Consolidometer test procedural factors affecting swell properties

D.G. Fredlund

Abstract: The one-dimensional oedometer was originally designed to test soft, compressible soils. The use of the oedometer for testing expansive soils has meant that a number of procedural factors must be taken into account. For example, the compressibility of the apparatus has a significant effect upon the measured swelling properties of a soil.

The apparatus compressibility characteristics of a number of oedometer were measured and the data were statistically analyzed. The compressibility characteristics of the filter paper placed above and below a specimen are also presented. Recommendations are presented regarding the corrections that should be applied to oedometer test data from expansive soils.

Key words: one-dimensional oedometer, compressibility characteristics, expansive soils, filter paper, porous stone, swelling pressure.

Test procedures for evaluating swelling properties

The one-dimensional consolidometer has become widely accepted for testing swelling soils. Holtz and Gibbs (1956), Jennings and Knight (1957–58) and Lambe and Whitman (1959) were among the first to report the use of consolidometer tests for predicting heave in swelling soils. Sampson et al. (1965) reported the use of the consolidometer to predict heave in heavily overconsolidated shales. The PVR (potential vertical rise) meter as mentioned by McDowell (1965) is a special type of consolidometer used primarily to measure swelling pressure, which in turn is correlated with the potential amount of volume change. The test, performed on remolded soil, has been used extensively by the Federal Housing Administration in the United States (Henry 1965). The swelling properties of compacted, unsaturated soils have also been investigated by use of the consolidometer (Seed et al. 1961; Gizienski and Lee 1965; Noble 1966). It appeared that the consolidometer had become widely accepted for evaluating swelling soils and predicting the problems that may be encountered during and after construction (Kassiff et al. 1965).

Although the consolidometer test is used extensively for evaluating swelling clays, it should be noted that the procedures used are quite varied. In Western Canada two types of swelling tests have been used extensively (Dyregrov and Hardy 1962; Gilchrist 1963). These are the free swell (FS) and the constant volume (CV) tests. In either test, the specimen is placed in the consolidometer and subjected to a token pressure of approximately 0.08 kg/cm^2 (7.84 kPa). The specimens are then submerged in water.

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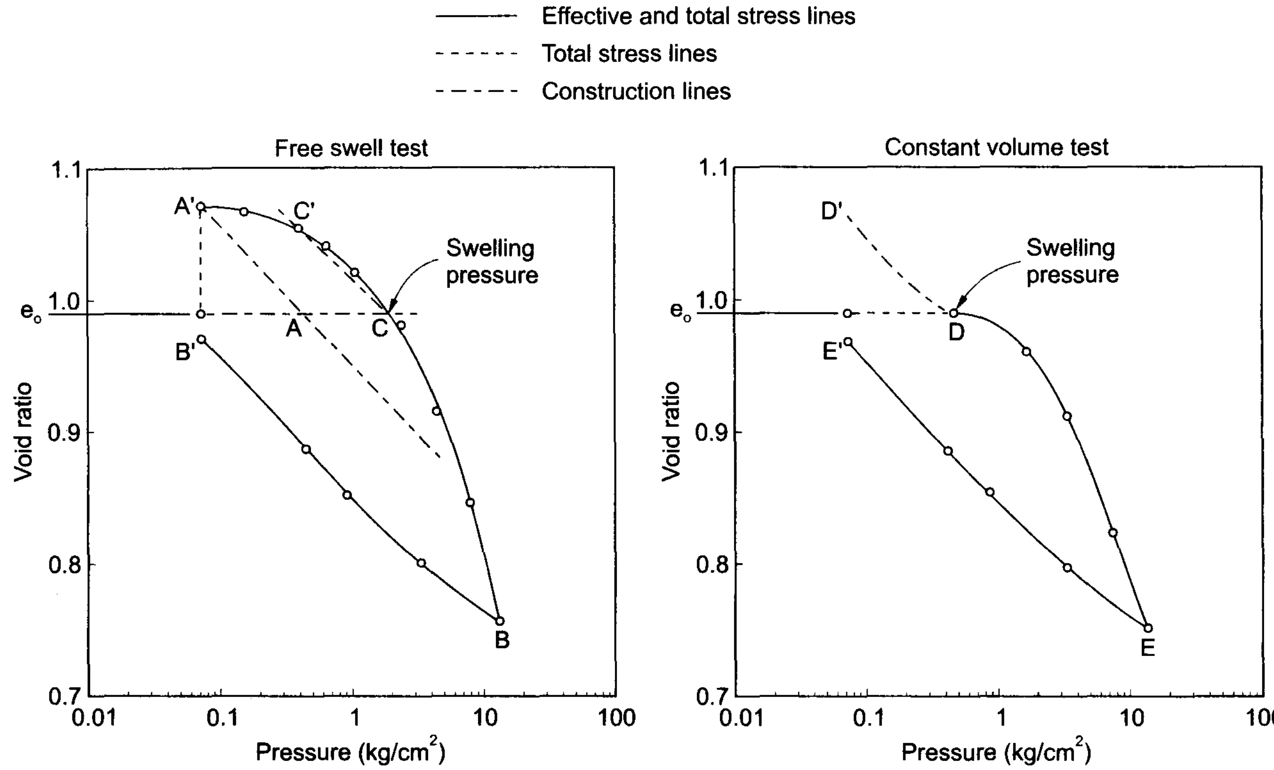
In the free swell test the specimen was allowed to change volume until equilibrium was reached. The specimen was then loaded and unloaded in the conventional manner. The pressure required to reduce the volume of the specimen to its original volume was termed the swelling pressure of the soil. In the constant volume test, the total stress on the specimen was increased after submersion in order to keep it at a constant volume. In this case, the pressure at which there was neither a tendency for volume increase or decrease was termed the swelling pressure of the soil.

The typical results shown in Fig. 1 are plotted using dashed and solid lines to show those portions of the curve which are only total stresses and those portions which are effective stresses. Additional construction lines are shown to demonstrate the interpretation of the results. The construction is based primarily on the assumption that the rebound curves remain parallel when shifted vertically on the void ratio versus pressure plot (Schmertmann 1953; Rutledge 1944; Sampson et al. 1965).

In the constant volume test, the initial effective stress in the soil was assumed equal to the value at point *D*. During submersion with water, the negative stresses in the pore water were released until atmospheric pressure was attained. Release of the total stress on the specimen allowed rebound along line $D - D'$. Using the same line of reasoning for the free swell test lead us to assume that point *A* should be of similar magnitude to point *D* from the CV test. However, a prediction of heave analysis, based upon the FS test, generally assumed the initial field effective stress equal to point *C*.

The two procedures outlined produced swelling pressure values which were considerably different in magnitude (Noble 1966). The swelling pressure obtained from the FS test (Point *C*) appeared to be incorrectly inter-

Fig. 1. Typical consolidation test results; *a*) Free swell, *b*) constant volume.



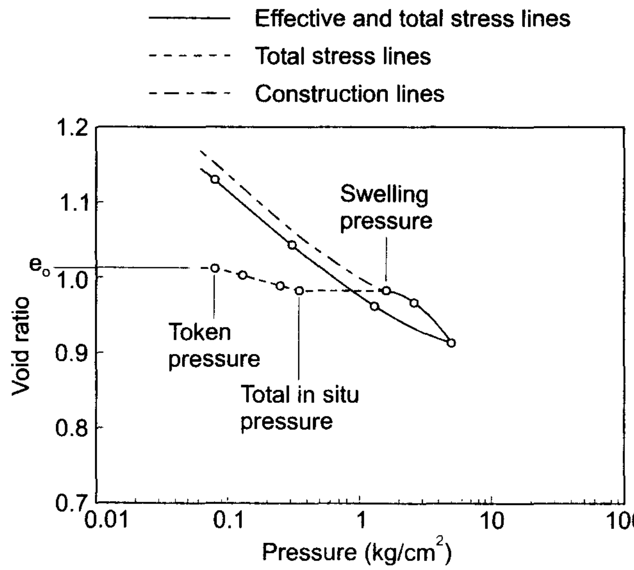
preted. In practice; however, the results are continued to be used, since they produce a more conservative design, and also appear more realistic when compared to the total pressure *in situ*.

