STATIC AND DYNAMIC EVALUATION OF ELASTIC PROPERTIES OF SOFIA SAND AND TOYOURA SAND BY SOPHISTICATED TRIAXIAL TESTS

STATIČKO I DINAMIČKO VREDNOVANJE ELASTIČNIH SVOJSTAVA PESKA IZ SOFIJE I TOJOURA SOFISTICIRANIM TRIAKSIJALNIM OPITOM

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1 INTRODUCTION

A well know fact is that the ground deformation in every day working condition is usually less than 0.1% strain. In soil mechanics a normal assumption is that the ground consists of a continuum and that its behaviour is linear and recoverable within very small strain range i.e. less than $10^{-3}\%$. Therefore „elastic“ deformation properties of soil such as Young's modulus and maximum shear modulus play important role in civil engineering design. In order to obtain these paramaters through in-situ tests it is common to use corss-hole logging, down hole and suspension sonde methods while resonant column, torsional shear and triaxial tests as well as bender elements are commonly used as laboratory tests to evaluate these properties.

In this study Toyoura sand and Sofia sand having various dry densities have been subjected to cyclic triaxial tests. Relatively very small unloading-reloading cycles have been applied at several stress states and strains have been measured locally by means of local deformation transducers (LDTs), [6], at the side surface of the specimen. This method is called „static“ herein. For the „dynamic“ measurement two types of wave propagation teqniques have been adopted. One is using bender elements and the other is composed of trigger-elements which transmit shear wave and two ceramic accelerometers which receive the shear wave. Based on these „static“ and „dynamic“ measurements elastic moduli of soil are compared with each other focusing on the following topics: 1) the difference between the two types of dynamic measurements and 2) the relations between dynamic and static measurement results.

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2 TESTED MATERIAL, EQUIPMENT AND TEST PROCEDURES

2.1 Specimen preparation and apparatus

All laboratory tests have been performed at the Geotechnical Laboratory of the University of Tokyo (Institute of Industrial Science – Komaba Campus) – [10]. Basic physical and mechanical properties are obtained by convetional tests. More sophisticated to determine parameters of soil (elastic moduli) have been evaluated by means of custom eqiupped triaxial apparatus (Fig. 1). Table 1 and Table 2 summarize the performed tests. Fifteen cyclic triaxial tests with shear wave velocity measurment in total have been performed at various confining stress and relative density.

Table 1. Test list for Sofia sand

Test List			
Test №	Material	σ'_c [kPa]	D_r [%]
Test 103	Sofia Sand	100	70
Test 104		50	70
Test 105		100	70
Test 106		100	90
Test 107		50	90
Test 109		100	90
Test 110		100	90
Test 111		100	90
Test 112		100	90

Table 2. Test list for Toyoura sand

Test List			
Test No	Material	σ'_c [kPa]	D_r [%]
Test 100	Japanese Toyoura Sand	80	50
Test 101		100	50
Test 102		50	50
Test 114		100	50
Test 115		100	50
Test 116		100	50

The main purpose of the tests is to evaluate the different methods for obtaining the Young's modulus and maximum shear modulus of soil and make a comparison between them.

Two types of material have been tested: one is typical Bulgarian sand from Sofia plateau (called "Sofia sand" herein) and the other is well studied over the years soil (reference material in many papers) - Japanese sand from Yamaguchi prefecture (called "Toyoura sand" herein).

Fig. 1 Sophisticated triaxial apparatus (Geotechnical Laboratory of "Komaba" Campus of the University of Tokyo – Institute of Industrial Science)

Fig. 2. Photograph of Sofia sand

Sofia sand is beige yellowish soil from Lozenetz region which dominant minerals are: amphibole, epidote minerals, titanite, zircon, tourmaline and rutile (Fig. 2) – [1]. Its physical and mechanical properties are shown on Table 3 and its grain size distribution is shown on Fig. 4.

Toyoura sand is obtained from the Toyoura beach in Yamaguchi prefecture (Japan) and consists mostly of quartz (over 85-90%) and limestone, mica and other materials (Fig. 3). This material is uniformly graded (with

almost no particles with diameter less than 75 μm) and with round particles. Toyoura sand is a widespread material for testing especially in Japanese laboratories. It has been well studied during the last few decades and has become a reference (standard) material. The physical and mechanical properties of this kind of sand are shown in Table 4 and its size distribution is presented in Fig. 4.

