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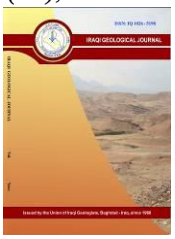

Experimental Investigation and Numerical Modeling of the Primary Consolidation Behavior of Fully and Partially Saturated Clayey Soils in Hilla City, Babylon Governorate, Iraq

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Abstract

The consolidation behavior of silty clay soils in Hilla City, Babylon Governorate, Central Iraq, is chosen for this research. Four boreholes, each three meters deep, were drilled. According to the Casagrande chart, the undisturbed samples obtained using Shelby tubes showed high clay content, ranging from 29.3% to 61.8%, thereby classifying the soils as CL–CH. Both fully saturated and partially saturated (S=50%) tissues underwent consolidation tests. Between dryness and complete saturation, the 50% saturation level is a crucial engineering state that significantly affects mechanical reaction and settling potential. The findings indicated that whereas cv and k were greater in partially saturated soils, indicating faster consolidation due to improved drainage and lower pore pressure, e^1, Pc, Cc, Cs, av, and mv were higher in fully saturated soils and were positively associated with clay content. The agreement between numerical modeling using the soft soil model in PLAXIS and laboratory testing was good, with values ranging from 2.17 to 2.50 cm and from 2.38 to 2.6 cm, respectively. The results indicate that soil compressibility and settling properties are strongly affected by seasonal fluctuations in groundwater. In order to guarantee the long-term stability of foundations in Babylon's fine-grained soils, soil improvement techniques like controlled compaction, preloading, or vertical drains are advised prior to construction, even when the measured settlements are within allowable bounds.

Keywords: Fully saturated; Partially saturated; Consolidation; Numerical modeling; Clay soils

1. Introduction

The importance of studying buildings and infrastructure in Hilla City, Babylon Governorate, lies in their differential settlement and shallow foundation settlement. Consolidation settlement, which is crucial for structural design and the prevention of geotechnical problems, accounts for the permeability variations associated with partial saturation.

Terzaghi's theory of soil mechanics (for evaluating the settlement of clayey soils) assumes that clayey soils are either fully saturated with water (water-saturated pores) or dry (air-saturated pores). Partially saturated soils are often neglected despite numerous geotechnical problems, as they contain water and air in their pores. Therefore, the behavior of both types will be different from each other. Consolidation is the process of lowering a saturated soil's water content without replacing it with air,

according to Terzaghi (1943). Sivakumar et al. (2006) conducted several tests on compacted clay soil to investigate the effect of wetting and drying on soil compression. They concluded that the yielding of the sample during drying is less than that during wetting. Namah (2014) studied the prediction of consolidation settlement of saturated and unsaturated soils from laboratory tests in the Musabe, Babylon governorate. It was noted that soil settlement is greatly affected by the degree of saturation. Settlement was studied for several degrees of soil saturation (100%, 91%, 85%, 75%, and 60%). Mathematical relationships were found linking these parameters (compressibility coefficient Cc, swelling coefficient Cs, volumetric compressibility mv, and coefficient of consolidation Cv) with the degree of saturation. Fredlund and Fredlund (2020) measured two less expensive soil property functions that can be combined with various estimation techniques and assumptions. The two laboratory tests assess the following: (i) the water content vs void ratio, also known as the shrinkage curve (SC), and (ii) the gravimetric water content versus soil suction, also known as the soil-water characteristic curve (w-SWCC). To extend unsaturated soil characteristics throughout the whole range of soil suctions, these two unsaturated soil property relationships can be employed in conjunction with saturated soil properties. (It is defined as the energy required to remove water from unsaturated soil, particularly in relation to shear strength and settlement. It is a measure of soil drying and depends on factors such as pore-water moisture content and pore-water impurities. Al-Amar and Alkhalidy (2024) determined the soil stability and susceptibility to erosion. The research assesses the soil characteristics of the banks along a portion of the Shatt al-Hilla in Hilla City, Babylon Governorate. To characterize soil behavior under environmental and hydrological conditions, a number of geological and geotechnical experiments were conducted and compared with engineering standards. The findings underscore the need for engineering solutions to preserve bank stability by identifying areas of relative vulnerability and variability in mechanical properties. The research provides a thorough geological and geotechnical description of the soils in Hilla District, Babylon Governorate. To ascertain soil classification, strength characteristics, compaction behavior, and engineering compatibility, laboratory and field investigations were carried out. The results promote safer, more effective construction in the area by providing crucial information for infrastructure planning and foundation design.

This study's primary goals are to: (1) describe the physical and engineering characteristics of Babylon's clay soils; (2) compare the consolidation behavior under fully and partially saturated conditions; and (3) assess the agreement between numerical modeling results and laboratory settlement results.

1.1. Location of the Study Area

The chosen area is in the Hilla city central region of the Babylon governorate and is located by latitudes 32°26'25-32°28'15.8 N and longitudes 44°25'18.3-44°26'22.1E (Fig. 1). The study area's climate is characterized by dry summers and high evaporation rates, which increase soil salinization and winter rainfall, thereby increasing soil moisture levels and thereby increasing saturation and settlement potential. As a result, groundwater fluctuations, soil saturation, and the consolidation behavior of Hilla's fine-grained clays are strongly affected by extreme climatic variability characterized by alternating wet and dry periods. Four boreholes, each three meters deep, were drilled. Borehole coordinates are shown in Table 1.

Table 1. Coordination of boreholes in the study area

Borholes No. and name of districts	Latitude (N)	Longitude (E)
1 - Nadir-1 district	32°26'25	44°25'18.3
2 - Alshaawy district	32°28'07.6	44°25'47.7
3 - Alzahra' district	32°27'44.6	44°25'45.8
4 - Aljumhuriu district	32°28'15.8	44°26'22.1

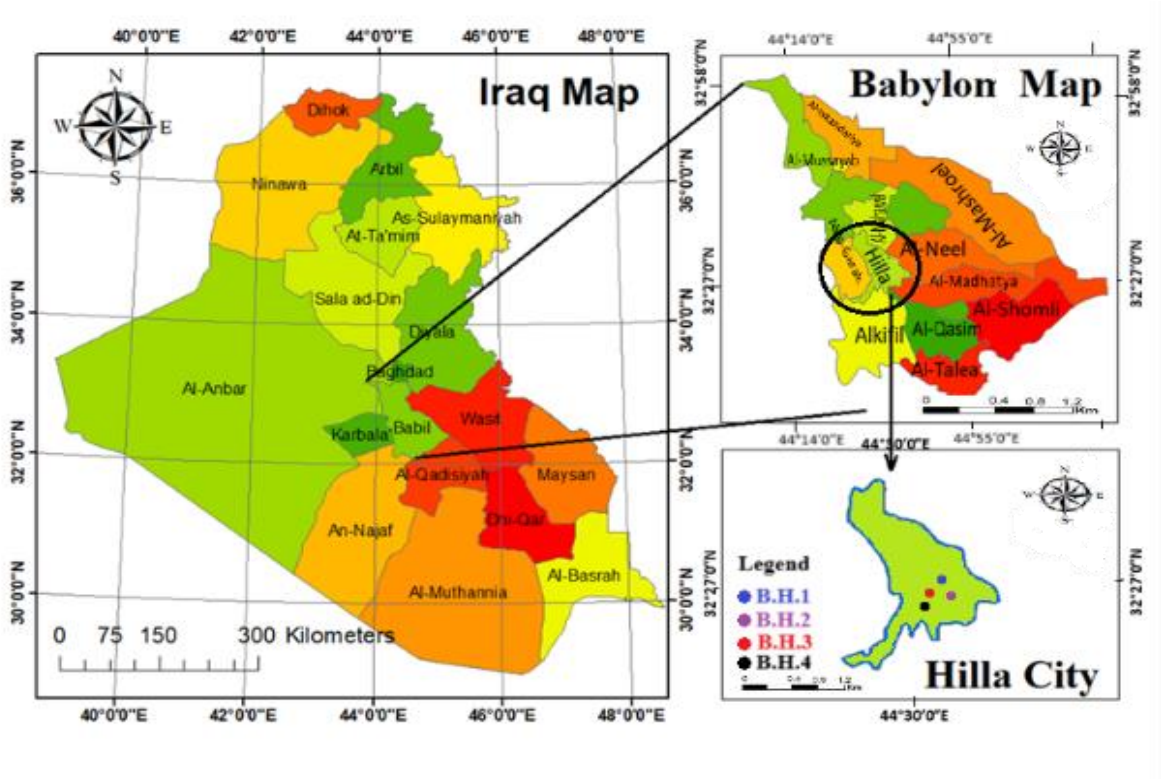

Fig. 1. Location map of the study area

1.2. Geology and Tectonics of the Study Area

The Babylon Governorate is located within the stable shelf and the sedimentary basin of the unstable shelf (Mesopotamian region) (Jassim and Goff, 2006). The Mesopotamian region is located in the Plateau in the southwest and the Zagros Mountains in the northeast (Al-Amar and Hadi, 2018). According to geology, the Quaternary, Pleistocene, and Holocene epochs are represented in the study area's contemporary deposits. Among these sediments are the Pleistocene Age alluvial deposits and the deposition of the Euphrates River floodplain and its tributaries (Al-Rubaiee and Al-Owaidi, 2024). Floods can also produce deposits that fill depressions; these deposits are often composed of fine sand and silty clay layers that the river flows through the sabkha soils, which include the Mahawil sabkha, the Hashimiya sabkha, and the Hilla sabkha, which are salt flats that are abundant at the sedimentary basins' bottom. Human activity, most of which is agricultural, affects soil formation. Irrigation and drainage channels, used to dig agricultural fields, have led to the accumulation of alluvial and sandy sediments in an irregular and heterogeneous manner (Abdullah, 2007).

2. Experimental Work

Four boreholes at a depth of 3 m were investigated for the physical and engineering properties and consolidation of fully saturated (S=100%) and partially saturated (S=50%) clay soils of the Hilla city center, Babylon Governorate, Central Iraq.