Skempton (1961) stated that the value obtained for swelling pressure from a constant volume consolidation test gave an indication of the negative pore pressures *in situ*, if the sample had not been disturbed or allowed to dry after sampling. Applying this reasoning to the interpretation of the CV tests performed on desiccated lacustrine clays in Western Canada would indicate that in many cases the *in situ* pore pressure was actually positive. Since the water table was well below the depth under consideration, the most logical error appeared to be in the measurement of swelling pressure. In other words, the measured swelling pressure was too low. This; however, did not mean that the FS test was a more accurate simulation of field conditions but, rather, that procedural factors produced an under-estimation of the swelling pressure measured in the CV test.

Seed et al. (1961) showed that small changes in volume during testing produce a pronounced decrease in the measured swelling pressure. Even while keeping the dial gauge on a consolidometer at a constant value immediately after submersion (CV test), the meniscii are released by the water and volume change is actually occurring in the specimen as it seats against the porous disks and compresses the components of the consolidation pot.

It should also be noted that the soil specimen has actually undergone some rebound between the time of sampling and testing. This rebound also decreases the

Fig. 2. Modified constant volume consolidation test.



measured swelling pressure below that of the *in situ* value. Figure 2 shows typical results using a modified constant volume test procedure which is superior. In this procedure, the sample is trimmed, placed in the consolidation pot and a token pressure applied for initial dial reading. The specimen is covered to prevent evaporation and the load on the specimen is doubled in increments (allowing each to come to equilibrium) until the load on the sample is equal to the total vertical pressure existing in the field (Hvorslev 1949). The specimen is then submerged with water and the test continued according to the constant volume test procedure. However, there is generally no need to load the specimen any greater than a pressure approximately twice the swelling pressure since the desired information has been obtained and the testing time can be kept to a minimum.

Test procedures used by other authors will not be dealt with here since they are felt to be outside the scope of this paper. It should be noted; however, that most of the procedural factors discussed in this paper apply to other procedures since, in all cases, an attempt is being made to reproduce *in situ* stress-strain conditions that will occur due to changes produced by construction or environmental changes. Using the above analysis, it is necessary to establish the initial stress conditions, estimate the final stress conditions and produce the proper stress-strain relationship for the problem.

Procedural factors

The procedural factors of importance when testing soft, sensitive clays are not necessarily of prime concern when testing swelling clays. Factors such as side friction, sample disturbance, sample size and temperature, are dealt with in the literature (Taylor 1942; Matlock and Dawson 1951; Finn 1951; Leonards and Girault 1961) mainly in connection with testing soft, sensitive soils. Procedural factors of concern when testing swelling clays include loading procedure (load-increment ratio and duration of load), apparatus friction, compressibility of consolidometer and the "seating" of soil and porous disks.

Loading procedure

The effects of the loading procedure are presently under investigation and the results are still incomplete. However, the results have shown that a considerable length of time is required to reach equilibrium at the swelling pressure of a soil. Specimens have been run with varying amounts of back pressure and the measurement of pore pressure at the base of the specimen. For specimen approximately 3/4 inch in thickness several days are required for equilibrium rather than the one day normally used.

Apparatus friction

Friction in the mechanical components of the apparatus is of interest since it affects the shape of the lower pressure end of the recompression and rebound curves. Figure 3 shows average results for the relationship between load applied to the hanger and load transmitted to the specimen for four light frame consolidometers. (Each of the consolidometers gave almost identical results.) A small, highly sensitive proving ring with strain gauges was substituted for the soil specimen and used to measure the load reaching the specimen. The theoretical mechanical advantage is obtained by precise measurement of lengths of the lever arms.

Fig. 3. Portion of the load transmitted to soil specimen.

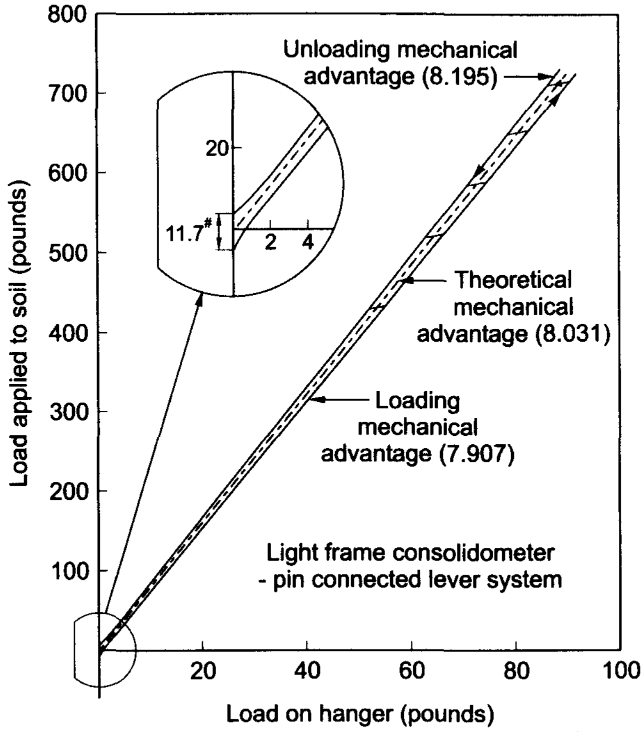
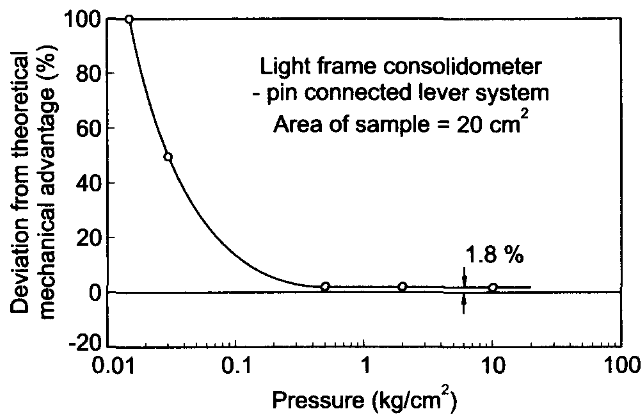


Fig. 4. Error in pressure measuring system due to friction.

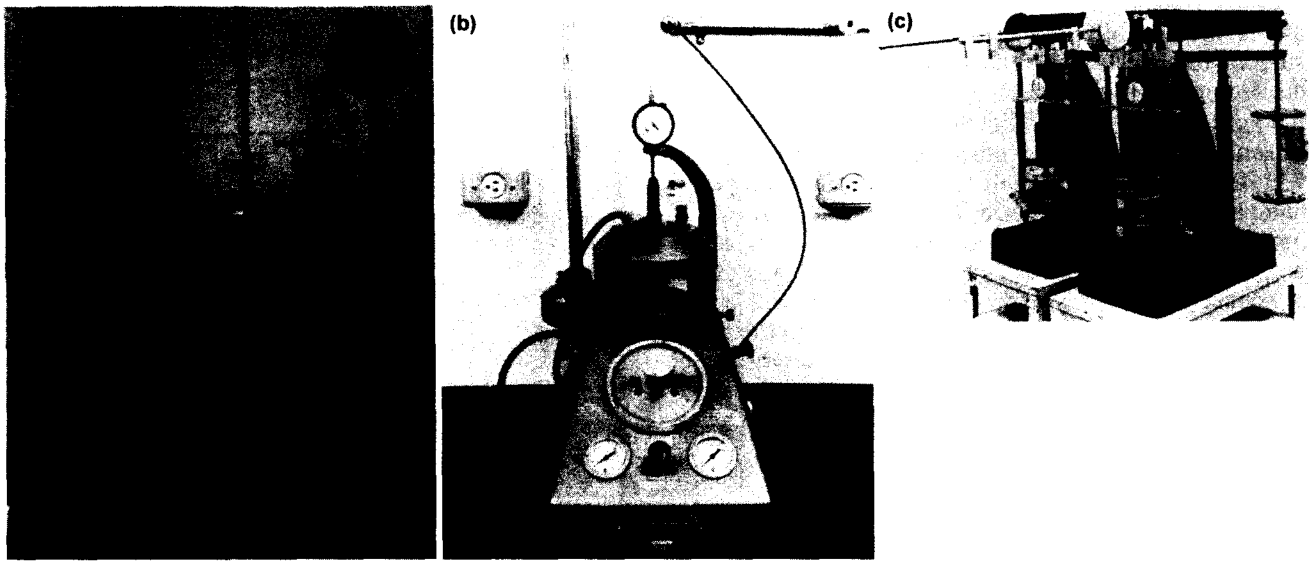


Throughout the loading and unloading range greater than 0.5 kg/cm^2 (49 kPa), the load applied to the specimen is within 1.8% of the theoretical value. However, at lower pressures the percent error increases rapidly (Fig. 4). At a pressure of 0.01 kg/cm^2 (0.98 kPa) the load applied to the sample may be in error by 100%.

