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Investigation Dynamic Properties of Soil (The Damping Ratio and Shear Modulus) For Resistance Design At the LNG BAC Lieu Gas Pipeline Project by Cyclic Triaxial Test

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ABSTRACT: The LNG Bac Lieu gas pipeline project is part of the 3.200MW LNG power plant complex in Bac Lieu province. The entire pipeline will be designed underground at the sea floor to be directly subjected to dynamic loads (earthquakes, waves ...). Soil response to dynamic loads is measured by the soil's dynamic properties such as dynamic strength, shear modulus and damping ratio. These soil parameters are very significant to study the movement of the ground as well as the local reaction of soil sediments under the effect of loads and cyclic soil structure. Therefore, it is very important to investigate the earth's dynamic properties (dynamic strength, damping ratio and shear modulus) to design seismic resistance for this project. From the relevant literature, it is known that the dynamic properties of the soil are influenced by the soil type and the position of the soil structure. 6 soil samples were examined randomly at different depths to determine soil properties. When studying dynamic strength, people often use direct test methods such as torsion cutting, cyclic flat cutting and cyclic triaxial test to determine the dynamic strength (dynamic resistance) of the soil. In which, the cyclic triaxial test method allows the simulation of real-world conditions to be easily simulated. The results of applying this method to soft clay and clay phases show that the damping ratio is 0.117-0.162D, the average is 0.136D, the shear module is 1650-2632kPa, the average is 2141kPa.

KEY WORD: resistance design, dynamic strength, damping ratio and shear modulus, cyclic triaxial test

1. INTRODUCTION

The dynamic parameters of the soil are important criteria in the calculation of foundations with dynamic loads. The origin of dynamic loads is very diverse such as earthquakes, ocean waves, ships, industrial machines, ... Therefore, when calculating the foundations of various types of works such as high-rise buildings, road foundations, machine foundations, the coastal and undersea constructions must include dynamic loads. When calculating the foundation subjected to dynamic loads, it is necessary to determine the dynamic characteristics of the soil (Young's Ed modulus, shear modulus Gd and damping coefficient D) corresponding to the coefficients of the Kelvin – Voigt model (coefficient of hardness K, coefficient of viscous resistance C), and at the same time determine the dynamic strength and liquefaction capacity of the soil (creep limit for Kelvin - Voigt model). The dynamic properties of the soil are used to calculate the strain and are an important input parameter for the modeling problem of the ground structure under dynamic loads, while the dynamic strength and liquefaction are used to evaluate soil dynamic load capacity. Thus, the dynamic parameters of the soil are important information needed for the calculation of the foundation with dynamic loads. In the world, there have been many studies on determining these parameters. Research results on theory, experiment, experimental methods and procedures are found in many relevant professional documents and standards. The methods and equipment used to determine the dynamic parameters are also very diverse, including field and laboratory test methods. The most commonly used laboratory test methods are the resonant-column method with oscillating axial or torsional loads, and the cyclic triaxial test with cyclic loads.

2. THEORETICAL BASIS FOR STUDYING DYNAMIC PARAMETERS OF SOIL BY THE CYCLIC TRIAXIAL EXPERIMENT

2.1. Forced oscillation differential equation of a one-degree-of-freedom system with resistance

When studying the dynamic behavior of the soil, the Kelvin - Voigt model is used (Figure 1a). It is the viscoelastic model, which is composed of two viscous and elastic bodies connected in parallel. The study of the behavior of this model under the effect of dynamic loads is based on dynamic analysis of a single-degree-of-freedom (SDOF) system. Accordingly, a weight M is attached to an elastic-viscous system and is acted upon by an excitation force F(t), which is called a dynamic-vibration system (Figure 1b).

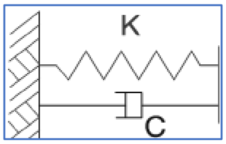
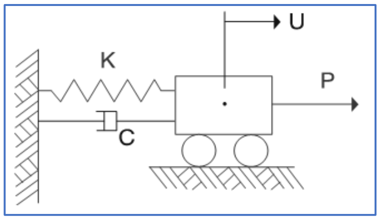


Figure 1a. Kelvin – Voigt Model



1b. One-degree-of-freedom oscillation system with resistance

The forces acting on M include: time-varying force F(t), inertial force Fa, elastic force Fe and viscous resistance Fc (ignoring dry friction). According to Newton's law, we have: Fa = F(t) - Fc - Fe, or:

$F_a + F_c + F_e = F_{(t)}$ (1)

- With m and U being the mass and displacement of the weight, respectively, the inertia force is determined by the expression:

$F_a = m.a = m.d^2U/dt^2 = m\ddot{U}$

- Viscosity resistance is proportional to the first order of speed, so: $F_c = c\, dU/dt = c\dot{U}$
- Elastic force is first-order proportional to displacement: $F_e = kU$

Substituting the above expressions into (1), we get the forced oscillation differential equation of a one-degree-of-freedom system with resistance:

$m\ddot{U}+c\dot{U}+kU= F_{(t)}$ (2)

For a linear system, the stiffness coefficients k and the drag coefficient c are constant. As for the nonlinear system, the coefficients k, c are functions of displacement or strain.

