Evaluation of Elasticity Modulus of Clayey Soil from Undrained Shear Strength

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Abstract. The modulus of elasticity represents the soil stiffness; it was used to design and analyze the foundation, slope stability, retaining structure, etc. It is one of the main input parameters used in the finite element method for analyzing soil behavior. The scope of this study is to evaluate the correlation between the modulus of elasticity (E) and the cohesion of the soil (c_u) for the remolded and undisturbed samples of clayey soil so it can assess the effect of lateral confining pressure on the soil modulus of elasticity. The unconfined test is chosen for remolded soil to identify the stress-strain behavior. After the experimental utilized is done, the test is modeled using the finite element method to study several states of soil. The PLAXIS program is utilized, and the results are compared with the practical results. The mohr-Coulomb model is chosen for this study because it is commonly used. Based on the results throughout this study, it can be concluded the simulation using the Mohr-Coulomb model of PLAXIS software gives good results for representing the unconfined compression test, so that for soft clay, the ratio between modulus of elasticity and cohesion is equal to (Eu = 30 c_u) for remolded clay and (Eu = 55 c_u) for undisturbed clay. While for stiff clay, it was equal (Eu = 65 cu) for remolded and (Eu = 120 c_u) for undisturbed clay. The modulus of elasticity for the undisturbed is higher than for remolded clay, so the difference is almost double in the case of stiff clay. The lateral confining pressure affects the modules of soil; however, for soft clay, the range of soil modulus in the case of the drained test was (5 to 25 MPa), while the range is higher for the undrained case (18 to 54 MPa). Moreover, for stiff clay, the range was equal (11 to 100 MPa) for a drained test and between (18 to 100 MPa) for an undrained case.

Keywords: Modulus of elasticity; Mohr-Coulomb model; undisturbed sample; clayey soil; unconfined test.

1. INTRODUCTION

The modulus of elasticity for any material (E), also called Young's modulus represents the ratio of stress to strain and provides a convenient measure of material stiffness. In geotechnical engineering, the modulus of elasticity of soil is an important property used for the design and analysis of foundations, slope stability, retaining structure, etc. Moreover, using the finite element method it is one of the main input parameters for analyzing soil behavior. Soil modulus of elasticity can be obtained from several laboratory tests, such as triaxial and unconfined compression tests or in situ tests like standard penetration tests, pressure meters, and plate-load tests. As the unconfined test is relatively simple and economical and can be conducted in the field, it is widely used in geotechnical investigation. Moreover, as some research that is performed in clayey soils is conducted on remolded soils due to difficulty in obtaining undisturbed samples, the value of the extracted elastic modulus may not represent the condition of the undisturbed soil.

Some studies on the relationship between the modulus of elasticity and cohesion are available in previous research. D' Appolonia [1] reported an average value of soil modulus (E) for load tests of (10) sites. The correlation is presented below in Equation (1):

$$\mathrm{E} = 1200\,\mathrm{cu} \tag{1}$$

But for the clay of high plasticity, the relation is:

$$\mathrm{E} = 80 - 400\,\mathrm{c}_u \tag{2}$$

Bjerrum [2] suggested the following Equation of value of (E), where this relation is determined from the vane shear test. The lowest value is for high-plasticity soil.

$$\mathrm{E} = 500 - 1000\,\mathrm{c}_u \tag{3}$$

Simon [3] published the relation of soil modulus according to the cases taken from the literature. It was found that there is much scatter in the results for a plasticity index lower than (50).

$$E = 40 - 3000\ cu \quad (4)$$

Duncan and Buchignani [4] suggested that the value of (E) for soil with a plasticity index lower than (30) and the over-consolidation ratio equal (1).

$$E = 600 - 1400\ cu \quad (5)$$

Bowles [5] suggested an empirical correlation to estimate the modulus of elasticity for normally consolidated clay as written in this Equation:

$$E = 200 - 500\ cu \quad (6)$$

However, very few works have been reported for assessing the correlation between modulus of elasticity (E_s) and cohesion according to the state of the specimen, whether it is undisturbed or remolded, so the relation presented in the literature does not take into account the effect of lateral confining pressure on the modulus of elasticity of soil. Thus, it is necessary to assess the relation between them according to the state of the soil and their confining pressure.