2.1. Fieldwork Stage

Four rotary-drilled boreholes (BH1 to BH4) are selected to a depth of 3 m with 0.5 m sample intervals, during the winter season, in February 2024. To guarantee spatial consistency, ground surface elevations were precisely leveled at each drill position. Following a 24-hour stabilization period after borehole completion, groundwater levels were monitored in compliance with ASTM D4750. ASTM

D1452 and ASTM D5783 standards were followed for collecting soil samples. While undisturbed samples were gathered utilizing Shelby tubes in compliance with ASTM D1587, disturbed samples were taken in line with ASTM D1586 (Standard Penetration Test). To preserve their inherent moisture and structure, every sample was meticulously packed, tagged, and transported to the laboratory under carefully controlled conditions. A field shot depicting the drilling and sample activities carried out during the site investigation is shown in Plate 1.



Plate 1. A collection of photos from the fieldwork stage

2.2. Laboratory Testing Stage

This stage began when the soil samples were delivered to the laboratory. Shelby tube specimens were carefully extracted and kept to maintain their natural moisture content using a mechanical extruder. Follow-up testing was carried out in accordance with international engineering standards (ASTM) by the Department of Applied Geology at the University of Babylon and the Soil Testing Division of the Al-Mawal Company.

2.2.1. Physical tests

Physical tests to determine moisture content and degree of saturation (ASTM D2216), specific gravity (ASTM D854), Atterberg's limits (ASTM D4318), grain size distribution (ASTM D422), void ratio and porosity (ASTM D2435, D7263), and unit weight (wet and dry) (ASTM D4318).

2.2.2. Engineering tests

For engineering tests such as consolidation (ASTM D2435) on fully saturated soil, the same procedures were also applied at 50% partial saturation. Partial-saturation tests (50%) were conducted using a ring with standard dimensions (20 mm high and 50 mm in diameter). The soil sample will be divided into two halves: first, the upper layer will be unsaturated and 10 mm thick.

The second: the underlayer will be fully saturated and 10 mm thick, and extract all consolidation parameters (e_o, Cc, Cs, pc, mv, av, cv, and k). Smith and Smith (1998) mentioned the values for different degrees of saturation and air content, S = 50-60% partial saturation in this water phase. The soil approaches the minimum relative permeability, as air has a continuous path in the voids, not the water phase (Partial saturation of soil containing 50-60% water and air in its voids). permeability (falling head test) (ASTM D2434-68), triaxial compression test (UU) (ASTM D2850).

3. Results

3.1. Soil Physical Test Results

Physical examinations were conducted on all disturbed and undisturbed samples, and the results are presented in Tables 2, 3, 4, and 5.

Table 2. Physical soil tests result in B.H.1

BH.NO.	**1 - Nadir-1 district**					
Depth(m)	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3
Type of samples	D.S	U.S	D.S	U.S	D.S	U.S
m.c%	20	21	28	28	22	22
Sand%	38.3	37.9	45.3	37.7	44.8	40.1
Silt%	32.4	29.8	21	20.3	16.1	13.8
Clay%	29.3	32.3	33.7	42	39.1	46.1
L.L%	36	39	33	35	37	51
P.L%	20	21	18	18	21	19
P.I%	16	18	15	17	16	32
Soil Activity(A%)	0.55	0.56	0.45	0.4	0.41	0.69
degree of saturation (S%)	72	89	97	78	88	78
e	0.76	0.64	0.79	0.99	0.69	0.77
n%	43	39	44	50	41	44
ɣwet (gm/cm3)	1.85	1.96	1.83	1.68	1.93	1.85
ɣdry (gm/cm3)	1.55	1.66	1.53	1.38	1.63	1.55
Gs	2.73	2.73	2.74	2.74	2.75	2.75
USCS	CL	CL	CL	CL	CL	CH
Soil description	Fill material	Brown silty clayey sand	brown silty clayey sand	Brown silty sandy clay	Brown silty clayey sand	Stiff brown silty sandy clay

Table 3. Physical soil tests result to B.H.2

BH No.	**2- Alshaawy district**					
Depth(m)	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3
Type of samples	D.S	U.S	D.S	U.S	D.S	U.D
m.c%	14	14	13	14	20	21
Sand%	33.7	33.5	27	35	25	20
Silt%	29.3	30.2	27	25.7	29	23
Clay%	37	36.3	46	39.3	46	57
L.L%	36	40	30	37	31	51
P.L%	18	19	16	18	17	23
P.I%	18	21	14	19	14	28
Soil Activity (A%)	0.49	0.58	0.3	0.48	0.3	0.49
degree of saturation (S%)	56	53	54	61	87	95
e	0.67	0.71	0.66	0.63	0.63	0.59
n%	40	42	40	38	39	37
ɣwet (gm/cm3)	1.91	1.87	1.94	1.98	1.98	1.99
ɣdry (gm/cm3)	1.61	1.57	1.64	1.68	1.68	1.69
Gs	2.69	2.69	2.72	2.73	2.74	2.69
USCS	CL	CL	CL	CL	CL	CH
Soil description	Fill material	Gray silty sandy clay	Gray silty sandy clay	Gray silty sandy clay	Gray sandy silty clay	Stiff gray sandy silty clay

Table 4. Physical soil tests result in B.H.3

BH No.	**3 – Al-Zahra District**					
Depth(m)	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3
Type of samples	D.S	U.S	D.S	U.S	D.S	U.S
m.c%	16	16	14	16	14	16
Sand%	28.5	29.3	25	24	15.2	10.1
Silt%	29.1	27.2	31.1	29.8	34.5	28.1
Clay%	42.4	43.5	43.9	46.2	50.3	61.8
L.L%	38	43	40	46	39	52
P.L%	19	21	20	19	17	23
P.I%	19	22	20	27	22	29
Soil Activity (A%)	0.45	0.51	0.46	0.58	0.44	0.47
degree of saturation (S%)	71	68	57	67	61	64
e	0.62	0.64	0.67	0.65	0.63	0.68
n%	38	39	40	40	39	41
ɣwet (gm/cm3)	1.99	1.96	1.93	1.95	1.98	1.93
ɣdry (gm/cm3)	1.69	1.66	1.63	1.65	1.68	1.63
Gs	2.73	2.73	2.73	2.73	2.74	2.74
USCS	CL	CL	CL	CL	CL	CH
Soil description	Fill material	Brown sandy silty clay	Brown sandy silty clay	Brown sandy silty clay	Brown sandy silty clay	Stiff brown sandy silty clay

Table 5. Physical soil test results for B.H.4.

BH No.	**4- Al-jumhuriu district**					
Depth(m)	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3
Type of samples	D.S	U.S	D.S	U.S	D.S	U.D
m.c%	23	23	22	22	23	23
Sand%	52.8	40.1	25	20	21.7	21
Silt%	12.8	10.5	35.9	37.1	34.4	35.2
Clay%	34.3	49.4	39.1	42.9	43.9	43.8
L.L%	28	33	25	30	35	42
P.L%	15	18	17	19	20	23
P.I%	13	15	8	11	15	19
Soil Activity (A%)	0.38	0.3	0.2	0.26	0.34	0.43
degree of saturation (S%)	82	90	96	82	69	82
e	0.76	0.7	0.63	0.73	0.92	0.77
n%	43	41	39	42	48	44
ɣwet (gm/cm3)	1.85	1.91	1.98	1.88	1.73	1.85
ɣdry (gm/cm3)	1.55	1.61	1.68	1.58	1.43	1.55
Gs	2.73	2.73	2.74	2.74	2.75	2.75
USCS	CL	CL	CL	CL	CL	CL
Soil description	Gray Silty clayey sand	Gray silty sandy clay	Gray silty sandy clay	Brown sandy silty clay	Brown sandy silty clay	Brown sandy silty clay

3.2. Soil Engineering Test Results

Engineering tests were performed on all borehole samples obtained from the study area, with detailed results ((initial voids ratio (e_o), compression index (Cc), swelling index (Cs), pre-consolidation pressure (pc), volumetric compressibility (mv), coefficients of compressibility (av), coefficient of consolidation (cv), permeability coefficient (k) and current pressure above the site (p_o). This represents the weight of the soil column (effective pressure) above the level of the sample being examined and can be calculated from($P_0 = \gamma_m * h$) where $\gamma_{m=}$ density of the layer examined and h= depth of the soil sample was taken. summarized in Tables 6, 7 and 8. Fig. 2 shows the relationship between pressure and the void ratio to BH4 for depth 2.5 to 3 m. Fig. 3 shows the cross-section of the soil with the groundwater level marked. current pressure above the site (p_o).

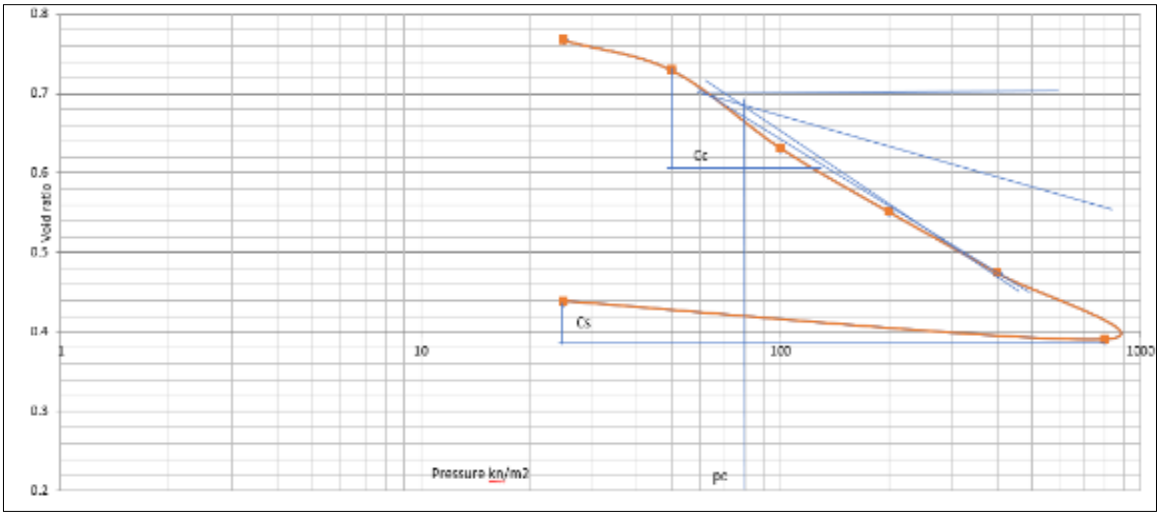

Fig. 2. The relationship between pressure and void ratio in BH4 at depth (2.5-3) m