Similar results on the Wykeham-Farrance bench model consolidometers showed an error of approximately 1.2% for pressure above 0.2 kg/cm^2 (19.6 kPa). There was a slight decrease in the frictional component due to the use of knife edges rather than pin-connectors on the loading mechanism.

The accuracy of the applied load using consolidometers with air pressure regulators depends on the accuracy of the pressure regulator. One regulator generally does

Plate 1. Low load capacity consolidometers: *a*) Light frame consolidometers, *b*) Anteus Testlab consolidometer, *c*) bench model consolidometer.



not provide accurate pressures for the entire range of loading. Two, and preferably three, pressure regulators are more satisfactory. The Anteus Testlab consolidometer uses a constant pressure head of water at low pressures which allows precise pressure measurements.

Irregular behavior often noticeable in the low range of loading may be largely attributable to inaccuracies in the load transmitted to the specimen. This problem is further discussed in connection with the seating of the soil specimen and the porous disks. Also, in the free swell test the interpretation of the results depends upon an accurate determination of the token pressure. Friction in the loading mechanism may be a primary factor in the flattening of the rebound curve often noticeable at low pressures. However, the above problems should not only be viewed from the standpoint of apparatus friction since factors such as friction between the consolidation ring and the soil are also of importance. The testing procedure for swelling clays should be one that tends to suppress inaccuracies in pressure measurements, if possible.

Compressibility of apparatus

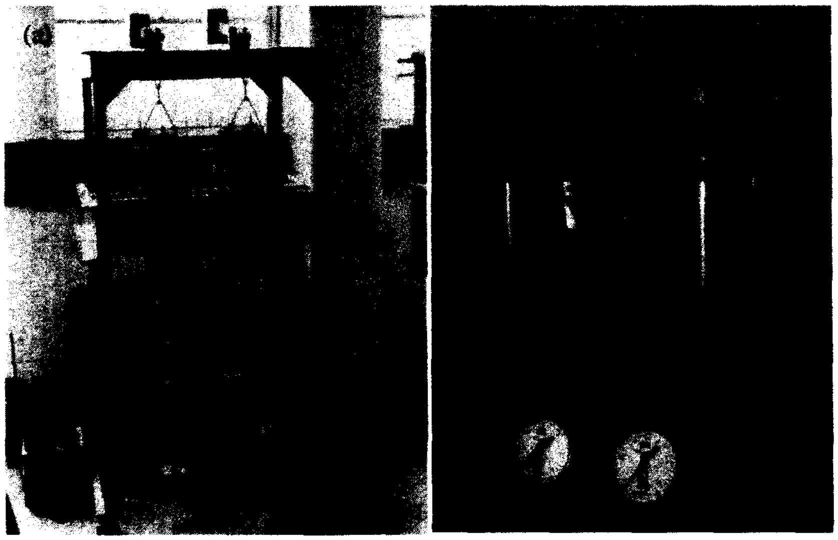
If a portion of the deflections measured during a consolidation test are due to volume changes in the apparatus rather than the soil specimen, the test results will be in error unless corrections are made. Compressibility of apparatus affects the measurement of swelling pressure and the slope of the compression and rebound curve. Attempts have been made to increase the stiffness of the measuring device (Seed et al. 1961; Kassiff et al. 1965) in order to more accurately measure swelling pressure by the constant volume procedure. Hveem (1958) in his suggested method for determining the expansive pressures of remolded soils states that a pressure measuring system with a stiffness of 0.04% per 0.5 psi (3.45 kPa) is satisfactory. However, at 30 psi (207 kPa) this would mean 2.4% volume change. This can cause serious errors in the measurement of swelling pressure. Increasing stiffness increases the swelling pressure; however, the problem of seating and compressibility of the various components of the apparatus between the points of measurement have still not been accounted for. The compression of the apparatus can be measured by substituting a steel plug for the soil specimen and performing the loading and unloading cycle. The effects of filter paper and seating of the soil and porous disks are discussed later.

Although the reliability of the above procedure has been questioned, it appears to be the best method available. Matlock and Dawson (1951) concluded that the evaluation of compressibility of apparatus is seldom justified, "first because there are no results except to alter the shape of the void ratio-pressure curves slightly; and second, because the deformations measured during such calibrations are usually only partially elastic and cannot be depended upon to repeat themselves during the actual consolidation test". Others (Means and Parcher 1963; Hamilton and Crawford 1960) have suggested that the compressibility of apparatus be determined prior to running the consolidation test and that corrections be applied to the results obtained. It is the author's opinion that the effects of compressibility should be taken into consideration when testing swelling soils.

The compressibility characteristics of the consolidometers tested are presented in terms of statistical properties. Deformations occurring for each logarithmic cycle of pressure were tabulated for five types of equipment. They are:

(1) Light Frame Consolidometer — Lever arm loading system with pin-connectors; with a mechanical advantage of 8 (Plate 1*a*).
(2) Anteus Testlab Consolidometer — Compressed air loading with one regulator; constant head water pot at low pressures (Plate 1*b*).

Plate 2. High load capacity consolidometers; *a*) Large frame consolidometers, *b*) Conbel consolidometer.



(3) Bench Model Consolidometer — Manufactured by Wykeham-Farrance; lever arm loading system with knife edges; mechanical advantage of 11:1 (Plate 1*c*).
(4) Large Frame Consolidometer — Lever arm loading system with knife edges; mechanical advantages of 40:1 and 50:1 (Plate 2*a*).
(5) Conbel Consolidometer — Manufactured by Karol Warner; compressed air loading with two regulators; capacity of 120 kg/cm^2 (11.76 MPa) on a 2-½ inch (63.5 mm) diameter sample (Plate 2*b*).

First cycle of loading and unloading

Generally only one cycle of loading and unloading is run in a consolidation test. To simulate this it would appear that only the first cycle in the compressibility tests should be considered. Several pieces of apparatus for each type of equipment mentioned were tested (Table 1).

The consolidometers do not compress in an elastic manner since too much deflection occurs at low pressures (Fig. 5). However, their shapes on a semi-logarithmic plot are similar to those expected from testing soil specimen. The light frame and bench model consolidometers show similar compressibility curves with approximately 0.0045 inches (0.114 mm) occurring at 10 kg/cm^2 (980 kPa). The large frame and Conbel consolidometers show considerably more compression. The Anteus Testlab consolidometer shows only 0.0016 inches (0.06 mm) at 10 kg/cm^2 (980 kPa).

The standard deviation of the compressibility for each log cycle of pressure increases as the pressure increases. However, when expressed as a percentage of the mean (i.e., coefficient of variation) it decreases.

All apparatuses, except the Anteus Consolidometer, show considerable hysteresis between loading and unloading. The larger the hysteresis, the more residual deflection there is remaining when the pressure is 0.01 kg/cm^2 (0.98 kPa). Although there is a wide variation in residual deflection, it should be noted that this value is dependent upon the maximum pressure applied. Since this varied from one apparatus to another, the residual deflections can also be expected to vary. Due to hysteresis and residual effects, there should be one compressibility correction curve for loading and another for the unloading of the specimen.

Comparison of first and second cycle of loading

Table 2 shows the change in compressibility that occurs upon the second cycle of loading. It is noteworthy that there is an insignificant difference in compressibility up to 1.0 kg/cm^2 (98 kPa) upon loading the second time and that only a slight decrease occurs with pressures up to 10 kg/cm^2 (980 kPa). The results on the unloading portion are not significantly different; however, the residual deformation is greater on the first cycle. Also, the standard deviations are not significantly different between the two cycles of loading. It appears that several cycles of loading and unloading could be performed on one apparatus and the average results used for the compressibility correction.

Cycling load on one apparatus

Since there appears to be only a small amount of difference in the deflection from the first and second cycle of loading, several runs were made on a single apparatus to check the reproducibility of the results (Table 3).

A high degree of reproducibility is shown by the low coefficients of variation and standard deviations. The highest variation occurs in the value for residual deformation. It would appear most satisfactory to apply the compressibility corrections from the loading end of the consolidation curve.