3. EXPERIMENTAL WORK

In order to achieve the goal of this study, experimental work was conducted to obtain the correlation between modulus of elasticity (E_s) and cohesion of clay according to a specimen of remolded state. The experimental work includes laboratory unconfined compression tests of clayey soil at several states. The soil used and the tests performed are described below.

3.1 Soil Used

The soil used in this study is taken from the area of Al Taji, north of Baghdad city. The properties of the soil and the results of the consistency limits tests are given in Table 1. The soil is brown silty clay, and the grain size distribution of the soil used is shown in Figure 1, the soil is classified as low plasticity clay (CL) according to the unified soil classification system.

Table 1: Physical properties of clay soil used.

Property	Value Index	Specification
Liquid limit (L.L)	48	ASTM-D4318-2010
Plastic limit (P.L)	25	ASTM-D4318-2010
Plasticity index (P.I)	23	ASTM-D4318-2010
Specific gravity (G_s)	2.69	ASTM-D854-2010
Gravel (larger than 4.75 mm)	0%	ASTM-D422-2010
Sand (4.75 mm to 0.075 mm)	4%	ASTM-D422-2010
Silt (0.075 mm to 0.005 mm)	45%	ASTM-D422-2010
Clay (less than 0.005 mm)	51%	ASTM-D422-2010
Soil Classification	CL	USCS

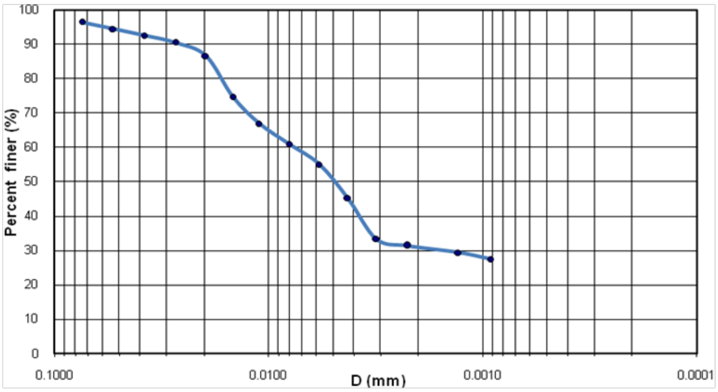

Figure 1: Grain size distribution of clayey soil used.

3.2 Laboratory Tests

In this part, experimental work was employed using the standard procedure of unconfined compression strength; the undrained shear strength (c_u) of clays is commonly determined from an unconfined compression test. The undrained shear strength of cohesive soil is equal to one-half the unconfined compressive strength (q_u). The most critical condition for the soil usually occurs immediately after construction, which represents undrained conditions, where the undrained shear strength (s_u) is basically equal to the cohesion (c_u). This is expressed as:

$$s_u = c_u = \frac{qu}{2}$$

The standard compaction test was performed according to (ASTM D 698) on soil mixed with an amount of water content equal (20, 22, and 30 %) to obtain a range of soil cohesion. The specimen is then extracted from the mold by a jack using a special tube to get a specimen of standard dimensions. Several tests were performed to determine a stress-strain behavior with various water content to get several states of undrained shear strength (c_u). The UCS tests were performed in accordance with (ASTM D 2166), as shown in Figure 2. The sample sizes were (36 mm) in diameter and (76 mm) in length, Figure 3. The primary purpose of this test is to determine the stress-strain behavior of soil, which is then used to calculate the unconsolidated-undrained shear strength of the clay under unconfined conditions.

Figure 2: Specimen under unconfined test.

Figure 3: The specimen after the test.

4. EXPERIMENTAL RESULTS AND ANALYSIS

The results of unconfined are shown in Figures 4 to 6, where the initial tangent is drawn to calculate the initial modulus of elasticity. The results of the modulus of elasticity and cohesion of clay are demonstrated in Table 2. It can be seen that this value of the elastic modulus is low in the case of remolded clay compared to the indications of previous studies.

