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Influence of cohesive soil depth on compressibility coefficient and coefficient of volume change

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***Abstract* – The settlement is the most serious problem of fine-grained soils which 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. These studies, in some cases, do not give a simulation of reality representation. It was necessary to study the effect of soil depth from ground surface on consolidation parameters to simulate what happens to the fine soil in nature. Therefore, the consolidation behavior of four cohesive soils was investigated in this paper. The studied soil samples were collected from different depths of cohesive soil layers at four different sites, in 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 compressibility coefficient (av) and volume change coefficient (mv) was checked. Also, the empirical equations were conducted according to the relationship between soil sample depths D vs. av and D vs. mv.**

***Keywords* – Fine-grained soil, cohesive soil, soil sample depth, consolidation, coefficient of compressibility, coefficient of volume change, settlement**

I. INTRODUCTION

Soil layer consolidation means water out between the soil particles when it is influenced by loads or stresses such as: foundations, above constructions and underground constructions loads. The seriousness of soil consolidation appears in the soil layerssettlements. This settlement of soil layers leads to many problems of 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. Where, fractures, partialcollapses and total collapses can occur in structures, especially in cases of high loads[1][7][8][9].

The researchers have exerted 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 it is 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 ofthe entire layer. It is necessary to study the change in the consolidation parameters with the variant depths of the cohesive layer.

In this research, the changes of consolidation parameters (av- mv) with 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 cohesivesoil 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 according to 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 oedometer apparatus.

2.1 The Studied Soils

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

- The three soil samples (D1, D2 and D3) from cohesive soil layer at site one (S1) were obtained at variant 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) were obtained at variant 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) were obtained at variant 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) were obtained at variant depths 5.00m, 8.00m and 11.00m respectively.
- . Tables 1 to 4 contains the engineering properties of 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=10.00 m
Natural density ($\gamma_{b)}$ 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 ($\gamma_{b)}$ 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=8.00 m	D3= 11.00m
Natural density (γ_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

2.2 Consolidation Apparatus and Testing

The ring from stainless steel are 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.

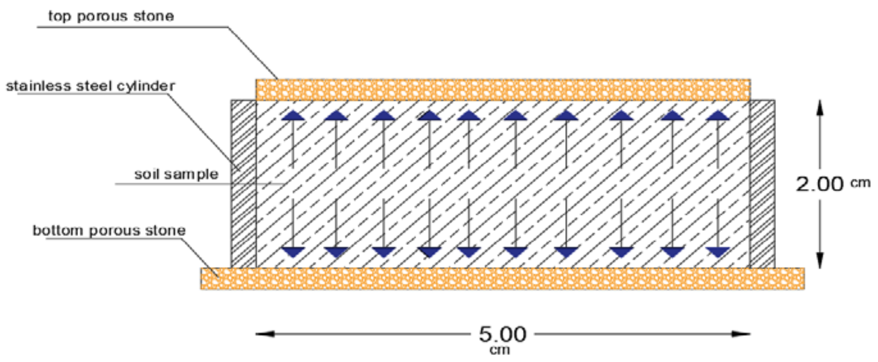


Fig. 1: Model of consolidated soil sample

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:

a. 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.
b. The used porous stones were immersed in distilled water for 8 hours. Then, the porous stones and filter paper were placed at the top and the bottom sides of drainage test as indicated.
c. 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 axial and should be centered with soil sample.
d. The dial gauge, with accuracy of 0.01 mm/division was arranged in apposition 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.
e. After completely compressed, the soil sample under a first stress of 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 similarly at, 0.2546, 0.509, 1.018, 2.037, 4.074,8.148 kg/cm^2.