Components of compressibility

Calculations of deflection based on the elastic moduli of the materials involved shows that many times as much deflection occurs when loading as would theoretically be expected. For example, at 10 kg/cm^2 (980 kPa) on the light frame consolidometers, the average ratio of the actual deflection to the theoretical deflection was 4.0. It is

Table 1. Compressibility of consolidometers. First cycle of loading and unloading.

Type of equipment	No. of observations	Pressure range[2] (kg/cm^2)	Deflection[3] (inches) Mean	Median	Standard deviation	95% Confid. limits	Coeff. of variation (%)
Light frame consolidometer	25	0.0 to 0.1	0.0002	0.0002	0.0001	0.0002	39.9
		0.1 to 1.0	0.0010	0.0010	0.0003	0.0006	30.3
		1.0 to 10.	0.0033	0.0033	0.0010	0.0019	28.7
		10. to 1.	0.0029	0.0030	0.0010	0.0020	34.7
		1.0 to 0.1	0.0010	0.0011	0.0004	0.0007	32.0
		0.1 to 0.01	0.0004	0.0004	0.0002	0.0004	44.5
		Residual[1]	0.0007	0.0006	0.0005	0.0010	65.9
Bench model consolidometer	6	0.0 to 0.1	0.0005	0.0004	0.0004	0.0009	88.5
		0.1 to 1.0	0.0009	0.0009	0.0003	0.0006	34.0
		1.0 to 10.	0.0030	0.0035	0.0010	0.0019	32.5
		10. to 1.	0.0024	0.0025	0.0005	0.0009	20.1
		1.0 to 0.1	0.0010	0.0010	0.0004	0.0007	34.6
		0.1 to 0.01	0.0007	0.0005	0.0006	0.0012	87.0
		Residual[1]	0.0007	0.0002	0.0012	0.0023	159.0
Anteus Test Lab consolidometer	3	0.0 to 0.1	0.0003				
		0.1 to 1.0	0.0005				
		1.0 to 10.	0.0008				
		10. to 1.	0.0008				
		1.0 to 0.1	0.0004				
		0.1 to 0.01	0.0001				
		Residual[1]	0.0004				
Large frame consolidometer	10	0.0 to 0.1	0.0015	0.0017	0.0009	0.0018	61.4
		0.1 to 1.0	0.0023	0.0026	0.0012	0.0024	53.8
		1.0 to 10.	0.0048	0.0052	0.0021	0.0041	43.2
		10. to 1.	0.0022	0.0021	0.0012	0.0023	51.8
		1.0 to 0.1	0.0029	0.0032	0.0014	0.0028	49.4
		0.1 to 0.01	0.0017	0.0019	0.0010	0.0020	57.4
		Residual[1]	0.0021	0.0012	0.0019	0.0037	87.1
Conbel consolidometer	2	0.0 to 0.1	0.0008				
		0.1 to 1.0	0.0023				
		1.0 to 10.	0.0028				
		10. to 100.	0.0065				
		100. to 10.	0.0050				
		10. to 1.	0.0021				
		1.0 to 0.1	0.0009				
		Residual[1]	0.0041				

[1]Residual is the term used for the difference between starting and finishing dial readings.
[2]1 kg/cm^2 is equal to 98 kPa.
[3]1 inch is equal to 25.4 mm.

therefore, of interest to observe the basis of the deflections measured.

Figure 6 shows the components giving rise to the deflections occurring during the loading and unloading of the Conbel consolidometer. At 30 kg/cm^2 (2941 kPa) approximately 13% of the deflection occurred in the loading ram and the base of the loading frame of the consolidation apparatus. Forty-eight percent occurred in the porous disks which also are the main contributors to the hysteresis effect and residual deformation. The remaining 39% of deformation occurred in the consolidation pot, loading cap and the seating of the ball on the loading cap. Due to the large deformation in the porous disks, their properties were further investigated.

Commercial manufacturers list the elastic modulus of corundum porous disks at approximately 10×10^6 psi. Measured values in the laboratory are shown in Fig. 7 and the computed moduli summarized in Table 4. Only the thick porous disks show a deformation modulus approaching the theoretical value. Factors such as roughness and warp in the disks appear to introduce high deflections and hysteresis.

Another factor producing a variation in results is the size and smoothness of the consolidation pot. All contact

Fig. 5. Compressibility of consolidometers.

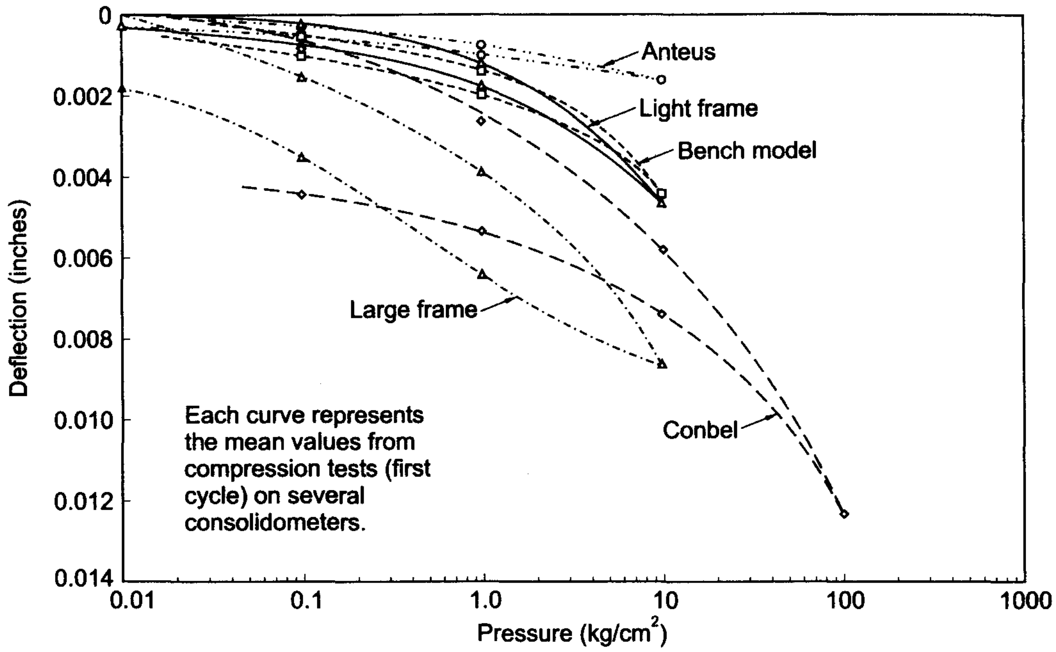


Table 2. Compressibility of consolidometers. Comparison of the first and second cycle of loading (Light frame consolidometer).

		Cycle #1		Cycle #2	
		Deflection[3] (inches)			
No. of observations	Pressure range[2] (kg/cm^2)	Mean	Standard deviation	Mean	Standard deviation
6	0.0 to 0.1	0.0002	0.0001	0.0002	0.0001
	0.1 to 1.0	0.0008	0.0002	0.0008	0.0003
	1.0 to 10.0	0.0030	0.0011	0.0026	0.0012
	10.0 to 1.0	0.0021	0.0009	0.0023	0.0011
	1.0 to 0.1	0.0009	0.0003	0.0008	0.0003
	0.1 to 0.01	0.0003	0.0001	0.0003	0.0001
	Residual[1]	0.0010	0.0003	0.0003	0.0001

[1]Residual is the term used for the difference between starting and finishing dial readings.
[2]1 kg/cm^2 is equal to 98 kPa.
[3]1 inch is equal to 25.4 mm.

areas should be machined smooth; however this is difficult to do on large size consolidation pot.

Even after machining the bases of several consolidation pots smooth, three times as much deformation occurred for a consolidation pot with a contact area of 150 cm^2 as one with a contact area of 30 cm^2, when loaded to 10 kg/cm^2 (980 kPa). The interchanging of any parts of the consolidometer pots between loading frames is poor practice since it changes the compressibility.

Prediction of compressibility of apparatus

By using the *t*-distribution for small samples it is possible to predict the number of compressibility tests necessary to statistically predict deformations within a certain limit of accuracy (Neville and Kennedy 1966).

$$Limit\ of\ Accuracy = \frac{t \cdot Standard\ Deviation}{\sqrt{Number\ of\ tests}}$$

where "t" is taken from tables in accordance with the number of observations used to define standard deviations. (A 95% level of significance is used in this paper).

