# The behaviour of natural cohesive soils under dynamic excitations

## Le comportement des sols cohérentes naturelles sous excitations dynamiques

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ABSTRACT: In the last forty years, a significant amount of research has been carried out to better understand the mechanical reaction of soils to dynamic excitations. A variety of laboratory techniques were used for these studies e.g. cyclic torsional shear tests, cyclic direct simple shear tests, cyclic triaxial tests and resonant column tests. They allowed researchers to measure above all strain amplitude and frequency of excitation on soil behaviour (Lai et al. 2001). The series of experiments and analysis in the presented paper were therefore carried out to evaluate dynamic properties of consolidated soils from Warsaw, the capital of Poland, using GDS Resonant Column Apparatus. Shear modulus ($G_0$) determined on the basis of shear wave velocity, measured during resonant tests, represented here the initial stiffness of the soil. Suitable number of tests showed that the change in initial stiffness was caused by many factors, among which was mean effective stress (p'). Numerous laboratory experiments confirmed the knowledge from the literature on growth of the material damping of soil (D) with the strain amplitude. Some considerations concerning the impact of low and very low shear strain ($\gamma$) on soil behaviour were also included.

RÉSUMÉ : Au cours des quarante dernières années on a mené un nombre significatif de recherches ayant pour but la meilleure compréhension des comportements des sols soumis aux charges dynamiques. Pendant les recherches, on a recouru à de différentes techniques de laboratoire telles que: le cisaillement de torsion en cycle, le cisaillement direct cyclique, les essais triaxiaux cycliques et les essais à la colonne résonnante. Le recours à ce type de recherches a permis d'obtenir surtout des mesures de l'amplitude et de la fréquence des vibrations et de leur influence sur les réactions du sol (Lai et al. 2001). Dans l'étude, on a presenté une série d'experimentations et d'analyses ayant pour but la reconnaissance et l'évaluation des propriétés dynamiques des sols consolidés, présentes dans la région de Varsovie, capitale de la Pologne, en recourant à la colonne résonnante fabriquée par la société britannique GDS. Le module de la déformation amorphe (G0), estimé à la base de la vitesse de l'onde transversale mesurée au cours de l'étude, représente la rigidité initiale du sol. Les recherches menées ont demontré qu'un changement de la rigidité initiale du sol est causée par de nombreuses facteurs, dont l'un très important est celle de la contrainte effective moyenne (p'). De nombreux essais en laboratoire ont prouvé l'augmentation de l'amortissement des vibrations dans le sol (D) avec l'augmentation de l'amplitude de la déformation amorphe et don't la prevue réside dans la littérature spécifique de référence. Dans l'étude, on a également incorporé des remarques et des précisions portant sur l'influence de l'ensemble de petites et minuscules déformations sur des propriétés dynamiques du sol.

KEYWORDS: dynamic excitations, resonant column tests, natural cohesive soils

## 1. INTRODUCTION

There exist in nature all kinds of vibrations on the ground, such as for example: earthquakes, water waves, storms, traffic loads, vibration machinery, construction operations, wind power and many others. In practical geoengineering, the response of dynamic characteristics of the subsoil under these oscillations has become lately a focus of a great interest.. Shear modulus and damping properties are required for a proper analyzing and a good understanding the response of the soil influenced by the dynamic load (Bai 2011).

The initial shear modulus ($G_0$) is extensively perceived to be a fundamental soil stiffness property and is a parameter for geotechnical researches, both in earthquake engineering as well as in the prediction of dynamic soil-structure interactions (Piriyakul and Haegeman 2009). Dobry et al. (1980) employed the stiffness method for foreseeing the liquefaction potential of saturated sand provided that the shear modulus at small strains for soil layers to define the threshold ground acceleration is known. The initial shear modulus can be measured in laboratory in the triaxial tests with bender elements technique or in resonant column apparatus while torsional mode.

Damping ratio (D) is another important parameter in the investigation of dynamic problems. Small-strain damping ratio ($D_{min}$) is rather difficult to accurately determine due to a lot of elements interfering with the experiment, like: equipment damping, environmental noise, back electromagnetic force. $D_{min}$ obtained by resonant column tests is therefore somewhat higher scatter, but these effects become inessential when researches are made at high strain amplitude.