To reduce equation (2) to the characteristic quadratic differential equation form, we divide both sides by m and enter the symbols: $\omega^2_o = k/m$; $2\delta = c/m$, we get:

$\ddot{U}+2\delta\dot{U}+kU= F_{(t)}$ (3)

Depending on the characteristics of the excitation force F(t) and with known parameters of the system (k,c), solving (3) we can determine the solution of the system.

2.2. Vibrations of a one-degree-of-freedom system subjected to harmonic excitation

In case the system is subjected to harmonic agitation: F(t) = F. Sin(ωt), the differential equation (3) has the form:

$\ddot{U}+2\delta\dot{U}+kU= \frac{F}{m}\sin(\omega t + \varphi)$ (4)

where F and ω are the amplitude and angular frequency of the harmonic excitation force, respectively.

The general solution of (4) has the form:

$U(t) = Ae^{-\delta t}\sin(\omega_0 + \beta) + \overline{U}\sin(\omega t + \varphi)$ (5)

The first term of (5) represents the damping component of free oscillation, which is characteristic of free oscillation with resistance. The deviation $Ae^{-\delta t}$ is the amplitude of the free oscillation with resistance. One uses logarithmic damping (Λ) to characterize this property: Λ = δT (where T is the period). The values ω_o, β are the natural frequency and phase angle of the system.

The second term has the frequency ω of the external force, representing the forced oscillation component of the system, or the oscillation of the system at steady state having an initial phase angle φ. The quantity $\overline{U}$ is the strain amplitude at steady state,

$$\overline{U} = \frac{F}{m.\varpi_o^2}.\frac{1}{\sqrt{(1-\eta^2)^2+4D^2\eta^2}}$$

Put V(η,D) = $\frac{1}{\sqrt{(1-\eta^2)^2+4D^2\eta^2}}$ he function V(η,D) represents the dynamic eff on force, so it is called the gain function. Therefore:

$\overline{U} = \frac{F}{m\omega_0^2}V_{(\eta,D)}$ (6)

Where, D is the Lehr drag (damping coefficient), which is determined by the formula:

$D = \frac{\delta}{\omega_0} = \frac{c}{\sqrt{mk}}$ (7)

η is the coefficient, equal to the ratio of the frequency of the excitation force to the natural frequency: η = ω/ωo. The initial phase angle ϕ is determined by the expression:

$tg(\varphi) = \frac{-2D\eta}{1-\eta^2}$ (8)

In case the load is not harmonized, replace the function F(t) (determined according to the characteristics of the load) into the differential equation (3) to get the solution.

2.3. The basis of the cyclic triaxial test method for determining the dynamic parameters of the soil

The cyclic triaxial test method is a widely used laboratory test method in the world. Regarding the structure diagram as well as the operating principle, the cyclic triaxial device is similar to the stationary three-axis type, but the basic difference is that the axial load acting on the soil sample is the dynamic load (F = F (t)). Normally, the test load applied to the sample is made to be harmonic. Some modern devices can also simulate real dynamic loads without harmonics (using Play Back feature to simulate earthquakes, impulses, ...) or change along the stress path

(Stress Path). During the experiment, information about loading, deformation, volume change, chamber pressure, pore water pressure is recorded.

The essence of the method is to treat the soil sample as a one-degree-of-freedom system whose resistance is oscillated by harmonic excitation forces. There are two problems posed:

- The first problem is to determine the dynamic parameters of the soil at the linear limit. Then, the basic differential equation of the system is equation (4) and its solution is expression (5). From the information about the load F(t) and strain U(t) in steady state, the dynamic parameters of the soil can be determined by the expressions (6), (7), (8) .
- The second problem is to determine the strength and liquefaction of the soil (creep). Soil strength is determined according to the number of cycles, frequency and amplitude of loads that cause excessive deformation or the load can no longer maintain a harmonic form. The liquefaction state of the soil is determined when the pore water pressure is equal to the compressive stress on all sides.

The soil-specific dynamic parameters to be determined are the damping coefficient D (the drag coefficient Lehr) and the dynamic elastic modulus Ed (or the shear modulus Gd). From there, the typical parameters for the simulation model of soil behavior under the effect of dynamic loads (coefficients k, c) will be determined.

According to the results of the triaxial harmonic load test, the line showing the stress and strain relationship is a loop corresponding to one cycle (Figure 2).

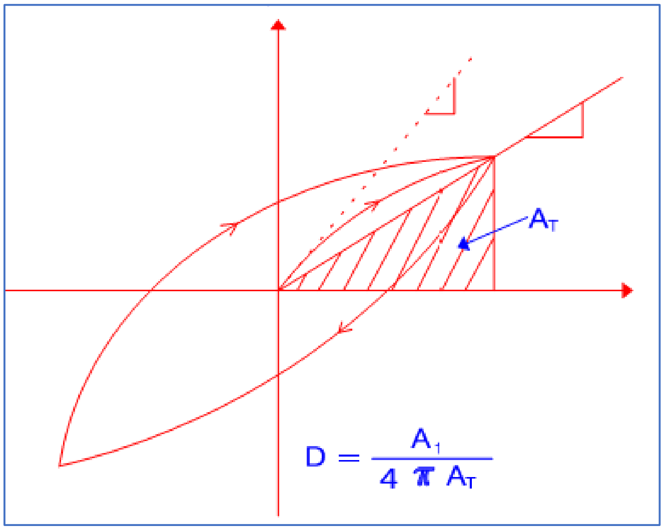


Figure 2. Stress and strain loop

From this graph, D and Ed are determined as follows:

$$D = \frac{1}{4\pi}\frac{A_1}{A_T} \quad (9)$$

$$E_d = \frac{\bar{\sigma}_a}{\bar{\varepsilon}_a} \quad (10)$$

where A_T, A_1 are the useful work and total work, respectively, as defined in Figure 2. $\bar{\varepsilon}_a$ is the axial stress amplitude (Axial Stress), is the relative axial strain amplitude (Axial Strain).