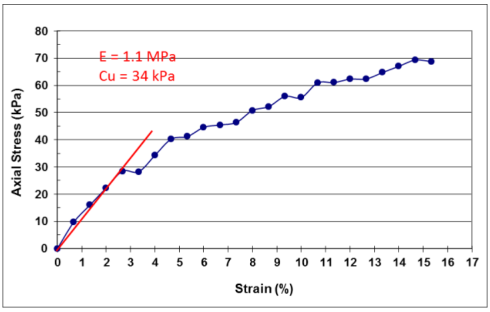

Figure 4: Unconfined compression test 1.

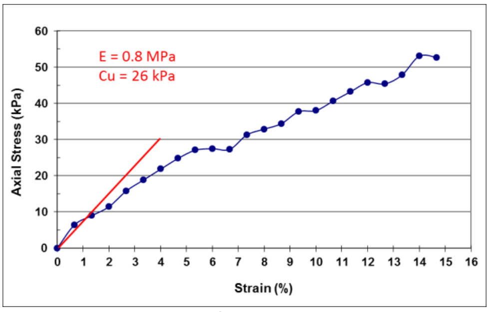

Figure 5: Unconfined compression test 2.

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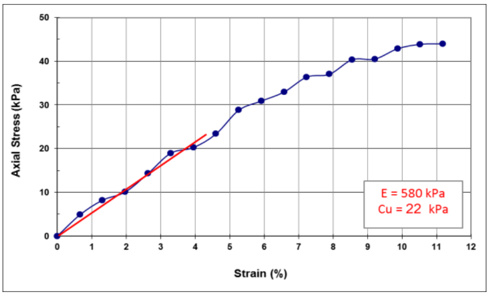

Figure 6: Unconfined compression test 3.

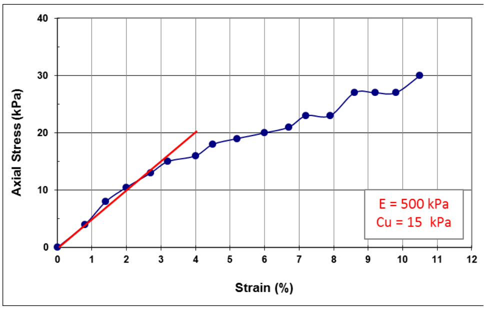

Figure 7: Unconfined compression test 4.

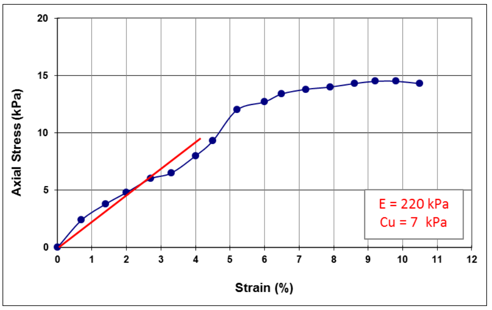

Figure 8: Unconfined compression test 5.

Table 2: Results of modulus of elasticity and soil cohesion.

Test No.	W.C. (%)	Modulus of Elasticity, E (kPa)	Cohesion, c_u (kPa)
1	17	1100	34
2	18	800	26
3	20	580	22
4	22	500	15
5	30	220	7

The average ratio of the three tests between the modulus of elasticity and cohesion can be found in Figure 9 for remolded soft clay by the Equation below:

$$E = 30 * cu \tag{7}$$

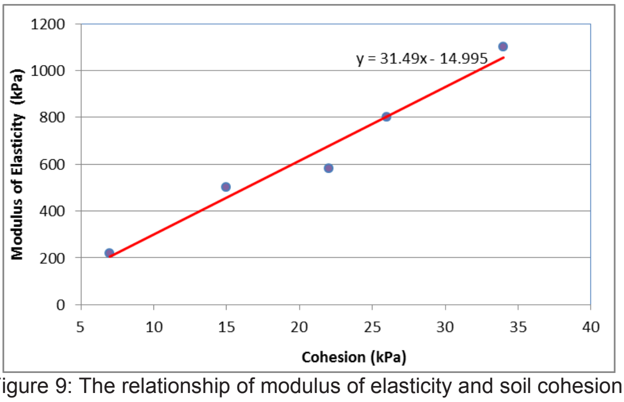

Figure 9: The relationship of modulus of elasticity and soil cohesion.

