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LABORATORY TESTING OF SMALL-STRAIN MODULI IN NATURAL SANDY DEPOSITS

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Abstract

A vast majority of experimental results have been accumulated to assess the shear modulus of natural sand at very small levels of strains, the so-called small strain modulus or maximum shear modulus, Gmax. This paper presents a part of a long-term study on the dynamic behaviour of alluvial deposits from ancient river terraces in the Skopje valley, Republic of North Macedonia. Extensive laboratory and field measurements have already clarified many aspects of the cyclic stress-strain characteristics of these natural sandy deposits. The main objective in this study is to contribute to improved understanding of the small strain shear modulus using laboratory element testing with advance measuring techniques. Integral static and dynamic triaxial apparatus equipped with bender element was used for testing of soil specimens and measurement of the parameters necessary for calculation of the small strain shear modulus. This reliable and efficient approach is non-destructive, simple to use and suited to perform multiple tests on a single soil specimen Because of the non-destructive nature of the bender elements the same prepared specimens were used to determine the shear methods as in the case of triaxial tests. Additionally, for finer granular soil materials, cyclic simple shear apparatus was also used to perform the cyclic shearing on soil samples for evaluation of the shear modulus in a more explicit way. Soil specimens were first prepared using the wet-tamping method varying the initial relative densities, from Dr=30% to Dr=70%, then confined at four levels of initial effective stress p_0 = 50, 100, 200 and 400kPa before application of loading. Results obtained from element tests show stable relationships between the small strain shear modulus, relative density, effective stress and shear strain amplitude, with strong dependence on the effective stress, which appears to be one of the key parameters.

Keywords: Small shear modulus Gmax, triaxial test, direct simple shear tests, bender elements

1. Introduction

Recent software developments compiled with various numerical techniques represent the most common way of solving geotechnical problems. The maximum shear modulus (Gmax) represents one of the fundamental parameters required for linear and non-linear dynamic analyses, foundation design, prediction of soil settlement prediction, soil improvement, etc. In particular, significant focus is placed on the implementation of Gmax in engineering practices for calculating the settlement and bearing capacity of spread foundations [1]. In earthquake prone regions, a better insight into Gmax of local soils is of vital importance for designing of earthquake-resistant structures. It can be concluded that correctly defined and proper use of shear modulus is of vital importance.

In this study, three types of experimental methods were used to determine the maximum shear modulus (Gmax) under laboratory conditions. The first method used is the cyclic triaxial test which due to overriding popularity in recent decades has become probably the most widely used method for measuring the small strain shear modulus. These tests were conducted herein according to the ASTM D-3999 standard, strain-controlled approach, where 40 cycles of strain were applied with an amplitude of 0.1% axial strain. To improve the output results, all loading cycles were considered in the analysis. The triaxial test first determines the initial elastic modulus Emax, which is then converted to initial shear modulus Gmax. Bender elements (BE), installed along the vertical axis of the triaxial specimen,

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constitute the second method for determining the small strain shear modulus. BE represents an efficient technique due to the non-destructive nature, simple use and ability to perform multiple tests on one specimen. In this way, it is possible to use the same prepared soil specimens from previous method to determine the shear methods as in the case of triaxial tests. ASTM D8295-19 standard prescribes the use of BE in laboratory conditions with the following statement "…*shear wave velocity determination involves very small strains and is non-destructive to a test specimen. As such, bender element shear wave velocity determinations can be made at any time and any number of times during a laboratory test*". Currently, BE can be added to multiple standard laboratory equipment such as triaxial apparatus [2], resonant column [3] or oedometer apparatus [4] and widely used in various scenarios. The third method applied in this study is the direct simple shear test (DSS), which is also commonly used for cyclic shearing of soil samples to evaluate shear modulus in a more explicit way. In this test two cylindrical specimens are simultaneously loaded with shear force while being rigidly restrained in the vertical direction. The soil specimens are placed in a series of Polytetrafluoroethylene PTFE (teflon) coated steel rings and dynamic shear excitation in the form of shear strains is applied in the horizontal direction through the central loading plate placed between the two models. Through the relative horizontal displacement of the rings, the dynamic excitation is uniformly applied along the entire height of the model. Due to simple cyclic shear in the element shear strains will develop and hysteresis relationships are obtained.

