Foreword

The academic articles here proposed concern some examples of design where the dynamic response of important structures have been analyzed through a campaign of laboratory investigation where a consistent number of cyclic simple shear tests have been carried out.
The CSS test consists in the application of a cyclic shear stress causing the angular distortion of a soil element and the continuous rotation of the principal axes of stresses and strains.
This condition of stresses simulates quite correctly the situation that occurs within the underground layers of soils when, for example, a seismic event occurs.

The paper has been presented in the Proceedings of the 20th International Conference on Nuclear Engineering (Anaheim - California, 2011) and summarizes the results of a testing program for seismic characterization of a subsoil concerned by the construction of a nuclear power plant. The work has been carried out by the research group that operates in the Institute of Earthquake Engineering of the University Ss Cyril and Methodius (Skopje - Macedonia), coordinated by Prof. Vlatko Sheshov.
Besides the common standard tests for physical and mechanical characterization, the cyclic simple shear tests have been performed for the evaluation of the dynamic properties (in terms of stiffness modulus and damping ratio) of each layer of the subsoil model.
It is a matter of fact that the shear modulus G and the damping ratio D are highly influenced by the level of strain induced by the stress conditions. From this point of view the simple shear tests performed for this project allowed a range of strain from 10^{-3} to 1% to be investigated.

From the documents presented herein, important indications can be drawn with reference to the design parameters, that laboratory investigations can define. Another important message is given from the awareness that it is necessary to operate with sophisticated automatic equipment with highly accurate and reliable measurement systems, that CONTROLS Group and his historical Wykeham Farrance brand can ensure.

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LABORATORY EXPERIMENTS ON SOIL DYNAMIC CHARACTERISTICS OF NPP SITE

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ABSTRACT

This paper summarized the results of dynamic properties of the soil samples collected from one NPP site which is still under construction. Geotechnical aspects related with seismic safety of structures and foundation ground is important issues to be investigated. Recommendations and procedures given in IAEA Safety Standards Series No. NS-G-2.13 Evaluation of seismic safety for existing nuclear installations ; IAEA Series No. NS-G-3.6 Geotechnical Aspects of Site Evaluation and Foundations for Nuclear Power Plants and US NRC Regulatory Guide 1.138 have been generally followed.

A series of strain controlled cyclic simple shear tests have been carried out on dry soil samples ranging from small-medium to large shear strain levels. Simple shear condition is the one of the most representative strain condition of in-situ ground during seismic event and very suitable for evaluating ground response. Laboratory testing using the Dynamic Simple Shear Apparatus with improved measuring devices were performed on samples taken from the site and the nonlinear stress-strain relationships were established. Stable hysteresis curves from the tests enable clear definition of G/G_{max}-γ and D-γ curves which describe the apparent reduction of the shear modulus G and the variation of damping ratio D of the investigated soil samples within the shear strain range of interest.

Based on the results from the performed cyclic simple shear tests the relationship between the initial shear moduli versus overburden pressure for the current soil layers was established. The results gathered from laboratory investigations regarding the dynamic characteristics of soils are important step in the process of site response analysis and developing specific site response spectra to evaluate the seismic loading and earthquake geotechnical aspects of sub-surface soil layers. This study clarifies that cyclic simple shear tests on careful prepare soil samples give reliable results over wide range of shear strain and therefore can be primarily solution for laboratory investigation on dynamic properties of soil layers.

INTRODUCTION

The earthquake case histories have revealed that the local geological conditions have specific effect on the characteristics of ground motion upon the surface during the earthquake. Depending on the characteristics of the soil layers and the characteristics of the excitation at the level of the seismic subsoil, the mentioned effect can be higher or lower. It is expressed through the amplitude-frequency modification of the surface seismic excitation in respect to the corresponding excitation at the level of seismic bedrock. The influence of soil layers on the amplitude and frequency content of ground motion can be substantially. Therefore investigation of the subsurface conditions at a nuclear power plant site is very important at all stages of the site evaluation process.

