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The effect of cohesive soil depth on consolidation coefficient and Compression index

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***Abstract* – The settlement is the most serious problem of fine-grained soils and caused by a phenomenon called soil consolidation. Most of previous studies were concerned with studying consolidation conditions depending on the consolidation's theories as Terzaghi's theory. In some cases, a simulation of reality is not given. It was necessary to study the effect of soil depth from ground surface on consolidation parameters to simulate what happens to the cohesive soil in nature. Therefore, the consolidation behavior of four cohesive soils was studied in this paper. The studied soil samples were collected from different depths of cohesive soil layers at four different sites, El-Qalubia governorate, Egypt. A series of laboratory consolidation tests were carried out using Oedometer apparatus. So, the effect of soil sample depths (D) from ground surface on consolidation coefficient (C_v) and compression index (C_c) was investigated. Also, the empirical equations were correlated depending on the relationship between soil sample depths (D) vs. C_v and D vs. C_c.**

***Keywords* – Fine- grained soil, cohesive soil, soil sample depth, consolidation, consolidation coefficient, compression index, settlement,**

I. INTRODUCTION

Soil layer consolidation means water out between the soil particles when influence on it by loads or stresses such as: foundations, above constructions and underground constructions loads. The seriousness of soil consolidation appears in the soil layers settlements. This soil layers settlement cause many problems for the foundations and structures [1][2][3][4], especially when there are differential settlements [5][6][7]. Moreover, the tendencies can occur in buildings and constructions since fractures, partial collapses and total collapses can occur in structures, especially in cases of high loads [1][7][8][9].

The researchers have done great efforts to investigate the consolidation parameters of the cohesive soil layers. That is to estimate realistic and appropriate values of the soil layer compressibility and settlement when exposed to stresses resulting from the implementation of foundations and structures. Most applied theories are interested in studying the consolidation parameters of the soil layer to give a simulated representation of the entire layer. It is necessary to study the change in the consolidation parameters at the variable depths of the cohesive layer.

In this research, the changes of consolidation parameters (C_v - C_c) upon increasing the depth of cohesive soil layer are investigated and studied. Laboratory tests are performed to determine the consolidation parameters on natural cohesive samples obtained from cohesive soil layers at different depths.

II. EXPERIMENTAL APPLICATION

For experimental applications, the physical properties (index properties) of the studied cohesive soil samples such as natural water content ($w_{nat.}$), natural unit weight (γ_{nat}), liquid limit (LL), plastic limit (PL), shrinkage limit (SL), specific gravity (G_s), free swell (FS), and particle size distribution (sedimentation analysis test) were determined in accordance with Egyptian code (2017). Then, by using Unified Soil Classification System (USCS), a series of consolidation tests were carried out as two-dimensional ones; these tests were performed using odometer apparatus.

2.1 The Studied Soils

The three studied cohesive soils samples were obtained from each site at variable depths. Due to the collected soil samples are located under the ground water table in each site, the studied cohesive soil samples at the variable depths are collected using mechanical boring as follows:

- The three soil samples (D1, D2 and D3) from cohesive soil layer at site one (S1) obtained at variable depths 4.00m, 7.00m and 10.00m respectively.
- The three soil samples (D1, D2 and D3) from cohesive soil layer at site two (S2) obtained at variable depths 7.00m, 10.00 and 13.00m respectively.
- The three soil samples (D1, D2 and D3) from cohesive soil layer at site three (S3) obtained at variable depths 3.00m, 6.00m and 9.00m respectively.
- The three soil samples (D1, D2 and D3) from cohesive soil layer at site four (S4) obtained at variable depths 5.00m, 8.00m and 11.00m respectively.

Tables 1 to 4 contain the engineering properties of the studied soils.

Table 1: Physical properties of the studied soil samples for site 1.

