Variation of Compression Index and Swelling Index with Degree of Saturation in Unsaturated Soils

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ABSTRACT

The variation of compression index C_c and swelling index C_s with the degree of saturation S was studied on unsaturated and fully saturated soils for different degrees of saturation (100%, 91%, 85%, 75%, 60%), several mathematical equations were found to describe these relationships, these equations can be used to predict settlement during the consolidation process in unsaturated and fully saturated soils.

Key words: unsaturated soils, soil compressibility, compression index, swelling index.

تغير معامل الانضغاط و معامل الانتفاخ مع تغير درجة التشبع في الترب غير المشبعة

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الخلاصة

تم دراسة تغير معامل الانضغاط و معامل الانتفاخ في الترب غير المشبعة والمشبعة كليا لعدد من درجات التشبع (100% ، 91% ، 85% ، 75% ، 60%) وتم ايجاد عدد من المعادلات التي تمثل العلاقات بين تلك المعاملات و درجات التشبع المختلفة، ويمكن لهذا المعادلات ان تستخدم لتخمين الهبوط الحاصل في التربة خلال عملية الانضمام في الترب غير المشبعة والترب المشبعة .

الكلمات الرئيسية: الترب غير المشبعة، انضغاطية التربة، معامل الانضغاط، معامل الانتفاخ.

1. INTRODUCTION

The general field of soil mechanics can be subdivided into the portion dealing with saturated soils and the portion dealing with unsaturated soils. The differentiation between saturated soils and unsaturated soils becomes necessary due to basic differences in the material nature and engineering response. An unsaturated soil has more than two phases, and the pore-water pressure is negative relative to pore-air pressure, **,Fredlund, and Rahardjo, 1993.**
Any soil near the ground surface, present in an environment where the water table is below the ground surface, will be subjected to negative pore-water pressures and possible reduction in degree of saturation.

In recent years, with growing interest in the field of partially saturated soil, and the development of powerful numerical techniques, a number of literatures have been published.
Researchers have dealt with partially saturated soils in many categories.
Mainly, those could be put as: –

1. Partially saturated soil physics and properties,
2. Partially saturated soil constitutive relations and volume change prediction,
3. Partially saturated soil consolidation,
4. Partially saturated soil strength,
5. Heat and mass transfer in partially saturated soil, and
6. Laboratory and field-testing of partially saturated soil.

Consolidation in general for both fully saturated and partially saturated soils is concerned with volume change and with time as the excess pore-water pressure dissipates **,Biot, M. A., 1941. ,Fredlund, and Hasan, 1979. ,Lloret, and Alonso, 1980. ,Fredlund, 1982. ,Chang, C. S., and J. M. Duncan, 1983. ,Dakshanamurthy et al., 1984. ,Fredlund, and Rahardjo, 1986. ,Zainal, 2000.**
A series of Oedometer tests were conducted to determine the compressibility of soil samples with different degrees of saturation.
The objectives of this study are:

1- The variation of the compression index C_c with different degrees of saturation.
2- The variation of the swelling index C_s with different degrees of saturations.
3- The variation of settlement with different degrees of saturation.

3. EXPERIMENTAL WORKS

Tests were conducted to obtain the physical properties of the clayey silt soil used for this study; all the results (Physical properties) are shown in **table. 1** then a series of Oedometer tests were conducted for different degrees of saturations (100%, 91%, 85%, 75%, and 60%), the results of settlement with loading and unloading were obtained to be investigated.

4. RESULTS OF TESTS

Oedometer tests were conducted according to ASTM D2435 (Non-observance of fully saturated sample) specifications to determine the variation of volume change described as void ratio (e) vs. the logarithm of the incremental loading to calculate the value of the compression index (Cc) and the value of swelling index (Cs) of the soil.

The same procedure was conducted for various values of degree of saturation namely (100%, 91%, 85%, 75%, and 60%). These values represent different air content states **,Smith, G. N., and Smith, I., 1988.**

1. Fully saturated state where S=100% represents no air in the voids.
2. Partially saturated where S=91% represents air as occluded bubbles in the voids where there is no continuous path for the air through the voids.
3. Partially saturated where S=85% represents air that has continuous path in the voids as well as water phase.
4. Partially saturated where S=75% represents air that has continuous path in the voids but not for the water phase.
5. Partially saturated where S=60% represents air that has continuous path in the voids but not for the water phase where the soil approaches minimum value of relative permeability of water phase.