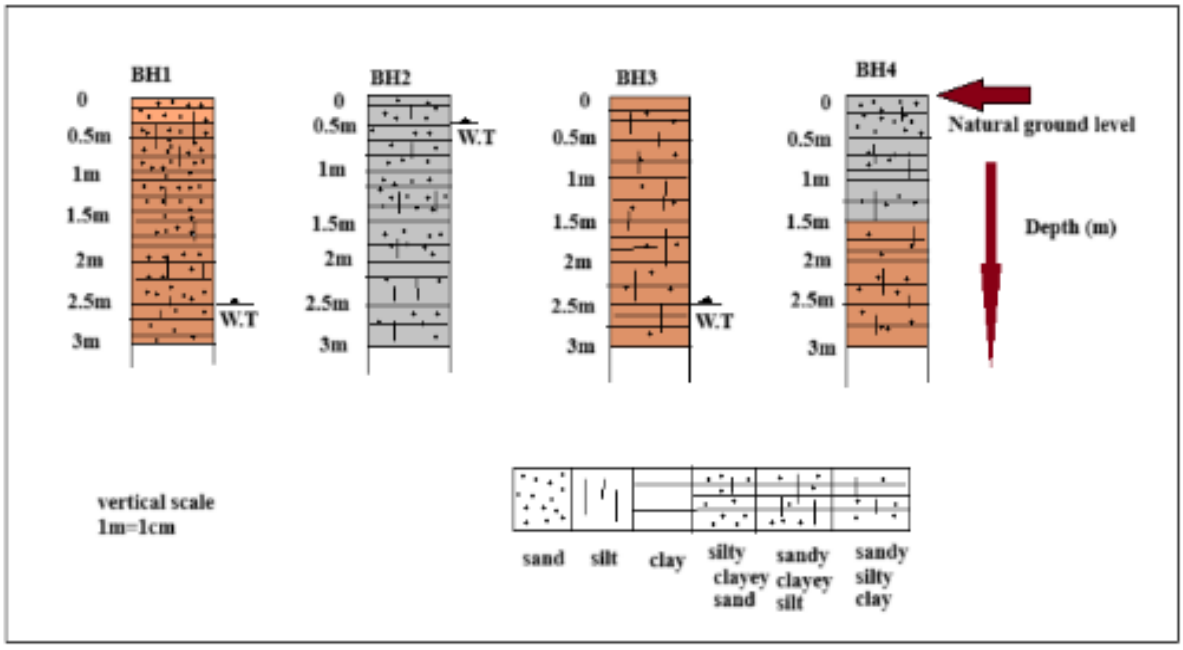

Fig. 3. A cross-section of the soil column in the study area

Table 6. Soil engineering test results (consolidation (fully saturated soil))

BH No.	Depth (m)	e_0	p_c (kN/m^2)	P_0 (kN/m^2)	OCR	Type of OCR	Cc	Cs	av *10^{-3} (kN/m^2)	mv *10^{-3} (kN/m^2)	E_O (kN/m^2)	√t 90 (min)	Cv (Cm^2/sec) *10^{-3}	K* 10^{-9} (cm/sec)
1- Nadir-1 district	0.5-1	0.91	105	'	'	-	0.224	0.022	6.4	3.4	298	6.3	0.356	11.932
	1.5-2	0.92	110	'	'	-	0.398	0.027	8.5	4.4	226	7.9	0.226	10.007
	2.5-3	0.94	70	185.07	0.38	UC	0.275	0.004	2.3	2.3	435	4.3	0.764	17.581
2- Alshaawy district	0.5-1	0.79	89	-	-	-	0.194	0.042	4.3	2.4	417	6.0	0.393	9.415
	1.5-2	0.71	68	-	-	-	0.118	0.008	3.1	1.8	558	8.8	0.183	3.271
	2.5-3	0.66	90	177.71	0.51	UC	0.39	0.050	2.9	1.7	573	7.0	0.288	5.037
3- Alzahra' district	0.5-1	0.91	105	-	-	-	0.224	0.022	6.4	3.4	298	6.4	0.345	11.562
	1.5-2	0.92	110	-	-	-	0.398	0.027	8.5	4.4	226	7.8	0.232	10.266
	2.5-3	0.94	70	196	0.36	UC	0.275	0.004.	2.4	2.4	417	4.3	0.764	18.345
4- Aljumhuriu district	0.5-1	0.65	170	-	-	-	0.329	0.069	5.3	3.2	311	10.2	0.136	4.367
	1.5-2	0.85	145	-	-	-	0.200	0.038	2.9	1.6	639	3.7	1.032	16.147
	2.5-3	0.71	80	190.71	0.42	UC	0.228	0.031	6.6	3.9	260	4.4	0.730	28.122

Table 7. Soil engineering test results **(**Consolidation (Partially saturated soil 50%)**)**

BH No.	Depth (m)	e_0	p_c (kN/m²)	P_0 (kN/m²)	OCR	Type of OCR	Cc	Cs	av *10^{-3} (kN/m²)	mv* 10^{-3} (kN/m²)	E_O (kN/m²)	√t 90 (min)	Cv (Cm²/sec) *10^{-3}	K*10^{-8} (cm/sec)
1-Nadir-1 district	0.5-1	0.374	62	-	-	-	0.125	0.014	1.0	0.8	1311	3.0	1.583	1.208
	1.5-2	0.599	60	-	-	-	0.388	0.016	2.3	1.4	694	2.3	2.672	3.853
	2.5-3	0.415	55	185.07	0.30	UC	0.082	0.003	0.9	0.6	1572	3.8	0.983	0.625
2-Alshaawy district	0.5-1	0.427	62	-	-	-	0.128	0.014	1.4	1.0	1019	2.0	3.617	3.549
	1.5-2	0.468	55	-	-	-	0.090	0.007	2.2	1.5	661	2.5	2.262	3.424
	2.5-3	0.520	60	177.71	0.34	UC	0.082	0.015	1.8	1.2	824	2.5	2.300	2.791
3-Alzahra' district	0.5-1	0.374	62				0.125	0.014	1.0	0.8	1312	3.0	1.617	1.233
	1.5-2	0.599	60				0.388	0.026	2.3	1.4	694	2.3	2.672	3.853
	2.5-3	0.415	55	196.11	0.28	UC	0.082	0.001	0.8	0.6	1769	3.5	1.150	0.650
4-Aljumhuriu	0.5-1	0.586	100				0.100	0.064	1.1	0.7	1442	3.0	1.570	1.089
	1.5-2	0.655	80				0.069	0.011	1.2	0.7	1379	3.0	1.570	1.139
	2.5-3	0.699	60	190.71	0.31	UC	0.182	0.029	0.7	0.4	24271	3.8	0.979	0.403

Table 8. Soil engineering test results

BH. No.	Depth (m)	K (cm/sec)	C (kN/m²)	ϕ	Depth (m)	P_0 (kN/m²)	u_w (kN/m²)	P (kN/m²)	Settlement cm	Settlement for partially saturated soil (cm)
1-Nadir-1 district	0.5-1	$1.96*10^{-4}$	-	-	0-1					
	1.5-2	=	6.7	19.5	1-2	185.07	4.905	189.97	2.60	1.06
	2.5-3	$1.94*10^{-4}$	-	-	2-3					
2-Alshaawy district	0.5-1	$6.93*10^{-4}$	-	-	0-1					
	1.5-2	$8.91*10^{-4}$	35.6	4.5	1-2	177.71	24.525	202.23	2.56	1.04
	2.5-3	$8.91*10^{-4}$	-	-	2-3					
3-Alzahra' district	0.5-1	$8.44*10^{-4}$	-	-	0-1					
	1.5-2	$9.22*10^{-4}$	59.1	4.6	1-2	196.11	4.905	201.01	2.46	1.003
	2.5-3	$2.94*10^{-5}$	-	-	2-3					
4-Aljumhuriu district	0.5-1	$2.97*10^{-4}$	-	-	0-1					
	1.5-2	$9.51*10^{-4}$	8.7	17	1-2	190.71	0	190.71	2.38	1.80
	2.5-3	$9.41*10^{-4}$	-	-	2-3					

4. Discussion

4.1. Soil Physical Test Results Discussion

Two important soil physical properties that distinguish among dry, partially saturated, and fully saturated conditions are moisture content and degree of saturation. The natural moisture content and degree of saturation in the area under study varied from 13% to 28% and 53% to 97%, respectively. Because of the comparatively shallow groundwater table (Winter season) , and the predominance of fine-grained clayey soils with high water-retention capacity and limited permeability, moisture content often rises with depth. The sand percentage ranges from 10.1% to 52.8%, the silt fraction from 10.5% to 35.9%, and the clay fraction from 29.3% to 61.8%, according to grain size studies. These findings show that fine-grained materials with a variety of textural compositions predominate. As seen in Fig.4, the soils under the surface fill layers vary from low-plasticity silty clay (CL) to high-plasticity silty clay (CH) according to the Casagrande plasticity chart. There was a range of 1.68 to 1.99 g/cm³ for the wet unit weight (γ_w) and 1.38 to 1.69 g/cm³ for the dry unit weight (γ_d). These figures are consistent with Vthe fine-grained, compressible character of the soils, with void ratios (e) between 0.59 and 0.99 and porVosities (n) between 37% and 50%. According to the categorization suggested by Al-Ashu (1991), the classification is less than 0.75 inactivity, 0.75 to 1.25 normal activity, and 1.25 to 2

activity. The activity (A) of the clays, which was determined as the ratio between the plasticity index and clay percentage, ranged between 0.20 and 0.69, suggesting that they are usually active clay soils. These soils typically exhibit a modest capacity for swelling and are susceptible to seasonal fluctuations in groundwater and moisture levels.