Property	Soil Sample No.		
	D1= 4.00m	D2= 7.00m	D3=10.00m
Natural density (γ_{b}) t/m^3	1.98	2.01	2.08
Natural Water content (W_c %)	34	33	30
Liquid limit (L.L%)	63	61	58
Plastic limit (PL%)	24	27	25
Plasticity index (PI%)	39	34	33
Shrinkage limit (SL%)	18	16	19
Specific gravity (GS)	2.72	2.74	2.73
Free swell (FS%)	80	75	70
Clay content (%)	41	43	40
Silt content (%)	54	53	54
Fine sand content (%)	5	4	6
Soil classification	CH	CH	CH

Table 2: Physical properties of the studied soil samples for site 2.

Property	Soil Sample No.		
	D1= 7.00	D2= 10.00m	D3= 13.00m
Natural density (γ_{b}) t/m^3	2.11	2.15	2.17
Natural Water content (W_c %)	36	34	33
Liquid limit (L.L%)	78	80	81
Plastic limit (PL%)	24	25	26
Plasticity index (PI%)	54	55	55
Shrinkage limit (SL%)	16	14	13
Specific gravity (GS)	2.75	2.74	2.75
Free swell (FS%)	125	150	125
Clay content (%)	57	60	61
Silt content (%)	43	46	39
Fine sand content (%)	----	----	----
Soil classification	CH	CH	CH

Table 3: Physical properties of the studied soil samples for site 3.

Property	Soil Sample No.		
	D1= 3.00m	D2= 6.00m	D3= 9.00m
Natural density (γ_{b}) t/m^3	1.95	2.00	2.01
Natural Water content (W_c %)	33	32	30
Liquid limit (L.L%)	74	73	70
Plastic limit (PL%)	25	26	24
Plasticity index (PI%)	49	47	46

Shrinkage limit (SL%)	15	17	14
Specific gravity (GS)	2.71	2.73	2.71
Free swell (FS%)	100	125	125
Clay content (%)	52	54	49
Silt content (%)	46	46	49
Fine sand content (%)	2	—	—
Soil classification	CH	CH	CH

Table 4: Physical properties of the studied soil samples for site 4.

Property	Soil Sample No.		
	D1= 5.00m	D2=8.00m	D3= 11.00m
Natural density ($\gamma_{b)}$ t/m^3	1.93	1.98	2.00
Natural Water content (W_c %)	37	34	33
Liquid limit (L.L%)	54	50	52
Plastic limit (PL%)	28	26	27
Plasticity index (PI%)	26	24	25
Shrinkage limit (SL%)	20	19	21
Specific gravity (GS)	2.73	2.74	2.72
Free swell (FS%)	60	70	65
Clay content (%)	40	39	41
Silt content (%)	54	51	54
Fine sand content (%)	6	10	5
Soil classification	CH	CH	CH

2.3 Consolidation Apparatus and Testing

The ring is made from stainless steel of 20 mm height and 50 mm diameter. The undisturbed natural soil sample was placed inside this ring. Then, the porous stones with 5 mm thickness were placed on top and bottom sides of the studied undisturbed soil sample.

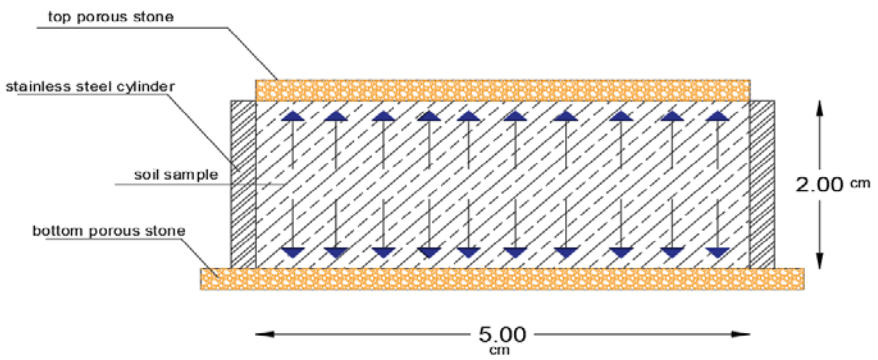


Fig. 1: Model of consolidated soil sample

Fig. 2: Preparation of soil samples for consolidation testing**.**

Three odometers apparatus were used for laboratory consolidation tests, Fig.3: The consolidation test procedures and reading results were recorded as the following steps:

1. The undisturbed cohesive soil sample was enclosed inside the consolidation ring. The weight of the ring must be known in order to measure the soil sample weight. Accordingly, the unit weight (γ_{nat}) of the studied soil can be estimated.
2. The used porous stones were immersed in distilled water for 8 hours. Then, the porous stones and filter paper were placed at top and bottom sides of drainage test as indicated.
3. The loading bad was placed at the top of porous stone and the whole assembly was mounted on the loading frame since the applied load should be axially and centered with soil sample.
4. The dial gauge, with accuracy 0.01 mm/division was arranged in a position to record the behavior of soil samples in swelling and compressibility. Then, the applied stress by about 0.02 kg/cm^2 was used to support and to start the consolidation test procedures.
5. After completely compressed, soil sample under a first stress 0.2546 kg/cm^2 was applied and stop watch started immediately. The readings of dial gauge were recorded at various time intervals since the readings were taken at 0.5, 1, 2, 4, 8, 15, 30 minutes, 1, 2, 4, 8, 12, 24 hours till the reading was completely constant. The same procedure was repeated similarity at, 0.2546, 0.509, 1.018, 2.037, 4.074, 8.148 kg/cm^2.

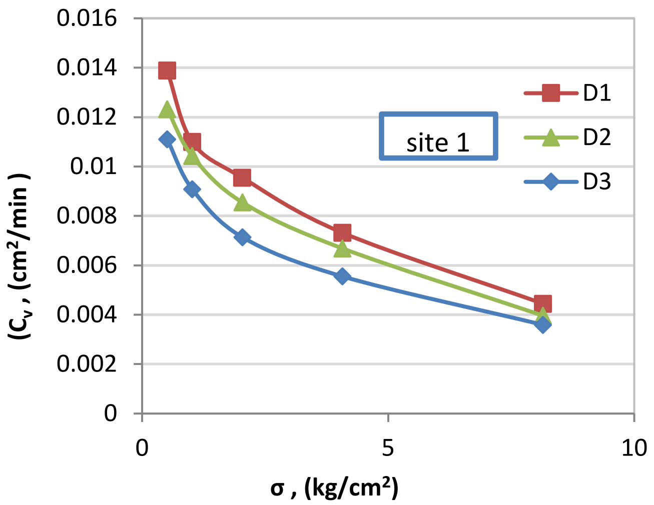
Fig.3. Odometer apparatus

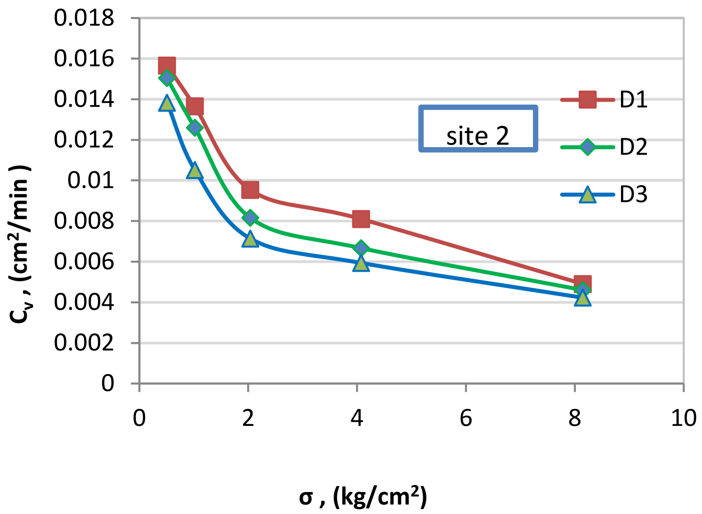
III. RESULTS AND ANALYSIS

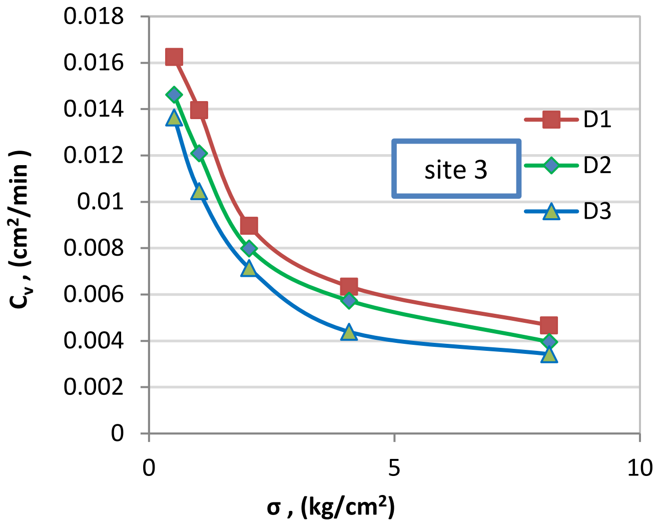