The investigation programme depend of the stage site evaluation should provide necessary information for appropriate characterization of the subsurface ground conditions**.** To perform reliable and realistic site specific seismic response analysis, which actually define the seismic input for the further seismic assessment of the structures and equipment performance of nuclear power plant, static and dynamic material properties of soil and rock profiles should be obtained. Shear moduli and material damping for each soil layer at the site are one the most important soil parameters for seismic site response analysis. In cases of ground response involving no residual displacement the response is determined mainly by the shear modulus and damping characteristics of the soil under reasonably symmetrical cyclic loading condition. A comprehensive research studies of the factors affecting the shear moduli (G) and damping (D) of soils have been made by many researchers (Seed and Idriss 1970; Hardin and Drnevich 1972; Lee and Finn 1978; Seed et al.1986; Vucetic and Dobry 1991; Rollins et al.1998; Vucetic et al.1998; Darendeli 2001; Roblee and Chiou 2004; Zhang et al. 2005). In these studies it was suggested that the primary factors affecting moduli and damping are: strain amplitude (γ), mean effective principal stress (σ_m'), soil type and plasticity index (PI). Other factors that appear to be lees important are: frequency of loading, number of loading cycles, overconsolidation ratio and degree of saturation.

In Fig. 1 a typical shear stress-strain relationship is shown for fine-grained soil materials at undrained cyclic loading. The maximum shear modulus (G_{max}) refers to modulus at very small strains in the range of $\gamma=10^{-4}$ and less. Taking into account the range of (γ) to which (G_{max}) refers in which the soil behaves as a linear material, (G_{max}) could be defined as a constant which in that range correlates stresses and strains.

The secant modulus (G) has been defined through the secant of the hysteresis loop which passes through the extreme points, as shown in Fig. 1. The secant modulus (G) could be interpreted as an average modulus in the (±γ) domain. In this way it is used for definition of an equivalent linear model for which (G) is a constant correlating (τ) and (γ) in amplitude range from (–γ) to (+γ).

The material damping ratio (D) represents the energy dissipated by the soil, Figure 2. Mechanisms that contribute to material damping are friction between soil particles, strain rate effect, and nonlinear soil behavior. The hysteretic damping ratio can be calculated as it shown on Fig.2 where:

A_H = the area enclosed within the hysteresis loop (τ–γ) representing the damping energy (ΔW)

A_{oab} = area of triangle (Oab) representing the strain energy (W).

Theoretically, there should be no dissipation of energy in the linear elastic range for the hysteretic damping model. However, even at very low strain levels, there is always some energy dissipation measured in laboratory specimens. At higher strains, nonlinearity in the stress strain relationship leads to an increase in material damping ratio with increasing strain amplitude.

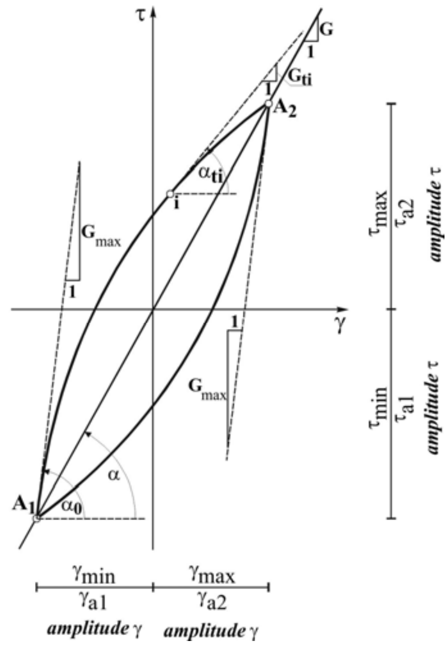

Fig. 1 Definition of shear moduli G from τ–γ relationship

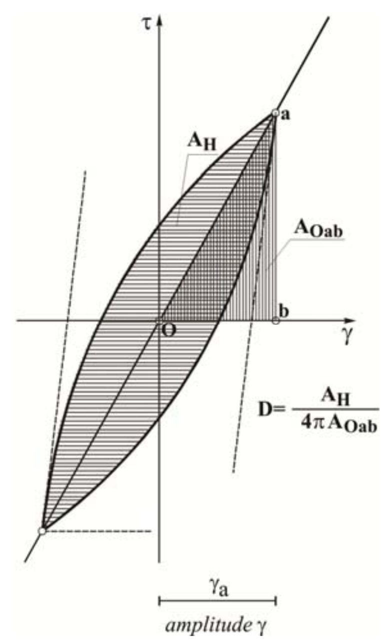

Fig. 2 Definition of damping D from τ–γ relationship

The factors which have dominant effects and influence of parameters upon moduli (G) have been studied by many researchers. Figure 3 shows results done by Hardin and Drnevich, 1972, regarding the level of mean principal effective stresses and number of cycles on G. They obtained a negligible difference of (G) for testing even a number of cycles exceeding

100. Effects of mean principal effective stresses can be clearly seen, increase of effective stresses leads to higher values of G.