2. Testing material and program

The soil material used in this study represents a natural fluvial sand, the so-called "Skopje sand", that has been frequently tested in the laboratory for dynamics of soils and foundation, UKIM-IZIIS [5] and a lot of reports have already been published using the same sand [6,7,8,9]. It consists mainly of silica oxides (about 78%) with particles of subangular shape. With only 2% fines it is highly uniform with mean grain size of d_{50} = 0.26mm and a uniformity coefficient Cu = 1.8. Since it is a natural sand, small differences in each batch can be expected. Initial investigation is therefore necessary to determine the physical properties (Table 1). The void ratios were determined using ASTM D4253-00 standards, where e_{min} = 0.51 and e_{max} = 0.95, at mean pressure p = 0kPa.

Table 1 – Physical properties of Skopje sand

e_{max}	e_{min}	G_s	D_{10} (mm)	D_{50} (mm)	D_{60} (mm)	Cu	Cc	φ (o)	Fines (%)
0.95	0.51	2.615	0.095	0.26	0.19	1.8	0.8	33.5	2

Table 2 – Testing programme

Triaxial apparatus			Bender elements			Direct simple shear apparatus		
No	σ_{eff}	Dr	No	σ_{eff}	Dr	No	σ_{eff}	Dr
1	50	30.73	1	50	32.03	1	50	27.09
2	50	59.26	2	50	56.5	2	50	49.29
3	50	78.2	3	50	73	3	50	71.61
4	100	27.08	4	100	27.14	4	100	29.61
5	100	64.45	5	100	48.15	5	100	49.28
6	100	82.02	6	100	74.65	6	100	69.7
7	200	33.52	7	200	33.38	7	200	33.8
8	200	69.11	8	200	53.53	8	200	50.38
9	200	79.85	9	200	74.19	9	200	69.1
10	400	35.84	10	400	31.14			
11	400	72.89	11	400	47.21			
12	400	86.53	12	400	64			

The testing program consisted of three series of tests according to the testing method/equipment and then grouped by the applied effective stress σ_{eff} and initial relative density Dr (table 2). In total, 33 tests

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were performed. The experiments on triaxial apparatus were confined to four different effective stress levels: 50, 100, 200, 400kPa, while the confining pressure on DSSA was applied only up to a vertical stress of 200 kPa. All soil samples in the triaxial apparatus were reconstituted using the wet-tamping method with an initial water content of 3% [10] height/diameter ratio of around 2, into roughly three groups of initial relative densities.

3. Results from Triaxial tests

The triaxial testing equipment used for the experiments is a feedback-controlled cyclic triaxial system that applies cyclic or dynamic loading to cylindrical soil specimens. This apparatus is a servo pneumatic system, with control on axial stress, confining pressure, and back pressure by incorporated Control and Data Acquisition System (CDAS). During the testing seven transducers were used for measuring the required physical quantities. This includes measurements of the cell, back and pore pressure, using pressure transducers, measurements of the applied axial load with submersible load cell and volume change of water entering or leaving the sample. As well, two axial transducers acquired the deformations directly on the samples. All data acquisition functions, critical control and timing were provided through CDAS (figure 1). The wet-tamping method was used for reconstitution of soil samples, where the sand was placed in identical layers using a three-piece steel cylinder lined with a rubber membrane. To achieve a better saturation, all samples were first saturated using CO_2 and then deaired water was applied to a B-value≥0.95. As mentioned, consolidation of the soil specimens was done at four levels (50, 100, 200 and 400kPa) until stabilization of the volume change. The cyclic loading was applied according to ASTM D-3999 standard, with 40 sinusoidal cycles with an axial strain amplitude of 0.1%.