Coefficient of consolidation (C_v) and compression index (c_c) were determined according to consolidation test data of the studied soil samples. These coefficients c_v and c_c were determined using general manner of consolidation theory. So, the relation between Coefficient of consolidation (C_v) and applied stress increments (*σ*) are shown in Figure 4 for the studied soil samples S1, S2, S3 and S4 respectively while Fig. 5, shows the relation between compression index (c_c) and each applied stress (*σ*) for the studied soil samples S1, S2, S3 and S4 respectively.

3.1 Coefficient of consolidation (C_v)

The obtained values of Coefficient of consolidation (C_v) which were determined for the studied cohesive soil samples with different depths of cohesive soil layer at variant sites (S1 to S4) are indicated in Figure 4 since this figure represents the relations between Coefficient of consolidation (C_v) and applied stress increment (*σ*). On the other hand, table 5 contains the comparison between c_v values of the studied soil samples for different depths at variant sites at (σ=1.018 kg/cm^2) on the studied cohesive soil samples at variant sites (S1 to S4) respectively.


0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
5
10
(Cv , (cm2/min)
σ , (kg/cm2)
site 1
D1
D2
D3


0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
2
4
6
8
10
Cv , (cm2/min)
σ , (kg/cm2)
site 2
D1
D2
D3


0.018
0.016
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0.012
0.01
0.008
0.006
0.004
0.002
0
0
5
10
Cv , (cm2/min)
σ , (kg/cm2)
site 3
D1
D2
D3

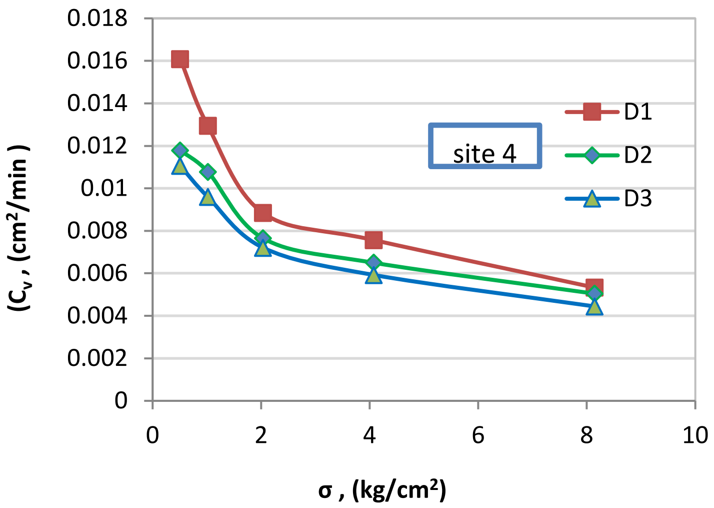


Fig. 4: Relation between C_v and $\boldsymbol{\sigma}$ for different soil samples depth at sites.

Table 5: Comparison *among* C_v values of soil samples for different depths at variant sites.