The standard procedure was conducted on the fully saturated sample. For the other sample where the degree of saturation is less than 100%, all the procedure steps were conducted except the soaking of the sample to maintain the degree of saturation as it is, so the deformation of the soil sample is determined for the degree of saturation of the sample.
The results for the soil samples with different degrees of saturation are shown in **table 2.** The table shows the load increment as the first field, other fields show the variation of the void ratio (e) in response to the applied load for different degrees of saturation.
Fig. 1 shows the results for the fully saturated soil sample (S=100%) showing the loading and the unloading conditions. Three lines are drawn in **Fig**. **1**, (Line 1) is the line connecting the Oedometer actual readings, (Line 2) is the unloading line to determine C_s, and (Line 3) is the Virgin line to determine C_c from the curve.
The same presentation of lines 1, 2 and 3 are also valid for **Fig. 2** which have the same details about Oedometer tests for the various degrees of saturation 91%, 85%, 75%, and 60% respectively.
Fig. 3 show the variation lines for unloading conditions respectively; also describing different degrees of saturation, 100%, 91%, 85%, 75%, and 60% respectively.

5. DISCUSSION

The results of these tests obtained were analyzed thoroughly, and many relationships were obtained trying to describe the effect of the variation of the compression index C_c and the variation of the swelling index C_s with the degree of saturation S. these variations are shown in **table 3.**
Fig. 4 shows the variation of C_c with the degree of saturation, this relationship can be described by finding the best fit curve from the data shown in **table 2.** There were two best fit curves found to describe the relationship between compression index C_c and the degree of saturation S as percentage (%), the first equation is a polynomial equation of the second degree and can be described as:

$$C_c = 2.8322\times10^{-5} S^2 - 2.1032\times10^{-3} S + 0.18857 \quad (1)$$

with R^2 = 0.99744
And the second equation is an exponential equation and can be described in eq.(2) with R^2 = 0.99708.

$$C_c = 2.2926336 \frac{e^{(0.02436263S)}}{S} \qquad (2)$$

The two equations were extended to cover the range of degree of saturation down to 40%, the two equations can still give very good prediction of the variation of compression index C_c with degree of saturation S; though eq. (2) was found to give more significant results for lower degrees of saturation, hence it is recommended to be used for prediction.

However, and for simplicity, a linear relationship can also be used to describe the variation between the compression index C_c and the degree of saturation without much loss of accuracy as can be seen in **Fig. 4** The mathematical relation is shown in eq. (3), with $R^2 = 0.9765$.

$$C_c = 0.0024S + 0.0148 \qquad (3)$$

Fig. 5 shows the variation of the swelling index C_s with the degree of saturation. Swelling index C_s has almost the same value for a particular soil (Suzuki et al., 2011), fig. 5 also shows that the best fit line has a slope of almost zero value (9×10^{-5}), average value is calculated to be 0.059775 and an average deviation of 0.001425, is defined as "the average of the absolute deviations of data points from their mean", and is shown in eq. (4).

$$\frac{1}{n}\sum |x - \bar{x}| \qquad (4)$$

where:
n= number of data points
x=data point, and
$\bar{x}$ = average

All this can tell that there is no loss of significant in using constant value for the value of C_s which represents the slope of the unloading curve.

6. VARIATION OF SETTLEMENT WITH THE DEGREE OF SATURATION.

It is noted from **fig. 6** that the settlement increases with the increase of the degree of saturation for the same loading that was used for all tests. **Table 4.** shows the variation of settlement ratio (s/H) which is the settlement normalized by dividing the settlement value (s=ΔH mm) by the height of the ring used (H=19 mm), and the value (s/H) is obtained for each degree of saturation.

The variation is shown in **Fig. 6** where the minimum value of settlement ratio is found at the lower degree of saturation and the maximum value of settlement ratio is found at the higher degree of saturation.

This is believed to be due to particles rearrangement caused by more lubrication provided by the presence of more water at higher degrees of saturation hence giving more settlement, and vice versa where less water provides more friction which resists settlement. This behavior is similar to the soil behavior in "wet of optimum" and "dry of optimum" sides of the compaction curve respectively.

From **Table 4.** we can also obtain the ratio of maximum over minimum value (max./min.) of s/H for each loading case, the variation is shown in **Fig. 7**.

