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CAPABILITY OF TRIAXIAL APPARATUS WITH RESPECT TO EVALUATION OF NONLINEARITY OF SOIL STIFFNESS

M.J. LIPIŃSKI[1], M.K. WDOWSKA[2], A. WUDZKA[3]

Abstract Reliable evaluation of stress-strain characteristics can be done only in the laboratory where boundary conditions with respect to stress and strain can be controlled. The most popular laboratory equipment is a triaxial apparatus. Unfortunately, standard version of triaxial apparatus can reliable measure strain not smaller than 0.1 %. Such accuracy does not allow to determine stiffness referred to strain range most often mobilized *in situ* i.e. $10^{-3} \div 10^{-1}$%, in which stiffness distribution is highly nonlinear. In order to overcome this problem fundamental modifications of standard triaxial apparatus should be done. The first one concerns construction of the cell. The second refers to method of measurement of vertical and horizontal deformation of a specimen. The paper compares three versions of triaxial equipment i.e. standard cell, the modified one and the cell with system of internal measurement of deformation. The comparison was made with respect to capability of stiffness measurement in strain range relevant for typical geotechnical applications. Examples of some test results are given, which are to illustrate an universal potential of the laboratory triaxial apparatus with proximity transducers capable to trace stress-strain response of soil in a reliable way.

*Keywords***:** nonlinear stiffness of soil, small and intermediate strain

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[1] D.Sc., Ph.D., Eng., Warsaw University of Life Sciences-SGGW, Faculty of Civil and Environmental Engineering, Nowoursynowska Str. 159, 02-776 Warsaw, Poland, e-mail: miroslaw_lipinski@sggw.pl

[2] Ph.D., Eng., Warsaw University of Life Sciences-SGGW, Faculty of Civil and Environmental Engineering, Nowoursynowska Str. 159, 02-776 Warsaw, Poland, e-mail: malgorzata_wdowska@sggw.pl

[3] M.Sc. Eng. Ove Arup & Partners Danmark A/S, Frederiksborggade 15, 1360 Copenhagen K Denmark, e-mail: anna.wudzka@arup.com

1. INTRODUCTION

It has been fairly well recognized that by practicing engineers that conventional elastic or even elastoplastic analyses do not give satisfactory results in prediction of structure and subsoil deformation. This particularly refers to big structures where large volume of soil is involved in stress distribution zone. The main reason for this results from the fact that initial part of stress-strain curve is described by two numbers representing elastic parameters i.e.: Young′s modulus E and Poisson′s ratio ν. In the light of considerable progress which has been realized since early 1980′s in area of pre-failure deformation of geomaterials, traditional approach based on standard triaxial cell designed for shear strength determination is not acceptable. Starting from 10th ECSMFE held in Florence in 1991 and further through all conferences organised by TC101 of ISSMGE focused on *Laboratory stress-strain strength testing of geomaterials* it has been explicitly shown that initial portion of stress-strain characteristic of soil is highly nonlinear. Substantial improvement of accuracy and resolution of specimen's deformation has caused that the term “small strain range” has acquired new meaning in comparison to research and engineering practice before thirty years ego. In this time, strain range corresponding to value 0.1% of linear strain was considered as a small one. Presently, the small strain range has been shifted in direction of zero on strain axis by three orders of magnitude. Such a wide range of working strain has consequences in specialization of laboratory equipment and thus assignment of various strain ranges to particular laboratory techniques. Capability of equipment with respect to working strain range is shown in Figure 1 [1] which is a modification of earlier works [2] and own experience concerning range of strain for particular device. Ranges of strain in this figure are adjusted to linear strain and stiffness is represented by deformation modulus. Field working range of strain corresponding to tunnels, foundations and diaphragm walls [3] are also shown in the Figure 1. It is worth to note that the most important strain range from engineering point of view does not exceed 1%, and the most pronounced nonlinearity of stiffness distribution corresponds to 0.3%. With respect to the above observations it is worth to explain reasons from which these capabilities and limitations result. The paper is focused on comparison of three types of triaxial cells which working strain range of stiffness is shown in Figure 1. Advantages of internal measurement of strain are illustrated in terms of deformation modulus E and Poisson′s ratio ν distribution against axial strain.