Limit of accuracy curves could be drawn for each pressure range; however, it is better to have only one curve for each consolidometer or each type of consolidometer. For this reason, the standard deviation associated with the total deflection for the 0 to 10 kg/cm^2 (0 to 980 kPa) loading and 10 to 0.01 kg/cm^2 (980 to 0.98 kPa) unloading have been used. Table 5 shows a summary of the standard deviations for the various apparatus tested. The limit of accuracy curves for the first cycle of loading on various types of apparatus are shown in Fig. 8 and similar curves for individual consolidometers are shown in Fig. 9.

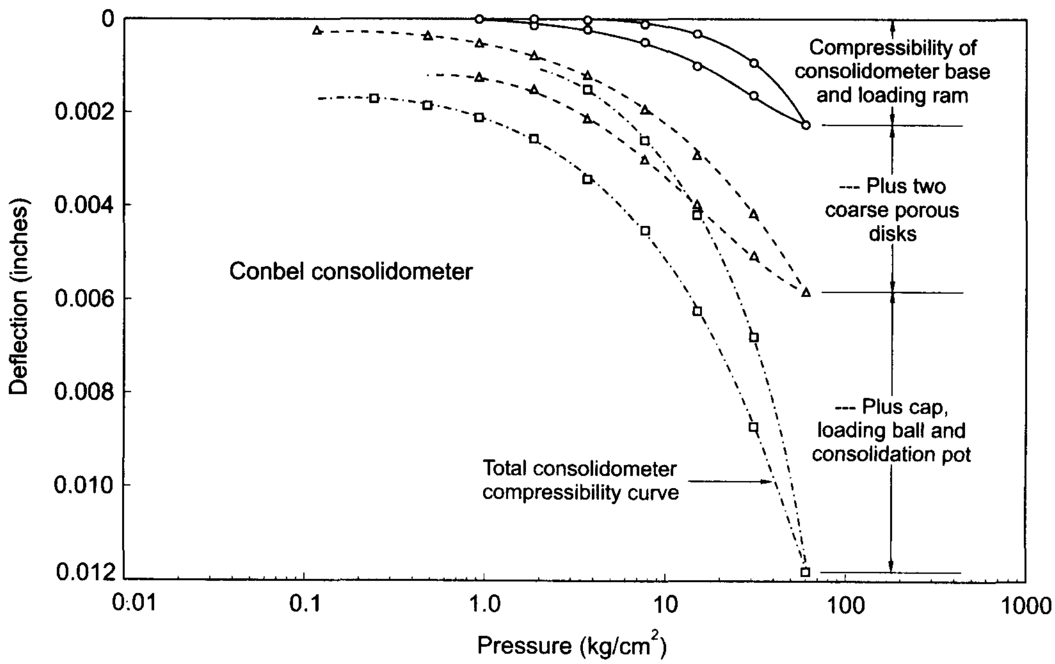
Depending upon the criteria set up, the number of compressibility tests necessary for a certain limit of accuracy can be established. For example, the curves show that for

Table 3. Compressibility of consolidometers. Repeated load cycling of a consolidometer.

Type of equipment	No. of observations	Pressure range[2] (kg/cm^2)	Deflection[3] (inches) Mean	Median	Standard deviation	95% Confid. limits	Coeff. of variation (%)
Light frame consolidometer #1	12	0.1 to 1.0	0.0012	0.0012	0.0002	0.0004	15.8
		1.0 to 10.0	0.0047	0.0047	0.0004	0.0008	8.3
		10.0 to 1.0	0.0040	0.0041	0.0002	0.0004	5.5
		1.0 to 0.1	0.0012	0.0012	0.0001	0.0002	9.0
		0.1 to 0.01	0.0003	0.0002	0.0001	0.0002	43.5
		Residual[1]	0.0007	0.0006	0.0005	0.0010	73.4
Light frame consolidometer #2	6	0.0 to 0.1	0.0001	0.0001			
		0.1 to 1.0	0.0007	0.0007	0.0002	0.0005	32.3
		1.0 to 10.0	0.0034	0.0035	0.0004	0.0008	12.3
		10.0 to 1.0	0.0029	0.0032	0.0005	0.0009	15.9
		1.0 to 0.1	0.0010	0.0010	0.0003	0.0005	25.3
		0.1 to 0.01	0.0023	0.0021	0.0008	0.0016	35.0
		Residual[1]	0.0010	0.0007	0.0009	0.0017	86.9
Large frame consolidometer #1	5	0.0 to 0.1	0.0026	0.0026	0.0002	0.0003	6.3
		0.1 to 1.0	0.0049	0.0046	0.0005	0.0009	9.5
		1.0 to 10.0	0.0059	0.0054	0.0013	0.0025	21.5
		10.0 to 1.0	0.0046	0.0047	0.0002	0.0004	4.2
		1.0 to 0.1	0.0049	0.0049	0.0002	0.0004	3.7
		0.1 to 0.01	0.0034	0.0035	0.0004	0.0008	11.6
		Residual[1]	0.0006	0.0003			

[1]Residual is the term used for the difference between starting and finishing dial readings.
[2]1 kg/cm^2 is equal to 98 kPa.
[3]1 inch is equal to 25.4 mm.

Fig. 6. Factors contributing to compressibility of consolidometer.



six compressibility tests on the light frame consolidometers, the total compressibility can be predicted within approximately 0.0012 inches (0.03 mm) using the first cycles of loading from several apparatus or within approximately 0.0005 inches (0.013 mm) using the results of six cycles on an individual consolidometer. The standard deviations for the loading and unloading portion of the compressibility curves are somewhat different but the highest standard deviation should be used to establish the number of tests necessary for a certain limit of accuracy.

Table 4. Elastic moduli of porous disks.

Type of porous disk	Pressure range[1] 0 to 0.1 kg/cm²	0.1 to 1.0 kg/cm²	1.0 to 10.0 kg/cm²
	Modulus of Elasticity in psi[2]		
Coarse corundum porous disks			8.28×10^4
2 — Fine, Norton porous disks	0.397×10^4	0.926×10^4	6.65×10^4
8 — Fine, Norton porous disks	0.339×10^4	0.802×10^4	3.85×10^4
Fine, thick Norton porous disks (Anteus)	9.26×10^4	46.3×10^4	160×10^4

[1] 1 kg/cm² is equal to 98 kPa.
[2] 1 psi is equal to 6.895 kPa.

Table 5. Compressibility of consolidometers. Data for limit of accuracy curves.

Type of consolidometer and procedure	No. of observations	Pressure range[1] (kg/cm²)	Deflection[2] (inches) Mean	Standard Deviation
First cycle of loading	25	0.0 to 10.0	0.0046	0.00113
Light frames		10.0 to 0.01	0.0044	0.00130
Bench models	6	0.0 to 10.0	0.0046	0.00298
		10.0 to 0.01	0.0044	0.00211
Large frames	10	0.0 to 10.0	0.0097	0.00384
		10.0 to 0.01	0.0074	0.00309
Cycling on one consolidometer				
Light frame #1	12	0.0 to 10.0	0.0062	0.00052
		10.0 to 0.01	0.0056	0.00060
Large frame #1	5	0.0 to 10.0	0.0135	0.00107
		10.0 to 0.01	0.0137	0.00205

[1] 1 kg/cm² is equal to 98 kPa.
[2] 1 inch is equal to 25.4 mm.

The lower load capacity consolidometers tested have lower standard deviations and, therefore the compressibilities can be predicted more accurately than for the higher load capacity consolidometers.

Compressibility of filter paper

Filter paper is often placed above and below the soil specimen during a consolidation test (Goris 1963; Fredlund 1962). However, its compressibility is of significant proportion. It not only has an instantaneous compression when the load is applied but also compresses with time (Fig. 10). The effects of varying the pressure and the load increment ratio on the slope of the log time deflection curves are shown in Fig. 11.

Figure 12 shows a plot of total compression after one day of loading versus applied load for a load increment ratio of one. At a pressure of 1 kg/cm² (98 kPa) the compression in the filter paper is approximately five times that of the apparatus and approximately 2½ times at a pressure of 10 kg/cm² (980 kPa).

The relatively large amount of compression and hysteresis effects make it advisable not to use filter paper when testing swelling soils. Various types of filter paper have been tested and each gives different results, although the general behavior is the same.

Seating of the porous stones and the soil specimen

Even after the compressibility of the apparatus is accounted for, there is still the problem of seating between the porous disks and the soil specimen (Seed et al. 1961). This is a volume change measured on the dial gauge but one which does not occur in the sample.