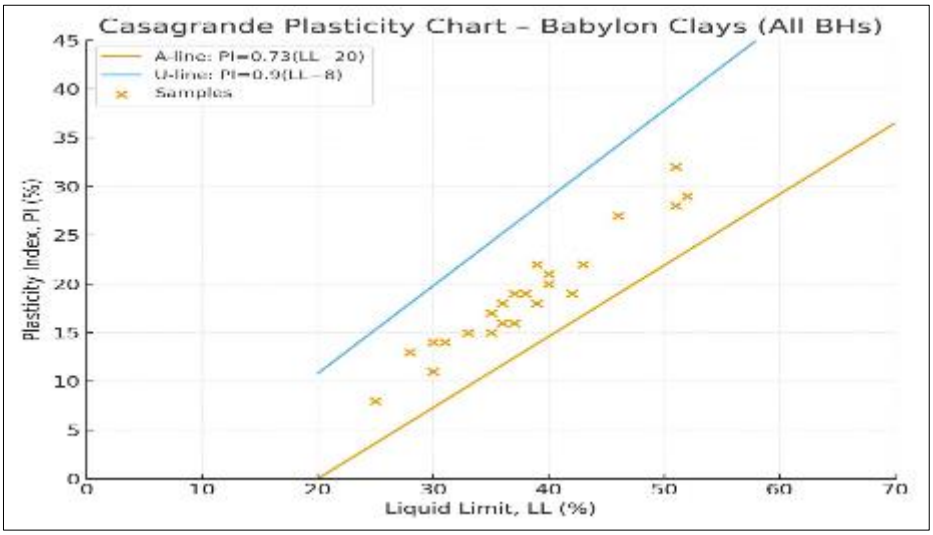

Fig. 4. Plasticity diagram for the samples of the study area

4.2. Soil Engineering Test Results Discussion

4.2.1. Consolidation of fully saturated soil

A consolidation test was performed on all undisturbed samples taken with a Shelby tube for silty clay soils (because this test is specifically for undisturbed clay soils). The initial void ratio(eo) values ranged between 0.65 and 0.94. The percentage of voids is related to the type of soil. If the soil is sandy, the percentage of voids will be higher, and the consolidation will be faster. However, if the soil is clayey, consolidation will be slow, and the void ratio will be low (Abdullah, 2007). The pre-consolidation pressure (pc) values ranged between (68-170) kN/m^2, and the compression index (Cc) values ranged between 0.118- 0.398. These values are considered to fluctuate with depth. The compressibility of layers in which the value of (Cc) is high, and the soil is more susceptible to settlement under loads. The value of (Cc) may also decrease for reasons including a change in the percentage of voids in the soil or a change in the quality of the soil to a soil containing sand, which may be a reason for reducing the value of (Cc). The swelling index (Cs) values ranged between 0.004 and 0.069, where the swelling index values depend on the presence or absence of clay minerals and their ability to swell. OCR ranged between (0.36-0.51) and according to the classification of Al-Ashu (1991) into incompletely consolidated soil, while the values of the coefficients of compressibility (av)ranged between $2.3*10^{-3}$-$8.5*10^{-3}$ kN/m^2 and the values of coefficients of volumetric compressibility (mv) ranged between ($1.6*10^{-3}$-$4.4*10^{-3}$) kN/m^2 and the values of oedometer elastic modulus (E_o) ranged between (226-639) kN/m^2, they have variable values because they depend on the physical and mechanical properties of the soil and the durability of the soil in the research area. The values of (√t 90) ranged between (3.7-10.2) min and the values of coefficient of consolidation (Cv) ranged between (0.136-1.032) $*10^{-3}cm^2/sec$ and according to the classification of Head and Epps (1982) the search area has a low coefficient of consolidation (Cv), the values of the permeability coefficient (k) ranged between ($3.271*10^{-9}$-$28.112*10^{-9}$) cm/sec and according to the classification of Al-Ashu (1991) it has a low permeability coefficient. The values of settlement (s) ranged between (2.38-2.6) cm. Where the values fluctuate with depth, and that settlement depends on the percentage of

clays, the more it increases, the more time increases, and thus the coefficient of consolidation (Cv) decreases, and the permeability decreases, and the settlement increases.

4.2.2. Consolidation of partially saturated soil (50% saturated)

From the results of the tests for consolidation partially saturated soils (S=50%), the values of the consolidation parameters (e_o, pc, Cc, Cs, av, mv) are higher in fully saturated soils than in partially saturated soils, The ratio of initial voids (eo) had the highest value (0.699) at (B.H.4) in depth (2.5-3m) and the lowest value (0.374) at (B.H.1 and B.H.3) in depth (0.5-1m); the highest value was (Cc)(0.388) at (B.H.1 and B.H.3) in depth (1.5-2m) and the lowest value (0.069) at (B.H.4) in depth (1.5-2m); and the highest values were (Cs)(0.064) at (B.H.4) in depth (0.5-1)m and the lowest value (0.001) at (B.H.3) in depth (2.5-3m) Pre-consolidation pressure (Pc) at (B.H.4) depth (0.5-1m) had the maximum value (100kN/m2), while the lowest value was (55kN/m^2) at (B.H.1, B.H.2 and B.H.3) depths (2.5-3,1.5-2 and 2.5-3m). Coefficients of compressibility (av) ranged from 2.3*10-3 kN/m^2 at (B.H.1 and B.H.2) depth (1.5-2m) to 0.7*10-3 kN/m^2 at (B.H.4) depth (2.5-3m) while volumetric compressibility (mv) ranged from 1.5*10-3 kN/m^2 at (B.H.2) depth (1.5-2m) and 0.4*10-3 kN/m^2 at (B.H.4) depth (2.5-3m).

While Oedometer elastic modulus (Eo) ranged from 661kn/m² at (B.H.2) depth (1.5-2m) to 24271kN/m² at (B.H.4) depth (2.5-3m). The greatest coefficient of consolidation (Cv) was 3.617*10-3 cm2/sec at (B.H.2) depth (0.5-1 m). The lowest value (0.979*10-3 cm2/sec) at a depth of 2.5–3 m (B.H.4). The permeability coefficient (k), the highest value was 3.853*10-7 cm/sec at (B.H.2) depth (1.5-2m), and the lowest value was 0.403*10-7 cm/sec at (B.H.4) depth (2.5-3m).

While the consolidation parameters (E_o cv, k) are higher in partially saturated soils than in fully saturated soils, The consolidation test results for partially saturated soils indicate a reduction in the values of the initial void ratio (e_0), compression index (Cc), swelling index (Cs), pre-consolidation pressure (Pc), coefficient of compressibility (a_v, m_v), time factor ($\sqrt{t90}$), coefficient of permeability (k), and settlement (S). Conversely, oedometer modulus (E_0), and coefficient of consolidation (Cv) were observed to increase compared to fully saturated soils. This behavior can be attributed to the soil's physical and mechanical properties, the clay fraction in the study area, and its compressibility.

The underlying reason is that at higher degrees of saturation, clayey soils contain more water in their pore spaces, thereby reducing interparticle friction and leading to greater settlement. In contrast, lower water content introduces additional effective stress, thereby reducing settlement. This behavior is analogous to the compaction curve, where soils exhibit different responses on the wet and dry sides of the optimum moisture content (Namah, 2014).

The reason is also due to suction. It is a tensile force that arises between soil particles due to the surface tension of water confined in pores, and it contributes significantly to the shear resistance of unsaturated soil As shown in the results in Fig. 5 and Table 9, the suction ratio (512 kPa) for low-plasticity clay soil (CL) with partial saturation (S = 50%), while the suction ratio (16,370 kPa) for high-plasticity clay soil (CH) with partial saturation (S = 50%). The higher the soil moisture and the lower its “suction,” the lower this force and the soil's elasticity. Mechanical effects: Shear strength: Suction contributes significantly to the shear strength of unsaturated soil, making it stronger in certain conditions. Saturation: As saturation increases, the water content in soil pores increases, reducing suction strength and weakening soil cohesion. As shown in Fig. 5, the soil water characteristic curve indicates the difference in suction across saturation levels in soil samples from the study area. The presence of matric suction increases the apparent cohesion and stiffness, resulting in smaller compressibility and less dissipation of pore pressure.

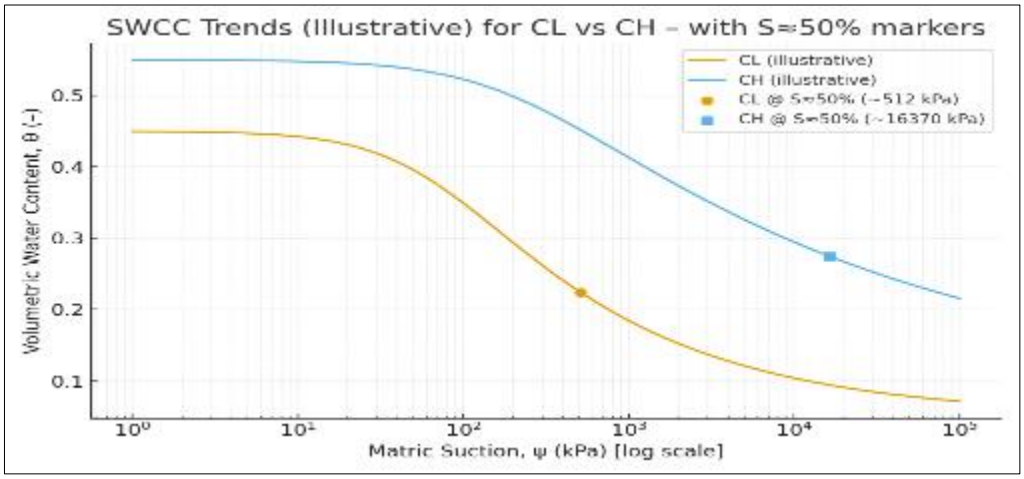

Fig. 5. Soil water characteristics curve (SWCC) for different degrees of soil saturation and plasticity

