EXPERIMENTAL STUDY OF INTERFACE SHEAR CHARACTERISTICS BETWEEN CALCAREOUS SOIL AND STEEL, APPLICATION TO ESTIMATE AXIAL BEARING CAPACITY OF STEEL PILE

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Abstract: *A modified direct shear tests of interface between well-graded coral sand and coral sandy-gravel with smooth steel plate were conducted in this study under various normal stress levels. The obsevation from experimental results indicates that: (1) interface shear behavior between well-graded coral soils and steel structure follows the strain hardening rules; (2) the magnitudes of friction resistances between two materials are related to the gradation and grain size of coral soils, for coral sand limit sliding displacement is around 1mm with interface friction angle of 27.9^o while for coral sandy-gravel these values are 2-3mm and 32.8^o respectively; (3) interface direct shear test can be used to accurately determine friction characteristics between calcareous soil and structural material, which can effectively support analysis and design of structures built on calcareous soil.*

Keywords: *interface friction angle, calcareous soils, coral soils, pile bearing capacity, direct shear test.*

1. Introduction

In the last few decades, Vietnam has contributed a lot of capital and efforts to develop infrastructures on the islands in Bien Dong. Many of these islands have geotechnical condition formed by calcareous sediment mainly from coral reefs. In marine engineering practices involving coral reefs, calcareous soils serve as backfill material and provide support for building foundations through steel driven piles.. Researchers and practitioners have faced significant challenges in understanding the complex mechanical properties of calcareous soil since the 1960s.. Therefore, scientists have paid an increased attention to the calcareous soil and have treated it as a special geo-material. In recent years, steel pile (H or pipe section) supported foundations, and friction anchored slope protection structures have been widely used in projects developed on the coral reefs. The frictional behavior at the interface between calcareous soil and steel is important for estimating the axial capacity of steel piles and predicting the tension forces of friction anchors. However, the most difficult problem in geotechnical engineering is how to accurately investigate the friction behavior of interfaces between calcareous soil and steel element. The key issue for solving this problem is characterizing the influencefactors and mechanical properties of the interfaces.

The authors of the current study performed an extensive literature review of previous studies on the interface properties between calcareous soil and various construction materials [2]. Additionally, they carried out experimental study on model and prototype steel piles in calcareous soil.. In the published documents [2-5], researchers have performed considerable studies on the mechanical properties of interfaces between quartz sand and various construction materials. However, when compared to these well studied geo-materials, calcareous soil has a significantly different mineral composition, particle shapes, and pore structure characteristics. Whether these well documented quartz sand-based interface influence factors have similar effect on the calcareous sand-based interface properties still need to be closely examined.

In this article, the authors present results of experimental study on the mechanical properties of the calcareous soil – steel structure interface by modified direct shear test. The objective of this article is to obtain a better understanding of the interface shearing properties between the calcareous soil and steel materials and application to estimate axial bearing capacity of steel piles in engineering practice.

2. Shear test of interfaces between calcareous soils and steel

2.1. Sample preparation and test device

The calcareous soil samples were obtained from an island in the Truong Sa archipelago. Soil samples were prepared for this study into two types of soil – calcareous sandy soil (coral sand) and calcareous sandy-gravel soil (coral sandy-gravel). For coral sand, particles with grain sizes >5 mm were removed prior to the sample preparation for the direct shear tests; whereas, particles with grain size >20mm were removed. The grain size distribution curve and the index properties of the calcareous soils for this study are shown in Figure 1 and Table 1, respectively. The grain size distribution curve indicates that the sample tested could be classified as well-graded medium-grained calcareous soils.

Table 1. *Physical properties of calcareous soil used in this study*

Physical properties	Coral sand	Coral sandy-gravel
Specific gravity of grain, ρ_s	2.71	2.616
Max void ratio, e_{max}	1.168	0.763
Min void ratio, e_{min}	0.585	0.469
Mean grain size, D_{50} (mm)	0.365	0.83
Relative density, D (%)	70	70