Table 3. Physical and mechanical properties of Sofia sand

Specific density	Dry density	Void ratio	Maximum void ratio	Minimum void ratio	Relative density	Mean particle diameter	Fines content	Coefficient of uniformity	Angle of shearing resistance
ρ_s	ρ_d	e	e_{max}	e_{min}	D_r	D_{50}	F_C	C_U	
[g/cm ³]	[g/cm ³]	[-]	[-]	[-]	[%]	[mm]	[%]	[-]	[°]
2.68	1.40	0.918	1.390	0.866	90	0.22	4.24	2.19	38.46

Fig. 3. Photograph of Toyoura sand

Table 4. Physical and mechanical properties of Toyoura sand

Specific density	Dry density	Void ratio	Maximum void ratio	Minimum void ratio	Relative density	Mean particle diameter	Fines content	Coefficient of uniformity	Angle of shearing resistance
ρ_s	ρ_d	e	e_{max}	e_{min}	D_r	D_{50}	F_C	C_U	
[g/cm ³]	[g/cm ³]	[-]	[-]	[-]	[%]	[mm]	[%]	[-]	[°]
2.65	1.47	0.801	0.989	0.613	50	0.21	0.19	1.20	36.87

Fig. 4. Grain size distribution curves of: a) Sofia sand; b) Toyoura sand

The standards JGS 0541-2009, JGS 0542-2009 and ASTM-D3999-11 have been adopted for the performance of the cyclic loading triaxial tests and the interpretation of their results. The soil specimens have been prepared in accordance with JGS 0520-2009 and the below described sequence has been followed:

1) A latex membrane with 0.3 mm thickness is slipped on the pedestal (Fig. 5a) which is equipped with a porous plate. The membrane is marked with a pen in order to set the spots on which the transducers would be set on a later stage of the test and then the membrane is attached to the pedestal by silicone and rubber bands (Fig. 5b);

2) The pedestal and the membrane are enclosed in a steel mold made of two parts in order to ensure the cylindrical shape of the specimen. The two parts of the mold are screwed together by means of a metal bracket and the connection between them is isolated through special grease;

3) The top end of the membrane is folded over the mold (Fig. 5c);

4) Negative pressure of -30 kPa is applied so that the membrane is vacuumed to the mold.

5) Since the used material is sandy soil (cohesionless) the "air-pluviation" technique [9] has been adopted for the specimen preparation. It is possible to create a very uniform specimen of dry poorly graded coarse-grained soils through slow pluviation. In the "air-

pluviation" method the material is placed in a container in this case a mold of 75 mm in diameter and 150 mm in height at a specific vertical distance (depending on the relative density which is aimed) above the specimen surface. The feed door is opened and the material is allowed to rain down in a slow constant stream. The hopper is continuously traversed across the specimen depositing a thin layer of material with each pass. The process is continued until the specimen mold is overfilled by about 1 cm. The top surface is formed with a straight edge;

6) The top cap is dropped down until it touches the top surface of the soil specimen and after that it is locked in order to avoid damaging the sample;

7) The top end of the membrane is slipped over and attached to the top cap through silicone and rubber bands;

8) The negative pressure of -30 kPa is transmitted to the soil specimen through the pedestal and the top cap and the metal mold is removed (Fig. 6a);

9) The top cap is supplied with counterbalance system and after that it is unlocked. The counterbalance ensures the absence of tension and compression in the specimen which is measured by means of a load cell – [13]. The top cap is locked once again and the counterbalance is removed;

10) Transducers for small strain measurement, bender-elements and accelerometers are attached to the specimen (Fig. 6b) – [7];

Fig. 5a) Preparation of the pedestal; b) Attaching of the membrane to the pedestal; c) Folding of the membrane over the metal mold used for preparation of the soil specimen

Fig. 6a) Soil specimen with negative pressure applied; b) Attaching of transducers to the soil specimen; c) Saturating of the soil specimen

11) The cell is set to the apparatus by means of three bolts. Three liters of water are poured into the cell. The counterbalance system is attached once again to the top cap in order to avoid tension and compression in the specimen;

12) A pressure of +30 kPa is reached in the cell on 5 kPa consequent steps and the initial negative pressure in the soil specimen of -30 kPa is reduced by 5 kPa on each step. After the last step the pressure in the specimen shall be 0 kPa. The absence of tension and compression in the sample is monitored during the whole operation (the "balance" is ensured by adding and removing of weight in the counterbalance system);