Table 9. SWCC curve values for CH and CL soil matric suction

θ-CH (High plasticity clay)	**θ-CL (Low plasticity clay)**	**Matric Suction ψ(Kpa)**
0.55	0.45	1
0.54	0.44	10
0.50	0.35	100
-	0.22	512
0.40	0.18	1000
0.30	0.10	10000
0.26	-	16370
0.20	0.07	100000

4.2.3. Discussing the results of other engineering tests (Permeability t and Undrained Triaxial (UU))

The values of the permeability coefficient range between ($2.94*10^{-4}$-$1.94*10^{-3}$) cm/sec and according to the classification of Al-Ashu (1991) where the classification is (greater than 10^{-3} high permeability, 10^{-3} – 10^{-5} medium permeability, 10^{-5} – 10^{-7} low permeability, 10^{-7}-10^{-9} very low permeability, and less than 10^{-9} mostly impermeable). They are considered low-permeability clayey soils. Variations in permeability across the study area are attributable to differences in clay soil type, particularly its swelling and shrinkage behavior and compressibility. These factors control the size and continuity of pore spaces, leading to spatial fluctuations in hydraulic conductivity. The results of the cohesive force (c) range between (6.7-59.1) and the angle of internal friction(Ø) ranges between (4.5-19.5) and the reason is due to the high percentage of clays that resist shear resistance and vice versa The reason, which depends on the proportion of clay and plasticity, is that it is often observed that highly plastic CH soils exhibit higher shear strength than CL soils at the same degree of saturation in partially saturated soils, whereas in fully saturated soils, shear strength decreases. Table 8 indicates that effective stress increases as the groundwater level (subsurface water table) decreases. A lowering of the water table reduces pore water pressure in the soil layers, thereby increasing effective stresses. Moreover, in soil layers located above the water table, the pore water pressure equals zero; hence, the effective stress becomes equal to the total stress in those layers. This relationship highlights the critical influence of groundwater fluctuations on soil strength and settlement behavior. Capillary tension acts as a temporary strengthening factor for unsaturated soil through effective stress without increasing external load, and is a key element in explaining the effect of groundwater level fluctuations on soil strength and settlement behavior.

4.3. Evaluation of Relationships between Soil Properties

The links between the geotechnical characteristics of soils have been the subject of several studies. The degree of linear association between two variables is commonly measured using the correlation coefficient (r), which quantifies the proportionality between changes in one variable and changes in the other. The correlation coefficient, which ranges from –1 to +1, is among the most commonly used statistical indicators in geotechnical investigations, according to Kong (1969). According to Jawad and Mazen (2011), r values near 0 suggest little to no linear association, values near +1 indicate a strong positive (direct) correlation, and values near -1 indicate a strong negative (inverse) correlation. Similarly, Ali (2006) used the correlation coefficient to assess soil behavior by quantifying the strength of relationships among various soil metrics. The correlations between several geotechnical factors were examined in the current study, and Table 9 summarizes the computed correlation coefficients (r). Fig. 6 shows a substantial positive association between clay content (C%) and compression index (Cc) among the correlations that have been identified. According to earlier studies on fine-grained soils, larger clay fractions and higher plasticity often lead to greater compressibility and settlement potential. This suggests that soil compressibility rises with increasing clay concentration.

Table 10. The values of the correlation coefficient and the linear relationships

B.H No.	The relationship of fully saturated soils	Correlation coefficient (r)	The relationship of partially saturated soils	Correlation coefficient (r)
BH1 to BH4	Cc= 0.0054c%+ 0.0278 R^2 = 0.2355	0.485	Cc= 0.003c% + 0.2801 R^2 = 0.0522	0.228
BH1 to BH4	Cv= -1E-05c% + 0.001 R^2 = 0.0772	-0.278	Cv= -2E-05c% + 0.0029 R^2 = 0.0511	-0.226
BH1 to BH4	k = -4E-10c%+ 3E-08 R^2 = 0.175	-0.418	k= -5E-10c% + 4E-08 R^2 = 0.0903	-0.300
BH1 to BH4	S = 0.0064c% + 2.2341 R^2 = 0.1066	0.326	S = 0.0186c% + 0.5382 R^2 = 0.0704	0.265
BH1 to BH4	k = -2E-07S + 4E-07 R^2 = 0.8946	-0. 946	k = -1E-08S + 3E-08 R^2 = 0.1385	-0.372

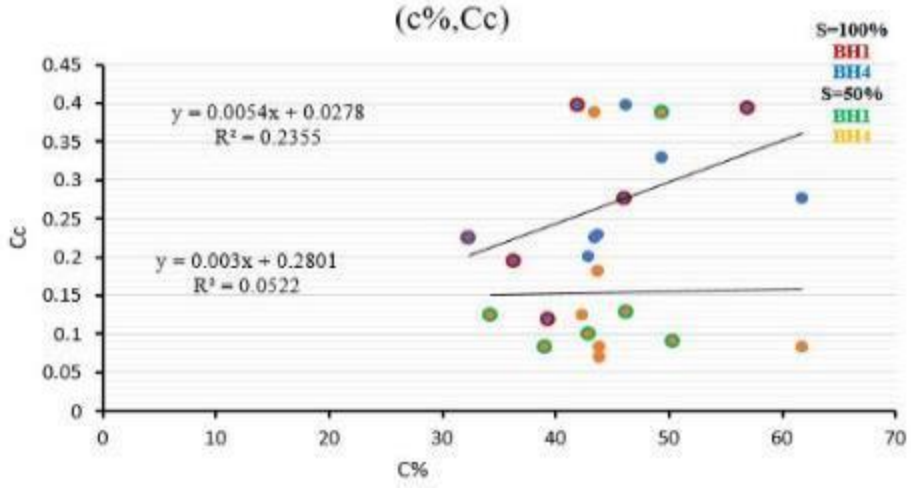

Fig. 6. The relationship between (C%) and (Cc) in B.H.1 and B.H.4

The relationships between the clay content (C%) and both the consolidation coefficient (cv) and the permeability coefficient (k) and the settlement (S) showed inverse relationships (r), while the relationship between the clay content (C%) and the settlement (S) was direct (r), as shown in Figs. 5 through 10, and Table 10. This is attributed to the increase in the proportion of clay, which reduces the consolidation and permeability coefficients and increases the time required for settlement.