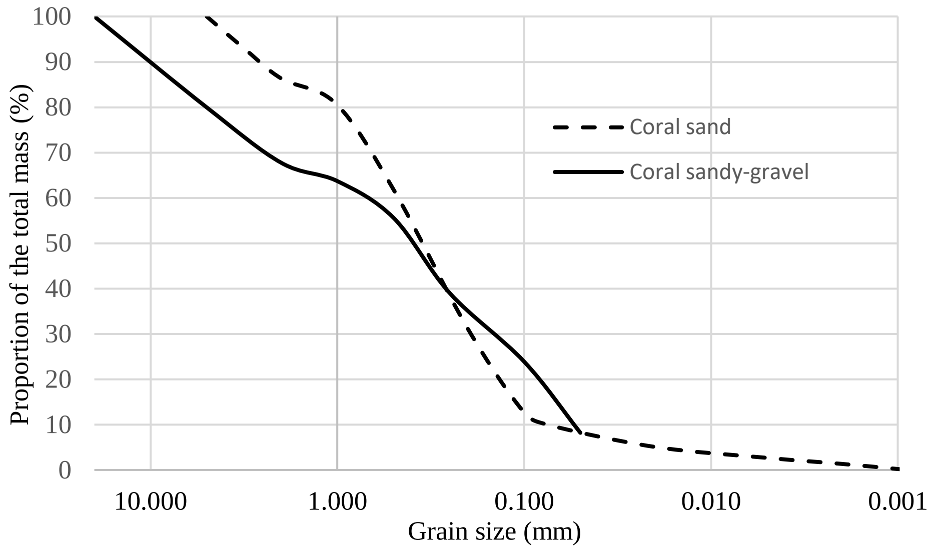

Figure 1. *Grain size distribution curves of soil samples*

The rectangular shaped direct shear device has an inner circular sample box with a diameter of 63.5 mm, and is horizontally divided to allow opposing shear forces to be applied to calcareous soil-steel plate system in the boxes (see Fig. 2). In the interface test, the steel plate is placed in the lower portion of the shear box and soil sample is prepared in the upper portion of the shear box.

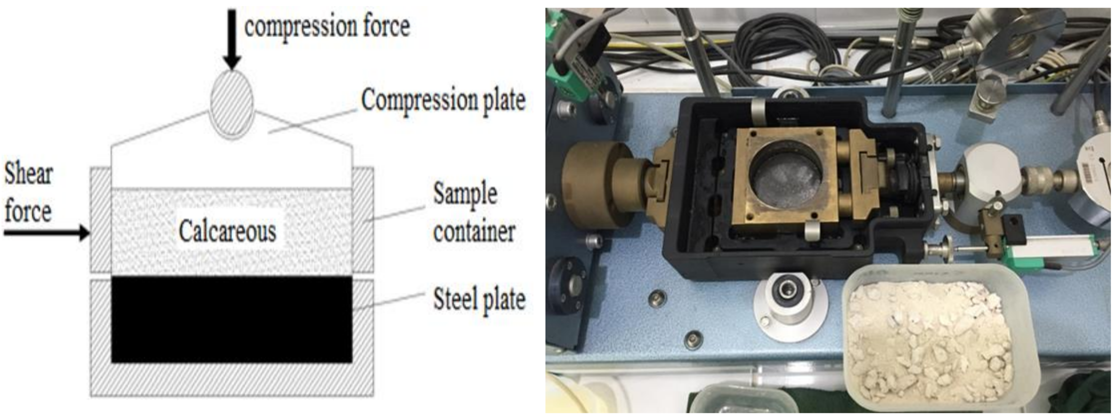

Figure 2. *Model for direct shear test of interface [3] and test samples preparation*

Direct shear test for interface of soil-steel was carried out on the automatic apparatus Shearmatic, produced by Controls – Italia in 2017, at the Geotechnical Lab of Institute of Techniques for Special Engineering (ITSE); layout of equipment used in this study as shown in Figure 3.

