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# Investigation of Vibrations Influence on Clay Soil Parameters

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The behavior of clay under different frequencies encountered during a dynamic loading events like impact, wind, explosions, seismic, machine foundations is very difficult to analyse, so an attempt has been made to study the behaviour of clay subjected to different range of frequency applied in a laboratory setting on a representative clay sample obtained from a local source in Lithuania. A detailed characterisation of clay has been conducted to classify its index properties and engineering properties to study its behaviour under static loading and subjected to cycling loading using a vibrating table to test its mechanical properties such as compressibility, cohesion, friction angle, oedometric modulus of elasticity. In this paper the range of frequencies that are to be applied to the clay sample vary between 10 Hz and 50 Hz. Direct shear tests on clay samples are conducted under static and cyclic loading and investigated vibrations influence to strength parameters of soil. The effect of vibrations on clay oedometric modulus is determined by doing oedometer tests under the same conditions as shear tests. The testing showed that vibrations change mechanical properties of clay and it is important to evaluate this influence on strength parameters of soil. The investigation suggested that the behavior of clay subjected to vibrations becomes similar to undrained clay

**KEYWORDS:** angle of friction, clay, consolidation, shear, vibrations.

## Introduction

Ground vibrations play an important role in modern structural and geotechnical engineering because incorrect assessment of vibrations in soil could cause harmful effect on structures. An earthquake is a force of nature that acts in many regions of the world every day and it is the most dangerous source of ground vibrations. High magnitude earthquakes result in immense vibrations of soil and produce seismic waves that are extremely hazardous to all kinds of structures. Such shaking effects often cause failure of structures which leads to death of people. Safety of humans is one of the most important things to be accomplished in structural engineering. Therefore, a lot of research and investigation have been carried out throughout the history of modern engineering to reduce the damage to buildings due to seismic activity. Euro-code 8: Seismic Design of Buildings applies to the design and construction of buildings and civil engineering works in seismic regions. Nowadays, buildings in seismic regions are more earthquake resistant than they used to be because of the vast knowledge of earthquake actions and effects accumulated throughout the history of construction and engineering. Luckily, Lithuania can be considered a region of low seismicity so there is no need for seismic activity to be taken into consideration in civil engineering here.



However, earthquakes are not the only source of ground vibrations as there are a number of ways vibrations in soil can be a result of man-made activity. Construction and industrial sources generate waves of a similar nature as seismic waves that can travel through different layers of soil and produce problems for adjacent and remote structures. Such external sources might include road traffic, train loading, blasting, friction pile driving, hydraulic hammer compaction and various vibrating machinery. Each of these vibration sources is unique since the frequency of waves that they produce are different for each one. Furthermore, geological conditions of all construction sites or areas are also unique because of the different soil layers and their own characteristics. Given these facts and also due to the lack of understanding of soil behaviour under specific types of vibrations, it is complicated to correctly assess the effects of construction and industrial vibrations on soil itself and on soil-structure interaction. Proper assessment of ground vibrations is essential in structural engineering and geotechnical engineering. Although vibrations effect on buildings is a well-known area of engineering, its effect on soil characteristics still needs investigation. There is no mention of how to assess vibration related problems in our national geotechnical building code so experiments with soil under vibrations is currently the best way to assess this problem.

The propagation of man-made ground vibration in frequency range of 1 to 100 Hz has been of interest to engineers and scientists for some time. A lot of data about the attenuation of waves and their main characteristics (dominating frequency, peak particle velocity i.e.) has been obtained through the measurements of vibrations using ground vibration monitors, seismographs and 3D geophones (Kim, Lee, 2000).