In a similar way, the shear modulus Gd is determined from the graph representing the relationship of shear stress (τ) with shear strain (γ). The values D and Ed are determined according to a period during which the system's oscillation reaches a steady state. According to ASTM D3999 [2], the number of cycles to be performed is 40.

3. Results and discussion

The project is built at Nha Mat - Bac Lieu province, about 7 km northeast of σ_a Lieu city (Figure 3). Distributed in the southwestern edge of the Mekong Delta, on the other hand is surrounded by sea to the west and northeast. The terrain here is quite flat with an absolute height of 0-2m. The area near Bac Lieu has eroded and eroded coastlines.

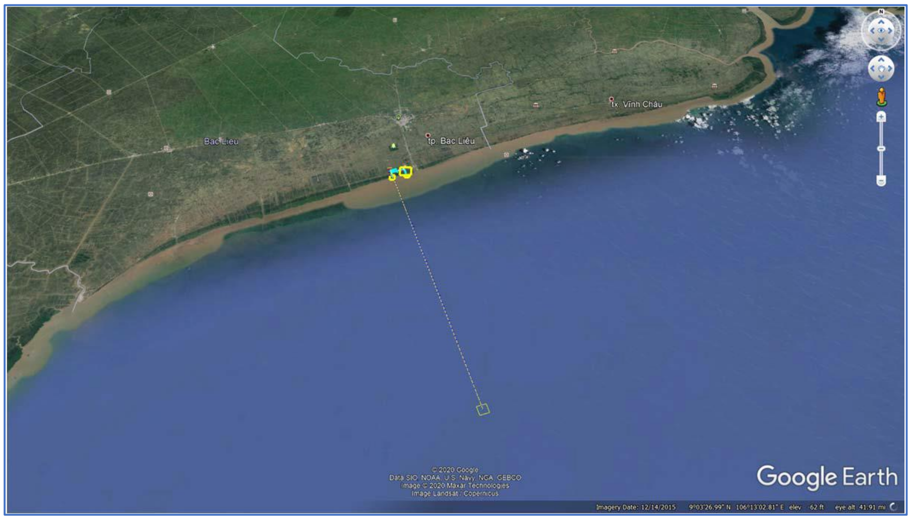


Figure 3. Project Location

Based on the Geological and Mineral Map of Vietnam, Ca Mau - Bac Lieu sheet, scale 1: 200,000, it is possible to describe the geology of the area from 10-30m as follows:

River-sea sediment, Middle-Upper Holocene, upper part (amQiv2-32), formation consisting of clay, gray powder, brownish-gray color containing little plant remains and fragments of shells and snails. The sediment thickness varies by 10-15m.

Marine sediments, Middle Holocene, Hau Giang Formation (mQiv2hg) are only found in boreholes at a depth of 4-5m or less. Sediment composition is mainly sand, clay powder with variable content depending on ancient environmental conditions. Sediment thickness varies from 10 to 30m.

Marine sediments, Upper Pleistocene, Long My Formation (mQiii 3lm) are only found in boreholes from a depth of 20m or less. The overall thickness is 29m.

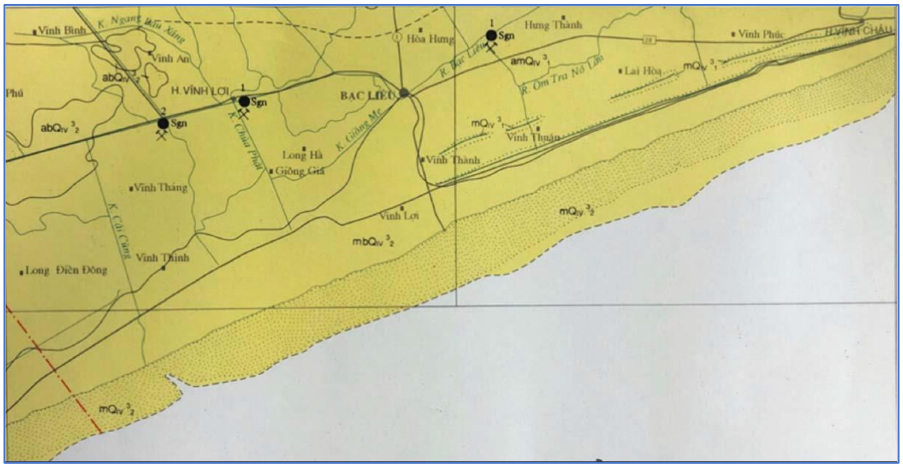


Figure 4. Geological map (enlarged) – Northeast of Bac Lieu - Ca Mau map sheet (Excerpt from Geological Map of Bac Lieu - Ca Mau area 1: 200.000 scale)

Southern Vietnam is considered an area with low earthquake intensity. However, construction activities still take place. In recent years, earthquakes have not only occurred in the North of Vietnam but also in the South of Vietnam. The most recent earthquake with seismic intensity I0 = 3.9 or M = 5 occurred in Ba Ria - Vung Tau province on August 28, 2002. According to QCVN 02: 2009, earthquake intensity I0 regulated according to the MKS scale with 12 steps. from I0 = 1 to I0 = 12. Based on QCVN 02: 2009 and the seismic risk map proposed by Nguyen Dinh Xuyen (1991) as shown in Figure 5, it is possible to choose a design earthquake in the project area with intensity I0 = 7 is equivalent to magnitude M = 5.1-5.5.