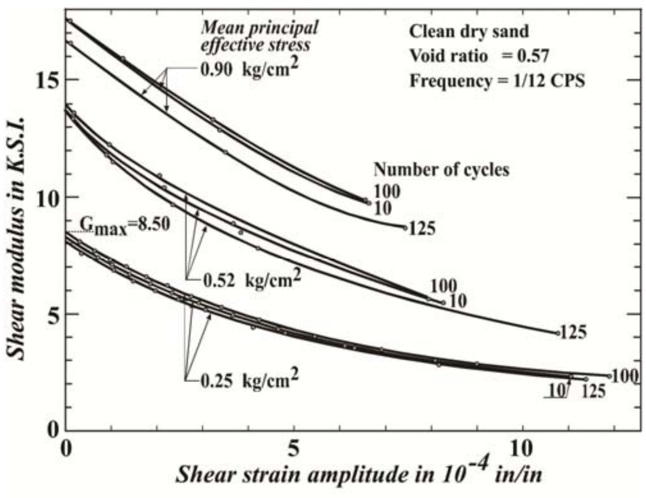

Fig.3 Effect of γ, σ_o' and number of cycles N upon G (Hardin and Drnevich, 1972)

Based on a review of laboratory test data published in the literature, Vucetic and Dobry 1991 [4] published stress-strain curves, which are shown in Fig. 4. The effect of soil plasticity and number of loading cycles on the stress-strain relationship are also indicated. They have been identified five aspects for which PI plays significant role in the undrained cyclic response of fine-grained soils. As the plasticity index of the soil increases: G_{max} increases faster with overconsolidation ratio OCR; G_{max} increases faster with geological age; the normalized curve G/ G_{max} versus γ rises; the curve of damping (D) versus γ falls and G degrades less after N cycles of a given γ. The first two effects relate to small strains $\gamma=10^{-4}$ while last three effects relate to larger strains above $\gamma=10^{-2}$.

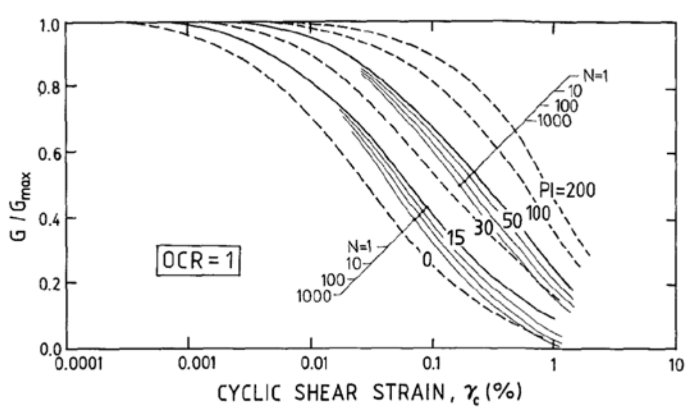

Fig.4 Effect of Cyclic stiffness degradation on G/G_{max} for soils of different plasticity indices (Vucetic & Dobry, 1991)

The current state of practice for determining G and D for ground response analysis involves: measuring shear wave velocity V_S in the field and estimating or measuring the variation of G and D with γ primarily in the laboratory. In-situ geophysical survey is one of the widely used methods for measurement of Vs which is directly related to small strain shear modulus G_{max}. ($G_{max}=\rho V_s^2$). Even the measuring accuracy of conventiaonal laboratory tests at small strain amplitudes has been improved most of the studies strongly suggested to used the G_{max} determined by in-situ measurements. The selection of testing techniques for measurement soil properties requires careful consideration and understanding of the specific problem at hand [2]. Efforts should always be made to use laboratory tests that replicate the initial in-situ stress conditions and the anticipated cyclic loading conditions as closely as possible.