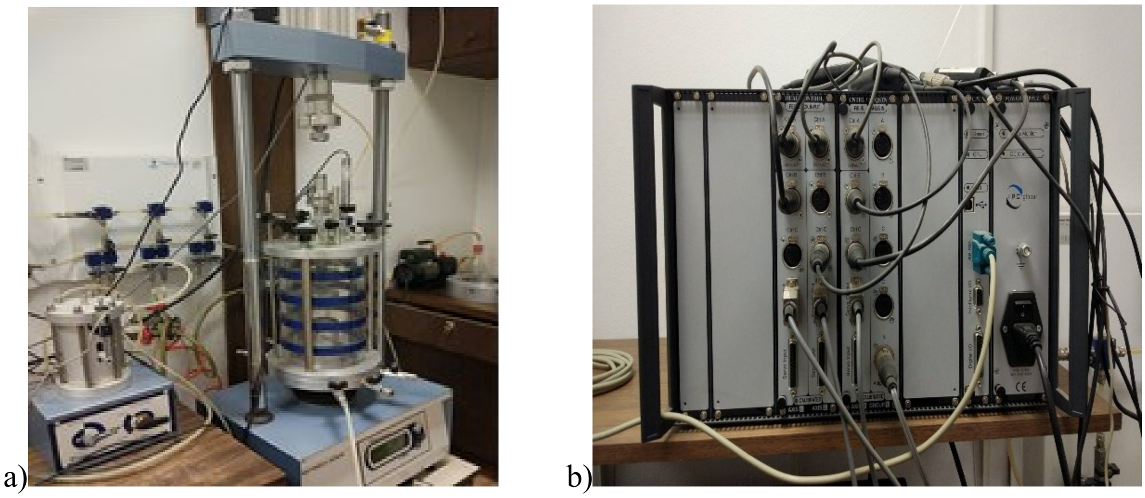

Figure 1. a) Triaxial and volume change equipment, b) Control and data acquisition system

First notion from the test results is the fact that there is small inconsistency in the amplitude of the axial strain applied on the samples for different experiments, even though in all cases the applied sinusoidal cycles are smooth the amplitudes vary from 0.08% to 0.105%. This limit of accuracy is known in literature and presented as inadequate practice particularly when small strain stiffness of the soil is being investigated [11,12]. Additionally, there is variance in the shear modulus for different cycles during a single experiment. This type of variance is expected and in our case is below the limit of 10% between the highest and lowest value of Gmax (figure 2). Figure 3 represents results from all triaxial experiments presented in terms of shear modulus and initial relative density. From the figure a strong initial pressure-dependence for the shear modulus can be noted, but in terms dependency from relative density no clear conclusion can be made. Inconsistency in applied axial strain significantly affects the scattering in results.

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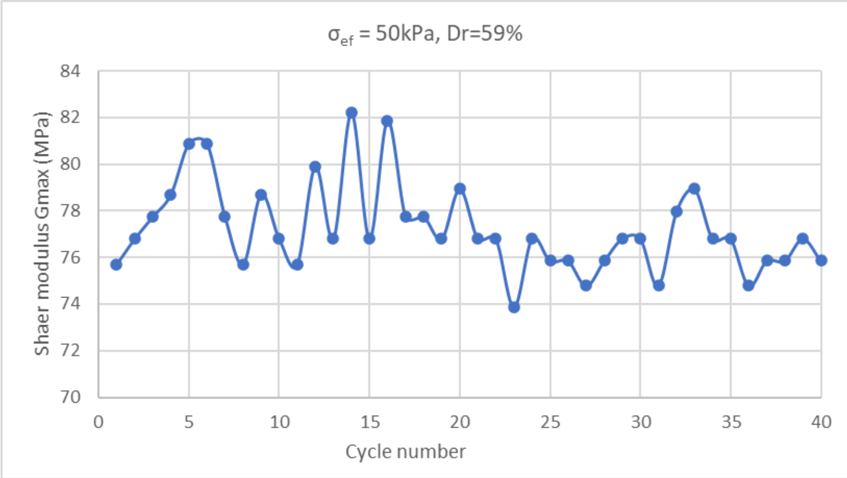