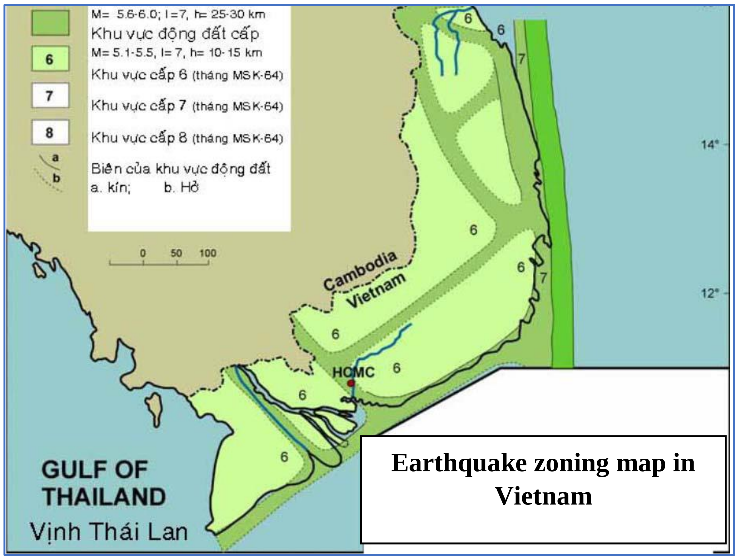
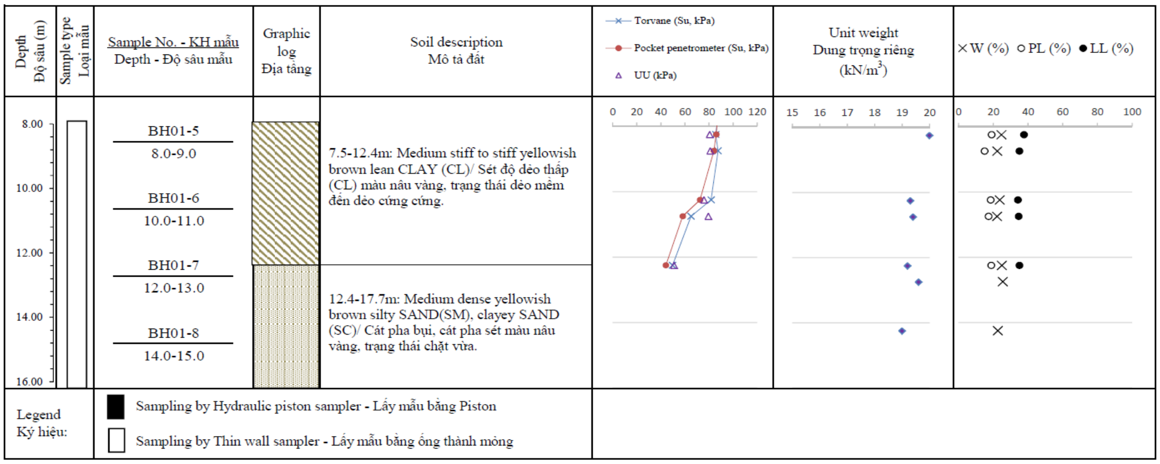


Figure 5. Earthquake zoning map in Vietnam. According to the probabilistic risk map of Vietnam (Phuong & Truyen, 2015), the peak elevation, PGA, in the Project area is about 100 - 150cm/s2.

Based on the results of the geological survey at the site and the laboratory experiment, the geological cross-section of the construction project in the project area is established. In order from top to bottom, the soil layers can be divided as follows:



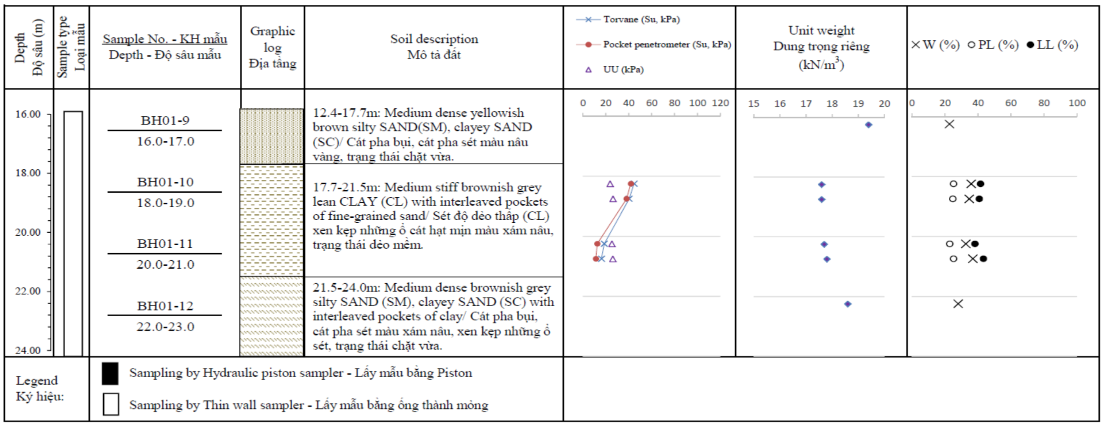
7.5-12.4m: Medium stiff to stiff yellowish brown lean CLAY (CL)/ Sét độ dẻo thấp (CL) màu nâu vàng, trạng thái dẻo mềm đến dẻo cứng cứng.