Procedures and techniques for several laboratory methods like triaxial testing method, resonant column method for evaluation of soil properties is given by many national and international standards (ASTM, JGS, BS etc). Cyclic simple shear test method for definition of shear moduli and damping of soil is not fully covered by any standard. Even it is generally difficult to perform simple shear tests in ideal conditions because of several disadvantages (non-uniformity of strain distribution and normal stresses, limitation due to K_0 condition) still the cyclic simple shear test is capable of reproducing earthquake stress condition much more accurately than is the cyclic triaxial test. Therefore it is not justified for the cyclic simple shear tests to set aside from standardized method for evaluation of dynamic properties of soils. Some of the disadvantages of cyclic triaxial and cyclic simple shear tests can be avoided by cyclic torsional shear tests which allow isotropic and anisotropic initial stress conditions and can impose cyclic shear stresses on horizontal plane with continuous rotation of principal stress axes [5].

The present study adresses applicability and usefulness of cyclic simple shear tests for evaluation of soil properties under dynamic loading at wide range of shear strain.

EXPERIMENTAL INVESTIGATIONS

Summarized in this paper is laboratory procedure for estimating the variation of G/Gmax and D with γ for representative soil sample collected from one NPP site. It should be emphasized that normalized shear moduli and damping were subject of this study while other soil investigations regarding site evaluation, ground conditions etc. are not discussed here.

Selection of the material

The NPP site is characterized by several soil layers. The soil deposit is stratified up to 35-30 m depth. Below 35 m engineering bedrock consisted of marly clay, marls and sandstone is located. The nonlinear behavior of these layers will have influence on ground motion parameters during the expected earthquakes and the dynamic interaction between soil and the facilities of the nuclear power plant. For analysis and definition of these effects, it is necessary to define dynamic characteristics of the site soil layers. For this purpose, laboratory testing of samples taken from characteristic soil layers was performed at University "Ss Cyril and Methodius", Institute of Earthquake Engineering and Engineering Seismology, IZIIS Soil dynamic laboratory in Skopje, Macedonia in order to define the strain compatible shear modulus values and damping values for representative soil layers. The selection of the tested materials was made by careful examination of the quality of the received samples. Depending on the type, nature and conditions upon arrival at the laboratory the soil samples were tested as relatively undisturbed and disturbed samples. Handling and storage of samples was done following the procedures prescribed in US NRC Regulatory Guide 1.138 [9]. The identification markings of all samples were verified immediately upon their arrival at the laboratory.Tested as relatively undisturbed samples were those from the coherent materials and materials containing a high percentage of clay fractions. Samples from sand material were tested as reconstituted samples. The velocity of pouring rate, height of pouring and tapping energy were parameters which were applied during the preparation process to re-produce as close as possible in-situ stress state [3].

Physical properties for soil materials subject to dynamic testing (grain size distribution, unit weight, specific gravity, water content, plasticity index etc..) were used from previous performed in-situ and laboratory investigations, Table 1.

Table 1. Physical properties of soil samples

	Lithological description	Bore-hole Depth (m)	Exp. No.	Vertical loading σ [kPa]	Dry unit weight γ_{max} [kN/m^3]	Dry unit weight γ_{min} [kN/m^3]	Relative density Dr [%]	Humidity w [%]
Sands	Silty clayey sand	Mc 7 10.0-10.7	1	161	17.2	12.2	60	
			2	165	17.2	12.2	65	
			3	161	17.2	12.2	62	
	Fine grain clayey sand	Mc 9 14.6-15.4	1	232	15.5	10.3	78	
			2	230	15.5	10.3	79	
			3	232	15.5	10.3	79	
	Clayey sand	Mc 5 15.5-16.0	1	290				19.7
			2	270				19.5
	Medium grained sand	Mc 2 19.0-19.5	1	340	18.4	13.0	64	
			2	337	18.4	13.0	67	
			3	337	18.4	13.0	67	
	Medium grained sand	Mc 4 25.0-26.0	1	439	18.4	13.3	65	
			2	433	18.4	13.3	66	
			3	429	18.4	13.3	69	
			4	431	18.4	13.3	68	
Clays	Clay	Mc 5 5.3-5.6	1	113				29
			2	120				28.3
			3	127				27.2
	Sandy Clay	Mc 5 9.1-9.4	1	19				21
			2	194				19.5
			3	192				19