13) The specimen is fully saturated by means of "double vacuum" method (for Sofia sand), [4], or "CO₂" (for Toyoura sand) method depending on the type of material tested (Fig. 6c);

14) High capacity differential pressure transducer (HCDPT) and low capacity differential pressure transducer (LCDPT) are set by flushing water through them until no bubbles in the water are observed. Thereafter HCDPT and LCDPT are connected to the triaxial apparatus;

15) In consequent steps of 10 kPa (drained condition) the cell pressure and the back pressure, P_{BP} (pressure in the specimen), are increased in parallel until reaching 230 kPa and 200 kPa respectively (effective confining stress, σ'_c , of 30 kPa). The absence of tension and compression in the sample is monitored during the whole operation (the "balance" is ensured by adding and removing the weight in the counterbalance system);

16) The saturation of the soil specimen is evaluated by measuring Skempton's B -value (the value should be larger than 0.96) – [11] and [14];

17) The top cap is locked and the counterbalance system is removed. The apparatus is shifted below the controlling system (AC servo-motor) and the top cap is attached to it;

18) An external disk transducer for strain measurement is set to the apparatus. The transducer measures the displacement of a steel plate which is attached to the top cap;

The computer is set for automatic performance of the test;

For the triaxial apparatus employed in this study an AC servo-motor has been used in the loading system so

that very small unloading-reloading cycles (cycling loading) under stress control could be applied accurately to the specimen in vertical direction. In order to measure the vertical stress, σ_1 , a load cell is located just above the top cap inside the triaxial cell in order to eliminate the effects of piston friction. The vertical strain, ϵ_1 , has been measured not only with external displacement transducer (EDT) but also with a pair of vertical local deformation transducers (LDTs) located on opposite sides of the specimen. The horizontal stress, σ_3 , has been applied through the air in the cell which has been measured with high capacity differential pressure transducer (HCDPT).

The total stress in the specimen during the tests and the corresponding strain are given as follows (Fig. 7):

$$\sigma_3 = \sigma_c - \text{radial (confining) stress (minimal principal stress)}, \quad (1)$$

$$\sigma_1 = \sigma_a = \sigma_c + (F_a / A_{\text{specimen}}) - \text{axial (vertical) stress - (maximum principal stress)}, \quad (2)$$

$$\epsilon_3 = \epsilon_c - \text{radial (horizontal) strain}; \quad (3)$$

$$\epsilon_1 = \epsilon_a - \text{axial (vertical) strain}; \quad (4)$$

where:

F_a – axial (vertical) force,

A_{specimen} – area of the cross section of the specimen

$$\sigma_{\text{dev}} = q = \sigma_1 - \sigma_3 - \text{stress deviator}, \quad (5)$$

The corresponding effective stress which consider pore pressure are determined as follows:

$$\sigma_3' = \sigma_c' = \sigma_c - u - \text{effective radial stress}, \quad (6)$$

$$\sigma_1' = \sigma_a' = \sigma_a - u - \text{effective axial stress}, \quad (7)$$

where:

u – pore pressure,

$$p' = \frac{\sigma_1' + \sigma_2' + \sigma_3'}{3} = \frac{\sigma_1' + 2\sigma_3'}{3} = \frac{\sigma_a' + 2\sigma_c'}{3} - \text{mean effective stress}, \quad (8)$$

Fig. 7. Schematic overview of triaxial cyclic test of soil specimen

For the sake of reaching $\sigma'_c = 100\text{ kPa}$ of isotropic consolidation the stress has been increased in three consequential steps (50 kPa, 80 kPa and 100 kPa). The stress has been kept constant for 30 minutes in each step so that the deformations could cease. During this stage of the test the shear wave velocity, V_s , has been obtained for various values of σ'_c as well. When the final isotropic consolidation phase is reached at $\sigma'_c = 100\text{ kPa}$ the stress has been kept constant until the vertical (axial) strains due to volume change cease. In the final stage cyclic loading in undrained conditions consisting of 10 cycles has been applied. The amplitude of the applied deviator stress, σ_{dev} , generates axial strain, ε_a , of about 10^{-6} which is in the elastic range of the soil behaviour. The whole procedure of the cyclic triaxial tests which have been performed are schematically shown in Fig. 8.