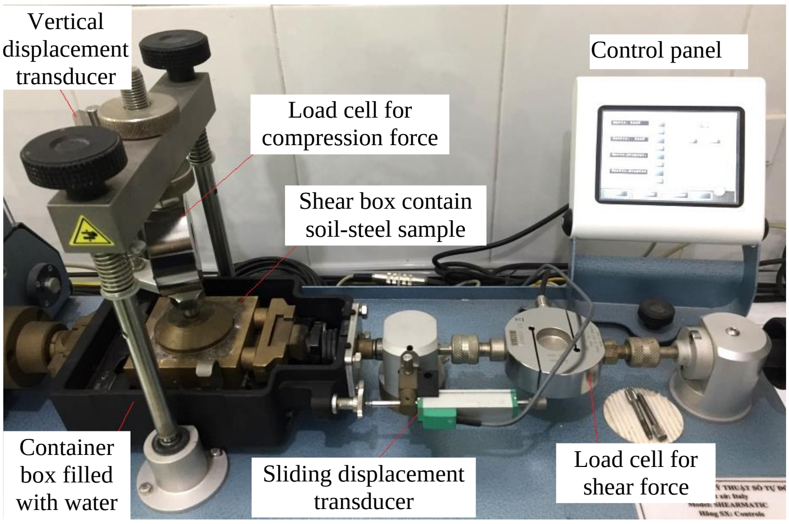

Figure 3. *Layout of equipment for direct shear test of interface between calcareous soil and steel on Shearmatic apparatus*

The test device has the ability to automatically perform experiment up to 50 load level with a loading rate ranging from 0.001 to 4.8 mm min^{-1}, but the shear rate used in the current study was 0.8 mm min^{-1}. Transducers of the test device includes: load cell with capacity of ±5 kN, accuracy ±0,003%; vertical displacement transducer has measurement range up to 10mm with accuracy of 0,002mm; horizontal displacement transducer has measurement range up to 25mm with accuracy of 0,002mm.

2.2. Test results and discussion

Direct shear test of interface between calcareous soils and steel plate were carried out for two types of aforementioned soil. All tests were terminated when a maximum horizontal displacement in the shear box reached values of 7 mm for coral sand and 10 mm for coral sandy-gravel. The normal stress used in this study ranges from 100 to 300 kPa.

The particle breakage under a low confining pressure is a distinctive property of calcareous soils. To maintain a consistent soil gradation in all tests, a new sample was prepared for each direct shear test without repetitive use of any calcareous samples after the test. To obtain the consistence results, the same test was repeated five to six times. The interface friction angle and strength reduction factor were the average value of these repeated tests using the least square method. This statistical data processing approach proved to be a viable way to reveal the interface properties under various test sample conditions and effectively reduced the data scattering.

Let δ represent for interface friction angle between soil and steel plate in the test shear box, from Fig. 3, this angle can be determined as:

$$\delta = \arctan\left(\tau_{\max} / p_{\max}\right) \quad (1)$$

where: τ_{max} is the maximum shear stress on the interface between soil sample and steel plate sample in the shear box, can be observed from the test, kPa; p_{max} is the maximum normal stress on the interface between soil and steel samples, which is also observed from the test, kPa.

Let R_{inter} represents a strength reduction factor of shear resistant on the interface between soil and structure, which can be determined by [4]:

$$R_{inter} = \frac{\tan(\delta)}{\tan(\varphi)} \quad (2)$$

Development of unit friction on the interface of soil-steel along with increasing sliding displacement between two materials for coral sand and coral sandy-gravel are shown in Figure 4 and Figure 5 respectively.

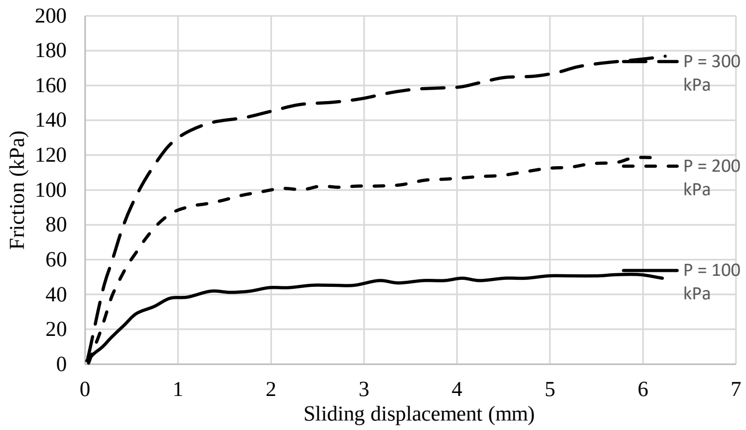

Figure 4. *Unit friction vesus sliding displacement between coral sand and steel*

For all of the tests carried out in this study, no peak value of friction between coral soil and steel was observed; shear stress – shear displacement curves were observed as nonlinear strain hardening rules. In the elastic stage, the shear stress increased linearly with increasing shear displacement; the shear stresses were mainly caused by the static friction between the structural surfaces and soil. In the elastic-plastic stage, static friction transitioned to sliding friction. In the strain hardening stage, soil particles on the interfaces were in the sliding frictional state; the shear stresses were only caused by sliding friction on the interfaces, with increasing shear displacement, the shear stresses increased at slower rates, such that the shear strengths also increased.