Fig.3. odometer apparatus

III. RESULTS AND ANALYSIS

Compressibility coefficient (a_v) and Volume change coefficient (m_v) were determined according to consolidation test data of the studied soil samples. These coefficients a_v and m_v were determined using general manner of consolidation theory. So, the relation between compressibility coefficient (a_v) and applied stress increments ($\Delta\sigma$) are shown in Figure 4 for the studied soil samples S1, S2, S3 and S4 respectively, while Fig. 5 shows the relationship between volume change coefficient (m_v) and each applied stress ($\Delta\sigma$) for the studied soil samples S1, S2, S3 and S4 respectively.

3.1 Coefficient of Compressibility (a_v)

The obtained values of compressibility coefficient (a_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 relationships between coefficient of compressibility (a_v) and applied stress increment ($\Delta\sigma$). In the other side, table 5 contains the comparison between a_v values of the studied soil samples for different depths at variant sites at ($\Delta\sigma$=1.018 kg/cm^2) on the studied cohesive soil samples at variant sites (S1 to S4) respectively.

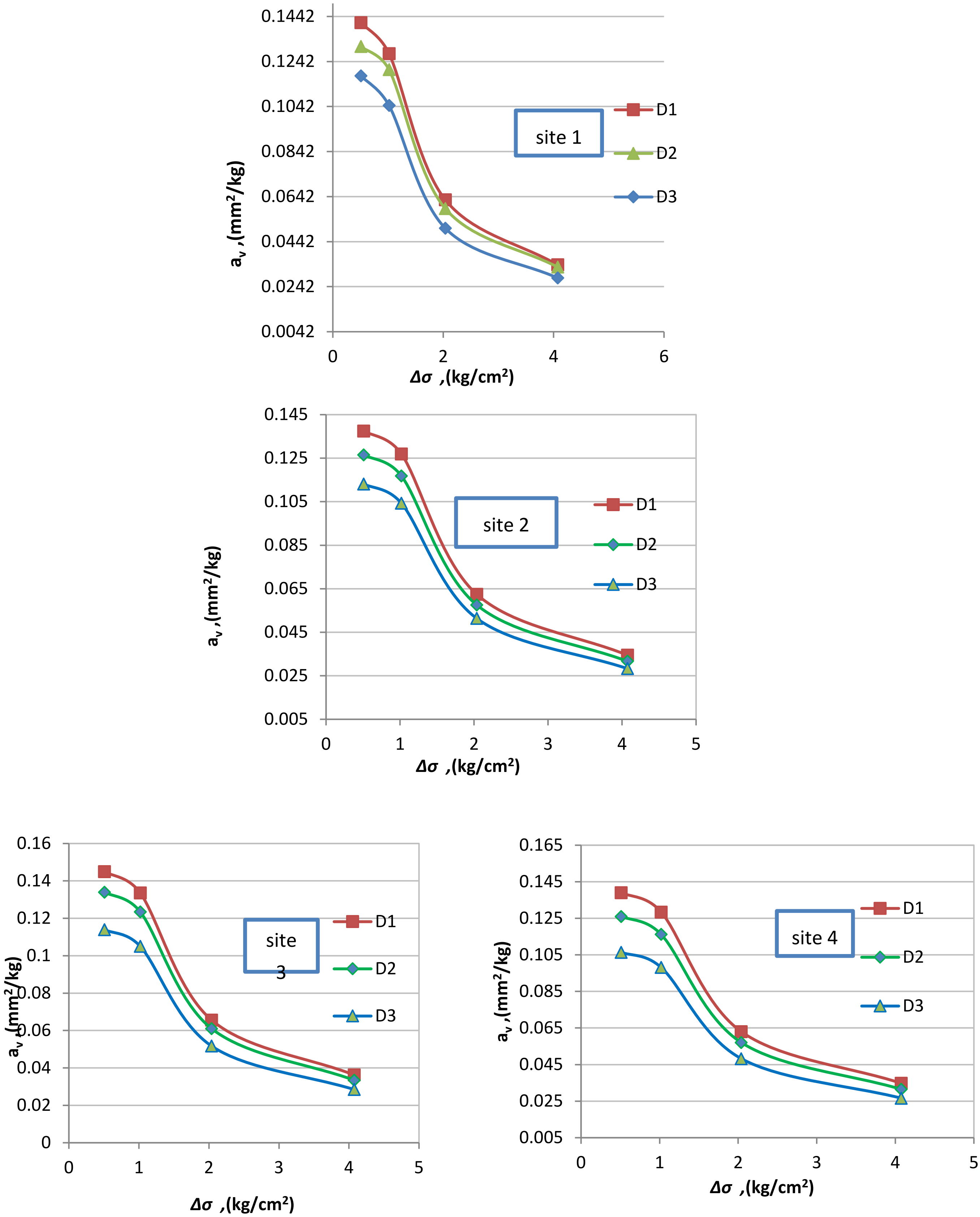


Fig. 4: Relation between a_v and $\Delta\sigma$ for different soil samples depths at sites.

Table 5: Comparison a_v values of soil samples for different depths at variant sites

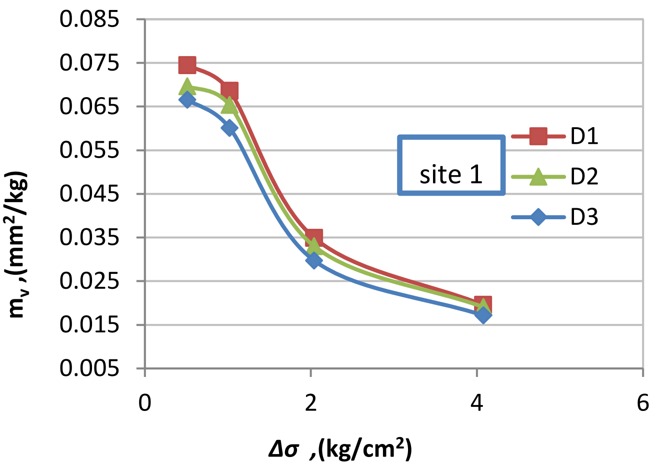
Site	a_v (mm^2/kg) at $\Delta\sigma$ =1.018 kg/cm^2			Decrease percentage at D3	
	D1	D2	D3	D1	D2
S1	0.06281	0.0589	0.05017	20.12%	14.82%
S2	0.0624	0.05753	0.05135	17.71%	10.75%
S3	0.0657	0.0611	0.0517	21.31%	15.38%