12.4-17.7m: Medium dense yellowish brown silty SAND(SM), clayey SAND (SC)/ Cát pha bụi, cát pha sét màu nâu vàng, trạng thái chặt vừa.

■ Sampling by Hydraulic piston sampler - Lấy mẫu bằng Piston

☐ Sampling by Thin wall sampler - Lấy mẫu bằng ống thành mỏng

a)



12.4-17.7m: Medium dense yellowish brown silty SAND(SM), clayey SAND (SC)/ Cát pha bụi, cát pha sét màu nâu vàng, trạng thái chặt vừa.

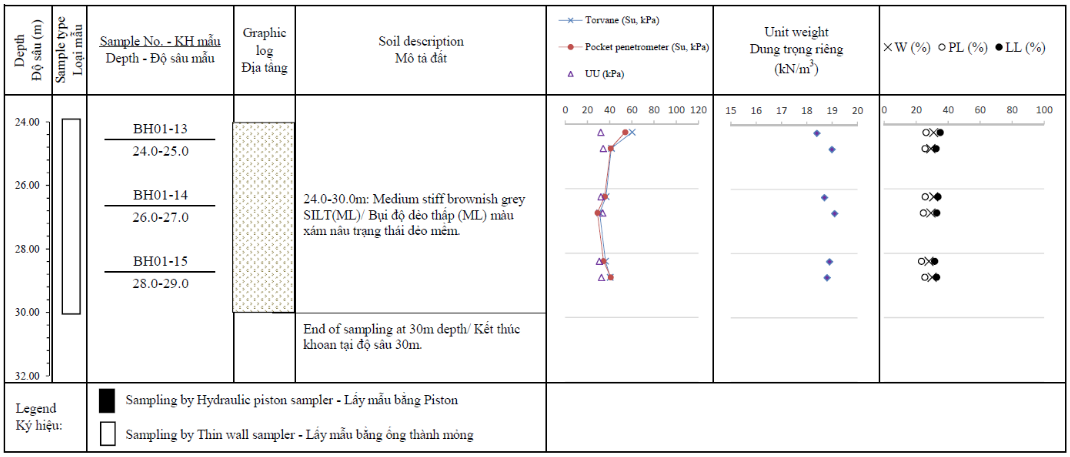
17.7-21.5m: Medium stiff brownish grey lean CLAY (CL) with interleaved pockets of fine-grained sand/ Sét độ dẻo thấp (CL) xen kẹp những ổ cát hạt mịn màu xám nâu, trạng thái dẻo mềm.

21.5-24.0m: Medium dense brownish grey silty SAND (SM), clayey SAND (SC) with interleaved pockets of clay/ Cát pha bụi, cát pha sét màu xám nâu, xen kẹp những ổ sét, trạng thái chặt vừa.

■ Sampling by Hydraulic piston sampler - Lấy mẫu bằng Piston

☐ Sampling by Thin wall sampler - Lấy mẫu bằng ống thành mỏng

b)



c)

Figure 6. Stratigraphy of 3 experimental samples: a) SIS_D 01 b) SIS_D 02 c) SIS_D 03

The instrument used to study soil dynamics parameters is the Tritech 100, manufactured by Controls-Wykeham Farrance in 2006 (Figure 7). This is an advanced type of device, allowing to load air-conditioned or non-air-conditioned (Play Back feature).

Initially, we conducted experiments to determine the dynamic parameters of the soil (first problem) with clay, yellow-gray, soft plastic (sample SIS_D 01); mixed clay, gray-brown, soft plastic (sample SIS_D 02, SIS_D 03). Clay soil samples were tested in their natural state. The test content for a soil sample includes testing of normal mechanical and physical parameters and the Cyclic Triaxial test. The sample size for the three-axis dynamic experiment is 70x140mm (Figure 8). The basic physico-mechanical parameters of the soil samples are given in Table 1.

The three-axis dynamic test procedure was performed in accordance with ASTM D3999 – 91 [2]. Accordingly, there are two experimental schemes:

- Diagram A - load control: Load condition is kept constant during the test.
- Diagram B - strain control: The strain condition is kept constant.