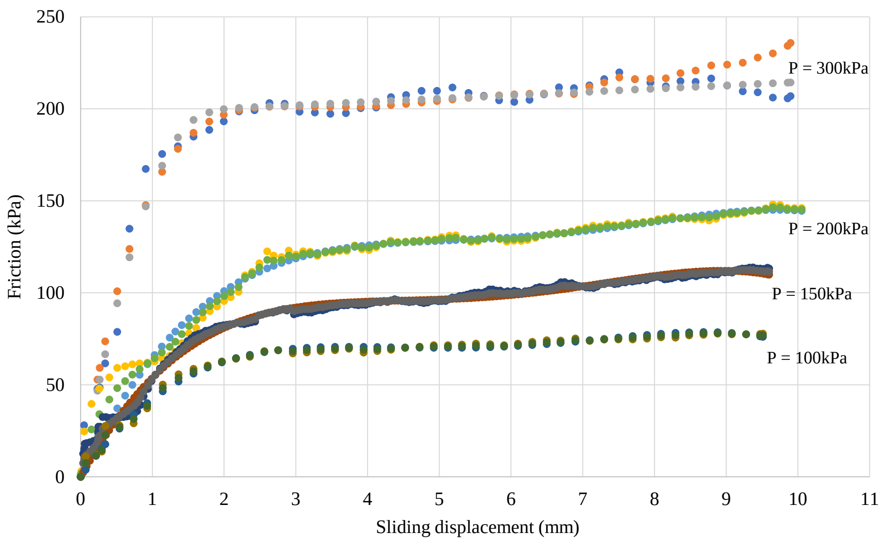

Figure 5. *Unit friction vesus sliding displacement between coral sandy-gravel and steel*

A total of fifteen (15) tests for interface coral sand-steel were performed at normal stresses ranging from 100 kPa to 300 kPa. The regression analysis demonstrates a good linear relationship between the interface shear stress and the correspondent normal stress. The interface friction angle was 27.9^o with an average coefficient of friction of 0.53. Meanwhile, with a total of twelve (12) tests for interface between coral sandy-gravel and steel in the same normal stresses range, the average interface friction angle was 32.8^o and an average coefficient of friction of 0.64. Effect of particle size was observed clearly from the results shown in Fig.4 and Fig.5: for coral sand with smaller particles, limit sliding displacement for static friction was around 1mm whereas this value for coral sandy-gravel was much larger in the range 2-3mm; maximum static interface friction of the coral sandy-gravel were observed (40-50)% higher than that of the coral sand.

An attemp was made with curve fitting for unit interface friction – sliding displacement, the results have indicated that this relationship might be represent by two families of curve: a quadratic curve for initial stage up to limit sliding displacement; a linear relationship for strain hardening stage of friction as indicates in Figure 6. This curve fitting could be useful for computing the shaft resistance of pile embedded in calcareous soil. However, this observation must be investigated further as this study only performed the interface shear test for one value of relative density of calcareous soils; other effects like different relative densities, different particle distribution,... have not yet been investigated.