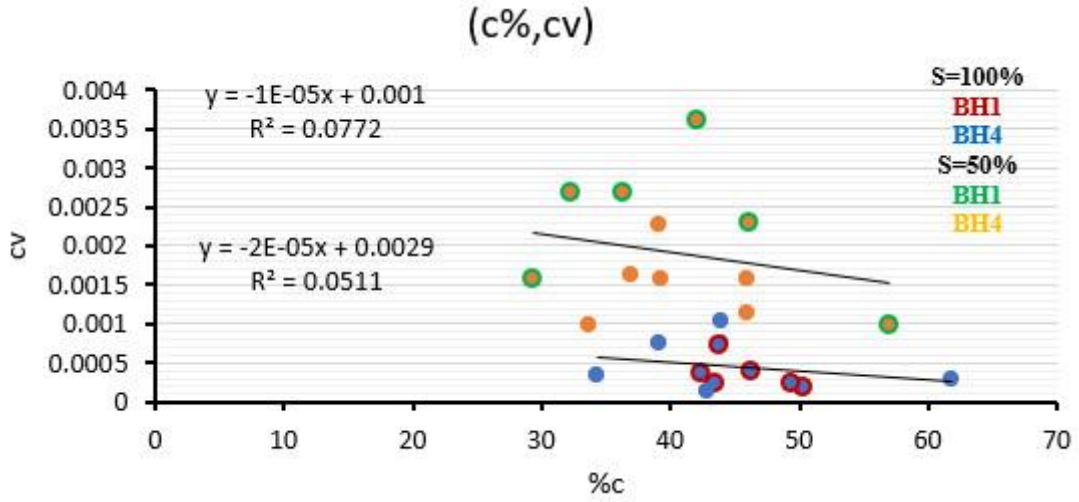

Fig. 7. The relationship between (C%) and (Cv) in B.H.1 and B.H.4

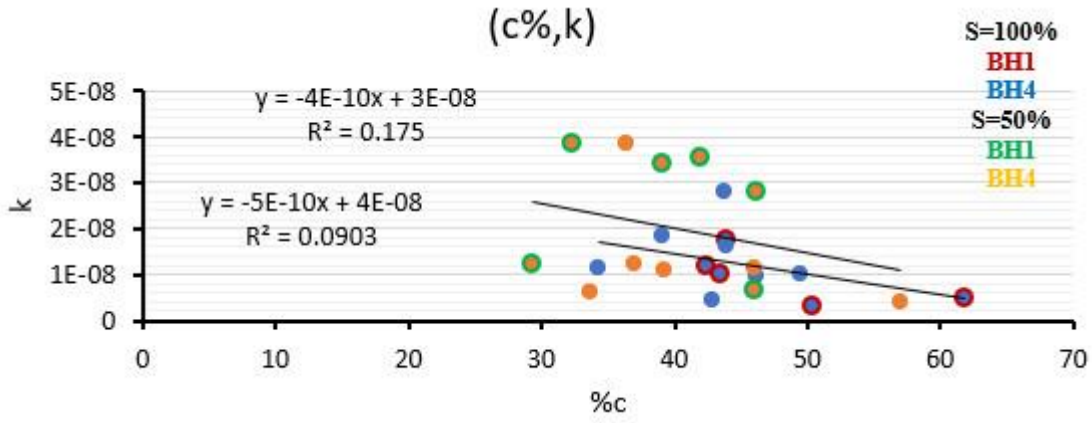

Fig. 8. The relationship between (C%) and (k) in B.H.1 and B.H.4

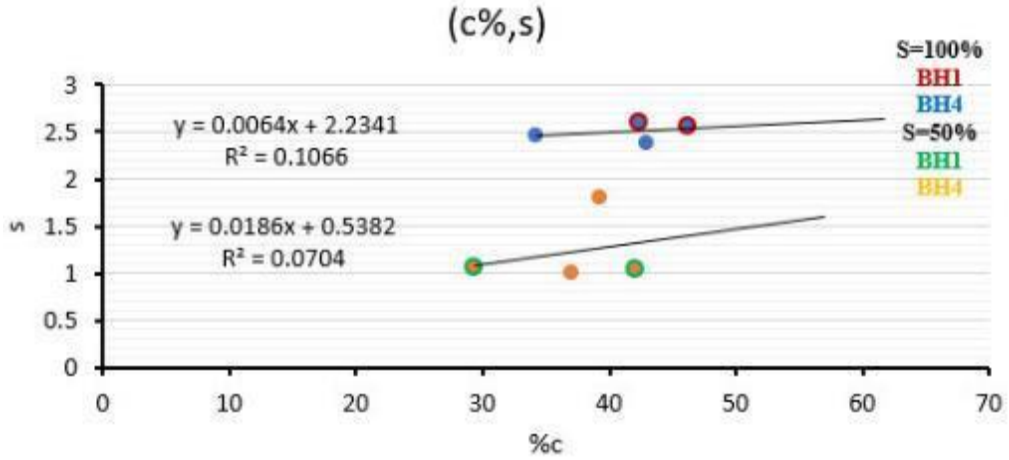

Fig. 9. The relationship between (C%) and (S) in B.H.1 and B.H.4

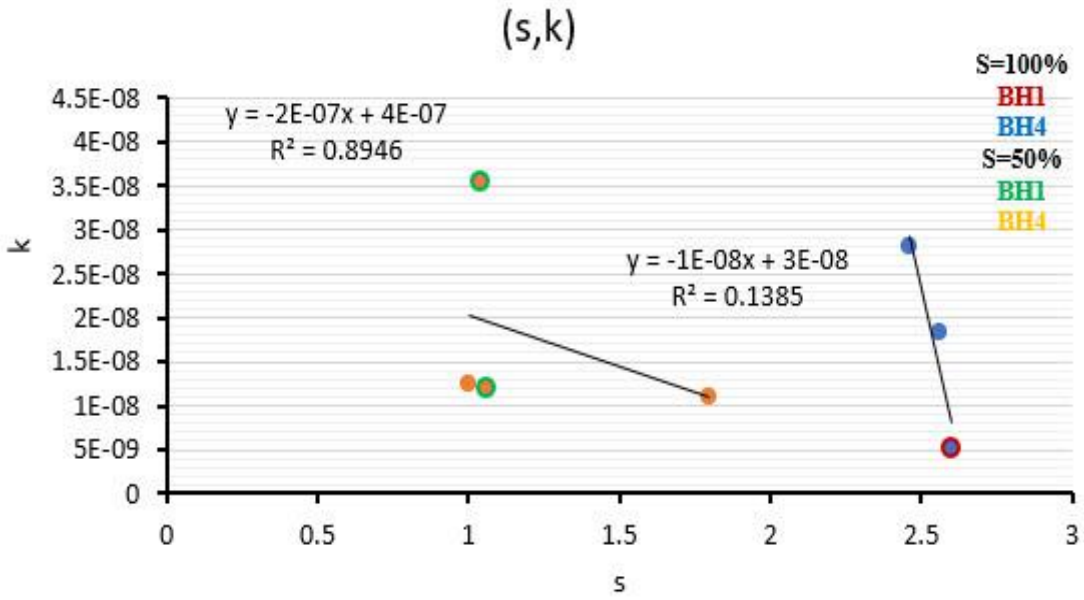

Fig. 10. The relationship between (S)and (K) in B.H.1 and B.H.4

4.4. Numerical Modeling

One of the most effective methods for understanding complex engineering problems and predicting the behavior of soil-structure interaction is numerical modeling using finite element analysis (FEA). It enables the simulation of realistic loading conditions and boundary conditions, providing important insights into the evolution of stress-strain and settlement mechanisms. In this study, the consolidation and settlement behavior of clayey soils in Hilla City, Babylon's governorate, was simulated numerically using PLAXIS 3D (Version 2024.2). A validation process was conducted by comparing PLAXIS results with experimental laboratory data to ensure the accuracy of the numerical results. The strong agreement between the two data sets increases confidence in the selected model and validates its ability to accurately represent real-world field and laboratory conditions.

4.4.1. Using the program PLAXIS 3D in numerical modeling of consolidation

To reproduce the laboratory setting, the consolidation test was numerically simulated in PLAXIS 3D (Version 2024.2) under precisely defined boundary and loading conditions.

The basic criteria on which the following hypotheses were proposed: (1) The sample does not expand laterally (2) Deformation is only vertical because the load is vertical (3) Lateral displacement is prevented by the ring in which the sample is placed, and there is no lateral drainage; drainage occurs above and below the sample due to the presence of porous stones (4) Settlement does not occur immediately; it requires a period of time. (5) The actual change is related to the effective stress.

These assumptions apply to soil, rock, concrete, and fill, but not to metal and plastic materials. The following is a summary of the input circumstances and modeling assumptions that were chosen:

1. Symmetry: By assuming axial symmetry regarding the soil sample's center vertical axis, the model was made simpler. This assumption preserves the accuracy of pore pressure and stress-strain distributions while minimizing computing cost.
2. Drainage limits: To replicate double-drainage circumstances and permit vertical flow through the sample during consolidation, the pore-water pressure was adjusted to zero at both the top and bottom limits. To guarantee one-dimensional flow, the lateral borders were thought to be impermeable.

3. Strength Parameters: To ensure consistency between laboratory results and model input, the cohesion (c) and angle of internal friction (ϕ) were determined using Unconsolidated–Undrained (UU) triaxial testing.
4. Input Data: The S
5. The oft Soil constitutive model developed in PLAXIS 3D employed the physical and engineering properties of the soil as established by laboratory tests (e.g., γ, e_0, Cc, Cs, k, v, Pc). For numerical simulation, only the parameters directly related to consolidation behavior were used.

4.4.2. Stages followed for numerical modeling in PLAXIS 3D

The following steps were followed in the numerical modeling of the clayey soils' consolidation experiment in the study area, using the entire borehole:
1. Start by entering data to draw the geometric model of the borehole, giving the borehole dimensions as shown in Fig. 11 boreholes ((a) toB.H.1-(b) toB.H.2 –(c) to B.H.3&(d) toB.H.4), And enter material model behavior using Plaxis 3D Soft Soil Model Specifically developed for very compressible soils such as peat and normally consolidated clays, accounting for volumetric compression during loading. And input the conditions (type of soil, wet, dry, eo, k, undrained). A behavior, and choose a consolidation test.

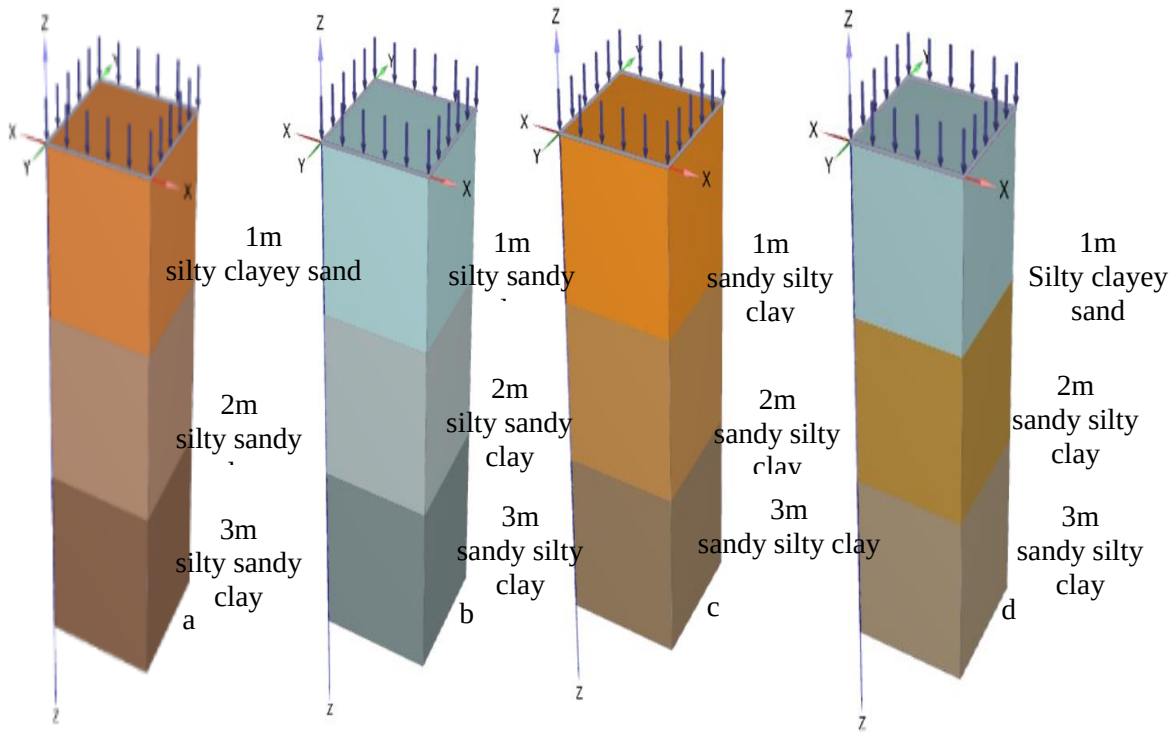

Fig. 11. geometric model to boreholes a) geometric model to B.H.1 b) geometric model to B.H.2 c) geometric model to B.H.3 d) geometric model to B.H.4

2. Generate a limited element mesh medium size as shown in Fig. 12 boreholes ((a) toB.H.1-(b) to B.H.2-(c) to B.H.3&(d) toB.H.4).