S4	0.0631	0.0571	0.0483	23.45%	15.41%
Average decrease percentage				20.29%	13.72%

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

A. The values of a_v decrease gradually with the increase of applied pressure.
B. The values of a_v are related to the change of voids ratio (Δe) and the complete compressibility of soil (U=100%).
C. The a_v values of consolidated soil are depending on the studied cohesive soil sample depth from ground surface.
D. The values of a_v are decreased with the increase of the soil sample depth under applied stress increment ($\Delta\sigma$). For example, at $\Delta\sigma$=1.018 kg/cm^2:
   - For site one (S1), the values of a_v for D3 are decreased by about 20.12% and 14.82% than that for D1 and D2 respectively.
   - For site two (S2), the values of a_v for D3 are decreased by about 17.71% and 10.75% than that for D1 and D2 respectively.
   - For site three (S3), the values of a_v for D3 are decreased by about 21.31% and 15.38% than that for D1 and D2 respectively.
   - For site four (S4), the values of a_v for D3 are decreased by about 23.45% and 15.41% than that for D1 and D2 respectively.

3.2 Coefficient Volume Change (m_v)

The obtained values of volume change coefficient (m_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 5, since this figure represents the relationships between volume change coefficient (m_v) and applied stress increment ($\Delta\sigma$). In the other side, table 6 contains the comparison between m_v values of the studied soil samples for different depths at variant sites at ($\Delta\sigma$=1.018 kg/cm^2) on the studied cohesive soil samples at variant sites (S1 to S4) respectively.