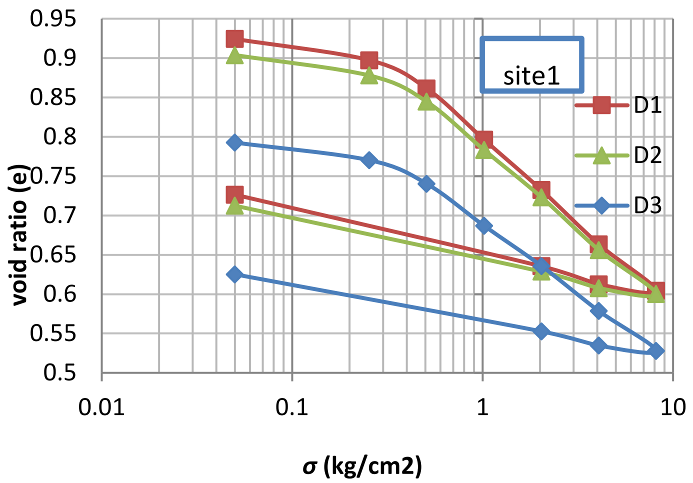
Site No.	Depth No	Values of C_v		Change value	decrease (%)
		σ = 0.2546	σ = 8.148		
S 2	D1	0.01755	0.00448	0.0131	74.5 %
	D2	0.0152	0.00396	0.0112	73.7 %
	D3	0.0137	0.0036	0.0101	73.7%
	Average Change Percentage				73.97%

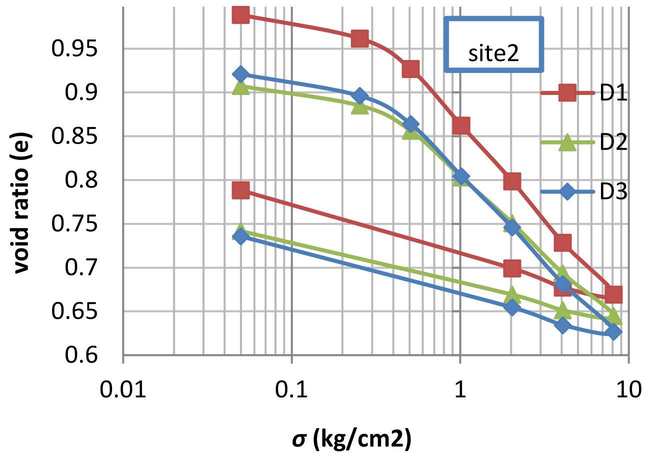
Referring to figure 4 and table 5 about the estimated values of the coefficient of consolidation (c_v), it is noticed that:

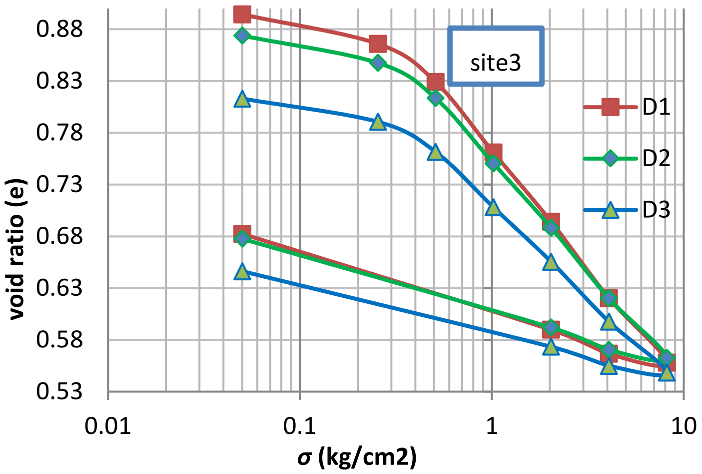
A. The values of c_v decreased gradually upon the increase of applied pressure.
B. The c_v values of consolidated soil depend on the studied cohesive soil sample depth from ground surface.
C. The values of c_v decreased upon the increase of the soil sample depth under applied stress increment (σ). For example, at σ=1.018 kg/cm^2:
   - For site one (S1), the values of c_v for D3 are less than those values for D1 and D2 by about 17.27% and 12.50% respectively.
   - For site two (S2), the values of c_v for D3 are less than those values for D1 and D2 by about 22.79% and 16.67% respectively.
   - For site three (S3), the values of c_v for D3 are less than those values for D1 and D2 by about 25.00% and 13.22% respectively.
   - For site four (S4), the values of c_v for D3 are less than those values for D1 and D2 by about 25.58% and 11.11% respectively.