4.1 Validation of Finite Element Modeling

For the purpose of studying other cases of soil, the PLAXIS program will be used to create a model that matches the method of unconfined tests to check the program's validity and then create other cases of soil with different cohesion values. PLAXIS program consists of three steps: input, calculation, and output. Geometry is created, and materials data is identified in the input step. After that, the two and three dimensions of meshing are performed, and then the initial state and loading phase are performed in the calculation steps. At the end of the calculation step, deformation and displacement graphs can be seen in the output segment. The mohr-Coulomb model is selected for this study because it is commonly used and does not require extra soil parameters. The specimen's geometry can be seen in Figure 10, and the vertical displacement of the specimen is shown in Figure 11.

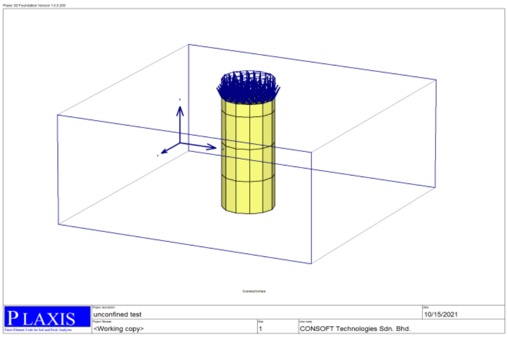

Figure 10: The geometry of unconfined test using finite element.

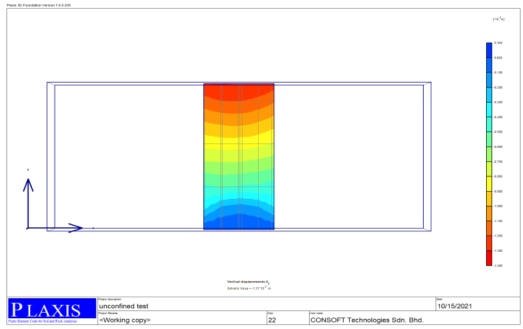

Figure 11: Vertical displacement of the specimen using finite element model.

The program results are compared in Figure 12, where the inputs used are shown in Table 3. It can be noted that the program is suitable for representing the unconfined test, and the simulation by the Mohr-Coulomb model gives good results.

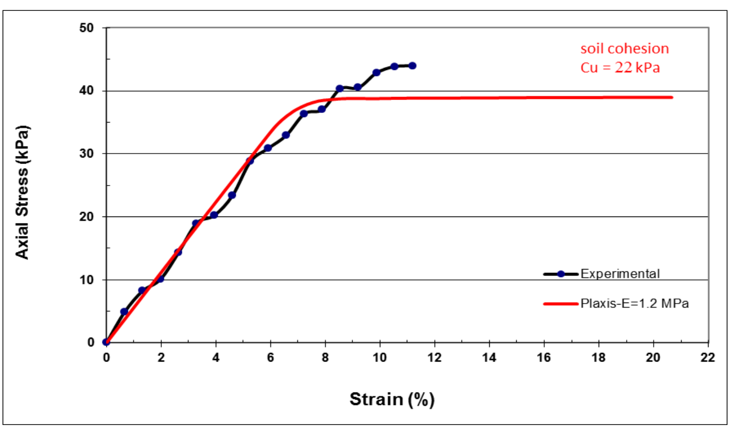

Figure 12: The results of the validation of the program.

Table 3: The input parameters used in the analysis of the validation case.

Description	Symbol	Unit	Value
Young`s modulus	E	MPa	1.2
Cohesion	c	kPa	22
Friction angle	Ø	ᴼ	1
Poisson’s Ratio	v	-	0.45

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4.2 Finite Element Analysis of Unconfined Test

To study other soil cases, a finite element analysis of unconfined tests under loading was conducted using three different states of soil cohesion (40, 60, and 100 kPa). The input parameters used in the numerical analysis are given in Table 4. The results of the analysis are given in Figure 13.

Table 4: The input parameters used in the numerical analysis of the unconfined test.