2. STANDARD AND MODIFIED TRIAXIAL CELL

Standard triaxial apparatus has been designed for determination of shear strength. In standard shear strength test a soil sample is sheared by application of vertical stress with horizontal one kept constant. Stage of shearing is usually preceded by application of isotropic stress. These two elements of test procedure (i.e. isotropic consolidation standard shearing) influenced to large extent construction of standard triaxial cell. In this configuration there was no need for top platen to be connected with a piston, since during isotropic consolidation, vertical and horizontal component of stress were imposed by increase of cell pressure. Such construction of apparatus implies that soil sample placed in the cell is a part of a column consisting of bottom plate, lower porous stone, a specimen, upper porous stone and top platen. It is difficult to assure perfect alignment of all elements of such a column, especially when soil sample is not perfectly trimmed. In addition, it should be emphasized that piston is put in contact with top platen when cell is assembled and filled with water. Such situation can lead to not perfect application of axial loading. Some examples of such imperfections are discussed in work [4]. For instance, acentric loading can be caused by imperfect construction of the cell as well as improper sample preparation. Both cases result in non-uniform stress distribution and error in deformation measurement. In order to perceive significance of this error it is worth to emphasize that deformation of 0.5 mm converted to strain covers the whole strain range of serviceability limit state, as indicated in Figure 1.

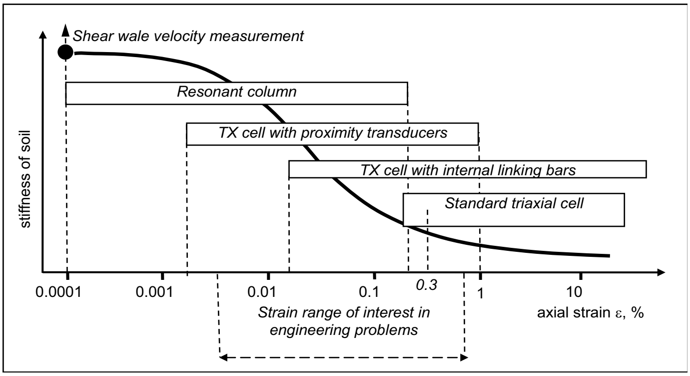

Fig.1. Capability of various lab equipment to determine stiffness with respect to measured strain range

To resolve the problem it was necessary to design a new cell with internal bar, which connect lower and upper part of the cell. Comparison of construction of the base of standard and modified triaxial cell is shown in Figure 2a. There are many advantages of modified cell in comparison with the standard one. In the standard cell measurements of height and diameter of a specimen are taken when a sample is outside of the cell, which is a source of significant errors. In the modified cell, access to a specimen is facilitated as specimen is already set up on the bottom platen. This enables measurement of height and diameter of a specimen set up already in the cell. It also helps to large extent to avoid or minimalize errors resulting from imperfect alignment. Besides, such solution facilitates installation of additional transducers e.g. for on sample pore pressure or deformation measurement. Plexiglas shell installation is the last stage of assembling the cell when all transducers are in measurement positions (Figure 2b).

Accuracy of vertical stress measurement is another important item to be considered during evaluation of soil stress-strain characteristics. In the standard cell, top cap and piston rod are usually (detachable) connected through small steel ball which enables downward application of stress (compression tests) exclusively. In consequence the cell enables to carry out only tests with isotropic consolidation and shearing along standard stress path. The most important drawback concerns error in measurement of actual vertical stress applied. The connection through a ball assumes that cell pressure applies isotropic stress to a specimen while additional vertical load applied through the piston rod divided by the area of a specimen induces vertical compression stress during shearing. Thus in the standard cell the vertical stress σ_v is calculated according to the following formula:

$$\sigma_v = \sigma_c + \frac{\Delta P}{A_p} \tag{2.1}$$

where: σ_c – cell pressure, ΔP – vertical load increment during shearing, A_P – area of a specimen

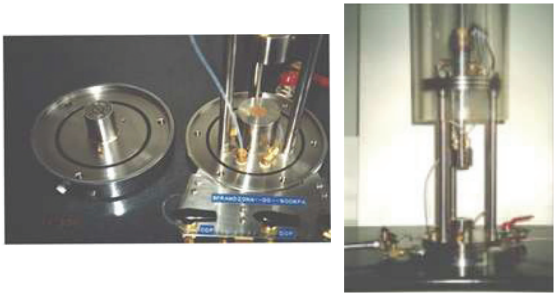

Fig.2. a) Differences in construction of the base of the standard and the modified triaxial cell, b) Easy access to a specimen at any stage in the modified triaxial cell with internal linking bars