There are two main types of waves that could be generated from industrial and construction sources: body waves and surface waves. Body waves propagate through the layers of underground soil while surface waves travel along the surface of earth. Also, body waves can be compressional (P) or shear (S) waves and surface waves consist of Love waves and Rayleigh waves. All these waves move in different ways. P waves are the fastest propagating waves. This type of wave causes particles vibration in the same direction that the wave is moving in. P waves can travel through all kinds of environment e.g. solid rock, different types of soil or water. S waves are slower than P waves and when S waves are moving through soil, they cause particles movement perpendicular to the direction that the waves are moving in. Near the surface of earth, S waves can lead to particles moving in both vertical and horizontal directions. This type of wave cannot move through liquid environment whilst in wet soil its amplitude is reduced. The speed of P and S waves depends on structure of soil that they are propagating through. Surface waves consist of Love and Rayleigh waves. Even though they usually come after body waves, it is this type of waves that are responsible for most damage to structures. When Love wave is propagating, soil is moving from side-to-side in the horizontal plane which is parallel to the Earth's surface and the movement of soil particles is perpendicular to the direction that this wave is moving in. Love waves propagate faster than Rayleigh waves and they do not have the vertical displacement component. The last type of waves that can be generated by industrial and construction sources is named for John William Strutt, Lord Rayleigh, who mathematically predicted the existence of this kind of wave in 1885. Rayleigh waves roll along the ground causing soil particles move vertically and horizontally in the same direction that the wave is moving (Gutowski, Dym, 1976).

Most of vibrations generated by industrial and construction sources are the result of various types of dynamic loading. In this age of modern technology the transport plays an important role in our life. With more and more cars being produced every year road traffics are expanding rapidly. However, moving loads, such as road traffic or train loading, generate ground vibrations of specific range of frequency. Depending on the location of traffic, different types of waves can be generated. If the movement is on ground, for example highway traffic, surface railways, or on an elevated structures like bridges, mostly Rayleigh waves are generated. Underground traffic e.g. vehicles

or trains moving in tunnels produce body waves. According to measurements of these vibrations (Kim, Lee, 2000), road traffic induced vibrations have the range of frequency from 5 to 25 Hz, while train loading induced vibrations frequency range is 7-70 Hz.

Another technical source of ground vibrations is friction pile driving. Pile foundations is one of the most common types of foundations due to easier and faster installation comparing to shallow foundations which require ground excavating machinery and more labour force. Also, pile foundations are often more economical than shallow foundations in Lithuania because strong soils lie deeper in most areas. One of the most popular pile foundations installation types is pile driving by vibrating since it is easier to penetrate through the soil using this method and no additional soil is excavated as in drilling method. Pile driving generates both surface and body waves but it is estimated that as much as 70% of the energy transferred to the soil travels away from the pile in surface waves (Woods, 1997). Such waves could have a negative effect on adjacent structures; hence it is important to take into account the distance to surrounding buildings to avoid vibrations related problems. The dominating frequency of waves generated from pile driving is 8-15 Hz (Khoubani, Ahmadi, 2012).

Impact loading is another source of ground vibrations. Ground compaction using hydraulic hammer is highly efficient, versatile and works very well for all kinds of non-cohesive soils. For dynamic compaction, steel and concrete weights of up to 400 kN are usually dropped from heights between 1.5 and 45 m. Such dynamic impacts generate surface waves with frequency between 2 and 20 Hz. The dominant frequency is in the limits of 3-10 Hz. Blasting is another impact loading that is used in several areas of construction. Sometimes explosives are used in dams, roads or tunnels construction when dealing with hard rocks that need to be removed. Also, building implosion which is a fast way of demolition and does not require a lot of machinery uses explosive materials. Blasting energy is much greater than energy of other sources of construction vibrations. Blasting generates body and surface waves of frequency from 5 to 50 Hz (Svinkin, 2008).

The main objective of this paper is to approach the effect of vibrations in the range of frequency that industrial and construction sources generate to parameters of normally consolidated clay by making experiments on clay samples with and without vibrations and comparing the results.