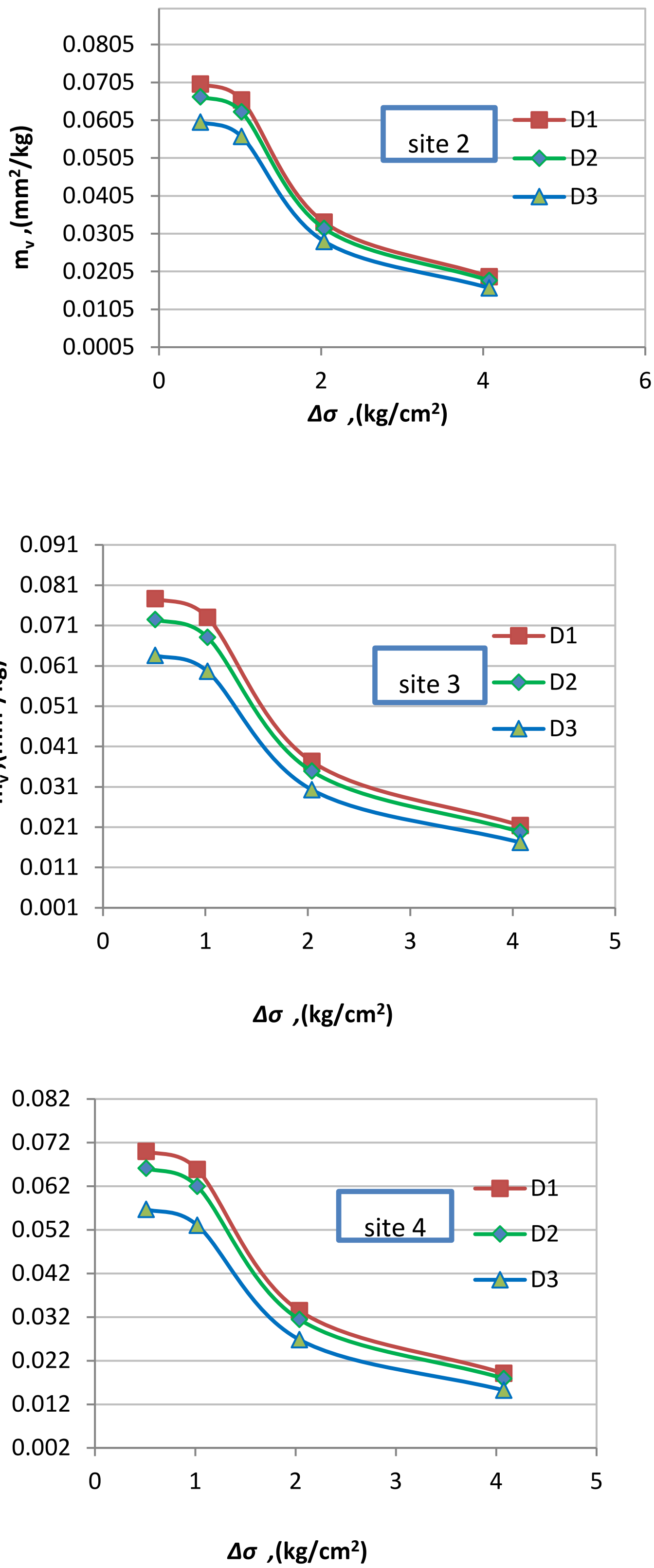


Fig. 5: Relation between m_v and $\Delta\sigma$ for different soil samples depths at sites.

Table 6: Comparison among m_v Values of Soil Samples for Different Depths at variant sites.