Examining these values reveals that the variation is close and an average value (max./min. = 1.63244) i.e.($\Delta H_{s=100}/\Delta H_{s=60}$=1.63244) can be taken as a suggested value for settlement ratio calculations, (e.g. if settlement for 1 m layer of fully saturated soil was found to be 5 cm (s/H=0.05) then for 60% saturation of the same soil and also for 1 m layer, the settlement ratio is 0.05/1.63244=0.03 and the settlement is 3 cm.). This ratio is a good aid in estimating the settlement value at any degree of saturation less than 100% by only knowing the settlement value of the fully saturated soil sample. **Fig. 8** shows the best fit lines obtained from the curves of **fig. 7** while **table 5.** shows their equations and the correlation coefficient squared.
For practical purposes of shallow foundation design usually q_{all} net for Iraqi soil which is approximately between 25 kPa to 100 kPa, it is recommended to use equations related to number 2, 3, and 4 **Table 5.** where these loading conditions are most common and cover most Iraqi soil types either soft soils in southern parts or stronger soil in northern parts. These equations give more accurate values of settlement ratio which can be used to predict settlement in unsaturated soils.
As an example, the loading of 100 kPa is discussed more thoroughly, and this procedure can be implemented to any loading case.
Three types of best fit lines are found to have the highest coefficient of regression. These suggested equations are ordered from highest coefficient of regression to the lowest as shown in **Fig. 9**

1) Polynomial of the second degree

$$\frac{s}{H} = 0.000027S^2 - 0.003132S + 0.173022 \qquad (5)$$

R^2 = 0.990775

2) Exponential relationship

$$\frac{s}{H} = 0.040036e^{0.011574S} \qquad (6)$$

R^2 = 0.949194

3) Linear relationship

$$\frac{s}{H} = 0.001210S + 0.005647 \qquad (7)$$

R^2 = 0.918432

For simplicity, the linear relationship is recommended to be used for prediction of the settlement without much loss of accuracy.

7. CONCLUSIONS

1. The settlement increases with the increase of the degree of saturation for the same loading that was used in all tests.
2. The compression index (C_c) variation with degree of saturation (S) can be expressed as an exponential relationship with very good accuracy (R^2=0.99), and as a second degree polynomial (also R^2=0.99); and for simplicity, it can be expressed as a linear relationship without too much loss of accuracy (R^2=0.98).

3. The swelling index value (Cs) is approximately constant for unloading curve for different degrees of saturation as expressed in the present work and previous work of (Suzuki et al., 2011).
4. The settlement ratio which can be expressed as ($\Delta H_{s=n}/\Delta H_{s=100}$ = constant) (n=any degree of saturation) can be approximated as a constant value for a specific soil, then this ratio can be used to predict settlement for any degree of saturation depending on the settlement of the fully saturated soil.
5. The variation of (s/H) with the degree of saturation for a specific loading can be expressed as linear relationship with very good approximation as best fit line gives good accuracy as shown in the **Table 5.** and **Fig. 8** an even more accurate expressions are found.

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Table 1 The Physical Properties Tests.

No.	Property	symbol	Value	Specific. standard test
1	Field water content	w_n	34%	ASTM D2216
2	Field Mass density	ρ_{wet}	1.92 gm/cm^3	ASTM D854
3	Specific Gravity	G_s	2.8	ASTM D854
4	Initial void ratio	e_o	0.95	$e_o = (G_s/\rho_d) - 1$
5	Plastic Limit	P.L.	30	ASTM D4318
6	Liquid Limit	L.L.	44	ASTM D4318
7	Plasticity index	P.I.	14	P.I = L.L – P.L
8	Liquidity index	L.I.	0.714	L.I. = (L.L – w_n)/ P.I
9	Sand	S	10%	>0.06 mm
10	Silt	M	50%	0.06>M>0.002 mm
11	Clay	C	40%	<0.002 mm
12	Soil Classification	ML	low Plasticity silt	ASTM D422

Table 2 Results of Oedometer Tests.

load (kPa)	(e) at S=100%	(e) at S=91 %	(e) at S=85%	(e) at S=75%	(e) at S=60%
12.5	0.863	0.878	0.889	0.895	0.9
25	0.824	0.838	0.856	0.868	0.878

50	0.768	0.796	0.819	0.827	0.823
100	0.692	0.724	0.753	0.769	0.788
200	0.608	0.666	0.704	0.728	0.746
400	0.512	0.571	0.643	0.669	0.695
800	0.425	0.475	0.56	0.573	0.616
1600	0.328	0.395	0.417	0.491	0.554
12.5	0.458	0.523	0.541	0.606	0.676

Table 3 Compression Index C_c and Swelling Index C_s.

S%	**Cc**	**Cs**
100	0.2607	0.0617
91	0.2345	0.0607
85	0.212	0.0588
75	0.1905	0.0546
60	0.1644	0.0579

Table 4 Variation of Settlement / Height Ratio with Degree of Saturation S%.