To well understand a complex nature of dynamic soil characteristics, the impact factors should be completely investigated. Dynamic soil properties are affected by various factors, among which strain amplitude, confining pressure, void ratio, overconsolidation ratio, loading frequency, temperature, anisotropic stress and so forth are the most significant (Hardin and Drnevich 1972).

As the same importance as small-strain dynamic attributes of soil, the non-linear dynamic properties play an essential role in analyzing the dynamic behavior of ground motion during, for instance, strong earthquake, like Sichuan Earthquake from 12$^{th}$ May 2008, with Richter magnitude scale M=8.0, which killed more than 70 000, injured around 300 000 people and millions caused homeless. The shear strains triggered in surface deposits while such big motions may be estimated around $10^{-2}$% up to 1% (Iwasaki and Tatsuoka 1977). Because of this is very necessary to search the strain-dependent dynamic characteristics of soils at the level of $10^{-4}$ till $10^{-2}$ in laboratory.

Based the background and problems mentioned above, this study aimed at determining the dynamic properties of natural cohesive soils from Warsaw area by defining the value of shear modulus ($G_0$) as well as damping ratio ($D_{min}$) at small strains. Moreover, the factors influence small-strain shear modulus, shear modulus reduction curve and damping curve were examined, with the particular attention paid to the mean effective stress (p'). In addition to this, the impact of low and very low shear strain ($\gamma$) on soil behaviour was also included. To achieve specified objects resonant column (RC) tests were conducted.

## 2. TEST MATERIAL AND EXPERIMENTAL PROCEDURE

The material investigated belongs to a natural cohesive soil formation in the Warsaw area, precisely from the region of the express way S2. It is a clayey sand, clSa, (see Figure 1) with index properties listed in the Table 1.

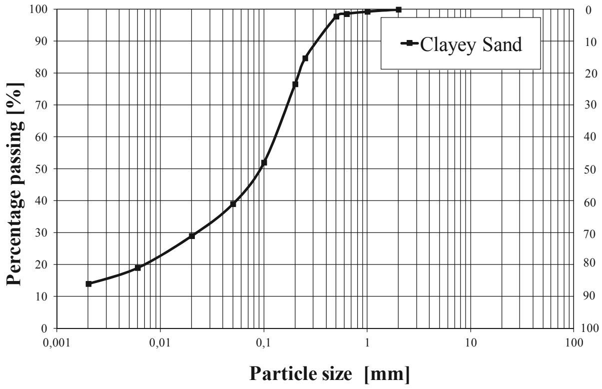


Figure 1. Grain size distribution of test material.

The samples were taken from the depth of around 2.0m selected carefully considering the uniformity of the soils structure, its physical properties and its double-phase.

Table 1. Index parameters of specimens.

| Parameter | *Value* |
| --- | --- |
| $w_L$ (%) | 31.20 |
| $w_P$ (%) | 12.62 |
| $I_P$ (%) | 18.58 |
| $G_S$ (-) | 2.68 |
| w (%) | 12.82 |
| $\rho$ (kg/m$^3$) | 2230 |

where $w_L$ is the liquid limit, $w_P$ is the plastic limit, $I_P$ is the plastic index, $G_S$ is the specific gravity, $w$ is the water content, $\rho$ is the mass density.

The details of the experimental program can be found in another article of the authors (Sas et al. 2012), which relates to the similar topic. Nevertheless, some important phases of the experiments should be outlined here as well. Before the proper dynamic measurements were performed, test material required correct preparation. The initial stages of the study, consisting in modelling of the natural conditions of the samples in field, included: flushing of the equipment, saturation, control of Skempton's B parameter and consolidation. Undisturbed sample was set up in the cell, then saturated by back pressure methods, which was increased accordingly to ensure the saturation of the sample until the Skemption's B value was higher than 0,90. When full saturation was achieved, consolidation process started. The soil was consolidated to predetermined isotropic stress. In every test, an isotropic effective confining pressure was applied in steps, namely 45, 90, 135, 180, 225, 270 and 315kPa. The experiments were stopped with the mean effective stress equal to 315kPa, due to the equipment's limitations. During the consolidation phase, the volume change and the axial deformation of the specimen were measured. Moreover, the void ratio of the specimens was updated during consolidation at each loading stage. In order to excite the electromagnetic field and induce a wave propagating through the examined material, the corresponding coil voltage values were placed, from the value 0.1V up to 1.0V, with a step of 0.1V. Then finally, RC tests were performed.