TESTING PROGRAM

Cyclic Simple Shear Apparatus, CSSA [1] was used to performed the cyclic shearing on soil samples. Several design features contribute to performance of the apparatus: a dual-sample concept which eliminates the frictional problems associated with bearing supported loading platens, dynamic loading system, custom designed for small displacement and high force applications uses a novel system of roiling diaphragms and flexural supports to achieve smooth high load performance and the control system which optimize dynamic range both in measurements and control of force and displacement. Two cylindrical samples both rigidly confined in the vertical and radial direction are simultaneously tested. The schematic view of the apparatus is given in Fig. 5.

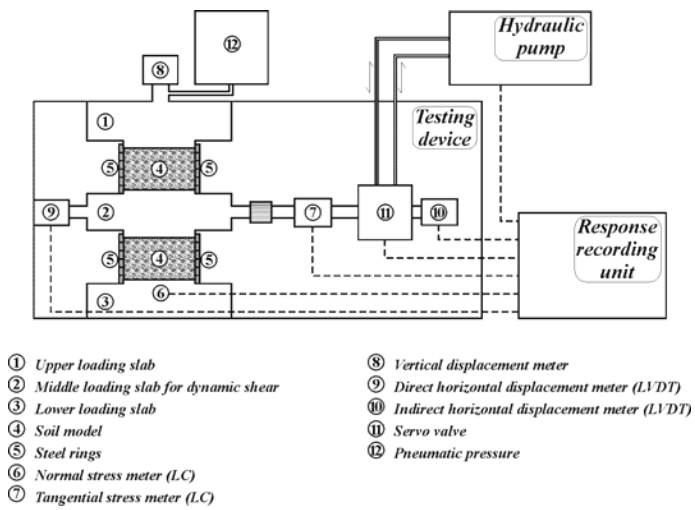

Fig. 5 Schematic view of the cyclic simple shear apparatus CSSA

The CSSA used in this study enables cyclic shear tests with constant volume and strain control; cyclic shear tests under constant vertical load with control of shear strains and cyclic shear tests with load control.

The cyclic simple shear tests on soil samples were performed in 7 series. Performed within each series were at least two to four experiments under equal loading and dynamic excitation conditions. Samples from 5 different sand soil layers were tested, Table 1. Dynamic excitation was applied in the form of short series of cyclic simple shear loads with frequency of 0.1 Hz by controlling the shear strains (strain control). The excitation was applied step-by-step, with variation of the maximum amplitude of shear strains. Permanent recording of horizontal displacements and shear stresses was performed throughout the experiment. In this way, the hysteretic $\tau-\gamma$ relationships were obtained for each strain level.

DEFINITION OF THE G/G_{MAX} - γ and D-γ CURVES

The dynamic shear moduli are defined as secant shear moduli G that correspond to the extreme points of the hysteretic curves. They are determined for each strain level γ. Figure 1 presents the basis for determination of secant shear moduli G. By using the obtained values for the shear moduli G for each strain level, established were the G-γ diagrams of the relationships between the shear moduli and the shear strains.
Dividing each value of the modulus G by G_{max} corresponding to the least shear strain that was obtained during the corresponding test, obtained were the normalized shear moduli G/G_{max} for each strain level. Based on the normalized shear moduli values, the functional G/G_{max}-γ curves were determined. The normalized curves (G/G_{max}-γ) are suitable for presentation of the phenomenon of moduli decrease with increase of shear strain (γ). A plot of G/G_{max} is known as normalized modulus reduction curve and this refers to very important nonlinearity in the soil behavior under dynamic loads.

Damping of soil was defined by damping ratio D that represents a percentage of the critical damping. It was determined by using the relation given in Fig.2.

Shear stress versus shear strain relationships for each selected soil material was derived from performed tests. Results for τ–γ relationships at seven different levels of shear strain are presented in Figures 6, 7 and 8.