	Load (kPa)							
S %	12.5	25	50	100	200	400	800	1600
100	0.04463	0.06442	0.09305	0.13242	0.17526	0.22442	0.26894	0.318947
91	0.03684	0.05747	0.07894	0.11578	0.14578	0.19473	0.24315	0.28452
85	0.03157	0.04736	0.06736	0.10105	0.12631	0.15789	0.20031	0.27336
75	0.02821	0.04221	0.06315	0.09305	0.11368	0.14421	0.19315	0.23467
60	0.02563	0.03689	0.06473	0.08305	0.10421	0.13078	0.17105	0.20310

Table 5 Load Cases and Best Fit Line Equations, and Correlation Coefficients.

No.	Load kPa	Best fit Line equation	R^2
1	12.5	s/H = 0.0005 S - 0.0044	0.8741
2	25	s/H = 0.0007 S - 0.0078	0.9212
3	50	s/H = 0.0007 S + 0.0172	0.6999
4	100	s/H = 0.0012 S + 0.0056	0.9184
5	200	s/H = 0.0017 S - 0.008	0.8718
6	400	s/H = 0.0023 S - 0.0213	0.8700
7	800	s/H = 0.0024 S + 0.0157	0.8830
8	1600	s/H = 0.0029 S + 0.0244	0.9858

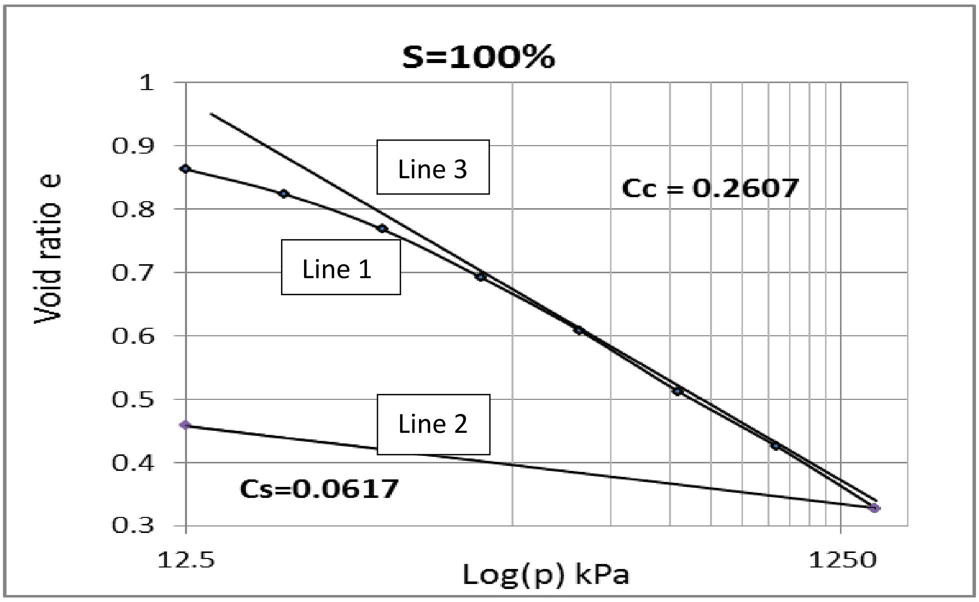

Figure 1 e –log (p) curve at S=100%.