## Methods

The object of research in this paper is normally consolidated clay soil. Clay monolith was taken from Kartupis quarry from approximately 10 meters depth. Such clay is considered overconsolidated moraine clay. A part of monolith needed for experiments was powdered and dried in 105°C temperature until it was completely dry. Then, by mixing clay powder with an appropriate content of water, normally consolidated clay for experiments was obtained. In this case, clay with 35% of moisture content has been made using the described method.

The consistency and behavior of clay soil depends on two limits: plastic limit and liquid limit, also known as Atterbergs limits. Plastic limit is such moisture content when soil changes from semi-solid state to plastic or vice versa. When the soil reaches liquid limit, it has no cohesive strength to retain its shape under its own weight. By knowing Atterberg's limits of soil we can calculate consistency index (Eq. 1.) which is needed to classify soil by consistency.

Classification of clay soil (EN ISO 14688-2:2004) by consistency index is given in table 1.

$$I_c = \frac{w_L - w}{I_p} ; \quad (1)$$

where:

$I_c$  – consistency index,  $w$  – natural water content,  $I_p$  – plasticity index,  $w_L$  – liquidity limit.

The tests to determine plastic and liquid limits of clay have been performed according to Lithuanian national standard LST 1360.4:1995. Soil for road construction. Test methods. Liquid and plastic limits. The tests have been performed in soil mechanics laboratory in Kaunas University of Technology, Faculty of Civil Engineering and Architecture.

State	Consistency index $I_c$
Very soft	$I_c < 0.25$
Soft	$0.25 \leq I_c \leq 0.5$
Firm	$0.5 \leq I_c \leq 0.75$
Stiff	$0.75 \leq I_c \leq 1$
Very stiff	$I_c > 1$

Table 1

Clay soil classification by consistency

The mechanical properties of soil are the most important ones for geotechnical engineers. For this paper laboratory tests have been performed to determine oedometric modulus of clay ( $E_{\text{oed}}$ ), as well as its cohesion ( $c$ ) and angle of friction ( $\varphi$ ). The tests first have been performed under static loading and by inducing vibrations on clay sample to determine the change of mechanical properties of clay affected by vibrations. Oedometer compressibility tests have been carried out to determine oedometric modulus of clay while cohesion and angle of friction have been determined by doing shear tests. All tests to find out mechanical properties of clay with and without vibrations have been performed using Field laboratory apparatus PLL-9. The principal scheme of this apparatus is shown in Fig. 1.