## 3. EXPERIMENTAL TECHNIQUE

The testing procedure applied by the authors is the resonant column technique. This method allow to determine shear modulus, shear damping, rod modulus (usually referred to as Young's modulus) and rod damping for solid cylindrical specimens of soil in the undisturbed and remolded conditions by vibrations. The vibration of the material may be superposed on a controlled ambient state of stress in the specimen. The apparatus and sample are commonly enclosed in a triaxial chamber and subjected to an all-around pressure, sometimes as well as an axial load. Additionally, the specimen can be subjected to another controlled conditions, such as pore-water pressure, temperature or degree of saturation. The resonant column technique is considered nondestructive if the strain amplitude of excitation is less than $10^{-4}$ rad. At that time many measurements may be done on the same sample but with various states of ambient stress (ASTM 2000).

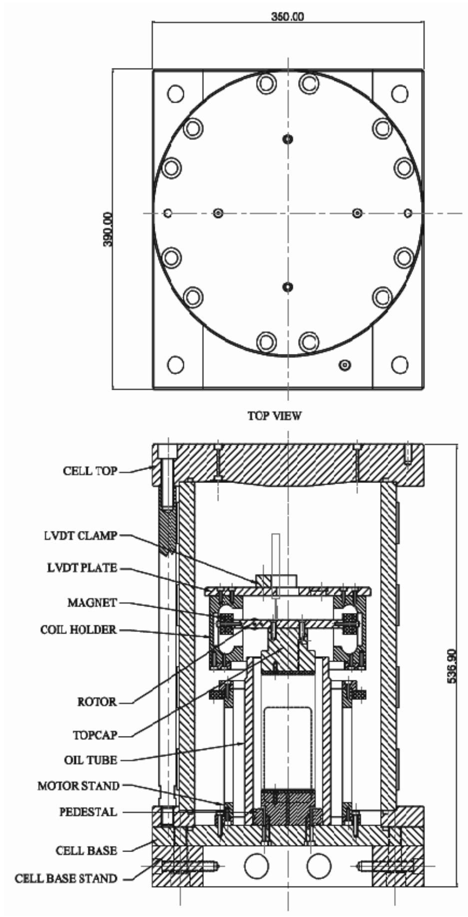


Figure 2. Schematic illustration of the resonant column implemented in the authors researches (GDS 2010).

The resonant column device successfully used in this work were manufactured by British company GDS Instruments Ltd. The apparatus is presented in details in the papers (Sas and Gabryś 2012, Gabryś et al. 2013). The scheme of the equipment is shown in Figure 2.

In this resonant column equipment, a fixed-free cylindrical soil specimen is excited in two modes: torsion and flexure. The resonant frequency and the damping ratio are obtained from the analysis of the input excitation and the response of the specimen in both time and frequency domains. The response of the sample is measured at the driving plate and its shear wave velocity is estimated by solving the equation of wave motion in a prismatic rod (Khan et al. 2008).

4. TEST RESULTS AND DISCUSSION

A complete description of the researches will be presented in the PhD thesis (Gabryś 2013). However, the illustration of some results will be given here as well. The shear modulus G is determined from torional vibration, based on the measured torsional resonant frequencies ($f_{0T}$) and later calculated shear wave velocity ($V_S$). According to Richart et al. (1970) the relationship between G and $V_S$ is formulated by the Eq. 1:

$$V_S = \sqrt{\frac{G}{\rho}} \tag{1}$$

where ρ is the mass density.

The energy dissipated by the system is a measure of the damping of the soil. Damping will be described by the rod damping ($D_L$) determined from longitudinal vibration and the shear damping ratio ($D_T$) defined from torsional vibration. Some results of $D_T$, derived in accordance with Eq. 2, will be shown in this section.

$$D_T = 0{,}5\frac{\mu\omega}{G} \tag{2}$$

where μ is the viscous coefficient for torsional motion, ω is the circular resonant frequency, G is the shear modulus.

For torsional motion, using the standard GDS RCA drive mechanism, the average shear strain amplitude (γ) can be calculated from:

$$\gamma = 4.596\frac{VR}{f_{0T}L} \tag{3}$$

where V is the accelerometer, R is the radius of sample, L is the length of sample, $f_{0T}$ is the torsional resonant frequency.

The stiffness of the natural cohesive soils is influenced by many various factors, among which essential are: strain amplitude, density, void ratio or water content (when saturated with water), effective stress, overconsolidation, time of consolidation and prestraining (previous cyclic loading). Three first elements have greater impact than others, but in this study only one of them was investigated, mean effective stress (p'), as mentioned in the introduction.