Soil case	1	2	3
Young`s modulus (MPa)	4	8	15
Cohesion (kPa)	40	60	100
Friction angle	1	1	1
Poisson's ratio	0.45	0.45	0.4

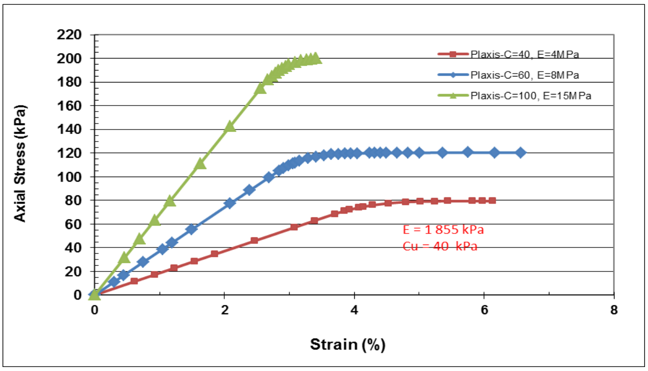

Figure 13: The numerical analysis of the unconfined compression test.

The relationship between the modulus of elasticity and soil cohesion of the numerical analysis can be seen in Table 5. It can be noticed that the value of the modulus of elasticity increases non-linearly with the value of cohesion by increasing the cohesion of the soil from soft to stiff state. For stiff clay, the modulus of elasticity can be calculated from the Equation below:

$$E = 65 * c_u \quad (8)$$

Table 5: Relation between modulus of elasticity and soil cohesion of the numerical analysis.

Test No.	Cohesion, c_u (kPa)	Modulus of Elasticity, E (MPa)	Ratio of (E/ c_u)
1	40	1.86	47
2	60	3.7	62
3	100	6.8	68

4.3 Finite Element Analysis of Undisturbed Clay

In order to find the correlation between modulus of elasticity (E_s) and soil cohesion according to the state of undisturbed samples, it was considered the experimental work conducted by Khan et al. [11]. The properties of soil are given in Table 6. Input parameters used in the validation are shown in Table 7; it can be observed from Figure 14, and there was a good agreement of the numerical with the experimental results.

Table 6: Results of laboratory undisturbed soil properties by Khan et al. [11].

Property	Value Index
Liquid limit (L.L)	54
Plastic limit (P.L)	28
Plasticity index (P.I)	26
Specific gravity (G_s)	2.7
Gravel	0 %
Sand	1.75 %
Silt	22.25 %
Clay	75 %
Soil	Silty clay

Table 7: The input parameters used in the validation of undisturbed samples and numerical analysis.

Soil case	Case study	1	2	3
Young`s modulus (MPa)	1.5	3.5	12	18
Cohesion (kPa)	27	40	100	150
Friction angle (degree)	1	1	1	1
Poisson's ratio	0.49	0.49	0.4	0.4

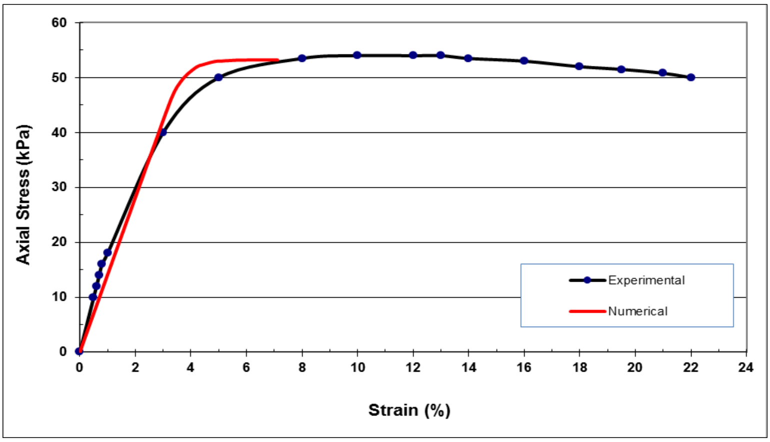

Figure 14: The results of validation of the undisturbed soil.