3.2 Compression Index (C_c)

The obtained values of compression index (c_c) which were determined for the studied cohesive soil samples with different depths of cohesive soil layer at variant sites (S1 to S4) are indicated in Figure 5 since this figure represents the relations between void ratio (e) and applied stress increment (σ). On the other hand, table 6 contains the comparison between c_c values of the studied soil samples for different depths at variant sites at (σ=1.018 kg/cm^2) on the studied cohesive soil samples at variant sites (S1 to S4) respectively.


site1
D1
D2
D3
void ratio (e)
σ (kg/cm2)
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.01
0.1
1
10


site2
D1
D2
D3
void ratio (e)
σ (kg/cm2)
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.01
0.1
1
10


site3
D1
D2
D3
void ratio (e)
σ (kg/cm2)
0.88
0.83
0.78
0.73
0.68
0.63
0.58
0.53
0.01
0.1
1
10

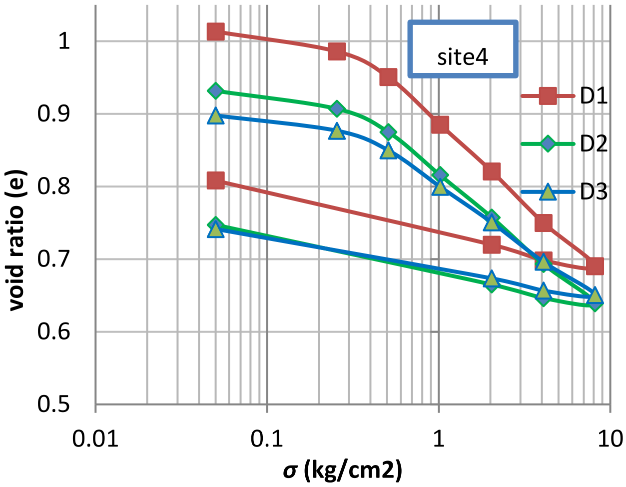


Fig. 5: Relation between e and log σ for different depths of soil samples at sites.

Table 6: Comparison among c_c values of soil samples for different depths at variant sites.

Site No.	Values of *Cc*			Decrease Percentage at D3	
	D1	D2	D3	D1	D2
S1	0.2125	0.1993	0.1727	18.73%	13.35%
S2	0.2111	0.1945	0.1737	17.72%	10.69%
S3	0.222	0.2064	0.1751	21.13%	15.16%
S4	0.2144	0.1933	0.1634	23.79%	15.47%
Average Change Percentage				20.34%	13.67%

Referring to figure 5 and table 6 about the estimated values of the compression index (c_c), it is noticed that:

A. The values of C_c decreased gradually upon the increase of the applied pressure.
B. The values of c_c are related to the change of voids ratio (Δe) and the complete compressibility of soil (U=100%).
C. The values of c_c and c_s of consolidated soil depend on the studied cohesive soil sample depth from ground surface.
D. The values of c_c decreased upon the increase of the soil sample depth under applied stress increment (σ):
   - For site one (S1), the values of c_c for D3 are less than those values for D1 and D2 by about 18.73% and 13.35% respectively.
   - For site two (S2), the values of c_c for D3 are less than those values for D1 and D2 by about 17.72% and 10.69% respectively.
   - For site three (S3), the values of c_c for D3 are less than that for D1 and D2 by about 21.13% and 15.16% respectively.
   - For site four (S4), the values of c_c for D3 are less than those values for D1 and D2 by about 23.79% and 15.46% respectively.

3.3 Correlation between coefficient of consolidation (c_v) and the different depths (D) of the studied cohesive soil samples.