The experimental parameters are determined as follows:

- Frequency of the load f = 1 – 2 Hz;
- With experimental diagram A, the amplitude of the load is determined according to the stress ratio SR (Stress ratio), with SR determined by the expression: SR = /2σ'c where σ'c is the fixed stress effective results. According to experimental diagram B, the amplitude of strain is taken ≤ 0.5% (0.5 - 0.7mm). aσ

Figure 7. Using the Cyclic Triaxial device system

Figure 8. Sample for the Cyclic Triaxial test

Table 1. Basic physico-mechanical parameters of soil samples

No.	Test No.	Borehole No.	Depth (m)	Type Sample	Grain size distribution			Plasicity Index PI	Liquidity Index I_L	Moisture Content W	Density Wet γ_w	Specific Gravity G_s
					Clay %	Silt %	Sand %	%		%	T/m^3	
10	BH01-6-1	BH01	10.0 - 10.5	UD	56	43	1	16	0.32	23.7	1.93	2.68
11	BH01-6-2	BH01	10.5 - 11.0	UD	54	30	16	17	0.28	22.2	1.94	2.72
16	BH01-10-1	BH01	18.0 - 18.5	UD	41	37	22	16	0.65	35.9	1.76	2.72
17	BH01-10-2	BH01	18.5 - 19.0	UD	42	39	19	16	0.61	34.7	1.76	2.73
21	BH01-13-1	BH01	24.0 - 24.5	UD	42	55	3	9	0.53	31.0	1.84	2.77
22	BH01-13-2	BH01	24.5 - 25.0	UD	28	56	4	7	0.52	29.2	1.90	2.79

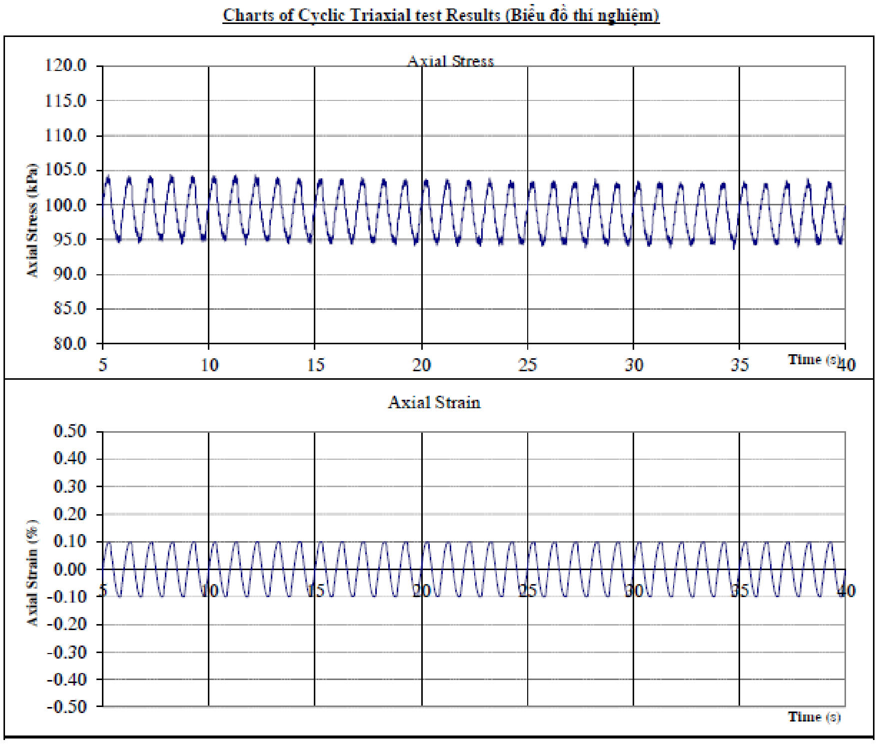
In order to determine the dynamic parameters of the soil as well as the parameters of the model in the stabilization stage, it is necessary to select the input parameters (test diagram, stress amplitude, strain amplitude) correctly. suitable. Conformity was assessed based on data analysis of each specific experiment.

For test samples according to diagram A, the frequency and amplitude of the load are kept constant during the test, there are two types of strain graphs depending on the type of sample and the magnitude of the load:

- Form 1: Strain amplitude is constant, but strain value increases gradually to a stable value.
- Form 2: Both strain amplitude and strain magnitude increase with the number of cycles.

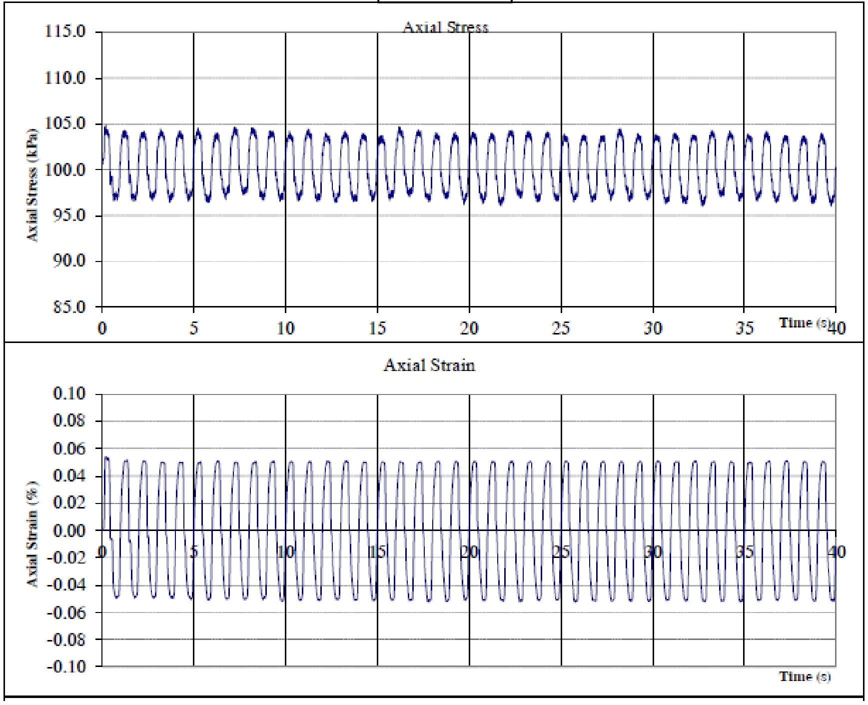
Three samples at the project were tested according to form 1 of diagram A with stress ratios SR = 0.021 (SIS_D 01), 0.017 (SIS_D 02) and 0.023 (SIS_D 03) (Figure 9).