The result of the analysis of the undisturbed soil is given in Figure (15); the relation between the modulus of elasticity and soil cohesion of the numerical analysis of the undisturbed soil can be seen in Table 8, it can be concluded that for soft clay, the modulus of elasticity can be calculated from the Equation below:

$$E = 55 * c_u \quad (9)$$

While for stiff clay, the relation is:

$$E = 120 * c_u \quad (10)$$

The modulus of elasticity for the undisturbed soil is higher than in the case of remolded clay, so the difference is almost double in the case of stiff clay and this must be taken into account for assessing the value in clayey soil.

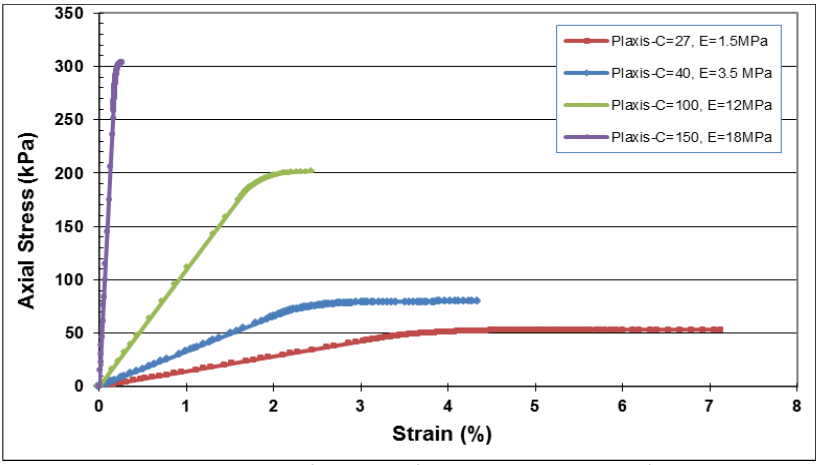

Figure 15: The numerical analysis of the unconfined compression test of the undisturbed soil.

Table 8: Relation between modulus of elasticity and soil cohesion of the numerical analysis.

Test No.	Cohesion, c_u (kPa)	Modulus of Elasticity, E (MPa)	The ratio of (E/c_u)
1	27	1.5	55
2	40	3.5	88
3	100	12	120
4	150	18	120

4.4 Variation of Modulus of Elasticity with Confining Pressure

The stress-strain curve for soil is dependent on the confining pressure (3). As the confining pressure subjected to soil (σ_3) increases, the strength of the soil and the steepness of the stress-strain curve increase, resulting in a high value of the modulus of elasticity of the soil, as can be seen in Figure 16, where (σ_1) represents the vertical stress.

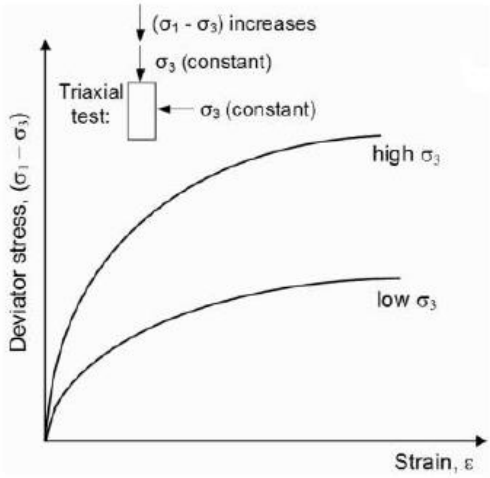

Figure 16: Effect of confining pressure and strain on modulus values for soil subjected to triaxial loading [12].

Moreover, in order to investigate the effect of lateral confining pressure (σ_3) on the modulus of elasticity to the soil, the triaxial tests results conducted by Surarak et al. [13] of Bangkok soil, tests are performed for soft and stiff clayey soil under undrained and drained conditions. The index properties for soft and stiff Bangkok clays are given in Table 9.

Table 9: The properties of Bangkok clay, Surarak [13].

Property	Soft clay	Stiff clay
Liquid limit (L.L)	118	46
Plastic limit (P.L)	43	17
Plasticity index (P.I)	75	29
Specific gravity (G_s)	2.75	2.74
Gravel	0	0
Sand	4	23
Silt	32	43
Clay	64	34

Table 10 presents a summary of parameters obtained from triaxial compression tests (CD and CU test) of both soft and stiff Bangkok clay. The effect of confining pressure (σ_3) on the modulus of elasticity of soil for both cases drained and undrained test can be seen in Figures 17 and 18. It can be deduced from these figures that for soft clay the range of soil modulus in case of the drained test was (5 to 25 MPa), while the range is higher for undrained case (18 to 54 MPa) according to the lateral confining pressure, moreover for stiff clay, the range equal (11 to 100 MPa) for the drained test, and it was between (18 to 100 MPa) for the undrained case.