Commercial porous disks of coarse texture have a roughness (difference between the peaks and depressions) in the order of 0.05 inches (1.27 kPa) and the finer textured disks with smooth surfaces have a roughness in the order of 0.02 inches (0.5 mm). Measurements on trimmed soil samples showed roughness values varying from 0.001 to 0.02 inches (0.025 to 0.5 mm). Placing the two rough surfaces together and applying pressure permits seating. Seating occurs as the peaks from the soil surface fail and fit into the porous disk. In addition to sample roughness on a local scale there is the unevenness of the specimen surface on a larger scale.

To more accurately understand the seating of the specimen, the time-deflection curves of a number of consolidation tests were analyzed. After subtracting the compressibility of apparatus and the theoretical correction to zero reading from the instantaneous deflection, the remaining compression was assumed to be due to compressibility of air in the specimen and seating of the porous disks and the soil. If no seating is occurring, a plot of accumulated deflection versus pressure should approximate a straight line in accordance with Boyle's Law (Hilf 1948; Hamilton and Crawford 1959).

Fig. 7. Stress-strain properties of porous disks.

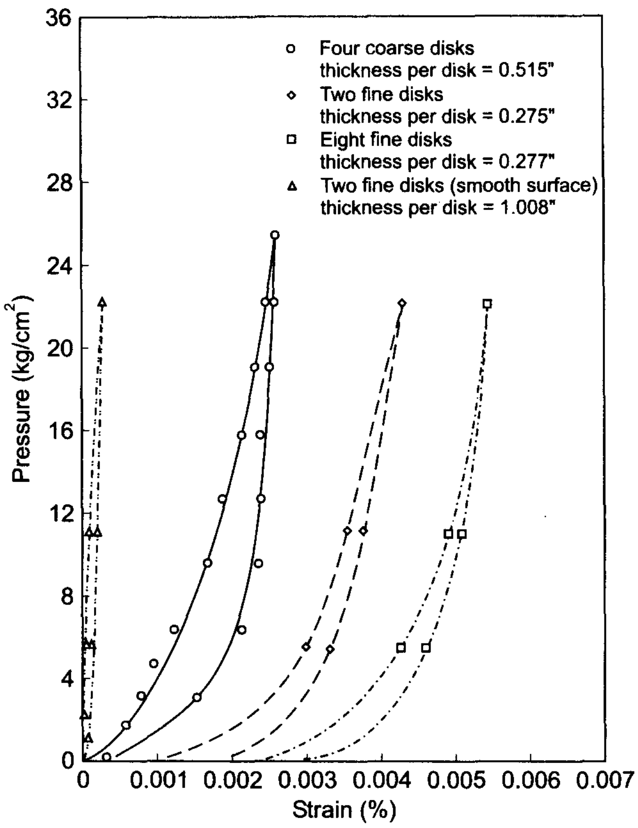


Figure 13 shows typical plots of accumulated deflection versus pressure for a constant volume and a free swell test. It should be noted that in the constant volume test, seating during the application of load up to the swelling pressure cannot be determined by this method. The free swell test shows the effects of seating during the lower loads. However, seating can also occur at higher pressures as shown by the example. Part of the deflection noticed at lower loads may be attributed to compression of air voids produced by cavitation as a result of sampling,

If no seating has occurred, the accumulated deflection versus pressure plot shows a straight line or a slightly concave shape. However, when seating is superimposed at various pressures, the plot shows distinct increases in accumulated deflection.

Since most seating occurs under low pressures, the modified procedure for the CV test gives a more accurate value for swelling pressure. Also, the seating correction does not appear to affect the rebound curve and therefore no correction for seating is necessary.

Discussion and applications

Compressibility of the consolidometer and accessories has a significant effect upon the interpretation of swell tests data. Two main properties are affected: first, the measurement of swelling pressure and second, the slope of the rebound curve.

Corrections for both properties can be made by subtracting deflections due to compressibility from the deflections measured during the test. In the FS test, deflections due to seating can also be evaluated and subtracted. In the conventional CV test the seating correction cannot be applied below the swelling pressure whereas in

Fig. 8. Limit of accuracy curves for first cycle of loading of consolidometers.

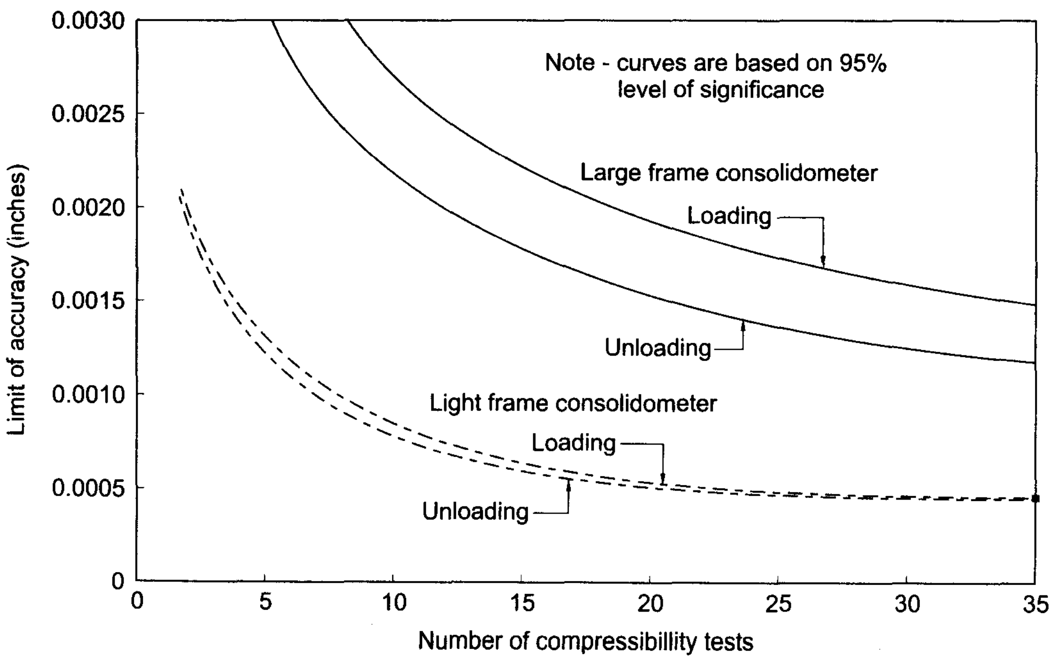


Fig. 9. Limit of accuracy curves for several cycles on one apparatus.

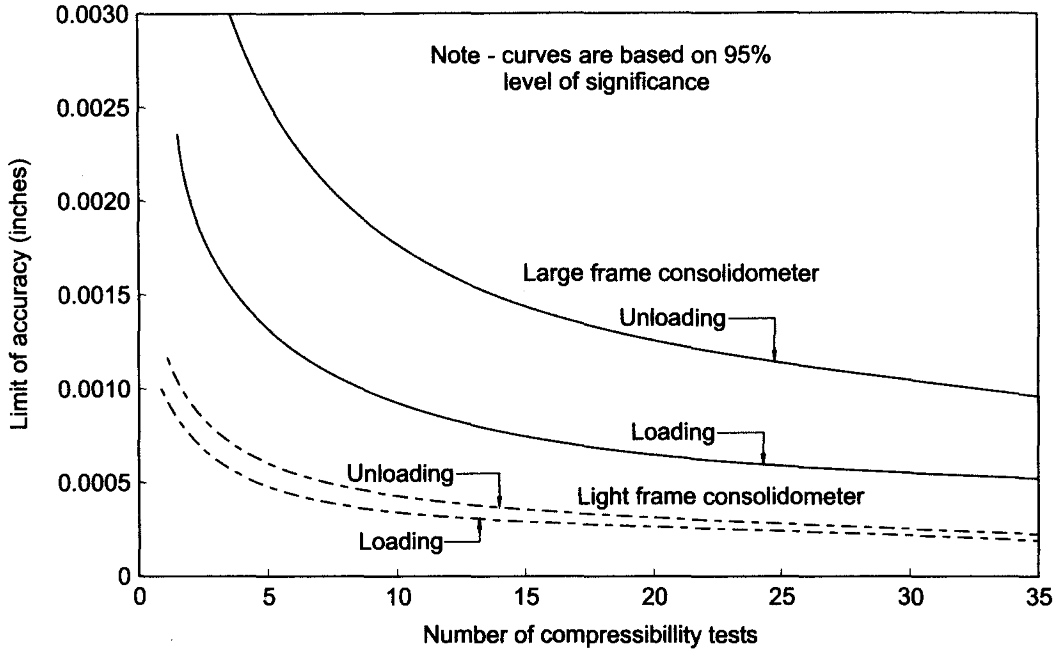
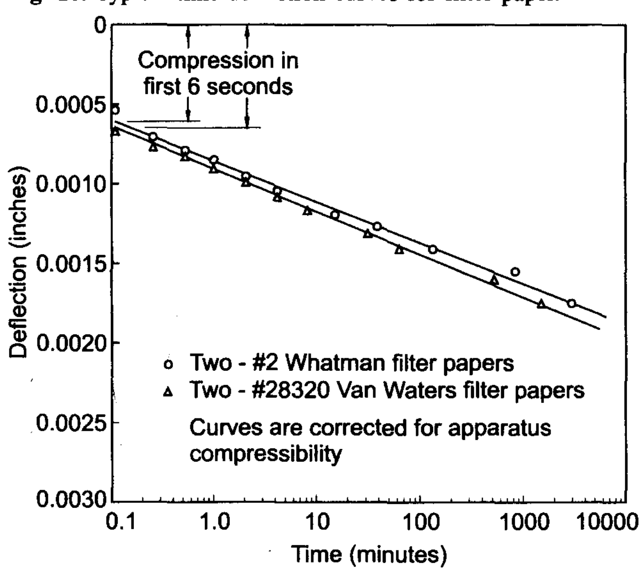