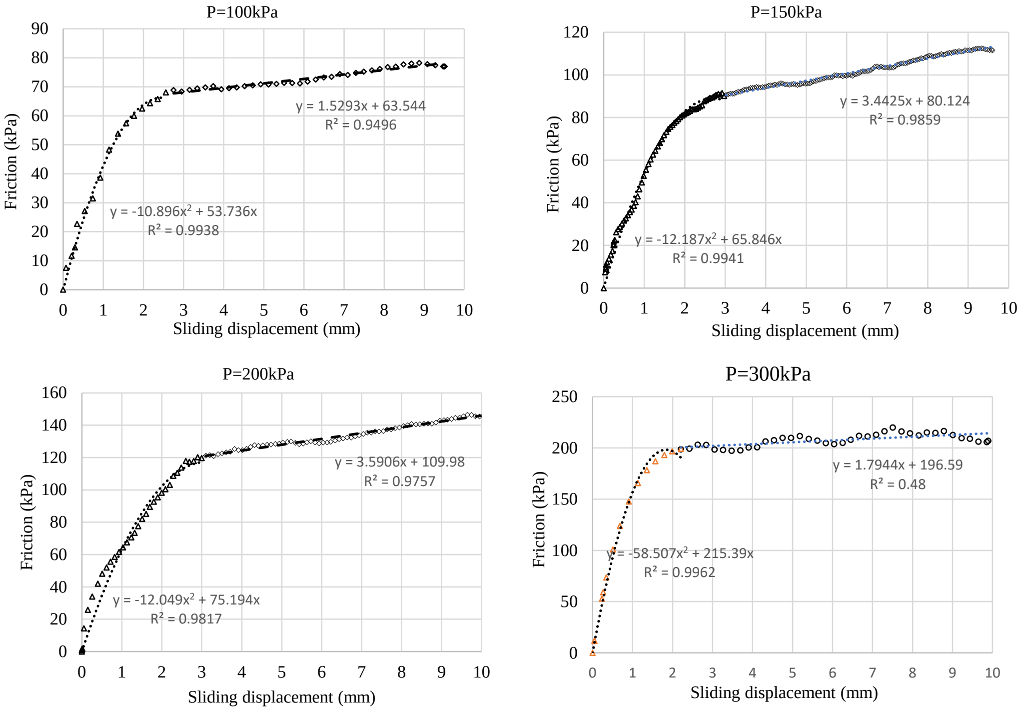

Figure 6. *Curve fitting for unit interface friction – sliding displacement between coral sandy-gravel and steel*

3. Application to estimate axial bearing capacity of steel pile in coral soil

3.1. Method to estimate axial bearing capacity of pile based on t-z and q-z curves

Axial bearing capacity of pile composed from pile shaft resistance (friction) and pile toe bearing (in case of compression load), can be written as:

$$P_{gh} = Q_f + Q_p \quad (3)$$

where: $Q_f = u.\sum f_i.\Delta z_i$ is total pile shaft resistance (4)

$Q_P = q_p A_c$ is the total pile toe bearing (5)

(q_p – unit bearing capacity of soil below the pile toe, A_c – area of pile toe cross section, u – perimeter of pile shaft cross section, f_i – unit friction along pile shaft, Δz_i - length of pile shaft segment)

Numerical model is shown in Fig. 7, pile is divided into segment along the embedment length, friction resistance along pile shaft represented by series of nonlinear spring with force-displacement characterized by t-z curve. Soil reaction at pile toe characterized by a nonlinear spring named q-z curve when pile is subjected to compression load, if tension load applied then this spring can be obmitted.

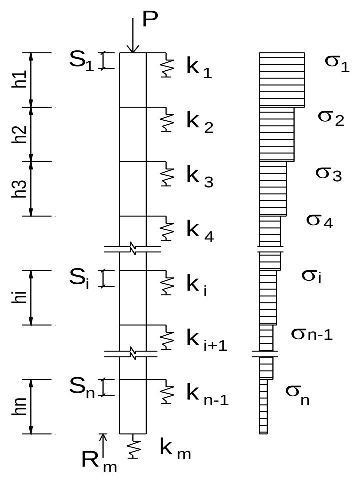

Figure 7. *Numerical model of steel pile subjected to axial load*

From expression (3)-(5) and Fig. 7, in order to estimate the axial bearing capacity of pile, we need to identify unit resistance of soil along the pile shaft and at the pile toe. In the published documents, various kinds of t-z curve and q-z curve have been proposed for different types of pile and geotechnical conditions [6], one of them as shown in Fig. 8. for cohessionless soil.