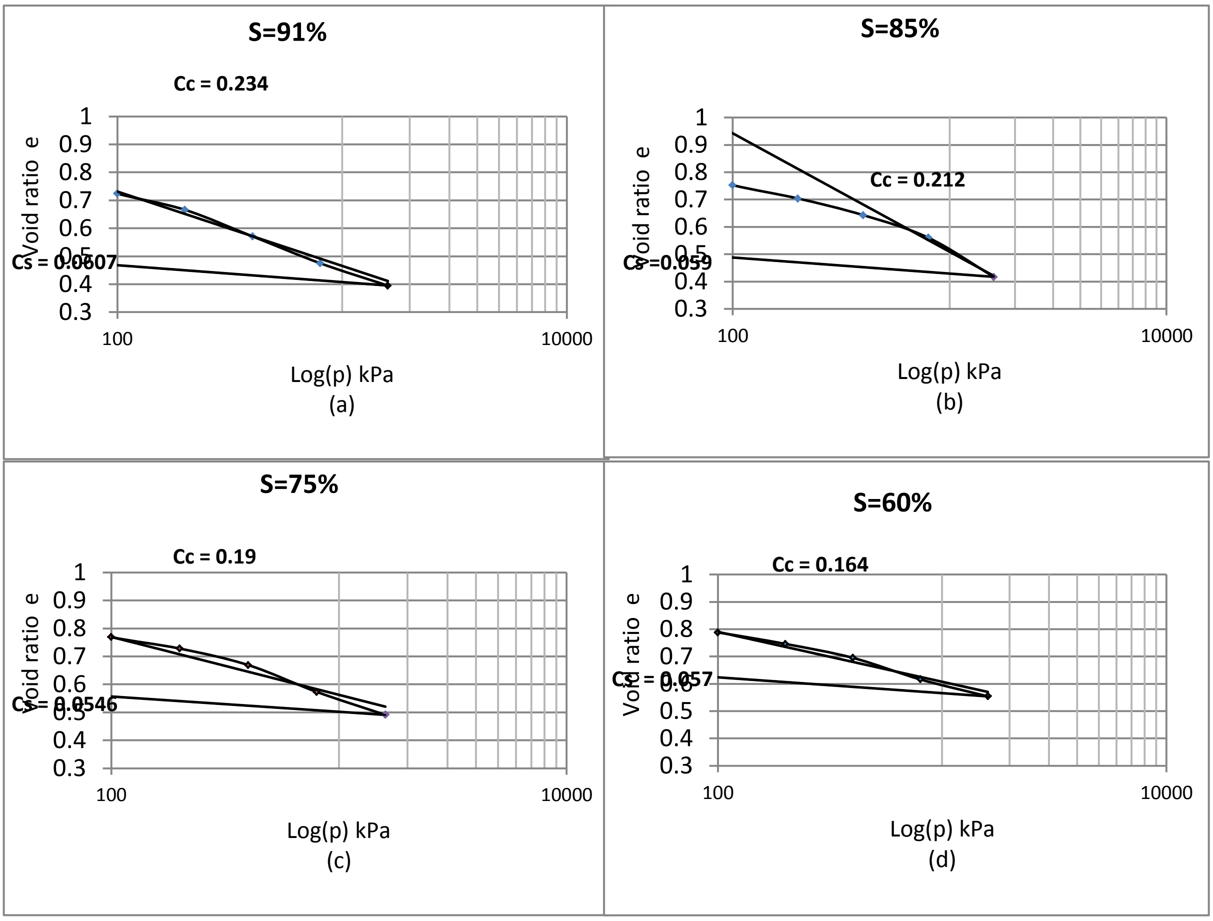

Figure 2. e – log (p) curve at S=91%,85%,75%,60% respectively.

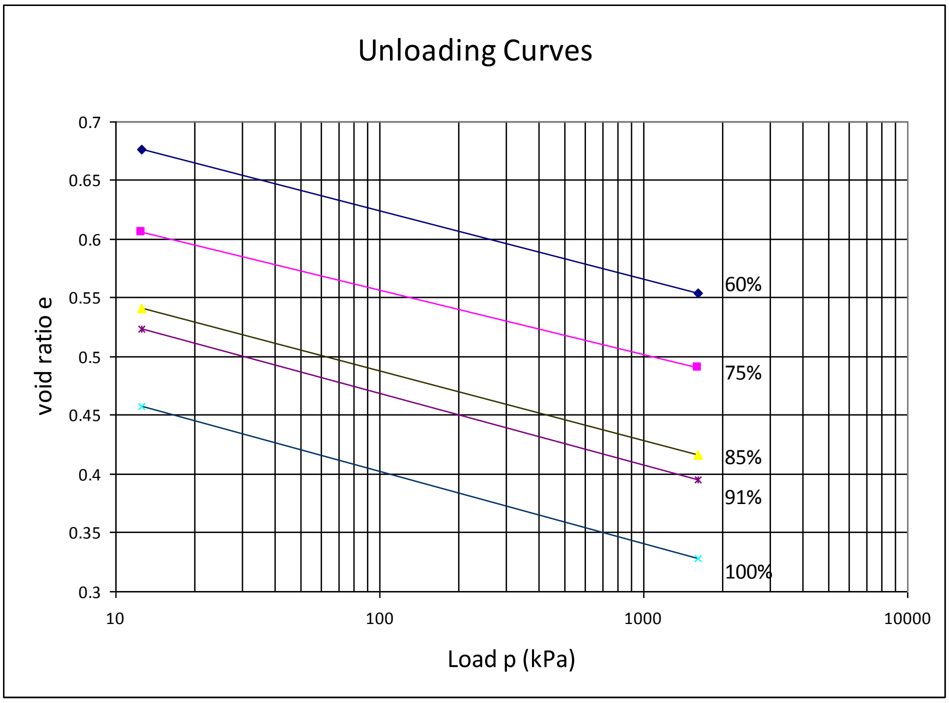

Figure 3 e-log(p) for Unloading Condition for Different Degrees of Saturation.