Figure 2. Gmax results for single triaxial experiment

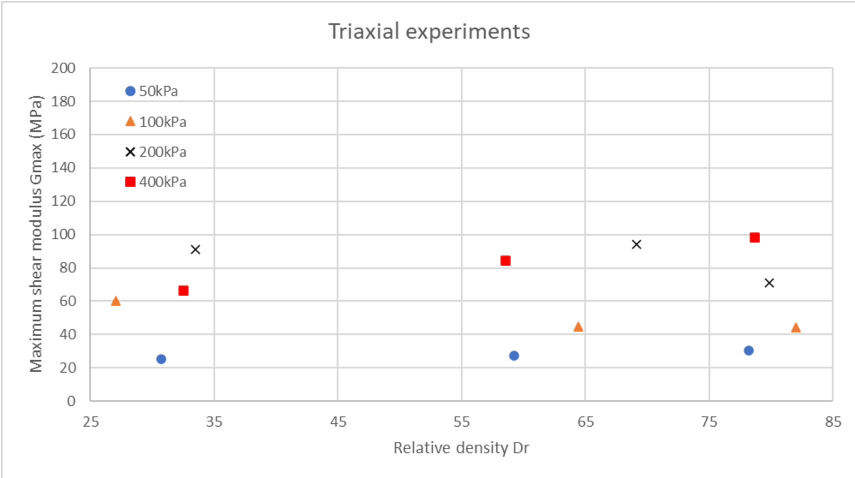

Figure 3. Gmax from triaxial experiments

4. Results from Bender element tests

The practice of using bender elements to determine the shear modulus of a soil sample is becoming widely popular in laboratory testing, especially knowing the previous mentioned limitation the triaxial apparatus. Many researchers have developed bender elements in their laboratories and used them on all types of soils [13,14,15], while for verification of the BE approach resonant column tests, torsional shear tests were used [16,17]. Additionally, because of their non-destructive nature researchers used bender elements multiple times during the experiments to determine the development of shear modulus [18]. The system installed in the laboratory for soil dynamics part of IZIIS represents a Wykeham Farrance bender element system. The bender element system consists of two bender elements (transmitter and receiver) which are connected to a single master signal conditioning control unit (28-WF4200). The unit includes waveform generator, analog-to-PC interface, virtual oscilloscope software and connecting cables. Advanced user-friendly software (figure 4) that automates the analysis is also incorporated. The system allows to measure shear modulus (Gmax) of a soil specimen in the shear strain levels of about 0.0001%. This system is constructed to be used in advanced triaxial systems but also can be used as a standalone product.

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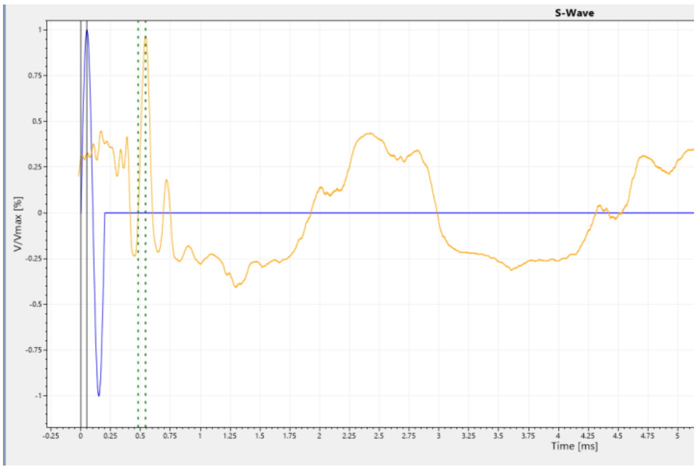

Figure 4. Typical waveforms response curve from bender element

Determination of Vs using bender elements was calculated by three methods: a) start-to-start, b) peak-to-peak and c) cross-correlation, with single sinusoidal input with frequency of 4Hz. This frequency proves to be the most effective and most consistent input parameters for calculating Vs. In the literature it has been recognized that the frequency effect on shear modulus is negligible for clean sands, but there are some authors that have determined that there is frequency dependence of the Vs results especially for high frequencies [17,19]. In this study no dependencies were noticed, bearing in mind that the transition frequency is much greater than the frequency used for standard determination of Vs using BE. The equation for computing Gmax can be written as:

$$\mathbf{G_{max} = V_s^2 \times \rho}$$

where Vs is shear wave velocity at which the wave propagates through the soil specimen, and ρ is the mass density of the soil. The results of the three above-mentioned methods show stable and reliable results for Vs, with max. differences of 2 to 5%. Figure 5 presents the shear modulus for different relative densities and different levels of effective stress. The results show strong pressure-dependence that increases with the increase of relative density.