Fig. 10. Typical time-deflection curves for filter paper.



the modified CV test most of the seating has occurred while applying pressures up to the *in situ* total pressure.

Seed et al. (1961) showed that volume changes even in the order of a fraction of one percent cause significant changes in swelling pressure. Goris (1965) performed swell tests on Bearpaw shale and found compressibility of apparatus and filter paper to have a very pronounced effect on the swelling pressure measured (Fig. 14). Due to the low compressibility of the shale, the swelling changed from an uncorrected value of 2.05 kg/cm^2 to 11.7 kg/cm^2 (200 to 1147 kPa) when corrected. This figure also demonstrates the manner in which the swelling pressure can be evaluated when taking into account compressibility.

Taking into account compressibility always increases the swelling pressure. An analysis of 244 free swell consolidation tests performed in a commercial laboratory shows that more realistic values of swelling pressure are obtained after compressibility corrections are applied (Figure 15). The results at the 15 foot depth are low even after the corrections for compressibility are applied. This is believed mainly due to the more silty nature of the soil and the possibility of cavitation during sampling. In this case, seating and recompression of the soil when loaded to its *in situ* total stress are probably significant factors which have not been taken into consideration.

Hamilton (1965, 1968) reported the rapid swelling beneath an industrial building in Regina, Saskatchewan. Consolidation tests were performed from three depths below the concrete slab (Fig. 16). Ground movement gauges were also installed at three depths and precise elevation readings taken with time. Flooding due to a break in the water line occurred during the summer of 1962 and the floor heaved in excess of three inches in approximately one week. The results of the classification tests and consolidation test data are summarized in Table 6.

Table 7 compares the predicted heave and actual heaves measured. The swelling pressure was assumed to be the initial effective stress in the field while the final effective stress was assumed equal to the total stress. In other words, the final pore-water pressure is assumed equal to zero.

The results show relatively good agreement between the actual and the predicted movement. It appears from this case that underestimating the swelling pressure results in too low a prediction of heave.

Fig. 11. Slope of the time-deflection curves for filter paper.

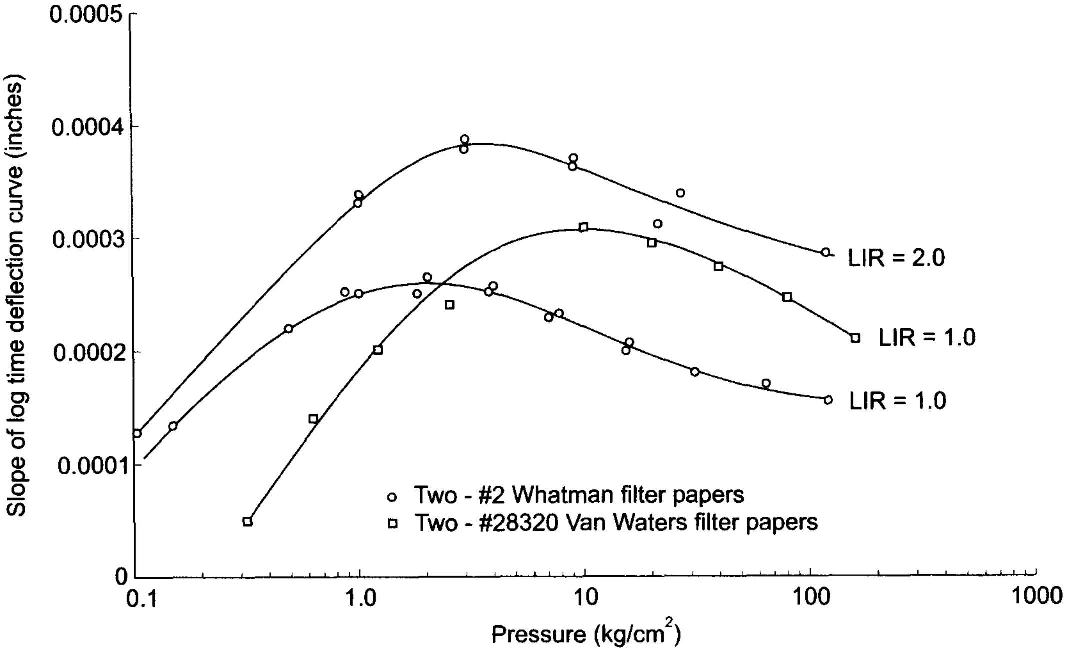
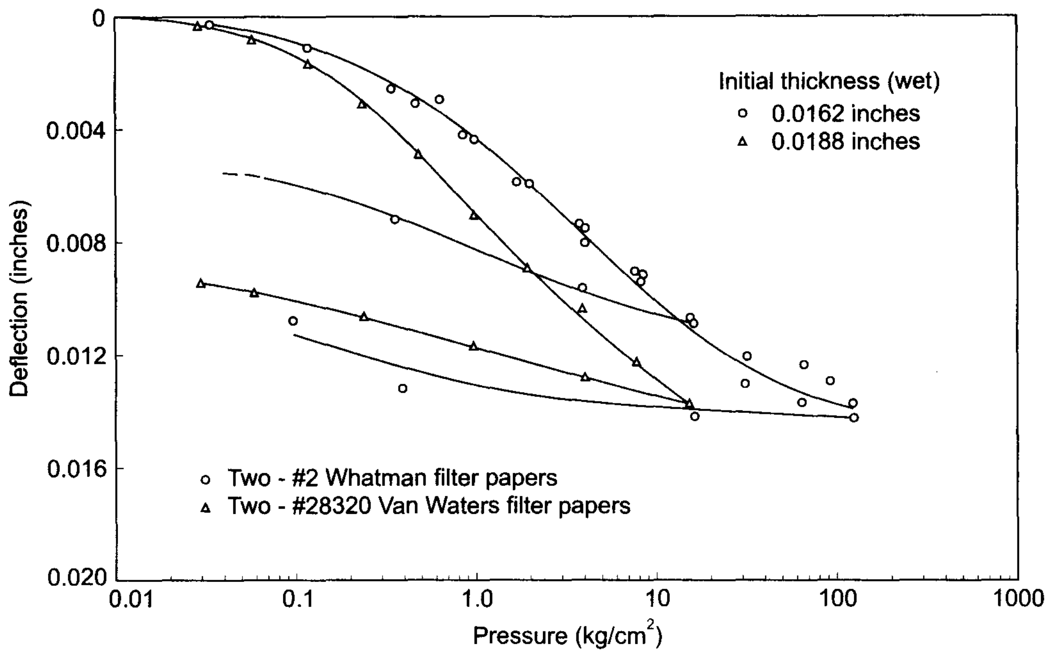


Fig. 12. Compressibility of filter paper.



Conclusions

The test procedure and apparatus used when testing for the properties of swelling clays have a significant effect upon the results obtained. The proposed modified CV swell test procedure overcomes many of the adverse procedural problems. The compressibility correction for the consolidometer should be applied to the results.