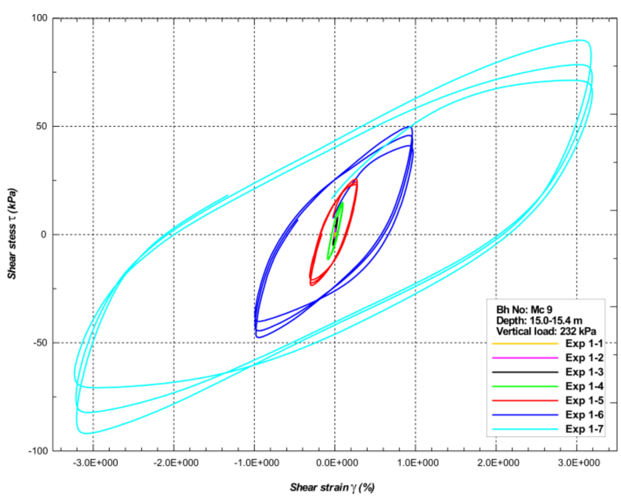

Fig. 6 τ–γ **relationships for different strain levels - Mc9**

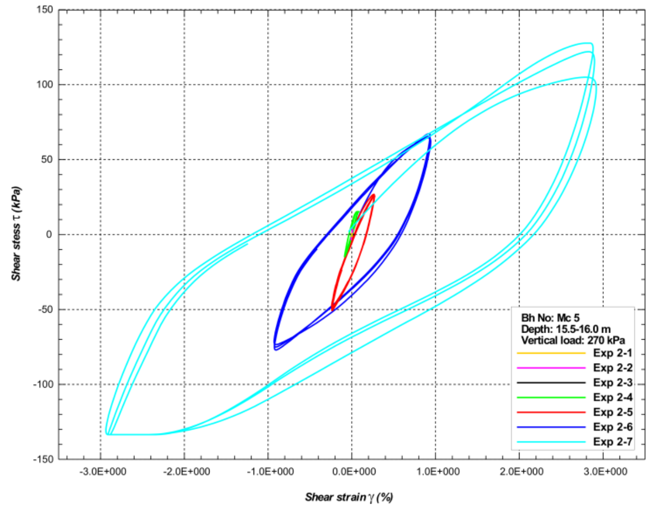

Fig. 7 τ–γ **relationships for different strain levels - Mc9**

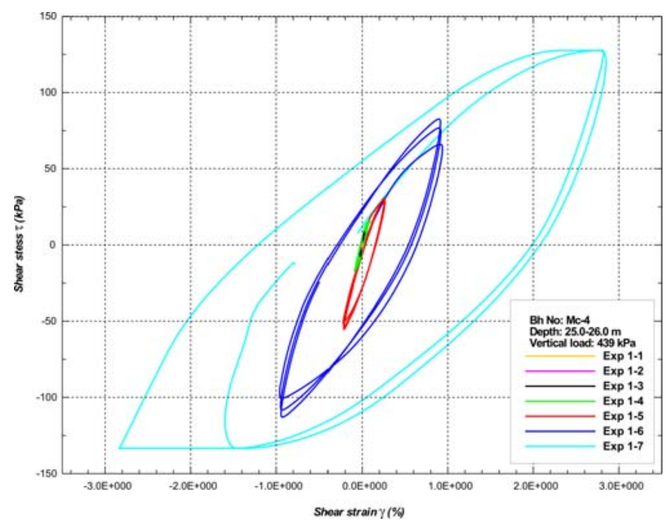

Fig. 8 τ–γ **relationships for different strain levels - Mc9**

Rotation and characteristic ‘widening’ of hysteresis curves at higher levels of strain are clearly observed. These relationships were basis for definition of normalized G/G_{max} and damping D curves for different level of shear strain, Figs 7, 8, 10, 11, 13, 14