Due to the aforementioned results, the relations between coefficient of consolidation (c_v) and the different depths of the studied cohesive soil samples at applied stress increment (σ=1.018 kg/cm^2) are shown in Fig. 7. So, by using Data-Fit software to correlate the relation between C_v and D, an empirical equation can be deduced for the decreased value of c_v upon the increase of D, as the following:

$$\Delta c_v = c_v \; (\text{-A* D + B})$$

Since:
c_v is the coefficient of consolidation (mm^2/kg).
Δc_v is the decreased value of the consolidation coefficient (mm^2/kg).

D is the cohesive soil sample depth from ground surface.
A&B are constant numbers.

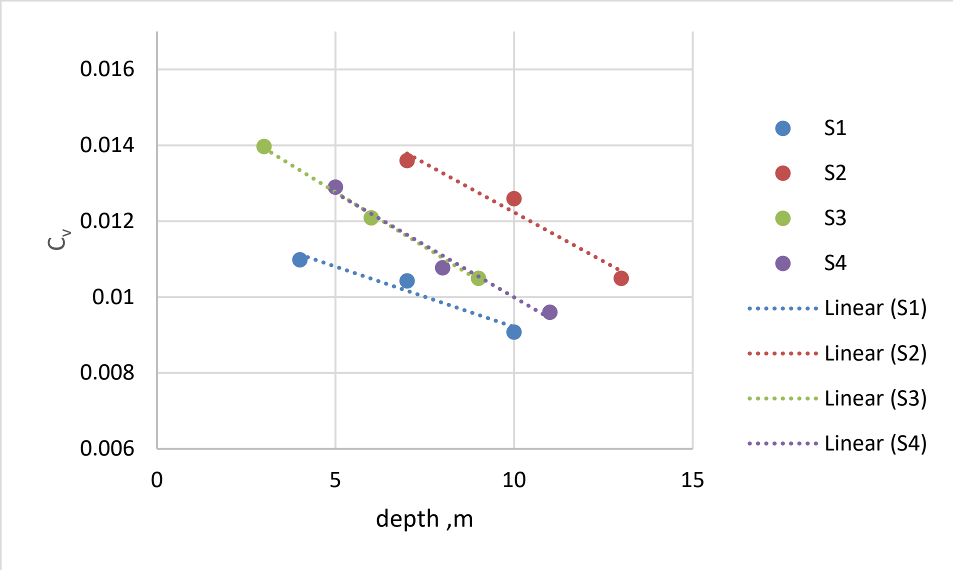


Fig.7: Relation between c_v and D at variant sites

Accordingly, A and B values depend on the fitting of the relations between c_v and D; it can be noted that:

A. At site 1, the fitting data can be as follows:

$$\Delta c_v = c_v*(-0.0003*D + 0.0124)$$

B. At site 2, the fitting data can be as follows:

$$\Delta c_v = c_v*(-0.0005\ D + 0.0174)$$

C. At site 3, the fitting data can be as follows:

$$\Delta c_v = c_v*(-0.0006\ D + 0.0157)$$

D. At site 4, the fitting data can be as follows:

$$\Delta c_v = c_v*(-0.0006\ D + 0.0155)$$

In general, the average value of constant A and B for the studied cohesive soil layers at variant sites are about (-0.0003 to -0.0006) and (0.0124 to 0.0174) respectively. So, the empirical equations can be applied as follows:

$$\Delta c_v = c_v*[-(0.0003 - 0.0006)\ D + (0.0124 \text{ to } 0.0174)$$

3.4 Correlation between compression index (C_c) and the different depths (D) of the studied cohesive soil samples.

Due to the aforementioned results, the relations between compression index (c_c) and the different depths of the studied cohesive soil samples at applied stress increment (σ=1.018 kg/cm^2) are shown in Fig. 8. So, by using Data-Fit software to correlate the relation between C_c and D, an empirical equation can be deduced for the decreased value of c_c upon the increase of D, as the following:

$$\Delta c_c = c_c\ (-A*\ D + B)$$

Since:

C_c is the compression index.
Δc_c is the decreased value of compression index.
D is the cohesive soil sample depth from ground surface.
A& B are constant number.