Site	m_v (mm^2/kg) at $\Delta\sigma$ =1.018 kg/cm^2			Decrease percentage at D3	
	D1	D2	D3	D1	D2
S1	0.0349	0.03304	0.02974	14.79%	9.99%
S2	0.03352	0.03188	0.02848	15.04%	10.67%
S3	0.0373	0.0349	0.0303	18.77%	13.18%
S4	0.03347	0.0315	0.0268	19.93%	14.92%
Average decrease percentage				17.13%	12.19%

Referring to figure 5 and table 6 about the estimated values of the volume change coefficient (m_v), it is noticed that:

A. The values of m_v decrease gradually with the increase of applied pressure.
B. The values of m_v are related to the change of voids ratio (Δe) and the complete compressibility of soil (U=100%).
C. The a_v values of consolidated soil depend on the studied cohesive soil sample depth from ground surface.
D. The values of m_v are decreased with the increase of the soil sample depth Under applied stress increment ($\Delta\sigma$). For example, at $\Delta\sigma$=1.018 kg/cm^2:
   - For site one (S1), the values of mv for D3 are less than those values for D1 and D2 by about 14.79% and 9.99% respectively.
   - For site two (S2), the values of mv for D3 are less than those values for D1 and D2 by about 15.04% and 10.67% respectively.
   - For site three (S3), the values of mv for D3 are less than those values for D1 and D2 by about 18.77% and 13.18% respectively.
   - For site four (S4), the values of mv for D3 are less than those values for D1 and D2 by about 19.93% and 14.92% respectively.

3.3 Correlation between compressibility coefficient (a_v) with the different depths (D) of the studied cohesive soil samples.

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

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

Since:
a_v is the compressibility coefficient (mm^2/kg)
Δa_v is the decreased value of compressibility coefficient (mm^2/kg)
D is the cohesive soil sample depth from ground surface
A&B are constant numbers

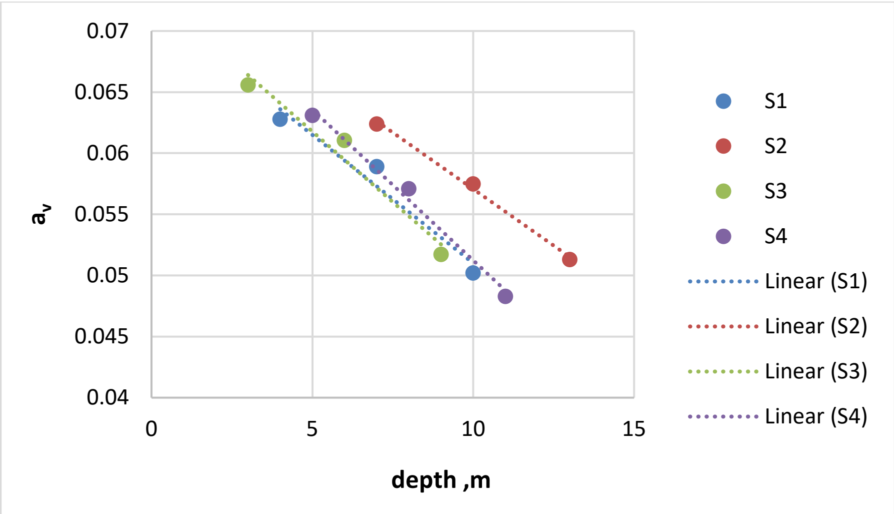


Fig.7: Relation between a_v and D at variant sites

Accordingly, A and B values due to the fitting of the relations between a_v and D, it can be noted that:

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

$$\Delta a_v = a_v*(-0.0021*D + 0.072)$$

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

$$\Delta a_v = a_v*(-0.0019\ D + 0.0756)$$

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

$$\Delta a_v = a_v*(-0.0023\ D + 0.0733)$$

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

$$\Delta a_v = a_v*(-.0025\ D + 0.0759)$$

In general, the value of constant A and B for the studied cohesive soil layers at variant sites are about (-0.0019 to -0.0025) and (0.072 to 0.0759) respectively. So, the empirical equations can be applied as:

$$\Delta a_v = a_v*[\ -(0.0019 - 0.0025)\ D + (0.072- 0.0759)]$$

3.4 Correlation between volume change coefficient (m_v) with the different depths (D) of the studied cohesive soil samples.