The use of modified cell enables application and measurement of vertical stress more accurately, independently if isotropic or anisotropic consolidation is imposed. Majority of problems associated with connection of a piston rod and top cap disappear since the connection is rigid as shown in Figure 3b. For comparison, the connection of top cup in standard cell (of unknown value of A_t) is shown in Figure 3a for comparison. The modified cell enables precise calculation of vertical stress component at each stage of a test in accordance with the following formula:

$$\sigma_v = \frac{P + M + F + \sigma_c (A_p - A_t)}{A_p} \tag{2.2}$$

where:
M – weight of piston rod (with a top cap and half of a specimen accounting for uplift), F – friction force on piston rod (sign depends on direction of movements), A_t – area of piston rod contact with a top cap

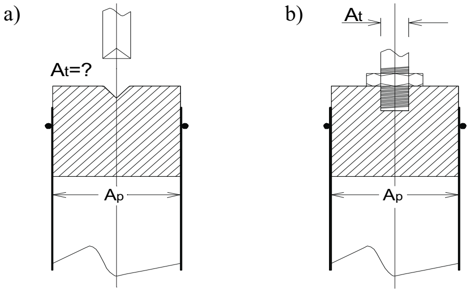

Fig. 3. Details of connection of piston rod and the top cap: a) standard cell, b) modified cell with internal linking bars

Sign of friction force F depends on direction of piston rod movement thus depends on whether a specimen is sheared in compression or extension mode. Value of friction force depends on whether a system of pressure application to a cell is pneumatic or hydraulic one. In case pneumatic system is considered, friction force is considerable lower than in case of hydraulic one and there is no need to use submersible load cell inside a triaxial cell.

3. INTERNAL MEASUREMENT OF DEFORMATION

As described above, standard version of triaxial apparatus can reliable measure strains not smaller than 0.1 %. Such accuracy does not allow to determine stiffness referred to strain range most often mobilized *in situ* i.e. $10^{-3} \div 10^{-1}$ % in which stiffness distribution is highly nonlinear, as shown in

Figure 1. Significant improvement of strain measurement accuracy can be obtained with the use of modified triaxial cell with internal linking bars.

Accuracy of strain measurement can be increased to at least one order of magnitude up to 0.01%, depending of soil response. In case this accuracy has to be increased even more, additional qualitative changes must be done. The use of modified triaxial cell enables use of internal measurement of specimen deformation which considerable increases displacement measurement accuracy. Comparison between results of resonant column (RC) test and triaxial test with local deformation measurement shows that both methods give very similar stiffness distribution for small strain range [5]. It is worth to emphasize that the triaxial test had an advantage (in comparison to RC) in application of anisotropic stress and strain measurement in horizontal direction.

Since the middle of 80s many different systems were developed and used for internal measurement of deformation in triaxial tests (e.g. [6], [7], [8]). A comprehensive review of various equipment was presented by [9]. According to the authors experience one of the most successful systems for deformation measurements is based on the application of proximity transducers Kaman Instrumentation's KD-2300. The system can be adjusted to modified triaxial cell with internal linking bars described above. The system KD-2300 works on eddy currents principle and consists of oscillator –demodulator, sensor and a target as shown in Figure 4. An alternative current flows through the sensor coil, generating electromagnetic field which radiates from the sensor. As the conductive target, which is fastened to a specimen, enters this field, the sensor induces a current flow. This signal is then conditioned and converted to deformation which, when accounting for initial dimensions of a specimen, is changed into strain. In order to effectively measure vertical and horizontal deformation at least six sets of KD-2300 transducers are necessary. Four transducers serve to measure change in height and at least two for radial deformation. The scheme of the simplest configuration of probes is shown in Figure 5a. Targets for vertical deformation are fastened in a certain distance from top and bottom platens. It reduces errors associated with bedding error. With regard to horizontal deformation measurement, two or three sensors can be used in one plane spaced respectively every 180° or 120°. For bigger specimens (20 cm in height) six sensors in two horizontal planes can be used. High resolution of deformation measurement with the Kaman system (less than 2 microns) causes limitation in working range of measured values which can't exceed 2 mm. This limitation implies that at certain stage of shearing transducers must be moved away from a sample in order not to be damaged. For this special mechanical devices for supporting probes must be designed. Depending on whether change of sensors position is done in one or more stage, various mechanical devices are used. A photo of triaxial cell with assembled systems for standard configuration of sensors is shown in Figure 5b.