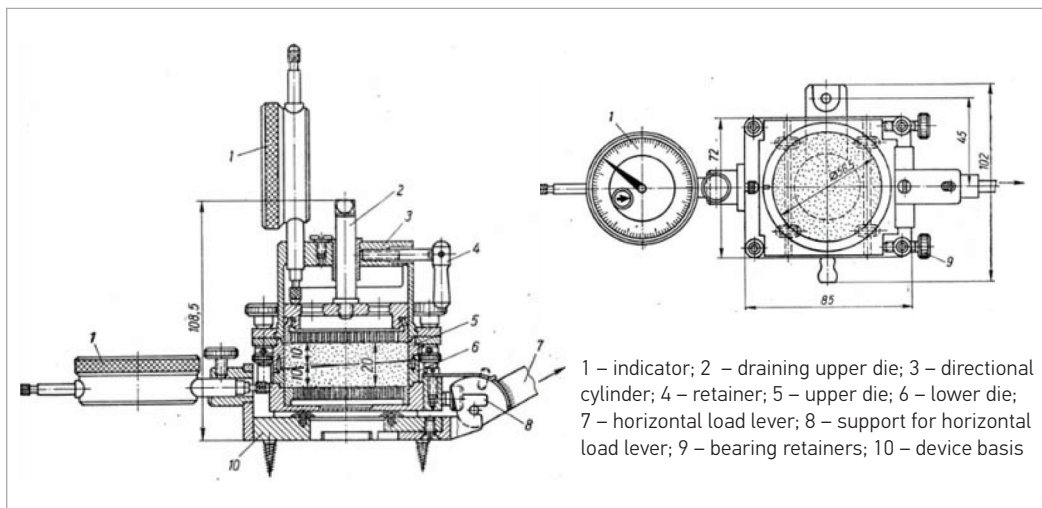


Fig. 1

Field laboratory apparatus PLL-9

The samples of clay used for testing were cylindrical shape of 56.5 mm diameter and 20 mm height. Oedometer tests have been performed with 4 different normal stresses: 50 kPa, 100 kPa, 200 kPa and 300 kPa. Clock-type indicators were used to measure deformation of samples with accuracy of 0.01 mm. Oedometer tests were done under static loading and placing the apparatus on laboratory shaking table that induces vibrations of 50 Hz frequency (Fig. 2). Shear tests on clay have been performed with three different normal stresses: 100 kPa, 200 kPa and 300 kPa. Horizontal load was increased with a step of 4.8 kPa shear stress on clay specimen until it reached limit state and failure shear stress. As known the shear strength of soil can be expressed by Coulomb equation:

$$\tau_f = c + \sigma \tan \varphi ; \quad (2)$$

where:

$\tau_f$  – failure shear stress;  $c$  – cohesion;  $\sigma$  – normal stress;  $\varphi$  – angle of friction.

Cohesion and angle of friction of soil can be calculated using Eq. (3) and Eq. (4) knowing failure shear stress of specimen under each normal stress.

$$c = \frac{1}{\Delta} \left( \sum_{i=1}^n \tau_{ui} \sum_{i=1}^n \sigma_i^2 - \sum_{i=1}^n \sigma_i \sum_{i=1}^n \tau_{ui} \sigma_i \right); \quad (3)$$

where:

$\sigma_i$  – normal stress of  $i$  test ( $i = 1;2;3\dots$ );  $\tau_{ui}$  – failure shear stress under normal stress  $\sigma_i$ .

$$\tan \varphi = \frac{1}{\Delta} \left( n \sum_{i=1}^n \tau_{ui} \sigma_i - \sum_{i=1}^n \tau_{ui} \sum_{i=1}^n \sigma_i \right); \quad (4)$$

where:

$\sigma_i$  – normal stress of  $i$  test ( $i = 1;2;3\dots$ );  $\tau_{ui}$  – failure shear stress under normal stress  $\sigma_i$ .

$$\Delta = n \sum_{i=1}^n \sigma_i^2 - \left( \sum_{i=1}^n \sigma_i \right)^2; \quad (5)$$

where:

$\sigma_i$  – normal stress of  $i$  test ( $i = 1;2;3\dots$ ).

Shear tests on clay have been carried out under static loads and with vibrations of 10 Hz, 30 Hz and 50 Hz frequency. Tests with 50 Hz vibrations were performed on laboratory shaking table (Fig. 3) while 10 Hz and 30 Hz frequency vibrations were induced using frequency changing vibration table in Technological Systems Diagnostics Institute of Kaunas University of Technology (Fig. 4). A view of clay specimen after shear test which has also been dried can be seen in Fig. 5. The amplitude of vibrations in all tests was set to be 0.3 mm.

Fig. 2

View of oedometer test under 50 Hz vibrations



Fig. 3

View of shear test under 50 Hz vibrations

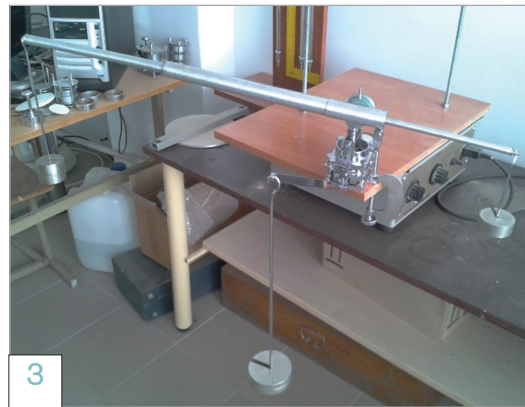


Fig. 4

View of shear test under 10 and 30 Hz vibrations



Fig. 5

View soil specimen after shear test





Atterberg limits experiments carried on normally consolidated clay and their results for the plasticity limit and liquidity limit tests results are illustrated in table 2.