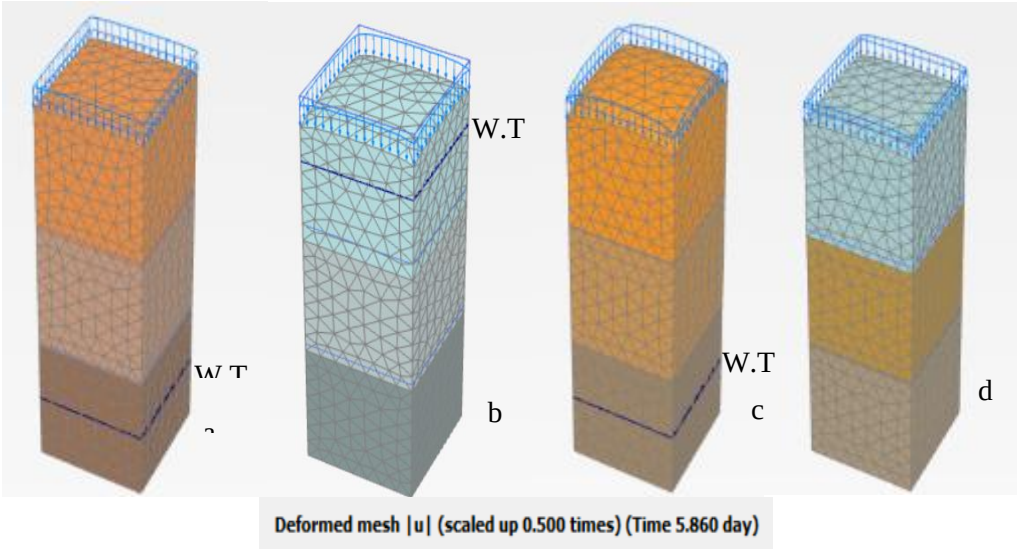

Fig. 12. Limited Elements mesh to boreholes (B.H.1-B.H.4) a) Limited Elements mesh to B.H.1 b) Limited Elements mesh to B.H.2 c) Limited Elements mesh to B.H.3 d) Limited Elements mesh to B.H.4

3. Select the same nodes and stress points to all boreholes, connectivity plot, as shown in Fig. 13.

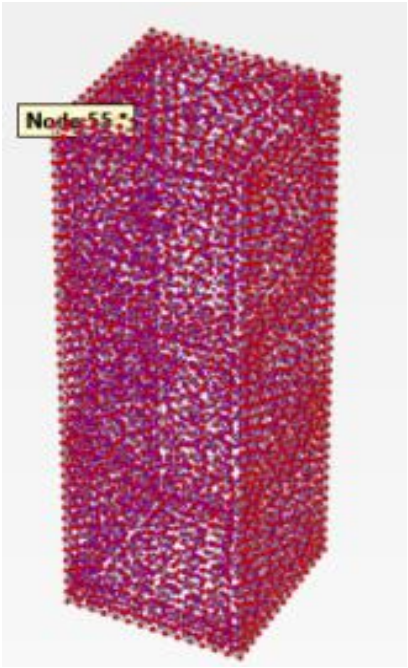

Fig.13. Select same nodes and stress points to all boreholes

4. The cross section is visually displayed for the results in the geometric model, pore pressure (excess pore pressure) The cross section in (excess pore pressure) shows the shadings, as in fig. 14 to boreholes ((a) toB.H.1-(b) to B.H.2-(c) to B.H.3&(d) toB.H.4).

5. Generation of initial stresses resulting from the self-weight of soil as in Fig. 15 to boreholes ((a) toB.H.1-(b) to B.H.2-(c) to B.H.3&(d) toB.H.4).

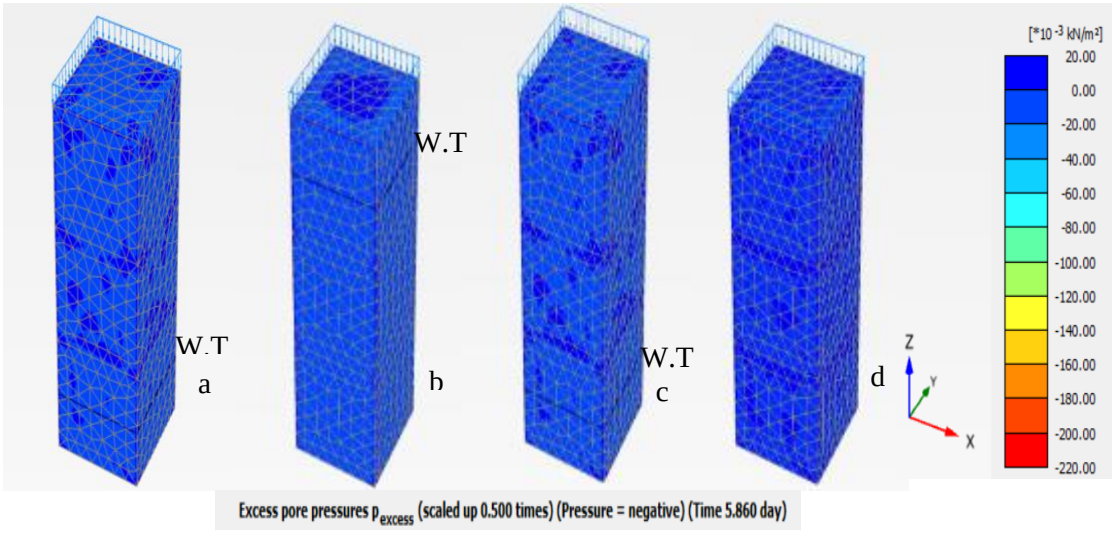

Fig. 14. excess pore pressure (shadings) in boreholes (B.H.1-B.H.4) a) excess pore pressure (shadings) to B.H.1 b) excess pore pressure (shadings) to B.H.2 c) excess pore pressure (shadings) to B.H.3 d) excess pore pressure (shadings) to B.H.4

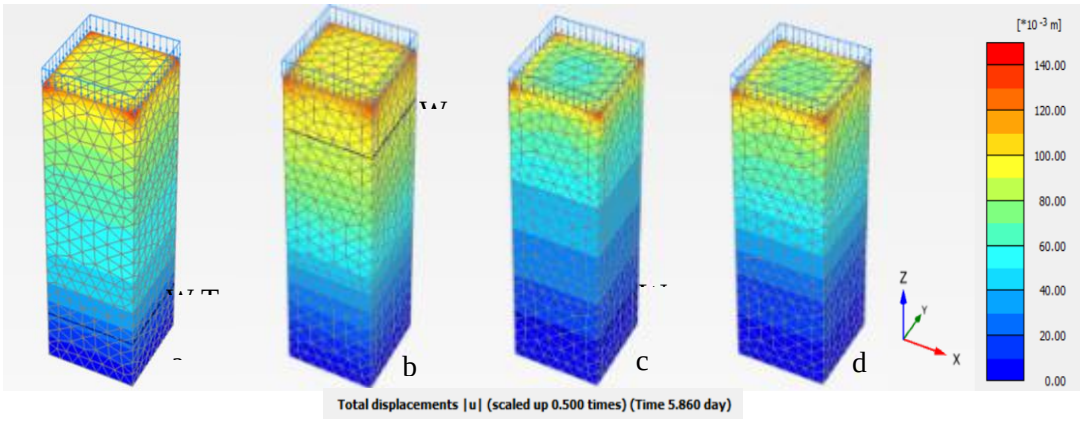

Fig. 15. Total displacements (shadings) in boreholes (B.H.1-B.H.4). a) Total displacements (shadings) to B.H.1 b) Total displacements (shadings) to B.H.2 c) Total displacements (shadings) to B.H.3. d) total displacements (shadings) to B.H.4

6. By contrasting the numerical outputs from PLAXIS 3D with the laboratory consolidation findings, the numerical model was calibrated. As shown in Figs. 15, 16, 17, 18, and 19. Settlement data for every borehole were taken from the simulations and shown as settlement–time curves. The behavior of the soil under consolidation loads was simulated using both the Soft Soil and Linear Elastic constitutive models. These models yielded settlement-time relationships that closely matched the laboratory findings, indicating a high degree of agreement between the two methods. The comparison shows clear agreement between the simulated and measured settlements, indicating that the Soft Soil model provides the most accurate representation of the compressibility of Babylon's clay soils. The tight match increases confidence in applying PLAXIS 3D to predictive settlement analysis and validates the selected calibration approach.

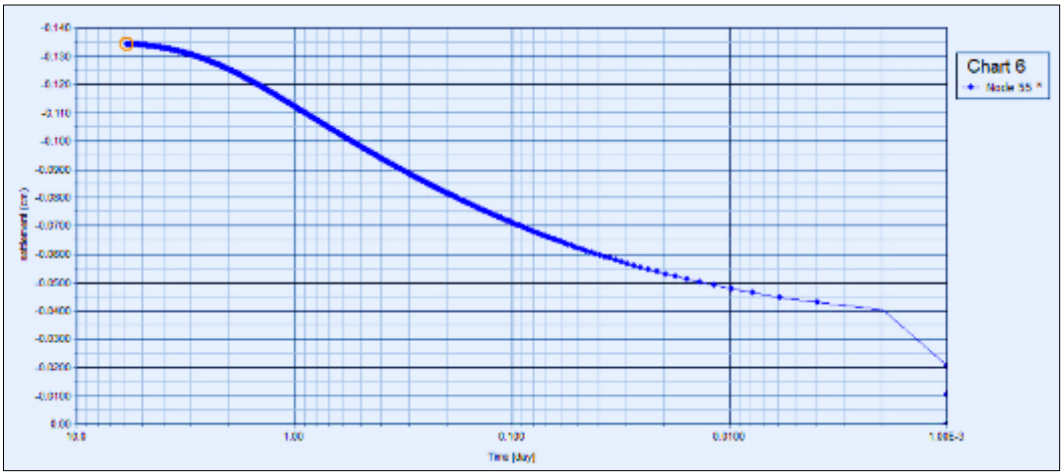

Fig. 16. Curve between settlement and time in borehole (B.H.1)