Fig.4. Kaman system KD2300 for small deformation measurement

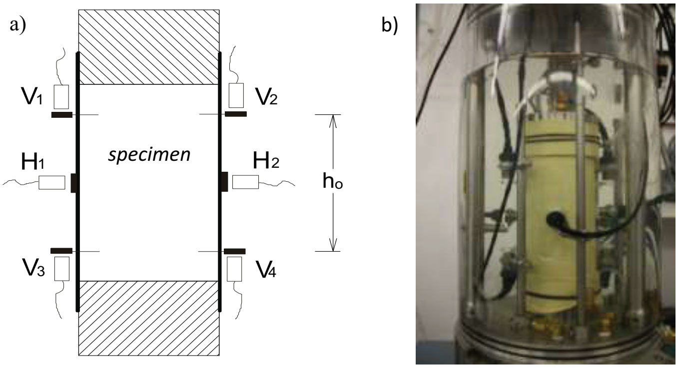

Fig 5. Triaxial cell with internal deformation measurement a) scheme of vertical and horizontal deformation measurement b) view of the cell assembled proximity transducers

4. INFLUENCE OF INTERNAL MEASUREMENT ON STIFFNESS DISTRIBUTION

As it was mentioned, limitation in deformation measurement in standard triaxial cell makes this kind of equipment useless with respect to deformation parameters determination. Therefore there is no rational to consider stiffness characteristic determined in standard cell used for shear strength determination. However, one might ask a question concerning added value of internal measurement of deformation comparing to external ones carried out for the same test in modified cell with internal linking bars. It should be explained that external measurement rely on vertical movement of piston and volume of water expelled or absorbed during test by a sample. Assuming that volumetric strain is a sum of linear components, external radial strain is calculated.

The major objective of internal measurement of deformation in triaxial test is to obtain more realistic values of geotechnical parameters which rely on deformation measurement. There are some geotechnical applications where accuracy of deformation measurement are of special importance.

Most eminent example concerns onset conditions of liquefaction phenomenon where precise measurement of void ratio is a key issue [10,11]. Another one, more commonly appearing in engineering practice, refers to parameters describing stiffness of material i.e. deformation modulus *E* and Poisson′s ratio ν, which represents elastic behaviour. However, "true" elastic response where strain is recoverable refers to strain range 10^{-4} %. Strain range mobilised in field is considerable higher and is obviously not longer "true elastic". That means that from practical point of view the most valuable are distributions of hypoelastic parameters. In order to show how method of measurement influences stiffness parameters the results of two pairs of loose and dense fine sand were compared. Distribution of deformation modulus *E* and Poisson′s ratio ν calculated on the basis of internal and external measurement is shown against axial strain for each tested samples. The results for loose sand are shown in Figure 6 while Figure 7 concerns dense material. In each figure the results of two tests consolidated to different effective stress are shown. On the basis of data presented in Figures 6 and 7 the following observations can be made:

- values of hypoelastic parameters determined by local measurements are considerably different from standard test results. E.g. values of Poisson′s ratio ν for certain strain range differ more than twice. These differences become bigger for higher stresses,
- range of both parameters change are wider in case of internal measurements. Nonlinearity of internally measured hypoelastic parameters is higher than in case of standard measurements,
- distribution of Poisson′s ratio against vertical strain for dense material does not have monotonic character. Depending on stress level, minimum value of ν is in the range 0.1÷0.3.