SIS_D 01



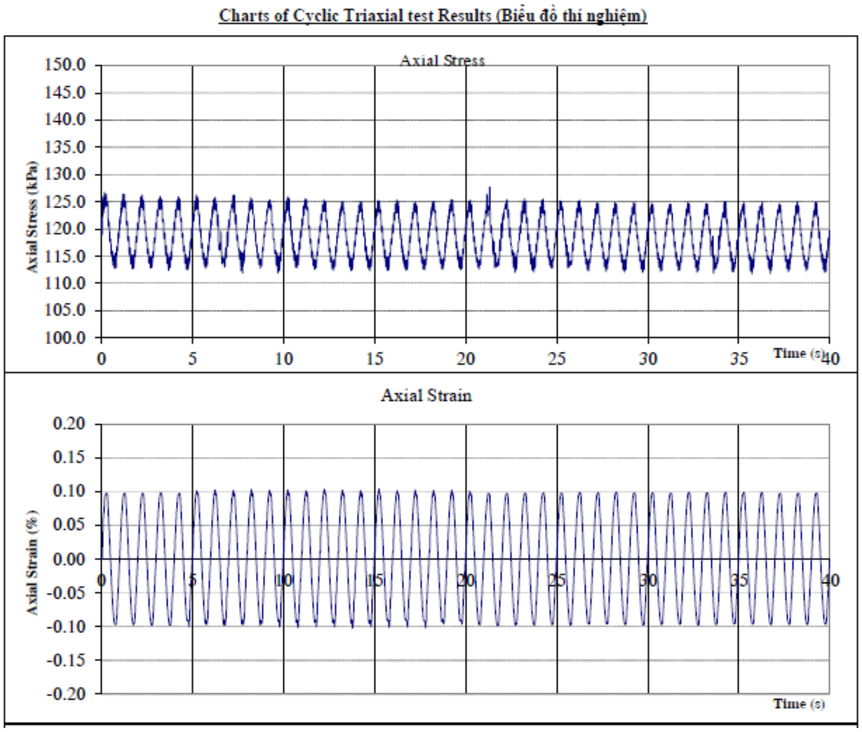
a)

SIS_D 02



b)

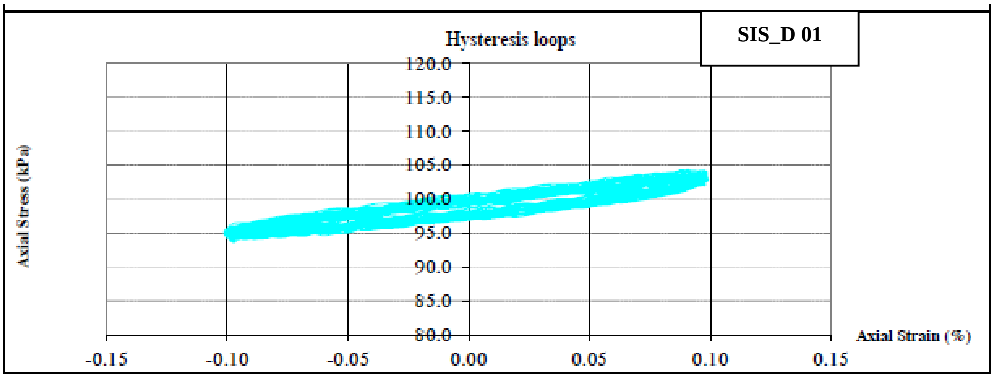
SIS_D 03



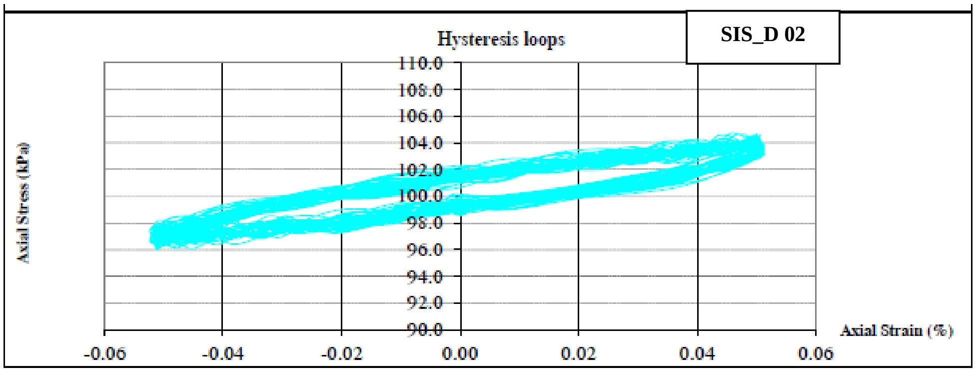
c)