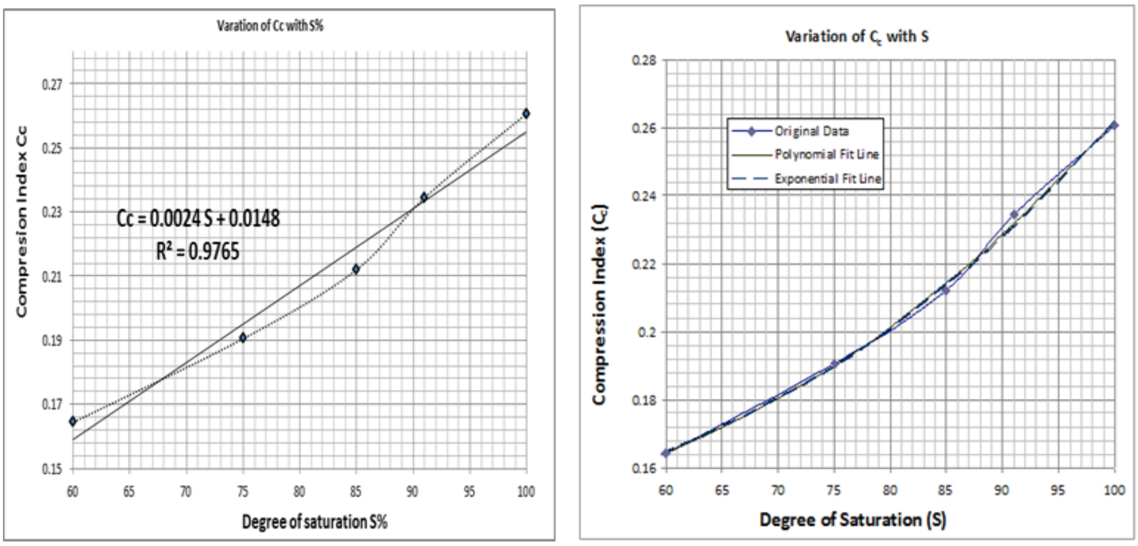

Figure 4 Variation of Compression index C_c with degree of saturation S% .

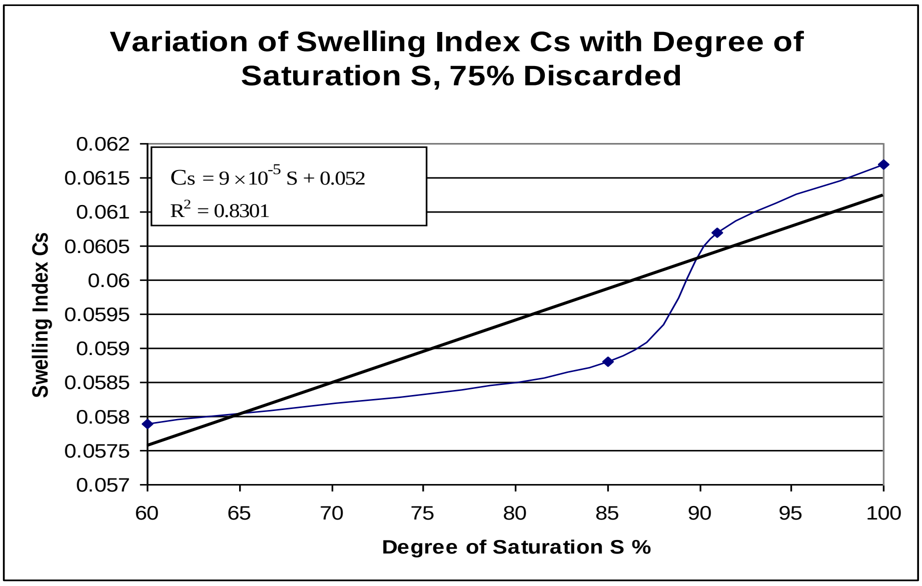

Figure 5. Variation of swelling index C_s with degree of saturation S%.