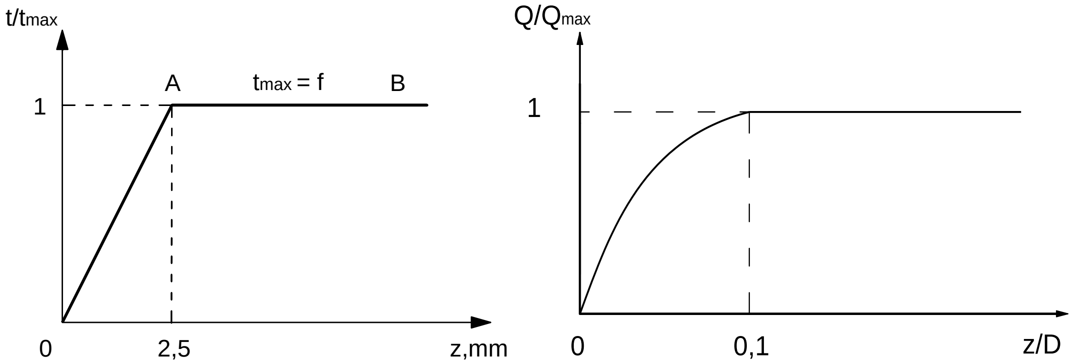

Figure 8. *t – z and Q-z curves for cohessionless soil [6]*

Axial bearing capacity of pile can be estimated from ultimate bearing capacity or from load-displacement curve at pile head according to design code or design standard applied. For example, Vietnamese design standard for bridge requires limit displacement of pile head to be U_{gh}=25.4mm.

For cohessionless soil, unit friction resistance of the pile shaft can be computed from interface friction angle between soil and pile material as [6]:

$$f_i = \beta.\sigma_V^{'}.tg(\delta) = \beta.\sum \gamma_i h_i.tg(\delta) \qquad (6)$$

where: β – coefficient of lateral soil pressure, $\sigma_V^{'} = \sum \gamma_i h_i$ is effective vertical stress in soil at elevation of i^{th} pile segment; δ - interface friction angle of pile and soil; h_i – length of i^{th} pile segment.

Unit resistance of soil at pile head in cohessionless soil can be computed as [6]:

$$q_p = N_q \sigma_v^{'} = e^{\Pi \tan\varphi} \tan^2\left(45^0 + \frac{\varphi}{2}\right).\sigma_v^{'} \qquad (7)$$

Where: N_q is coefficient dependent on internal friction angle, φ, of soil below the pile toe; $\sigma_v^{'}$ is effective vertical stress at pile toe.

Due to nonlinear relationship between pile displacement and soil resistances of t-z and q-z curves, determination of load-displacement curve for pile is not straight forward. Authors have used Newton – Raphson iteration algorism to develop a program written in MATLAB R2008. This program allows users to import experimental data of t-z and q-z curve at different elevation along the pile shaft and at the pile toe to support computation, or use regression expressions for t-z and q-z curves from the literatures. The user interface of the program as shown in Fig. 9, used Vietnamese language. Input data for program includes soil profile, pile characteristics, interface shear characteristics (t-z) at soil layers, base resistance characteristics of soil at pile toe, user must select division of pile segments.