Figure 9. Axial stress and strain diagram of three test specimens: a) SIS_D 01 b) SIS_D 02 c) SIS_D 03

According to the theoretical basis presented, each loop (hysteresis loop) corresponding to a cycle will determine a pair of Ed, D values. These values change according to the number of cycles or the degree of deformation. When the oscillation of the system reaches a steady state, the values remain unchanged. Samples tested according to scheme A usually reach steady state after about 20 to 30 cycles. On the other hand, the concordance of the test results must also be evaluated according to the shape and bias of the loops. At the linear deformation stage, the shape of the loop has a symmetrical lenticular (or elliptical) shape (Figure 10), beyond this limit the loop becomes unbalanced. Since the deformation characteristics of the soil are mostly residual strain, there is often a deviation between successive loops. According to ASTM D3999 [2], the deviation between two consecutive loops should not exceed 0.2%. Based on these conditions, the test results of samples with stress ratio SR as above are satisfied.



a)



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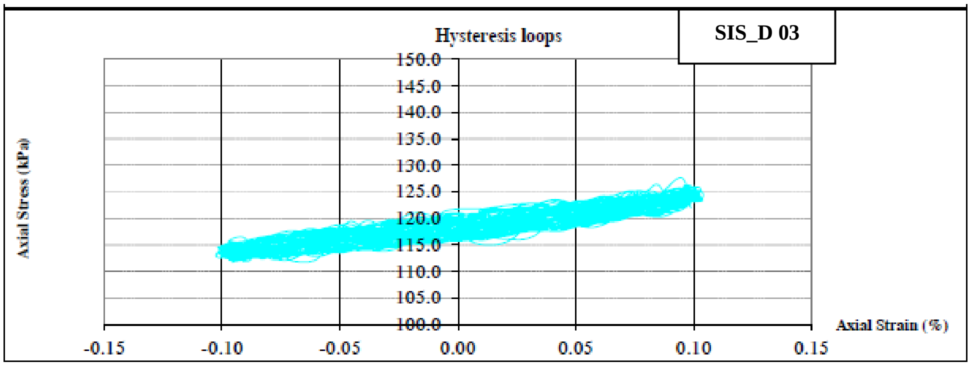

c)

Figure 10. Hysteresis loop diagram of three experimental samples: a) SIS_D 01 b) SIS_D 02 c) SIS_D 03

According to diagram B, the strain amplitude is kept constant with the first half cycle of compression and the second half cycle of expansion. For soil samples with large residual strain (unsaturated clay soil), after the first half cycle of compression, the deformation of the soil cannot be recovered. Therefore, the effect of stress to maintain strain with constant compression-expansion amplitude is mainly tensile. Such experimental conditions are clearly not suitable for the actual working conditions of the soil (mainly in compression). Hence not used in this project.

Summary of the three-axis dynamic test results for soil samples and their evaluation are given in Table 2.

Table 2. Experimental parameters and results with dynamic loads

No.	Test No.	Borehole No.	Depth (m)	(□$_{cell}$) kPa	(□$_{back}$) kPa	(□$_{3}$') kPa	Test frequency	(Stress Amplitude)	(Strain Amplitude)	Tỷ số ứng suất	Mô đun Modulus (E)	Shear Modulus (G)	Damping Ratio
							Hz	kPa	%	SR	kPa	kPa	D
1	SIS_D 01	BH 01-6	10.0-10.5	200	100	100	1	4	0.100	0.021	4291	1650	0.128
2	SIS_D 02	BH 01-10	18.0-18.5	120	20	100	1	3	0.050	0.017	6844	2632	0.162
3	SIS_D 03	BH 01-13	24.0-24.5	160	40	120	1	6	0.100	0.023	5565	2140	0.117

4. CONCLUSIONS

The ground under the foundation of the structure with dynamic loads under stable working conditions is usually in the linear limit. The 3-axis test to determine the dynamic parameters within this limit needs to determine the appropriate test load diagram, frequency, and amplitude. Based on the initial research results, some comments are made as follows:

- The test results to determine Ed, D depend largely on the test scheme, load amplitude (or SR) and strain. For soil samples with large residual strain (unsaturated clay soil), the choice of test scheme B with compression-expansion strain, the applied stress is mainly tensile.

- The number of test cycles for the system's oscillations to stabilize in most samples is usually more than 20 cycles.

- The damping coefficients of the tested soil samples are in the range of 0.1 - 0.2 and the shear modulus is in the range of 1000-3000kPa. Comparatively, it can be found that good soil samples usually have a smaller D than weak soil, and good soil samples often have a higher G than weak soil.

- Due to the small number of experiments, the law of variation of dynamic parameters according to strain as well as the limiting stress ratio SR for each type of soil has not been determined. To solve this problem, it is necessary to test each soil type at different load amplitudes (eg σa = 5; 10; 15; 20; 25 kPa).

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