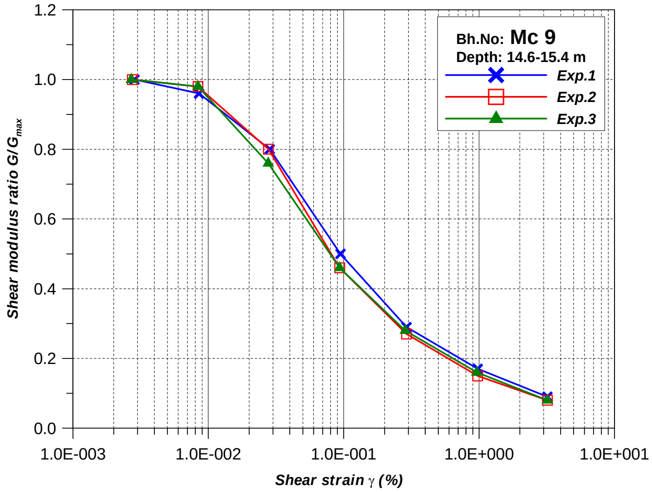

Fig. 9 G/Gmax curves versus γ - Mc9

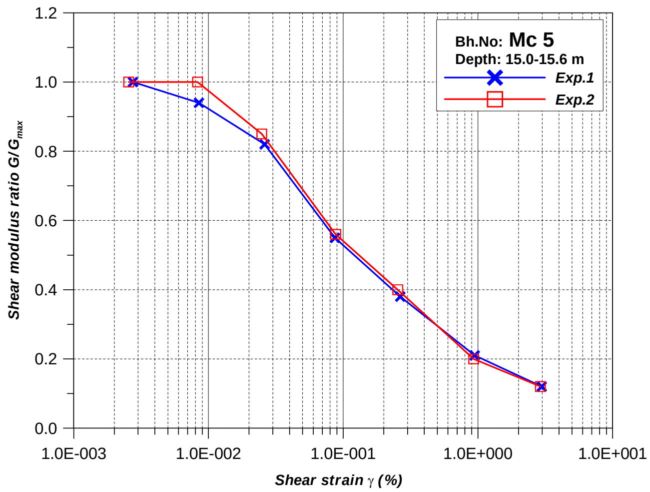

Fig. 10 G/Gmax curves versus γ - Mc5

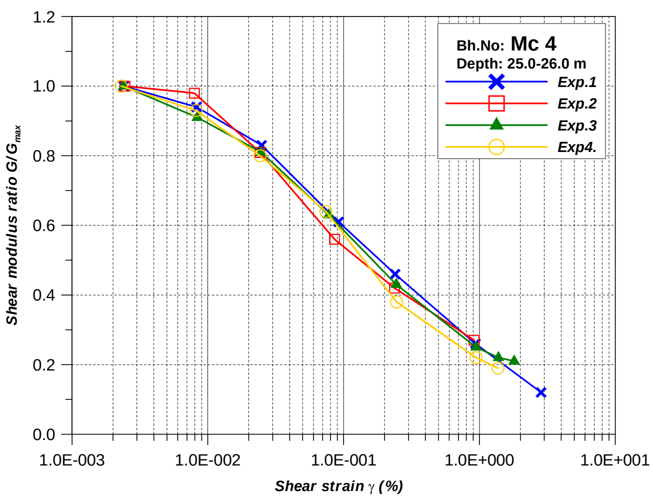

Fig. 11 G/Gmax curves versus γ - Mc5

It can be seen from Figures 9 and 10 that reduction G/Gmax curves slightly differ in the medium range of shear strain values. Soil material from the same depth, for borehole Mc5, Fig. 10 behave more rigidly compare to results for material from borehole Mc9, Fig.9.