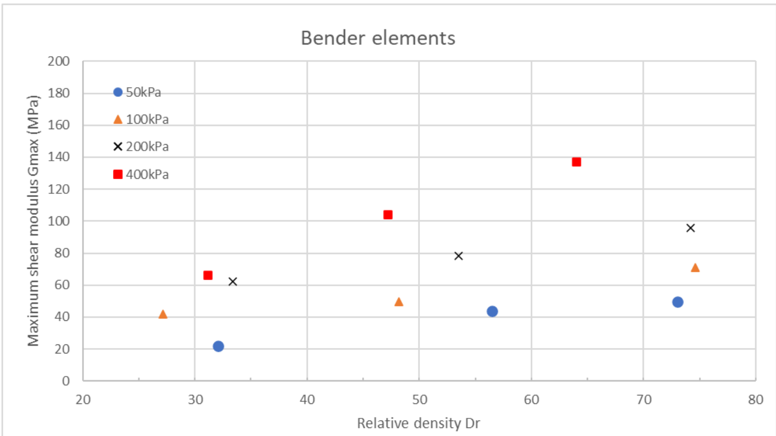

Figure 5. Maximum shear modulus results from bender elements

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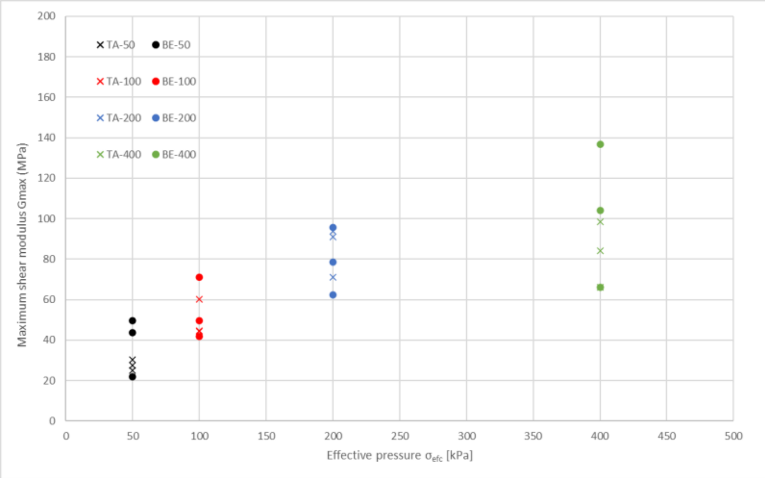

Figure 6. Results for Gmax from triaxial and bender element test

5. Results from Direct simple shear tests

Direct simple shear devices historically have been the most used laboratory apparatus to determine the shear modulus, and it is still present in almost every geotechnical laboratory. The apparatus in the Laboratory for Soil Dynamic DSSA is manufactured by Dames & Moore, London [20], and it is consisted of four main components: testing device, hydraulic pump, data acquisition digital units and response recording PC control console. This apparatus has been in use for more than 35 years [21], improved and digitalized throw out the years. While testing, the device considers simultaneously two dry soil specimens with cylindrical shape of 6.1cm diameter of and height can range from 1.5 to 2cm, restrained in vertical direction, placed between three loading plates. The dynamic excitation in the form of shear strains is applied in horizontal direction through a central loading plate placed between the two models. As shown in Figure 7 shear strain amplitudes that can be applied are raging from 1x10^{-4} % up to 5% from which hysteresis curves shear stress-shear strain are obtained successfully. Series of cyclic tests are performed on soil specimens with around 30, 50 and 70% relative densities, while the effective pressure of 50,100 and 200kPa are applied. The dynamic excitation was applied step by step in form of short series of cyclic simple shear loads with frequency of 0.1Hz and constant vertical load by controlling the shear strains.

