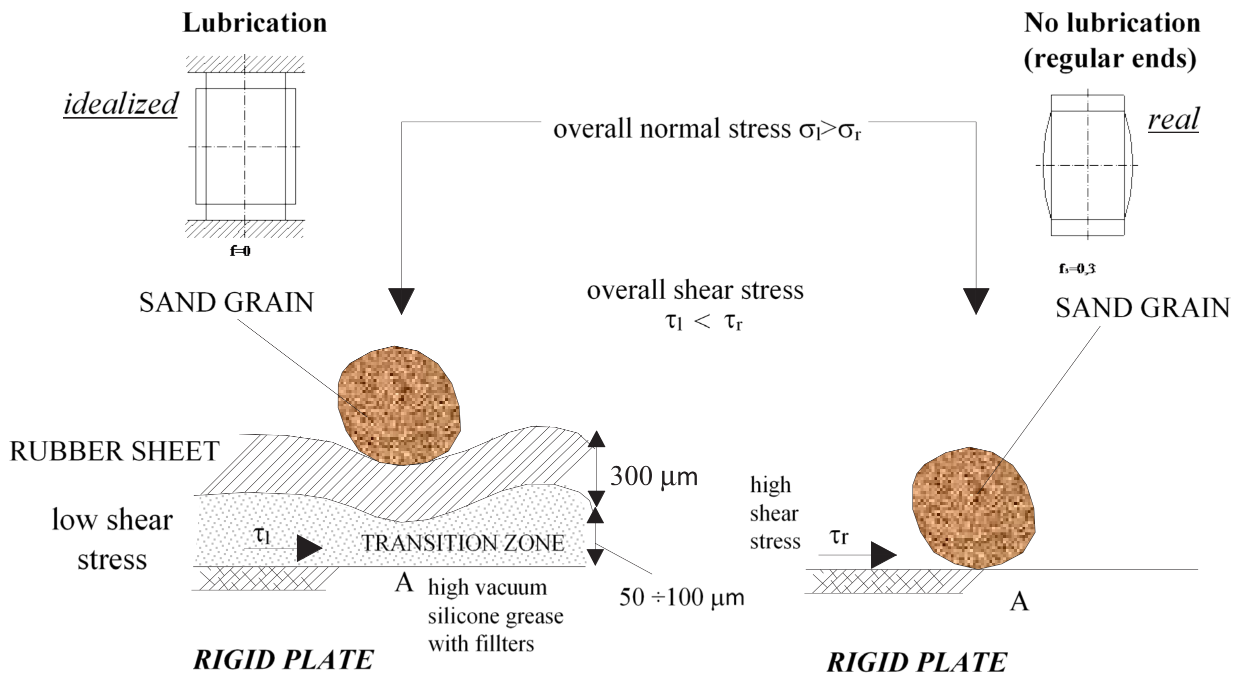

Figure 9: Reduction of friction on the top and bottom platens of triaxial apparatus (Lipinski & Wdowska, 2004).

Uniformity of stress and strains is much more enhanced when lubrication of top and bottom at the ends of a specimen is applied. This issue was the subject of extensive work during the preparatory stage of this research.

The theoretical considerations regarding the theory of cylinder compression are the premises for examining the phenomenon of friction between the soil sample and the top and bottom platens of the triaxial apparatus, between which the sample is located. The use of lubrication increases the uniformity of stress and strain in the sample. Lubrication efficiency can be tested in many ways. Tatsuoka et al. (1984) found that the use of latex diaphragms with silicone grease between the sample and the platens of the apparatus reduced the measured values of the angle of internal friction by up to 1°. Other lubrication methods, such as applying a layer of Teflon, a glass plate, or smooth stainless steel between the sample and platens domes, are less effective. In the authors' own research, friction reduction was obtained by using a latex membrane between the soil and the platens of the apparatus. The lubrication method used was slightly different from that proposed by Tatsuoka et al. (1984).

In the authors' test program, soil tests were also performed using triaxial compression apparatus with plates made of smooth stainless steel. Based on previous studies with latex diaphragms (applied in two layers), a single layer of latex diaphragm was found to be sufficient when using high-vacuum silicone grease mixed with filler. This prevents the silicone from being squeezed out of the membrane when applying stresses up to 700 kPa.