Figure 3 illustrates the influence of mean effective stress (p') on small strain shear modulus ($G_0$) and shear damping ratio ($D_{Tmin}$) for Warsaw natural cohesive soil. The measurements show that $G_0$ values increase with mean effective stress at the third-degree polynomial function. The coefficient of determination gives the quality of the function's matching to the data at 96%. The smallest value of $G_0$, around 47MPa was noted for p' equal to 45kPa, the biggest one $G_0$ = 237MPa for p'=315kPa. From this figure can be perceived as well that with the mean effective stress at the level of 180kPa, no significant changes in the value of $G_0$ are observed. The opposite trend of variations applies to the relation between $D_{Tmin}$ and mean effective stress (see Figure 3) with the coefficient of determination of the third-degree polynomial function in the range of 94%. The values of shear damping ratio decrease with increasing mean effective stress, although these differences are not very big. In this study, the decline in the value of $D_{Tmin}$ from around 3,5% till 1,1% was noticed. As previously caught, there is a limited value of p' (around 180kPa) up to which the reduction in $D_{Tmin}$ value is more evident.

Usually the shear modulus is normalized by normalized by the small strain shear modulus ($G/G_0$) to analyze the nonlinear shear modulus properties versus shearing strain amplitude. Figure 4 is an example of the normalized shear modulus versus shearing strain amplitude for Warsaw cohesive soil. The typical normalized shear modulus reduction curve is shifted to the right higher position as increasing mean effective stress.

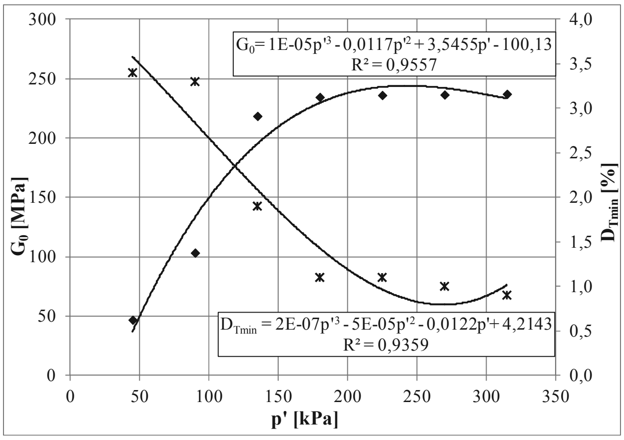


Figure 3. Relation between small strain shear modulus and shear damping ratio with mean effective stress for Warsaw natural cohesive soil.

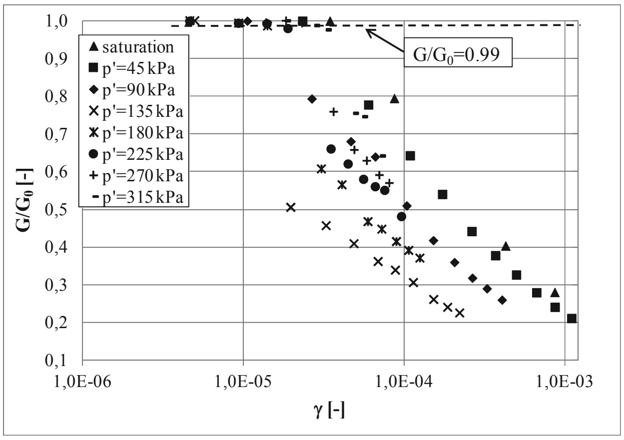


Figure 4. Effect of mean effective stress on normalized shear modulus reduction curve for Warsaw natural cohesive soil.

Figure 5 presents the degradation of shear modulus (G) with shearing strain amplitude (γ) for examined samples under different mean effective stresses. Strong non-linearity and dependence on stress level is evidence. At small strain ($<10^{-5}$), a stress-strain loop is reduced to a nearly straight line: and elastic behaviour. The secant modulus of G decreases as the strain amplitude increases. The decline of G oscillates between the values 230MPa and even 30MPa, depending on the test conditions, namely on the mean effective stress (p'). Shear strain (γ) varies from the value around 5E-04% till 9E-02%, as well as a function of p'. The first measurement of resonant frequency and thus the small strain shear modulus was made immediately after saturation and before consolidation phase of the soil; is called here simply "saturation". The results got from this stage of the studies are the smallest, then gradually increase together with the raise of the mean effective stress, up to the largest values for p'=315kPa.