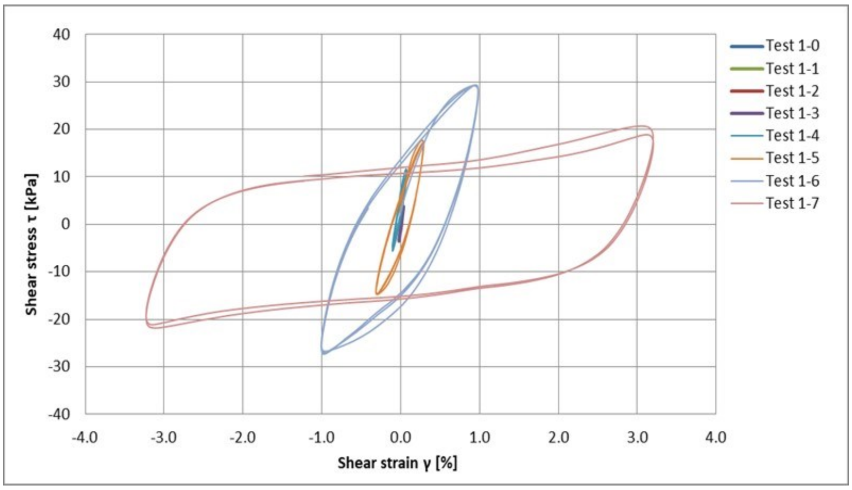

Figure 7. Shear stress–strain relationship from DSS test

Figure 8 presents the summary of the results for DSSA from which some conclusions can be made. Again, strong pressure dependence is noticed that increases with the increase of specimen relative density, contrary to this the

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relative density dependence compared to previous results is lower and only noticeable when specimen are reconstituted with high Dr.

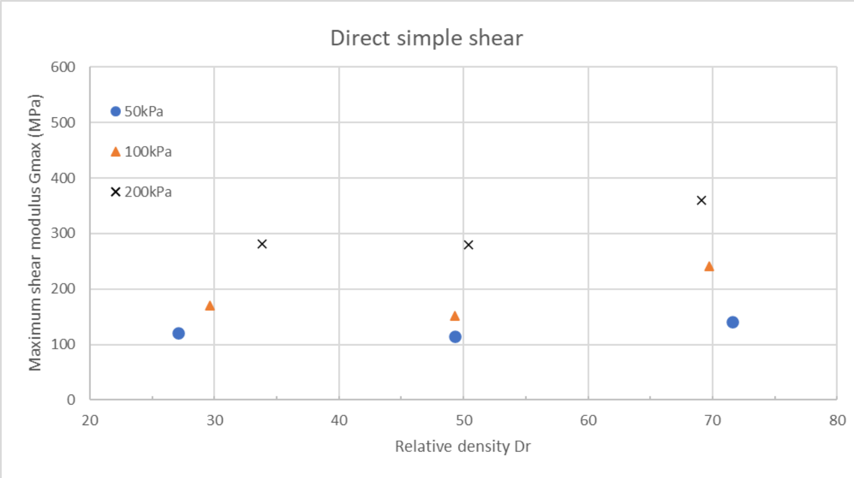

Figure 8. Results from DSSA

6. Conclusions

Extensive laboratory element testing of Skopje sand specimens was performed aiming to better understanding of key parameters which influence the determination of small strain shear modulus Gmax. Triaxial integral system and Direct Simple shear apparatus were used to run the respective triaxial, bender element and direct simple shear tests. Particular attention was paid to investigate the impacts initial stress conditions and relative densities exert on Gmax. Although the above mentioned testing equipment work on different stress states of the soil specimens, the obtained results for Gmax clearly show the significant stress dependency of Gmax (figure 9). The relative density also influenced small strain modules, particularly at high level of initial stresses. These findings are important outputs of the present study and have to be considered during the design and running of element testing for assessment of small strain modulus.

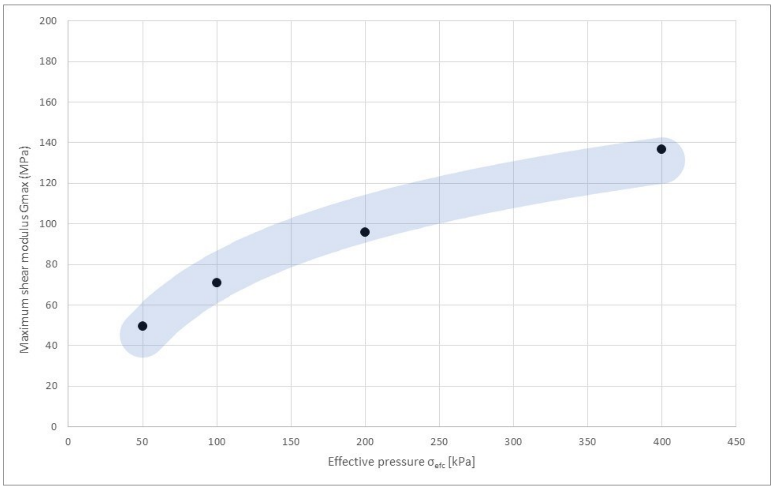

Figure 9. Dependance of the small strain shear modulus to the effective stress – envelope trend

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