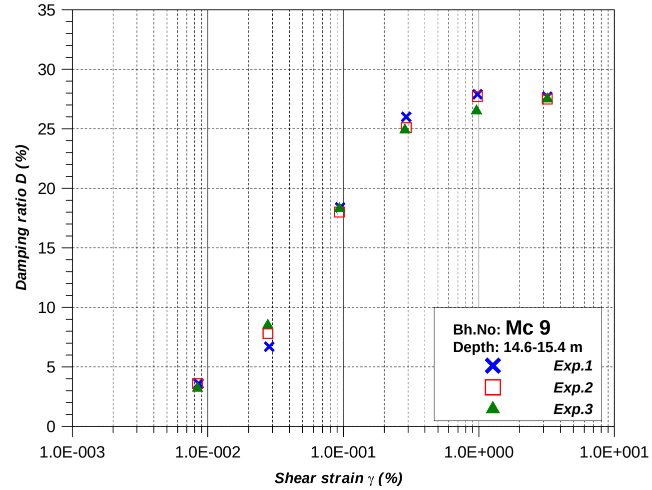

Fig. 12 Damping ratios versus γ - Mc9

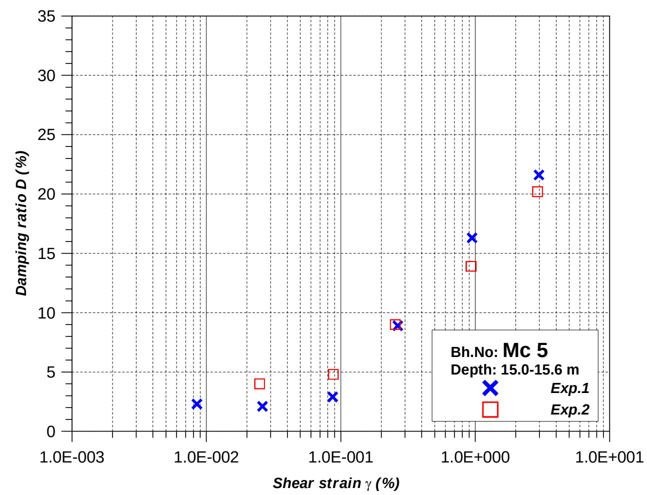

Fig. 13 Damping ratios versus γ - Mc5

At the same time if we look at the results for damping D, Figures 12 and 13 the material from borehole Mc 9 shows higher damping than material from borehole Mc 11 from medium to large levels of shear strain. This characteristic behavior of soil material under medium to large levels of shearing is one of the crucial step that has to be take into account when site response analysis is performed.

Results from the cyclic simple shear tests were used also to define the influence of the effective stresses upon shear moduli G, Figure 14.

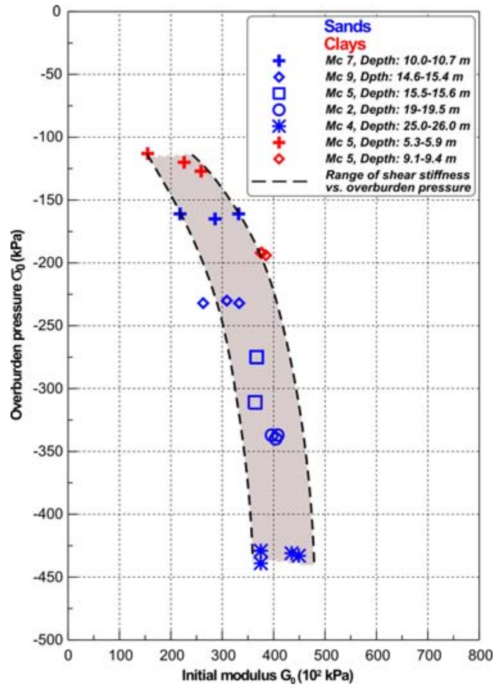

Fig. 14 Variation of Initial shear moduli G with depth

Presented results in Figure 14 show increase in values of initial G moduli with the depth (increasing of overburden pressure). The results can be used for modeling of soil stiffness along the depth of the foundation soil.

Results from the tests show stable τ-γ hysteretic behavior for medium to large strain level while for small strains less than 10^{-3} it was observed relatively large scattering of data. Therefore some of the results for Gmax and damping D for low level of strains were not take into account and not presented in figures. Even the measurement system of the apparatus was improved with two LVDT (direct and indirect measurements) it was not enough to get stable data for strain level less than 10^{-3}. Regarding the estimation of G_{max} (low shear strain moduli) strong suggestion was given to designer to upgrade the given G/G_{max} curves with the results from in-situ geophysical survey.

CONCLUSIONS

For layered soil, the strain compatible shear modulus values and damping values for each layer are the bases for the derivation of the mathematical model of the layered soil and necessary input for realistic site response analysis of the NPP site. Strain dependent G/Gmax and D curves for representative soil layes at one NPP site are developed by series of strain controlled cyclic simple shear tests. Tests were performed taking into account the most important factors which influenced the shear moduli and damping of soils: shear strain amplitude, mean principal effective stress and PI. Cyclic simple shear apparatus used in this study enables to produce reliable and very stable modulus reduction and damping curve for wide range of strain (medium to large level of shear strain). Results from performed experimental investigations used in site response analysis provide better understanding of seismic performance of foundation soil and reliable estimation of ground motion. Experimentally defined relationships for shear modulus and damping provide solid base for modeling of soil structure interaction. Improvement concerning the estimation of small strain shear moduli can be done by combining the in-situ G_{max} with laboratory derived G/G_{max} curves.

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