As shown in Figure 4, the normalized shear modulus decreases as the strain amplitude increases. Therefore, it can be concluded that the effect of shear strain amplitude (γ) on the normalized shear modulus ($G/G_0$) is significant, but for the $\gamma<10^{-5}$ there is no apparent difference between the values of $G/G_0$.

Figure 6 illustrates the variation of shear damping ratio ($D_T$) with shearing strain amplitude ($\gamma$) for Warsaw natural cohesive soil under various mean effective stress (p'). It is a clear increase of shear damping ratio with increasing shearing strain amplitude. Quite significant scatter in the data might have been caused by the impact of the factors mentioned in the introduction of this paper.

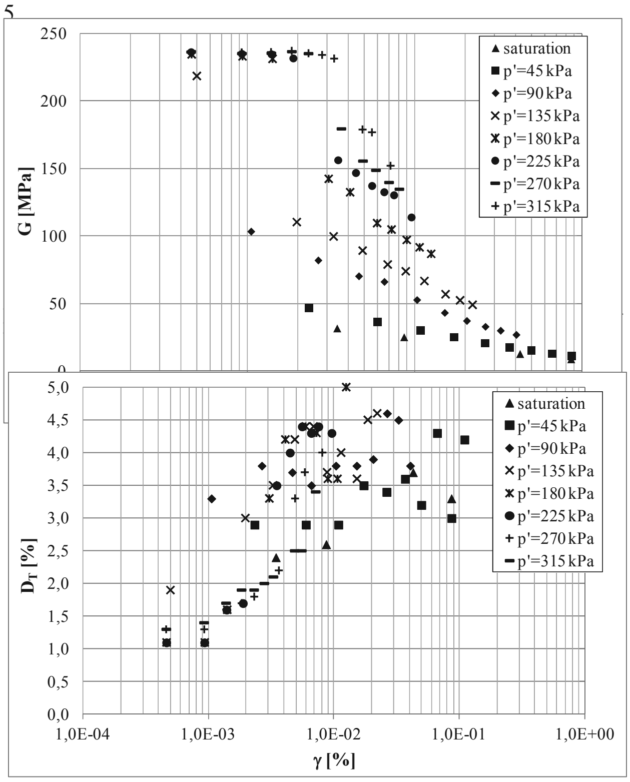


Figure 6. Variation of shear damping ratio with shearing strain amplitude for Warsaw natural cohesive soil under various mean effective stresses.

## 10. CONCLUSIONS

The present article provided some insight into the stress-strain behaviour of natural cohesive soils from Warsaw area test site. Stiffness characteristics is the key parameter for, exemplary, seismic design and performance evaluation of dams. In order to define the dynamic properties of testing material small strain measurements were performed. Laboratory experiments were conducted by means of resonant column, developed by a British company GDS Instruments Ltd. The apparatus applied by the authors of this paper is an example of Hardin-Drnevich device, projected in configuration "fixed-free". The results from the studies were summarized on the graphs. The conclusions can be as follows:

✓ Small-strain shear modulus ($G_0$) increases with mean effective stress (p') in contrast to shear damping ratio. Shear damping ratio decreases with p'.

✓ The effect of mean effective stress on dynamic properties of natural cohesive soil from Warsaw can be then observed.

✓ The effect of shear strain amplitude ($\gamma$) on the soil stiffness and damping is noticeable. Degradation in value of the small strain shear modulus and shear modulus ratio, as well as increase of the damping ratio, correspond to the raise in the strain amplitude. The impact of strain amplitude on G, D and $G/G_0$ is important.

✓ The distribution of the soil stiffness, represented in the article by the shear modulus, shows a significant non-linearity as a function of strain, which is particularly marked in the range of small strains ($\gamma=10^{-5}$-$10^{-3}$).

✓ For the strains $\gamma<10^{-5}$ there is no apparent difference between the values of normalized shear modulus ($G/G_0$).

✓ Difference in the value of shear modulus and damping ratio is closely related to the test conditions, that is to the mean effective stress. The more important effect of p' occurs in $G_0$ at small strain amplitude. At higher amplitudes, the variations of G are not so important.

Although quite a lot of work was performed to investigate the dynamic properties of natural cohesive soil from Warsaw area, some more tests are necessary to be carried out in the future.

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