Table 10: Summary of parameters obtained from Bangkok clay triaxial compression tests.

Case	σ'_3	$\sigma'_1 - \sigma'_3$	σ'_1	Strain %	E kPa
CD- soft Bangkok clay	138	50	188	0.03	6267
CD- soft Bangkok clay	207	55	262	0.03	8733
CD- soft Bangkok clay	276	95	371	0.03	12367
CD- soft Bangkok clay	345	100	445	0.03	14833
CD- soft Bangkok clay	414	100	514	0.02	25700
CU- soft Bangkok clay	138	45	183	0.01	18300
CU- soft Bangkok clay	207	65	272	0.01	27200
CU- soft Bangkok clay	276	80	356	0.01	35600
CU- soft Bangkok clay	345	122	467	0.01	46700
CU- soft Bangkok clay	414	130	544	0.01	54400
CD- stiff Bangkok clay	34	80	114	0.01	11400
CD- stiff Bangkok clay	103	80	183	0.0064	28594
CD- stiff Bangkok clay	414	350	764	0.012	63667
CD- stiff Bangkok clay	552	400	952	0.008	119000
CU- stiff Bangkok clay	138	200	338	0.018	18778
CU- stiff Bangkok clay	207	280	487	0.01	48700
CU- stiff Bangkok clay	552	420	972	0.01	97200

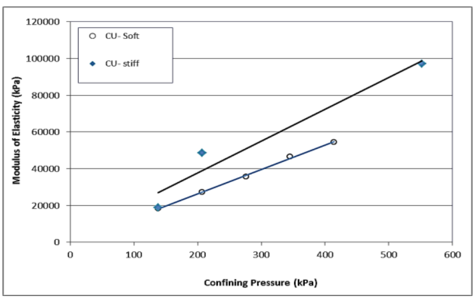

Figure 17: Effect of confining pressure on the modulus of elasticity values for soil for triaxial (CU) tests.

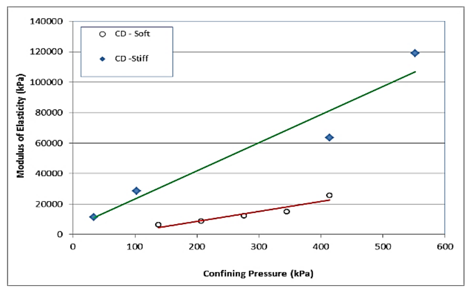

Figure 18: Effect of confining pressure on modulus of elasticity values for soil for triaxial (CD) tests.

5. CONCLUSIONS

In the present study, experimental investigations are carried out, and then numerical analysis is conducted. According to the results of this study, the following conclusion can be drawn:

- The simulation using the Mohr-Coulomb model of PLAXIS software gives good results for representing the unconfined compression test.
- The value of the modulus of elasticity increases non-linearly with the value of soil cohesion.
- The ratio between the modulus of elasticity and cohesion for soft clay can be found by Equation (E_u = 30 cu) for remolded and equal to (E_u = 55 cu) for undisturbed clay.
- The relation between the modulus of elasticity (E_u) and soil cohesion for remolded stiff clay was equal (E_u = 65 c_u), while it was equal to (E_u = 120 c_u) for undisturbed clay.
- The modulus of elasticity of the undisturbed soil is higher than remolded clay, so the difference is almost double in the case of stiff clay.
- The lateral confining pressure affects the modules of soil. However, for soft clay, the range of soil modulus in the case of the drained test was (5 to 25 MPa), while the range was higher for the undrained case (18 to 54 MPa).
- For stiff clay, the range soil modulus was (11 to 100 MPa) for a drained test, and it was between (18 to 100 MPa) for the undrained case due to the effect of lateral confining pressure on the soil.

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