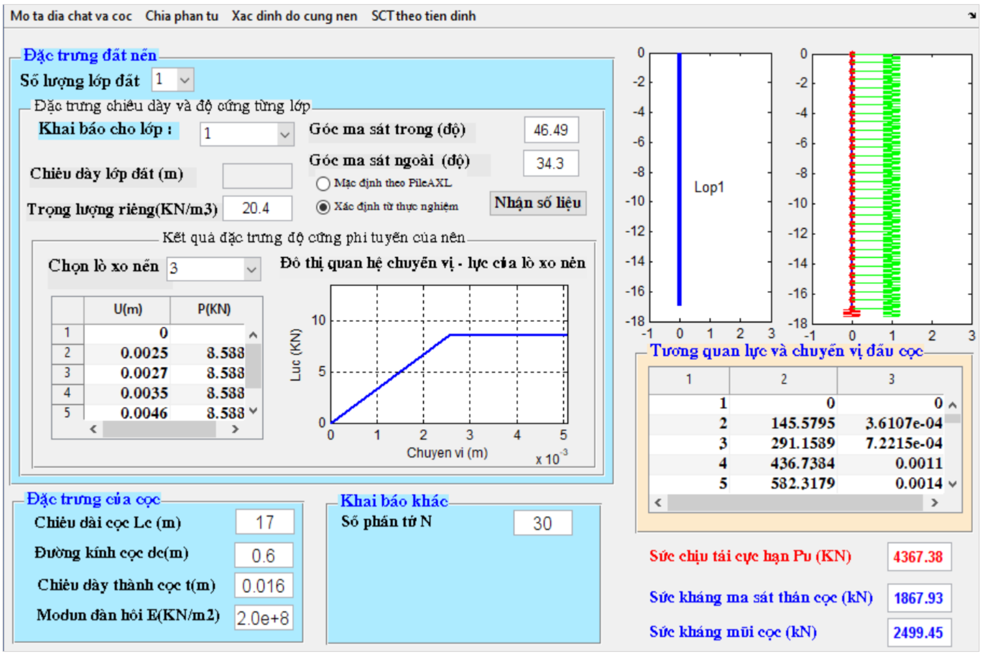

Figure 9. *User interface of self developed program for computation of axial pile bearing based on t-z and q-z curves*

3.2. Testing of self developed program

Accuracy of the developed program was test in comparison with a commercial program PileAXL from Australia [7] with t-z and q-z curve determined according to API [6], using data from coral sandy-gravel soil in this study. A result computed by the developed program with experimental interface shear of this study is also presented.

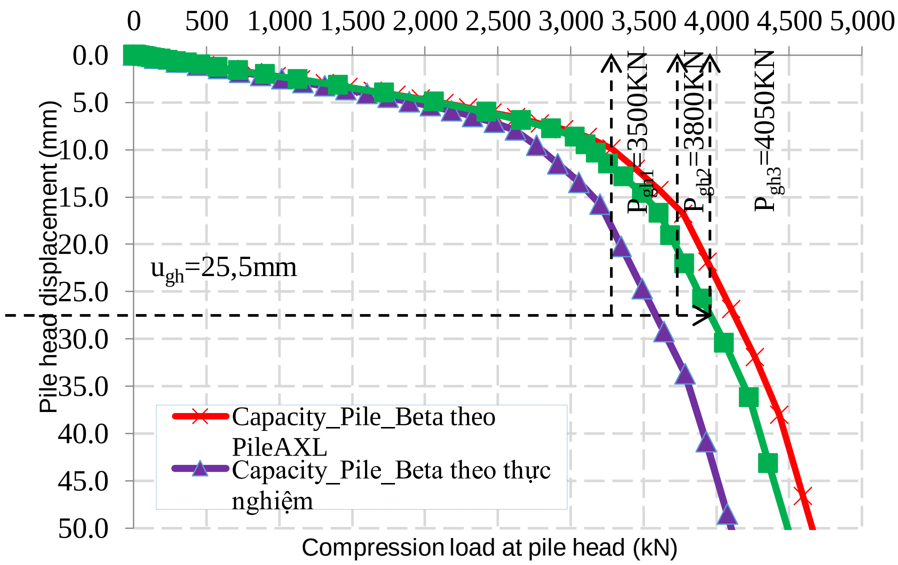

Figure 10. *Pile head load-displacement curve for checking accuracy of program*

When used, t-z curve follows perfectly elasto-plastic behavior, with limit displacement of interface shear equals to 2.5mm, differences between results computed from the developed program and those computed from PileAXL is 6%, which is acceptable.

4. Conclusion and recommendations

In this study, the shear characteristics on the interface between calcareous soil has been experimentally investigated, the following conclusions can be drawn from the obtained results:

For well-graded calcareous soil (coral sand and coral sandy-gravel), interface shear behavior follows a strain hardening rule, limit sliding displacement and interface friction angle depend on particles size of the soil, larger particle size would provide larger friction resistance. For coral sand, these values observed of 1mm for limit sliding and 27.9° for interface friction angle; whereas for coral sandy-gravel these are 2-3mm and 32.8° respectively.

A modified direct shear test can be used to determined interface shear characteristics between calcareous soil and structural materials to provide accurate data for analysis and design of structures built on calcareous soils.

A simple numerical model using t-z and q-z curves with data from material samples test could be used to predict axial bearing capacity of steel piles in coral soil as well as to predict load-displacement of pile subjected to axial loads.

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