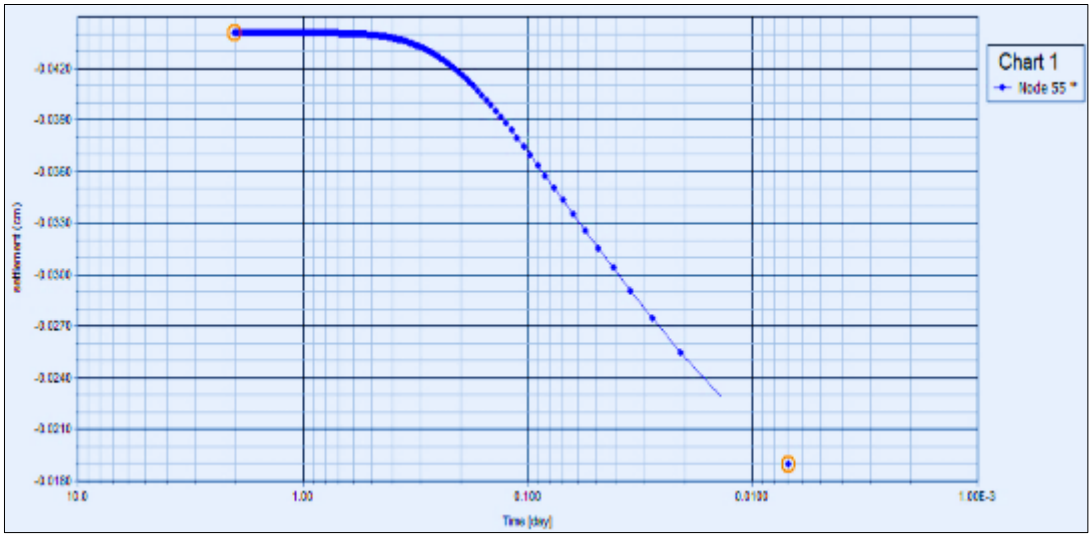

Fig. 17. Curve between settlement and time in borehole (B.H.2)

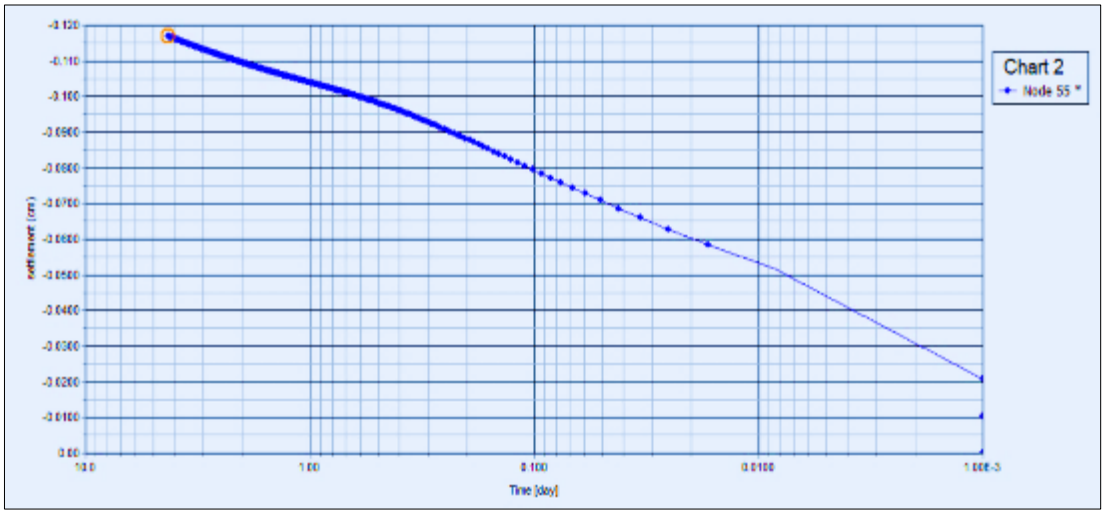

Fig. 18. Curve between settlement and time in borehole (B.H.3)

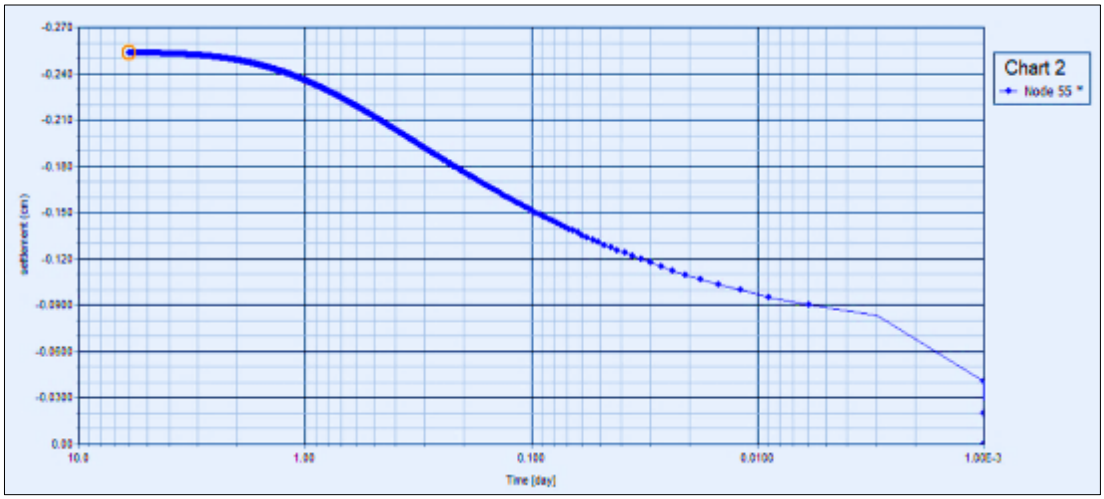

Fig. 19. Curve between settlement and time in borehole (B.H.4)

4.4.3. Final results of numerical modeling of the study area's soil

Both the Soft Soil and Linear Elastic constitutive models predicted settlement values that closely matched the experimental findings. The numerical simulations accurately replicated the laboratory consolidation behavior, as shown in Fig. 18 and Table 10, indicating a high degree of consistency between the modeled and observed data. The numerical model's material idealization and boundary-condition simplifications account for the small differences between the two methods. However, the overall relationship supports the use of the Soft Soil model for predictive settlement analysis in comparable fine-grained deposits, confirming that it accurately captures the compressibility properties of Babylon's clay soils under one-dimensional consolidation.

Table 11. Comparison of settlement results between consolidation and numerical modeling

B.H.NO.	Total settlement value in oedometer (cm)	Total settlement value from numerical modeling (cm)
1- Nadir-1 district	2.60	2.26
2- Alshaawy district	2.56	2.50
3- Alzahra' district	2.46	2.21
4- Aljumhuriu district	2.38	2.17

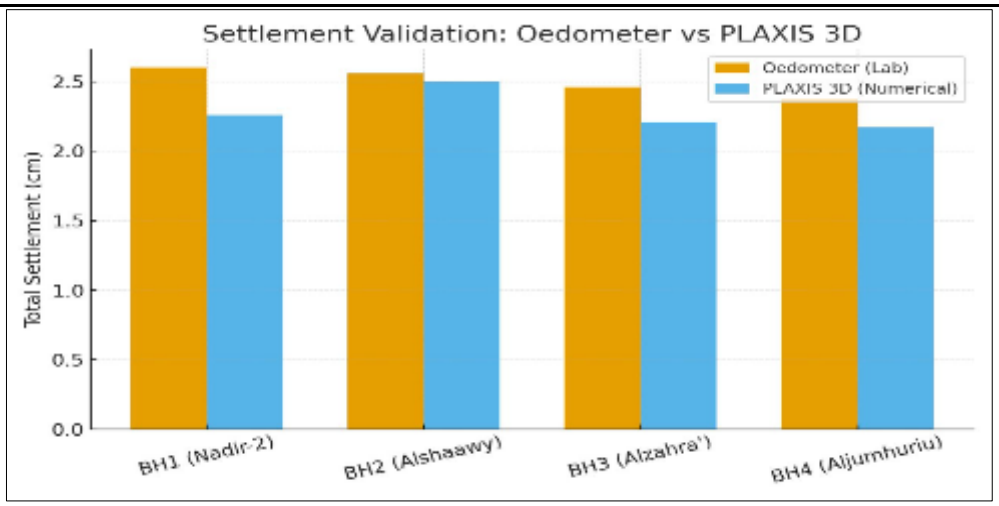

Fig. 20. Settlement validation using the Oedometer and PLEXIS 3D software

5. Conclusions

According to the study findings, the soils in the region under investigation are divided into two primary zones: a coarser zone made mostly of sand, the sand percentage varies through the study area, with the highest percentage of sand occurring in BH4 at a depth of 0-0.5 m, and a soft, fine-grained zone made mostly of clay and silty clay. The soils are categorized as low-plasticity clay (CL) to high-plasticity clay (CH) in three samples according to the Casagrande plasticity chart. Due to differences in the percentages of sand, silt, and clay, which are almost identical, in CH, the percentage of clay is higher than that of sand and silt, and it has low permeability. Consolidation test results show that the parameters e_o, Pc, Cc, Cs, av, mv, and $\sqrt{t90}$ have larger values when fully saturated than when evaluated at 50% saturation. These metrics demonstrate a clear relationship with clay content, demonstrating that higher water saturation improves basic consolidation properties and compressibility. On the other hand, in partly saturated soils, the values E_o, cv, and k are greater and show an inverse relationship with clay content. Variations in soil strength, structure, and pore composition—more especially, the presence of both water and air in the pores of partially saturated soils, which enhances drainage and increases stiffness—are responsible for this behavior. Settlement values from numerical modeling using PLAXIS 3D closely matched those found in experiments, and all findings were within allowable bounds(Allowed range: 2.5-5 cm) . Using the Soft Soil constitutive model yielded the best agreement between numerical and laboratory results, demonstrating its applicability for modeling the consolidation behavior of Babylon's fine-grained soils across various degrees of saturation.

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- Validation: Raid A. Mahmood, Amer A. Al-Khalidy
- Visualization: Samhar A. Rida
- Writing – original draft: Samhar A. Rida, Amer A. Al-Khalidy
- Writing – review and editing: Amer A. Al-Khalidy, Raid A. Mahmood

Declaration of Competing Interest

The authors declare that they have no competing financial interests or personal relationships that could have influenced the work reported in this study.

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Data Availability

Data are included in the article or supplementary material

All data generated or analyzed during this study are included in this published article and/or its supplementary materials.

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