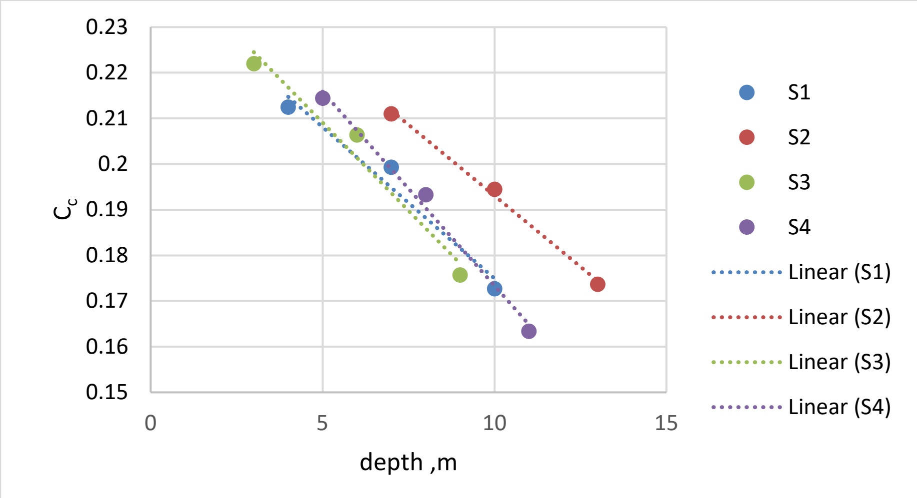


Fig.8: Relation between C_c and D at variant sites.

Accordingly, A and B values depend on the fitting of the relations between c_c and D; it can be noted that:

A. At site 1, the fitting data can be as follows:

$$\Delta c_c = c_c*(-0.0066*D + 0.2413)$$

B. At site 2, the fitting data can be as follows:

$$\Delta c_c = c_c*(-0.0062 D + 0.2552)$$

C. At site 3, the fitting data can be as follows:

$$\Delta c_c = c_c*(-0.0077 D + 0.2477)$$

D. At site 4, the fitting data can be as follows:

$$\Delta c_c = c_c*(-0.0085 D + 0. 2584)$$

In general, the value of constant A and B for the studied cohesive soil layers at variant sites are about (-0.0062 to -0.0085) and (0.2413 to 0.2584) respectively. So, the empirical equations can be applied as follows:

$$\Delta c_c = c_c*\mathbf{[}\ -(0.0062 - 0.0085)\ D + (0.2413 - 0.2584)\mathbf{]}$$

IV. CONCLUSION

The following conclusions are related to the analysis of consolidation parameters that obtained from experimentally laboratory application tests of consolidation for studied soils. Accordingly, it can be drawn that:

1. The average values of natural soil density (γ_{nat}) at sites for D3 are more than those average values for D1 and D2 by about 3.65% and 1.48% respectively.
2. The average values of natural water content (w_{nat}) at sites for D3 are less than that for D1 and D2 by about 11.14% and 5.68% respectively.
3. The average values of coefficient of consolidation (C_v) for sites at D3 are less than that for D1 and D2 by about 22.66% and 13.38% respectively under each applied stress.
4. The relation between coefficient of consolidation (C_v) and depth (D) is suggested by the following empirical formula:

$$\Delta c_v = c_v*\mathbf{[}-(0.0003 - 0.0006)\ D + (0.0124\text{ to }0.0174)$$

5. The average values of compression index (Cc) for sites at D3 are less than those average values for D1 and D2 by about 20.34% and 13.67% respectively under each applied stress.
6. The relation between compression index (Cc) and depth (D) is suggested by the following empirical formula:

$$\Delta c_c = c_c*\mathbf{[}\ -(0.0062 - 0.0085)\ D + (0.2413 - 0.2584)\mathbf{]}$$

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