The shear stress reduction mechanism is shown in Fig. 9. When lubrication is not performed, direct contact of the uneven soil particles with the rigid surface of the platen causes stress concentration at each contact point between the sample and the surface of the platen. In the case of applying a vertical load to the soil grain, additionally, large shear stresses arise, resulting from the friction between the soil grain and the surface of the platen. Lubrication, through the use of a latex membrane and silicone grease for high vacuum, allows to significantly reduce the arising shear stresses in the contact zones. More on effectiveness of the applied lubrication system can be found in Lipiński & Wdowska (2004).

Another subject considered during the preparatory stage of the study was associated with acquisition of data during shearing realized in real time. In liquefaction tests carried out by load controlled tests, a rate of deformation achieved during post-peak part of stress–strain characteristics can be very high. Registration of so rapid phenomenon requires very fast data acquisition system; otherwise, some data can be missed. It is particularly important in clean sands, which have contractive–dilative behavior. This situation is visualized in Fig. 10 where

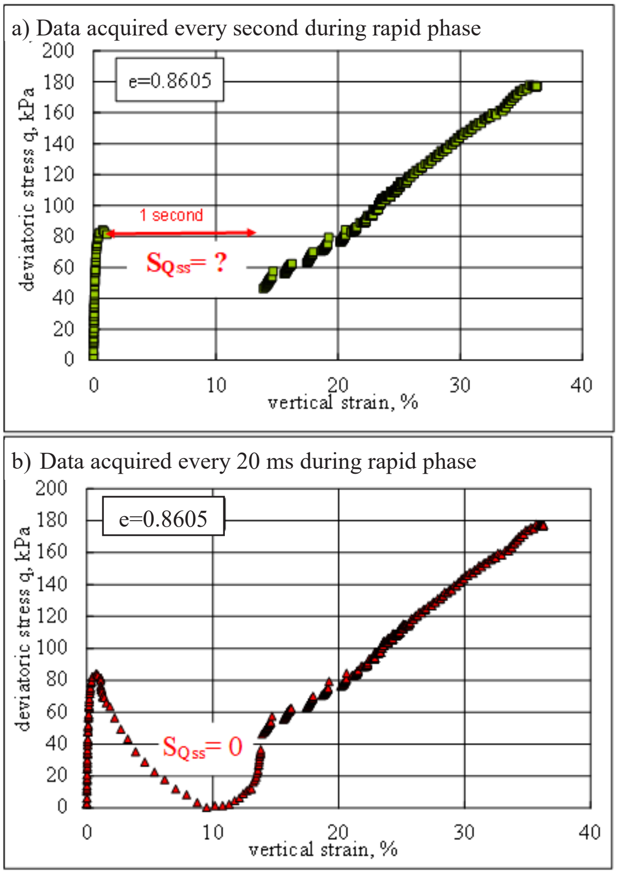

Figure 10: Significance of data acquisition system velocity in reconstruction of stress–strain curve in load controlled test: a) data acquired every second, b) data acquired every 20 ms.

comparison of stress–strain curve for contractive response is shown with data acquired during the fast stage of the test every 1 s (relatively slow) and 50 times faster (every 20 ms). Comparison of deviatoric stress values in the range of strain corresponding to around 14% indicates that very fast data acquisition system is indispensable in load controlled tests on a contractive specimen; otherwise, the most important part of the data is missing.

5 Conclusions

The complex nature of liquefaction phenomenon implies application of not only most updated, but also robust experimental methods and techniques complying with the *State of the Art* in the subject. If such advanced techniques are not used, a resolution of any "average" technique will not allow to obtain reliable results for quantitative analysis. Without misleading simplification, the study shows how the test procedure can be improved to obtain correct results of static liquefaction test. These are recommended guidelines for liquefaction research of soil (from pure coarse sand to tailings material containing 36% of fines) in a triaxial apparatus. Much attention was drawn in the paper to those issues which allow to decrease epistemic uncertainty of the measurements. Possible errors should be minimized (since they cannot be eliminated) by application of advanced triaxial system with implementation of special equipment (e.g., high-precision proximity transducers) and modifications, like lubrication system for top and bottom platens. It was also shown how tracing of collapse behavior in a real time (load controlled shearing with fast data acquisition system) can reveal true stress–strain characteristics during failure.

It is important to emphasize that majority of geotechnical literature concerns steady-state conditions for which the quality of tests does not play such important role as for identification of instability conditions when the response is contractive or contractive–dilative. Precise determination of onset conditions of liquefaction needs enhanced quality of tests to determine effective stress at the start of instability as well as the threshold void ratio which separates contractive and dilative zones for a given soil.

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