Due to the aforementioned results, the relationships between volume change coefficient (m_v) and the different depths of the studied cohesive soil samples at applied stress increment ($\Delta\sigma$=1.018 kg/cm^2) are shown in Fig. 8. So, by using Data-Fit software to correlate the relation between m_v and D, an empirical equation can be deduced for the decreased value of a_v with the increase of D, as the following:

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

Since:
m_v is the volume change coefficient (mm^2/kg)
Δm_v is the decreased value of the volume change coefficient (mm^2/kg)
D is the cohesive soil sample depth from ground surface
A&B are constant numbers

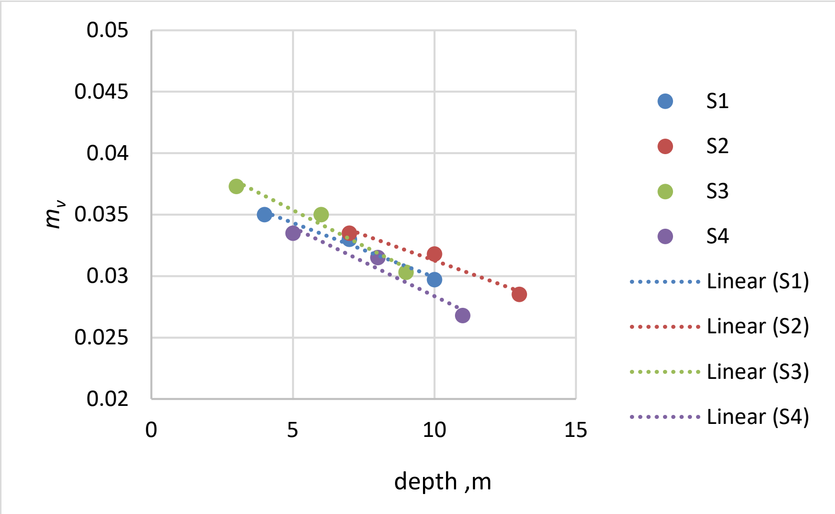


Fig. 8: Relation between m_v and D at variant sites

Accordingly, A and B values due to the fitting of the relations between m_v and D, it can be noted that:

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

$$\Delta m_v = m_v*(-0.0009*D + 0.0388)$$

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

$$\Delta m_v = m_v*(-0.0008\ D + 0.0396)$$

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

$$\Delta m_v = m_v*(-0.0012\ D + 0.0412)$$

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

$$\Delta m_v = m_v*(-0.0011D + 0.0395)$$

In general, the value of constant A and B for the studied cohesive soil layers at variant sites are about (-0.0009 to 0.0011) and (0.0388 to 0.0412) respectively. So, the empirical equations can be applied as:

$$\Delta m_v = m_v*[- (0.0009 - 0.0011) D + (0.0388 - 0.0412)]$$

IV. CONCLUSION

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

1. The average values of natural soil density ($\gamma_{nat)}$ at sites for D3 are more than that 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 compressibility coefficients (a_v) for sites at D3 are less than that for D1 and D2 by about 20.29% and 13.72% respectively under each applied stress increment.
4. The relation between compressibility coefficients (a_v) and depth (D) is suggested by the following empirical formula:

$$\Delta a_v = a_v*[-(0.0019 - 0.0025) D + (0.072- 0.0759)]$$

- The average values volume change coefficients (m_v) for sites at D3 are less than that for D1 and D2 by about 17.13% and 12.19% respectively under each applied stress increment.
- The relation between volume change coefficients (m_v) and depth (D) is suggested by the following empirical formula:

$$\Delta m_v = m_v*[- (0.0009 - 0.0011) D + (0.0388 - 0.0412)]$$

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