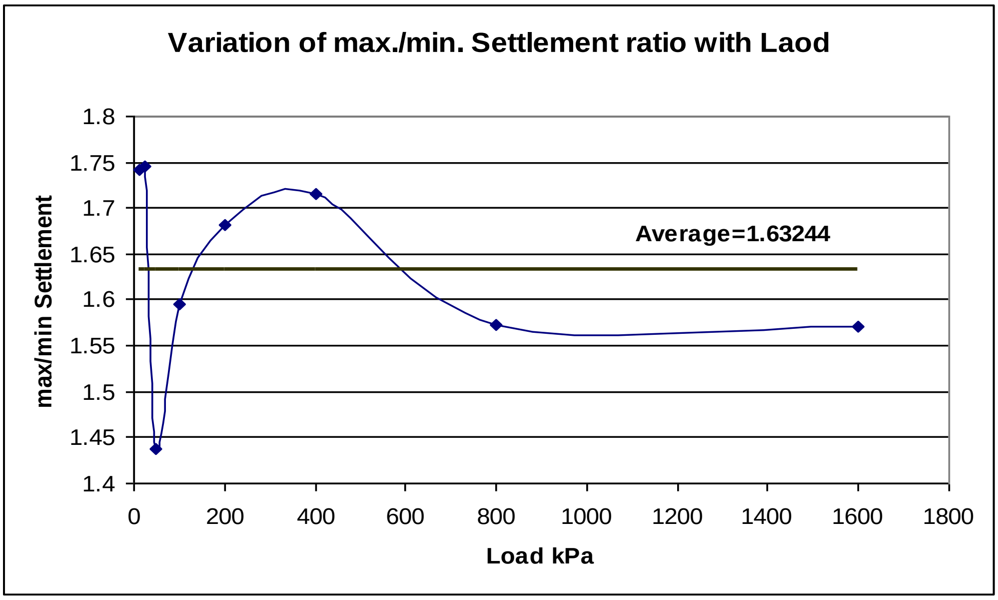

Figure 6. Variation of max./min. settlement ratio with load.

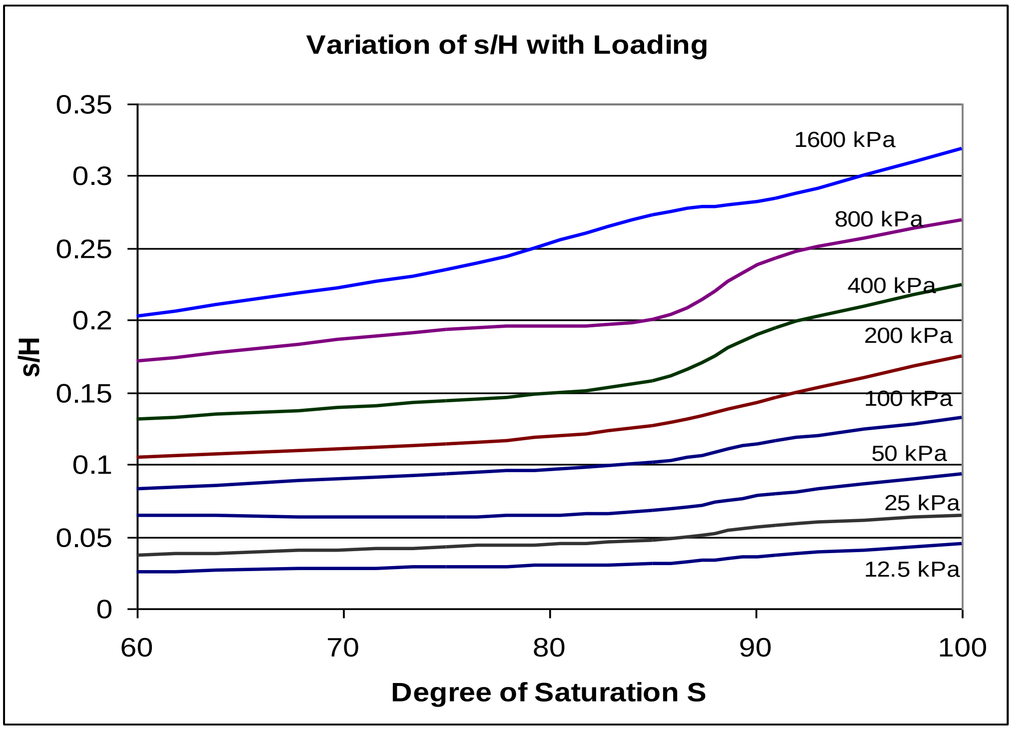

Figure 7. Variation of s/H with degree of saturation S% for each load.