Vessel number	Plasticity limit results		Liquidity limit results	
	1	2	1	2
Empty vessel weight (g)	15.73	14.57	15.51	16.85
Vessel with moist soil weight (g)	26.06	25.51	39.85	41.32
Vessel with dry soil weight (g)	23.99	23.26	31.74	32.98
The water content of sample (%)	25.06	25.89	49.97	51.7
Plasticity/liquidity limit (%)	25.48		50.84	

As shown in the table above the plasticity limit of clay is 25.48% and liquidity limit is equal to 50.84%. The natural water content of clay used for experiments is 35%, therefore according to (Eq. 1) the consistency index of clay is:

$$I_c = \frac{w - w_p}{I_p} = \frac{w - w_p}{w_L - w_p} = \frac{35 - 25.48}{50.84 - 25.48} = 0.375. \quad (6)$$

Following the information given in table 1 the clay used for the experiments can be classified as soft clay. During the oedometer test when the load is acting, not only the soil in the apparatus but also the parts of the apparatus itself and the filtering papers are deforming. Therefore, when the data of oedometer test is being analysed these deformations have to be subtracted from the change of specimen height. The correction of results due to apparatus deformation has been determined by measuring deformations when the metal cylinder is placed instead of soil sample and taken into account for the results of oedometer tests. The results of oedometer tests are represented in stress-strain curve (Fig. 6).

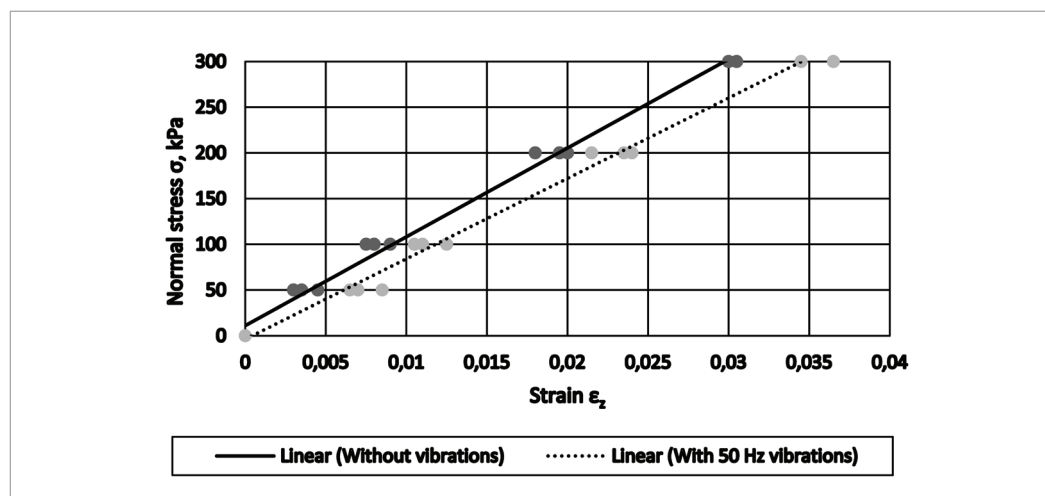


Fig. 6

Stress-strain diagram of oedometer test

The stress-strain diagram (Fig. 6) indicates that vibrations have a negative effect on oedometer modulus of clay. The solid line representing the results from oedometer tests under static loads is steeper than the dashed line which represents the results under 50 Hz vibrations. This means that

## Results

Table 2

Plasticity and liquidity limit results

vibrations decrease oedometric modulus of clay. According to the calculations oedometric modulus of clay under static loading is 11.7 MPa while clay affected by vibrations showed the decrease of oedometric modulus to 8.3 MPa.