2.2 Dynamic measurements using trigger elements-accelerometers method

In order to generate shear waves a special type of source called „trigger elements“ has been employed (Fig. 7). The trigger elements are composed of multi-layered piezoelectric actuator made of ceramics (dimensions 10 mm x 10 mm x 20 mm, mass of 35 g and

natural frequency of 69 kHz) and U-shaped thick steel bar to provide reaction force. Trigger elements have been used in pairs in order to apply large excitation equally. In the sake of receiving dynamic waves piezoelectric accelerometers (cylindrical in shape with diameter of 3.6 mm, height of 3 mm, mass of 0.16 g and natural frequency of 60 kHz) as shown in Fig. 9 have been used (glued on the side surface of the specimen at two different heights).

2.3 Dynamic measurements using bender elements method

Bender elements are small piezo-electrical transducers which either bend as an applied voltage is changed or generate a voltage as they are bent. For the case of this study two bender elements have been glued on each side of the specimen so that shear waves could be transmitted and received in the cross section of the sample. There have been two ways for inducing shear waves in the cross section as it could be seen in Fig. 10. In the first the wave could be propagated perpendicularly through the cross section and the second parallel through the cross section.

A schematic figure of how all the equipment has been set on the specimen is shown on Fig. 10.

Fig. 8. Test loading sequence for elastic moduli determination of soil ($\sigma'_c = 100\text{ kPa}$)

Fig. 9. Measurement of shear waves by means of trigger-elements/accelerometers method

Fig. 10. Measurement of shear waves by means of bender elements method

2.4 Recording techniques of dynamic waves

A digital oscilloscope has been employed for recording of electrical outputs from accelerometers and bender elements with an interval of 10^{-6} sec (Fig. 11). To obtain clear signals a stacking (averaging) technique which has been originally installed in the oscilloscope and introduced instead of using filtering methods. The number of stacking which has been adopted is 256 with the bender elements and 128 with the accelerometers.

2.5 Testing procedures

A flow chart of the procedures for each measurement is shown in Fig. 12. Each specimen has been kept under saturated condition and subjected to isotropic consolidation. After the effective stress in the specimen, σ'_c , has reached 30 kPa, 50 kPa, 80 kPa and 100 kPa „dynamic“ measurements have been conducted. „Static“ measurements have been conducted only at the final stage of consolidation.

Fig. 11 Schematic overview of a soil specimen and location of the used equipment

Fig. 12. Flow chart for determination of elastic moduli of soil by static and dynamic measurements

3 EVALUATION PROCEDURES OF STATIC AND DYNAMIC MODULI

3.1 Evaluating elastic modulus

Typical stress-strain relation during relatively small vertical unloading-reloading cycle is shown in Fig. 13. At each stress state the stress-strain relation has been fitted by a linear function and the small-strain Young's modulus has been evaluated on the basis of its inclination

The "static" Young's modulus obtained from undrained cyclic loading tests for cycle i , $E_{u,cyclic,i}$ is defined as follows:

$$E_{u,cyclic,i} = \frac{2\sigma_{dev,i}}{\varepsilon_{a,i}} = \frac{\sigma_{dev,i,max} + \sigma_{dev,i,min}}{\varepsilon_{a,i,max} + \varepsilon_{a,i,min}}, \quad (9)$$

where:

- $\sigma_{dev,i,max}$ – maximum deviator stress for cycle i ,
- $\sigma_{dev,i,min}$ – minimum deviator stress for cycle i ,
- $\varepsilon_{a,i,max}$ – maximum axial strain for cycle i ,
- $\varepsilon_{a,i,min}$ – minimum axial strain for cycle i .

In order to set the final value of the "static" Young's modulus the mean value of $E_{u,cyclic,5}$ and $E_{u,cyclic,10}$ is considered:

$$E_{u,cyclic} = \frac{E_{u,cyclic,5} + E_{u,cyclic,10}}{2}, \quad (10)$$

As the Young's modulus is already evaluated and the Poisson's ratio of soil, ν , in undrained condition of 0.5 is adopted the shear modulus could be determined as follows:

$$G_u = G' = \frac{E_{u,cyclic}}{2(1+\nu)} = \frac{E_{u,cyclic}}{3}, \quad (11)$$

Typical results of a triaxial cycling loading test (10 cycles) are presented on Fig. 14.