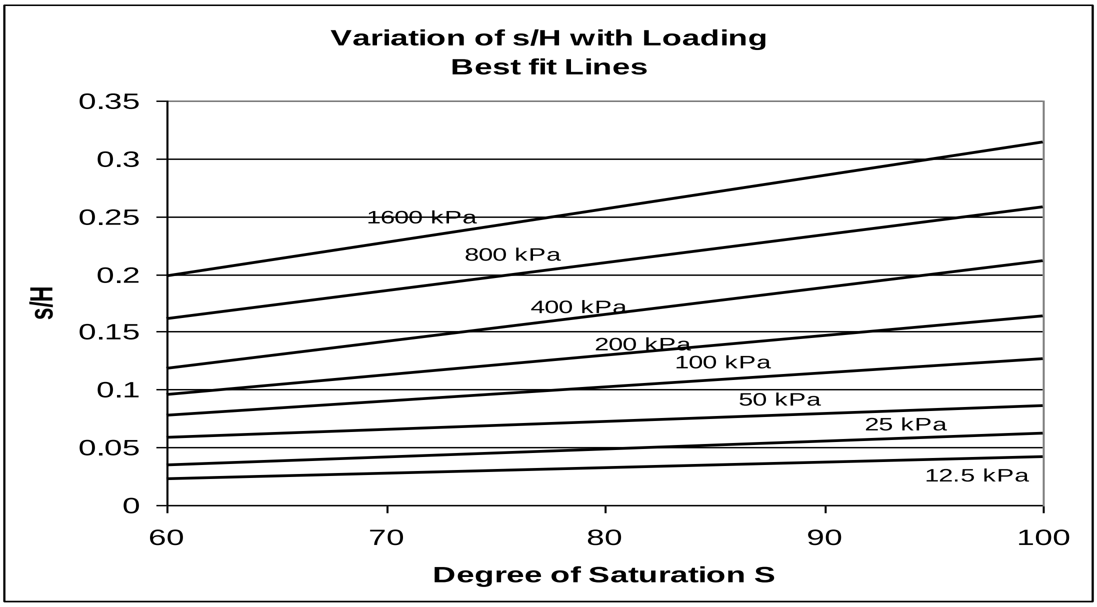

Figure 8. Best fit lines for s/H for different loading cases of variation with degree of saturation S%.

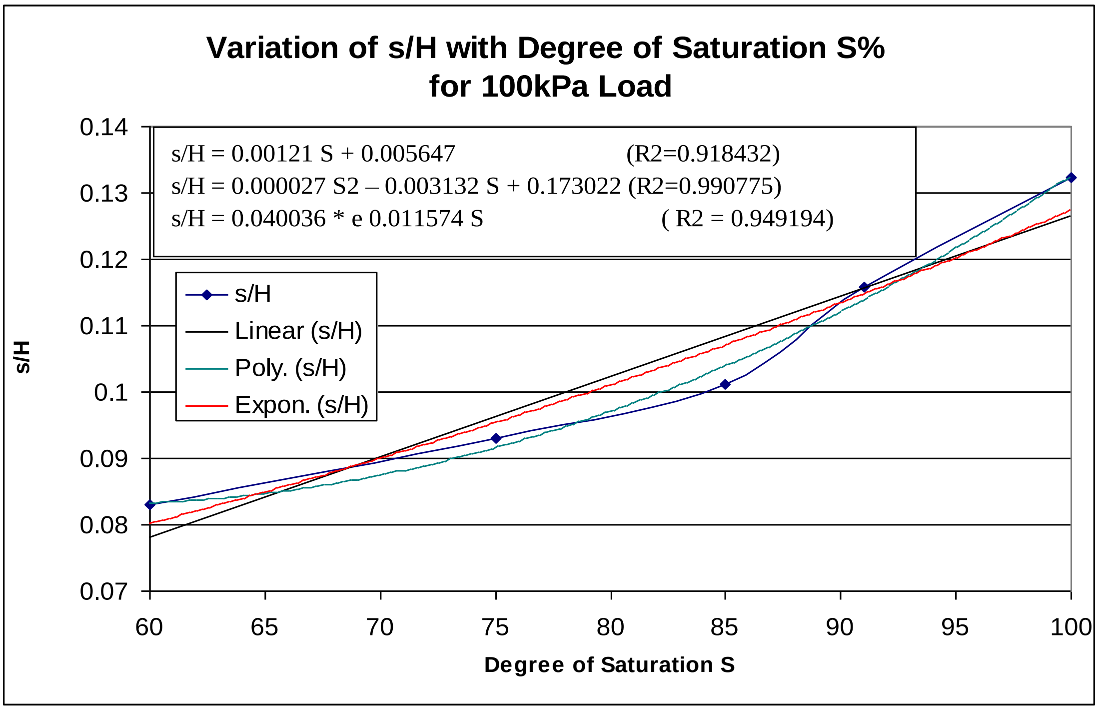

Figure 9. Variation of s/H with degree of saturation S% for 100 kPa load.