The results of direct shear tests on normally consolidated clay are illustrated in Fig. 7.

According to calculations by (Eq. 3) and (Eq. 4) the effect of vibrations on clay soil strength parameters is represented in table 3.

Fig. 7

Results of direct shear tests

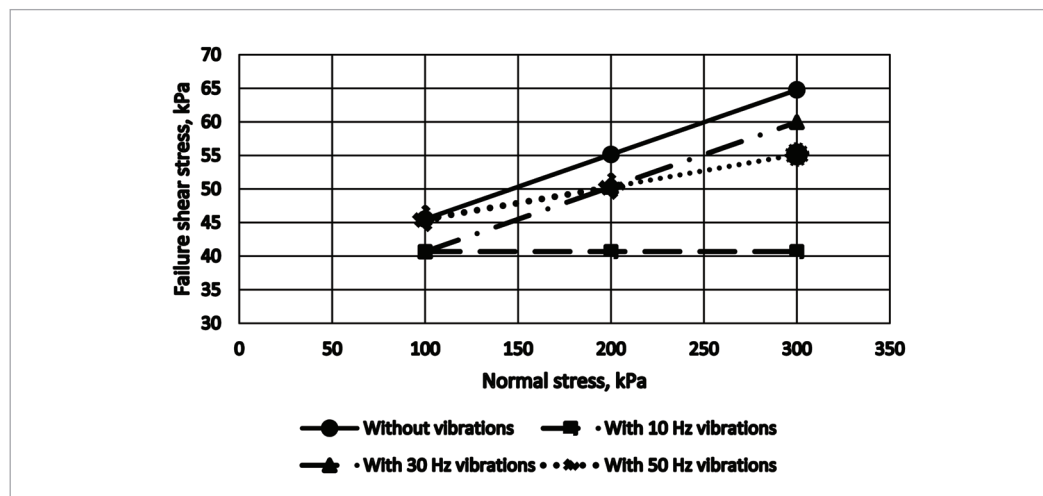


Table 3

Vibrations influence on strength parameters of clay soil

Vibration frequency (Hz)	-	10	30	50
Cohesion (kPa)	35.9	40.7	31.1	40.7
Angle of friction (°)	6	0	6	3

The experiments show that different frequency vibrations have different effect on strength parameters of clay. Cohesion of clay has decreased under vibrations of 30 Hz frequency while 50 Hz frequency vibrations reduced angle of friction of clay by 50%. Testing with 10 Hz vibrations indicate that under lower frequency the clay soil starts to behave like undrained clay as it completely loses angle of friction. In this case the testing frequency matched with natural frequency of soft clay which resulted an excess porewater pressure and all pores of clay became saturated with water.

## Conclusions

Vibrations in ground can be generated from various industrial and constructional sources e.g. road traffic, pile driving, explosions and hydraulic hammer usage. These external sources generate waves with frequency up to 70 Hz. Experimental analysis of such vibrations on normally consolidated clay soil showed that:

- \_ They have a negative effect on mechanical properties of clay, especially on angle of friction.
- \_ Clay soil affected by 50 Hz vibrations indicated decrease of oedometric modulus by almost 30%;
- \_ It is important to take such change into account in geotechnical engineering because the decrease of oedometric modulus can lead to unexpectedly higher soil deformations which can cause unpredicted foundation settlements and other problems.

The main strength parameters of clay (cohesion and angle of friction) are also affected by vibrations. As the experiments have showed:

- \_ The angle of friction is hugely affected by different frequency of vibrations;

Under 50 Hz vibrations the angle of friction decreased by 50% while under low frequency vibrations (10 Hz) clay soil acted like in undrained conditions – its angle of friction was equal to 0°. This could be the case of resonance as soft clay tends to have characteristic frequency between 5 and 20 Hz.

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