Fig. 13. 5th and 10th cycle of a cyclic triaxial test at small strain

Fig. 14. Typical results from cyclic loading triaxial test

3.2 Travel time definitions

The propagation of shear waves through the soil specimen has been used to study the elastic properties of soils. All the methods involve measuring arrival time of propagated wave from the source to the receiver transducer, and as the distance between transducers is known, wave velocity can be determined.

In some cases shear waves are difficult to be identified due to near field effect, reflection and refraction of waves. These three factors make difficult to detect the accurate arrival point. There are a lot of methods to estimate the arrival time of waves, such as the cross-correlation method, time domain analysis, frequency domain approach, multiple reflections, wavelet analysis and variable path method.

Two different techniques have been adopted for this study – both related to the time domain analysis – [3], [5] and [15]. One technique detects arrival time by visual pick and the other uses mathematical procedure (cross correlation) to match the first rise points of the signals. Both methods will be explained below.

Time domain techniques are direct extraction of travel time based on the plots of the electrical signals versus time. The most commonly employed technique

for detecting arrival time is a visual inspection of the received signal. Fig. 15 shows typical shear waveform in time domain series obtained on Toyoura sand.

In Fig. 15 main points have been selected for analysis:

- A: First deflection – where the output signal starts. This zone is part of the disturbance generated by the primary waves;
- B: Trough point – lowest peak before the starting of arrival of S-waves;
- C: First point on zero base line – the inflection point of the part of the wave where shear wave starts (also called “rise point”);
- D: First major peak – first peak of the shear wave.

According to the reference points to consider in determining the arrival time the “first major peak to peak” approach has been adopted in the bender element method.

The time lapse between major peaks in input and output signals is considered as the travel time. Point 1 on Fig. 16 is the first major peak of the input signal and Point 2' or Point 2'' (depending on the polarity of the bender elements) on the same figure is the first major peak of the received signal.

Fig. 15. Typical input and output signal of bender elements

Fig. 16. Evaluation of time travel of shear waves by “first major peak to peak” approach – bender elements method

Fig. 17. Polarity check of bender elements: a) setup; b) recorded signals

When the bender elements method is adopted the question “which peak in the output signal should be chosen in order to evaluate the shear velocity – the first positive or negative major peak?” rises. For the sake of answering this question a polarity check of the bender elements is required. This is done through generating a signal and direct touch of the bender-transmitter to the bender-receiver (Fig. 17a). This means that the transmitted and received oscillations coincide almost completely in the time-domain (the difference occurs due to the distance between them – the thickness of the metal blocks which are attached to the bender elements) and in such way the two peaks could be distinguished in the analysis.

In the particular case Fig. 17b shows that the first major peak of the input signal corresponds to the first negative major peak (point 2' on Fig. 16).

The “first major rise to rise” approach has been adopted for shear wave velocity evaluation in the trigger elements-accelerometers method – [2] and [12]. It is the most common approach used for detecting the arrival point in time domain. The time lapse between the first major deflections of the two output signals from the accelerometers is considered as the travel time (Fig. 18). In order to mathematically obtain the inflection point (rise) a cross-correlation has been adopted – [16].

Fig. 18. Evaluation of time travel of shear waves by “first major rise to rise” approach – trigger elements/accelerometers method

3.3 Void ratio function – $f(e)$

Due to the difference in the relative density of the soil for each test the use of “void ratio function”, $f(e)$, is obligatory in order to eliminate the various void quantity effect. There is a number of suggested equations in the literature for $f(e)$ which allows the direct comparison of the results from tests performed at several values of the relative density of the soil. The experience of many researchers shows that the best results for tests with cohesionless soil specimens are obtained through the “void ratio function”, $f(e)$, suggested in [8]:

$$f(e) = \frac{(2.17 - e)^2}{(1 + e)}, \quad (12)$$

where:

e – void ratio.

The monitoring of the isotropic consolidation for each test allows measurement of the volume change in the specimen during the increase of the effective stress, σ'_c , until a stage where stabilization of the vertical axial strain, ε_a , accompanied by void ratio, e , stabilization is observed. During the stage of isotropic consolidation in the soil specimen the relation between the volume change, ε_{vol} , and the vertical axial strain, ε_a , should be theoretically 3 ($\varepsilon_{vol} / \varepsilon_a \approx 3$) – Fig. 19.