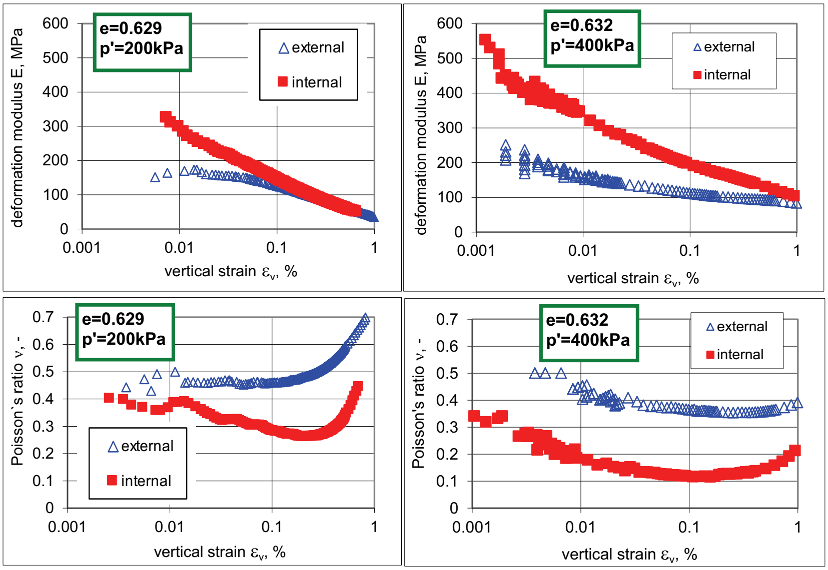

Fig. 6. Internally and externally measured deformation modulus E and Poisson's ratio ν distribution for dense fine sand

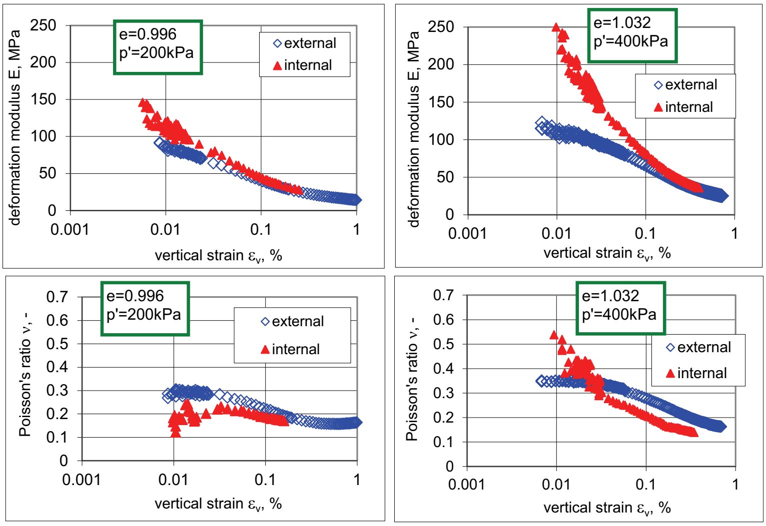

Fig. 7. Internally and externally measured deformation modulus E and Poisson's ratio ν distribution for loose fine sand

CONCLUDING REMARKS

Comparison of three types of triaxial cell i.e. the standard one, the modified with internal linking bars and the modified with internal measurement of deformation, revealed significant differences in stiffness measurement capability. Analysis of construction of the cells and examples of experimental data carried out on loose and dense fine sand at different confining effective stress allow to formulate the following conclusions:

1. Standard triaxial cell used for shear strength determination should not be used for stiffness parameters determination.
2. Hypoelastic parameters of fine sand determined in triaxial test can't be considered constant in strain range of interest from practical point of view.
3. Internally measured parameters differ considerably from those obtained on the basis of standard measurements. Deformation modulus E measured internally are bigger than those determined on the basis of external measurement. The difference is more pronounced for higher stress level and small strain range. Values of Poisson's ratio ν measured internally are smaller than those measured externally.
4. Differences in distribution of hypoelastic parameters determined by externally and internally depends to large extent on state components i.e. void ratio and stress level.

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MOŻLIWOŚCI APARATU TRÓJOSIOWEGO ŚCISKANIA ZE WZGLĘDU NA OKREŚLENIE NIELINIOWOŚCI ROZKŁADU SZTYWNOŚCI GRUNTU

Słowa kluczowe: nieliniowość sztywności gruntu, zakres małych i średnich odkształceń

STRESZCZENIE:

W zagadnieniach doświadczalnych mechaniki gruntów dotyczących wytrzymałości i charakterystyk odkształceniowych badaniami referencyjnymi są testy wykonywane w laboratorium przy poprawnie kontrolowanych warunkach brzegowych ze względu na stan naprężenia, odkształcenia i możliwości odpływu wody z porów. Najbardziej uniwersalnym i popularnym urządzeniem wykorzystywanym do tych badań jest aparat trójosiowego ściskania. O ile standardowe wersje tego aparatu wyposażone w system do nasączania gruntu metodą ciśnienia wyrównawczego można wykorzystywać do badań wytrzymałościowych, to jednak ten rodzaj aparatury nie powinien być wykorzystywany do określania charakterystyk sztywności gruntu. Wynika to z faktu, że ze względów konstrukcyjnych dokładność wyznaczenia odkształceń w standardowej komorze aparatu trójosiowego nie jest większa niż 0.1 %. Budowa komory aparatu wręcz uniemożliwia dokładne wyznaczenie odkształceń próbki a także może powodować błędy w dokładnym określeniu składowej pionowej naprężenia normalnego. Z drugiej strony, dynamiczny rozwój, jaki się dokonał w ostatnich latach w zakresie laboratoryjnych metod badania charakterystyk naprężenie−odkształcenie pozwolił na stwierdzenie silnej nieliniowości fizycznej ośrodka gruntowego w zakresie małych i średnich odkształceń, czyli mniejszych niż 0,1%. Pojęcia małych i średnich odkształceń nabrały obecnie innego znaczenia i określają inne wielkości aniżeli przed dwudziestoma laty, a różnice wyrażają się w dwóch, a nawet trzech rzędach wielkości. Zakres przemieszczeń, który odpowiada warunkom pracy konstrukcji w większości konstrukcji inżynierskich takich jak tunele, fundamenty i ściany odpowiada odkształceniom rzędu 10^{-3}-10^{-1} %, a zatem dokładność możliwa do osiągnięcia w wersji standardowej aparatu trójosiowego ściskania jest niewystarczająca. Z tego względu konieczna jest modyfikacja aparatu, która dotyczy przede wszystkim komory aparatu. W artykule wskazano i przeanalizowano błędy jakie wynikają z konstrukcji komory standardowej. Następnie przedstawiono dwie modyfikacje aparatu, które znacząco zwiększają dokładność wyznaczania sztywności gruntu. Pierwsza modyfikacja polega na innej konstrukcji komory aparatu, która charakteryzuje się wewnętrznymi prętami łączącymi. Takie rozwiązanie pozwala na sztywne połączenie górnej części komory z dolną co pozwala m.in. na wyeliminowanie większości błędów braku współliniowości w dwóch płaszczyznach, pozwala na stały dostęp do próbki na etapie przygotowania (depozycja materiału, pomiary średnicy) a także zwiększa dokładność zadawania i pomiaru składowej wartości naprężenia pionowego. Taki rodzaj modyfikacji zwiększa dokładność pomiaru nawet o jeden rząd wielkości. Następnym etapem w doskonaleniu techniki określania charakterystyki naprężenie odkształcenie w aparacie trójosiowym są wewnątrzkomorowe systemy pomiaru przemieszczeń próbki. W artykule przedstawiono system, który według doświadczenia i opinii Autorów jest bardzo efektywny w porównaniu z innymi systemami. System oparty jest na czujnikach mikroprzemieszczeń działających na zasadzie prądów wirowych, których rozdzielczość pomiaru wynosi 1 μm. System pomiarowy oparty na konfiguracji sześciu takich czujników pozwala na zwiększenie dokładności pomiaru o następny rząd wielkości. Należy podkreślić, że omówione powyżej modyfikacje aparatu trójosiowego były dokonane samodzielnie, w ramach własnej pracy badawczej a nie w drodze zakupu całego systemu dostępnego komercyjnie.

W celu wykazania efektywności przedstawionych modyfikacji aparatu trójosiowego ściskania, w artykule przedstawiono wyniki pomiarów w postaci rozkładu parametrów określających sztywność gruntu tj. modułu odkształcenia E i współczynnika Poissona ν. Wyniki badań przedstawiono dla zagęszczonego i luźnego piasku drobnego przy różnych wartościach naprężenia poprzedzającego ścinanie. Zmienność parametrów przedstawiono w zależności od odkształcenia pionowego dla pomiarów wewnętrznych i zewnętrznych. Wyniki wskazują na istotny wpływ analizowanych czynników tj. zakresu odkształcenia, sposobu pomiaru i stanu materiału reprezentowanego przez wskaźnik porowatości i wielkość naprężenia na przebieg zmienności parametrów określających sztywność gruntu.

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