The change of the void ratio, e , with the increase of the effective stress, σ'_c , during the isotropic consolidation is presented in Fig. 20 and Fig. 21 for all tests which have been performed.

Fig. 19. Evolution of volume change versus axial strain during isotropic consolidation (Test 105)

Fig. 20. Sofia sand: change of the void ratio with increase of the effective stress during isotropic consolidation

Fig. 21. Toyoura sand: change of the void ratio with increase of the effective stress during isotropic consolidation

4 TEST RESULTS

Fig. 22 ÷ Fig. 24 show the results from nine tests which have been performed with Sofia sand specimens. Both “static” and “dynamic” measurements are presented. Elastic moduli of soil have been normalized

by a void ratio function in order to make a correction of void ratio's changes (changes of density) – [16].

Analogically the results from six tests which have been performed with Toyoura sand specimens are shown on Fig. 25 ÷ Fig. 27.

Fig. 22. Sofia sand: normalized Young's modulus determined by “static” method

Fig. 23. Sofia sand: normalized maximum shear modulus determined by “dynamic” trigger-elements/accelerometers method

Fig. 24. Sofia sand: normalized maximum shear modulus determined by “dynamic” bender elements method

Fig. 25. Toyoura sand: normalized Young's modulus determined by “static” method

Fig. 26. Toyoura sand: normalized maximum shear modulus determined by “dynamic” trigger-elements/accelerometers method

Fig. 27. Toyoura sand: normalized maximum shear modulus determined by “dynamic” bender elements method

5 CONCLUSION

The following conclusions could be drawn from the results presented in this study.

1. Dynamic measurement results in terms of elastic moduli based on shear wave velocity using two independent methods have shown good agreement to each other;

2. Dynamic Young's moduli based on shear wave velocity are larger than those by static measurement;

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SUMMARY

STATIC AND DYNAMIC EVALUATION OF ELASTIC PROPERTIES OF SOFIA SAND AND TOYOURA SAND BY SOPHISTICATED TRIAXIAL TESTS

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The main purpose of the presented paper is to show the advantages and disadvantages of evaluating the small strain stiffness of cohesionless soils by means of different types of laboratory equipment. A series of consolidated undrained cyclic triaxial tests have been performed on saturated specimens made of Toyoura sand and Sofia sand having various dry densities. Relatively small unloading-reloading cycles have been applied on the specimens in order to obtain the "static" Young's modulus. Furthermore two types of wave propagation techniques have been adopted for the sake of a "dynamic" Young's modulus determination: one is using bender elements in the cross section of the specimen and the other is using trigger elements in the longitudinal section of the specimen to excite shear waves and two accelerometers which capture the waves' arrival in two points. On one hand the difference between the two types of dynamic measurements and static measurements is discussed and on the other hand some relationships between the abovementioned approaches are given.

Key words: triaxial test, small strain cyclic loading, shear wave velocity, accelerometer, bender element, shear modulus

REZIME

STATIČKO I DINAMIČKO VREDNOVANJE ELASTIČNIH SVOJSTAVA PESKA IZ SOFIJE I TOJOURA SOFISTICIRANIM TRIAKSIJALNIM OPITOM

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Osnovni cilj ovog rada jeste da pokaže prednosti i nedostatke vrednujući krutosti pri malim deformacijama nekoherentnog tla pomoću različitih tipova laboratorijske opreme. Serija konsolidacionih nedreniranih cikličkih triaksijalnih opita na uzorcima je peska iz Sofije i Tojoura, koji su imali različite gustine u suvom stanju. Relativno mali ciklusi rasterećenja i ponovnog opterećenja urađeni/izvedeni su na uzorcima s ciljem određivanja „statičkog Jungovog modula“. Osim toga, korišćena su dva postupka prostiranja talasa radi određivanja „dinamičkog Jungovog modula“: jedan je korišćenje „bender“ link elemenata u poprečnom preseku uzorka, a drugi je korišćenje „trigger“ elemenata u podužnom preseku uzorka da bi se izazvali smičući talasi i dva akceleroograma koji hvataju/registruju dolazeće talase u dve tačke. U radu su analizirane razlike između ova dva tipa dinamičkog merenja i statičkog merenja, kao i zavisnosti između prethodno pomenutih pristupa.

Ključne reči: triaksijalni test, male dilatacije pod cikličnim opterećenjem, brzina smičućih talasa, akcelometar, „bender“ element, smičući modul