The characteristics of the consolidometer being used should be established prior to performing swell tests:

(1) Friction in the pressure measuring device appears to be of significance only under small pressures. Special significance should not be placed on the shape of the rebound curve at low pressures unless the applied pressures can be precisely determined.

(2) Consolidometer compression for both loading and unloading is of the same order of magnitude for apparatus produced by a specific manufacturer. However, the compressibility can be determined approximately twice as accurately by performing

Fig. 13. Typical plots of accumulated seating of porous disks and soil, and compression of the air in the soil.

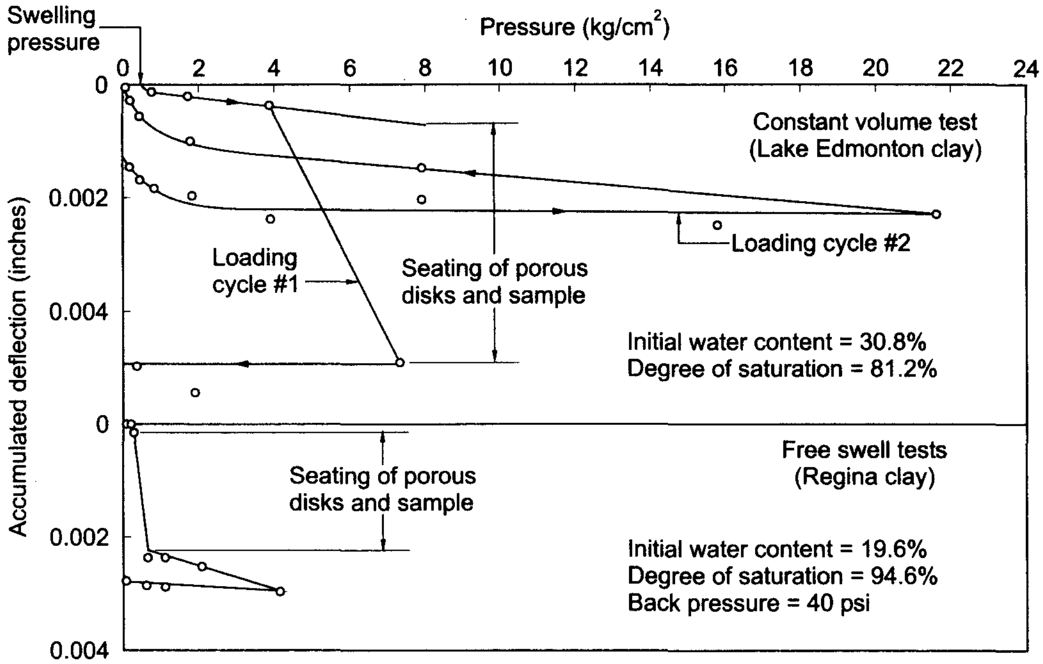
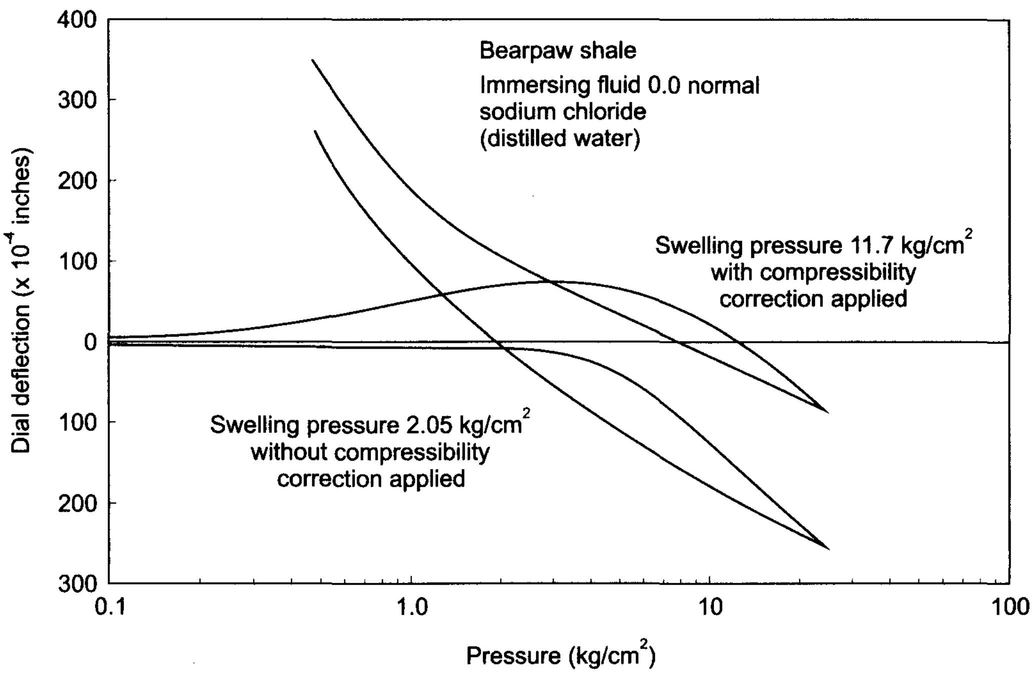


Fig. 14. Comparison of constant volume consolidation curves with and without compressibility correction applied (after Goris 1965).



compressibility tests on each consolidometer and always using the same components and accessories when testing.

The difference in compression between the first and succeeding cycles does not appear to be of significant magnitude.

(3) A high percentage of the compressibility is produced by the porous disks. Smoothly ground, thick stones appear to be the most satisfactory.

(4) Filter paper undergoes several times as much compression as the consolidometer upon loading and should not be used when testing for the swelling properties of soils.

(5) The seating of the porous disks and the soil specimen is difficult to evaluate and is of significance primarily under low pressures.

Attempts should always be made to evaluate the compressibility characteristics of the consolidometer when

Table 6. Summary of classification and constant volume consolidation test data.

Test No.	Depth[1] (feet)	Atterberg limits: Liquid limit	Atterberg limits: Plastic limit	% clay	Initial water content	Initial void ratio	Corrected slope of rebound curve C_s	Swelling pressure: Uncorrected[2] (psf)	Swelling pressure: Corrected (psf)
1	2.4	82	34	49	27.4	0.859	0.0940	6400	9240
2	4.6	74	32	46	27.9	0.983	0.0848	5200	7000
3	7.4	73	32	52	30.0	0.975	0.0962	1400	1700

[1] 1 foot equals 0.3048 m.
[2] 1 psf equals 48 Pa.

Table 7. Summary of predicted and actual heave (industrial building in Regina, SK, Canada).

Layer No.	Actual heave[1] (feet)	Predicted heave[1] (no corrections)(feet)	Predicted heave (%)	Corrected swelling pressure and rebound curve: Predicted heave[1] (feet)	Corrected swelling pressure and rebound curve: Predicted heave[1] (%)
1	0.175	0.0778	106	0.096	84
2		0.0878		0.113	
3	0.0333	0.0481		0.061	55
4	0.0667	0.1630	69	0.227	29
Total	0.2750	0.3767	41	0.497	

[1] 1 foot equals 0.3048 m.

Fig. 15. Uncorrected and corrected mean swelling pressured for Lake Edmonton clay.

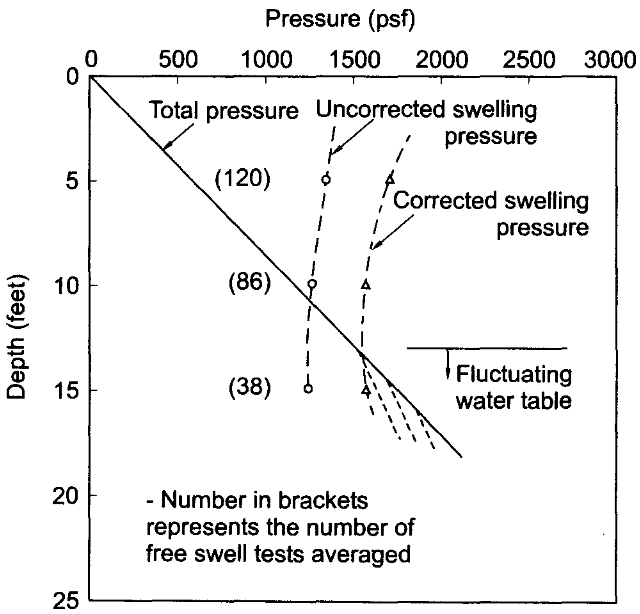
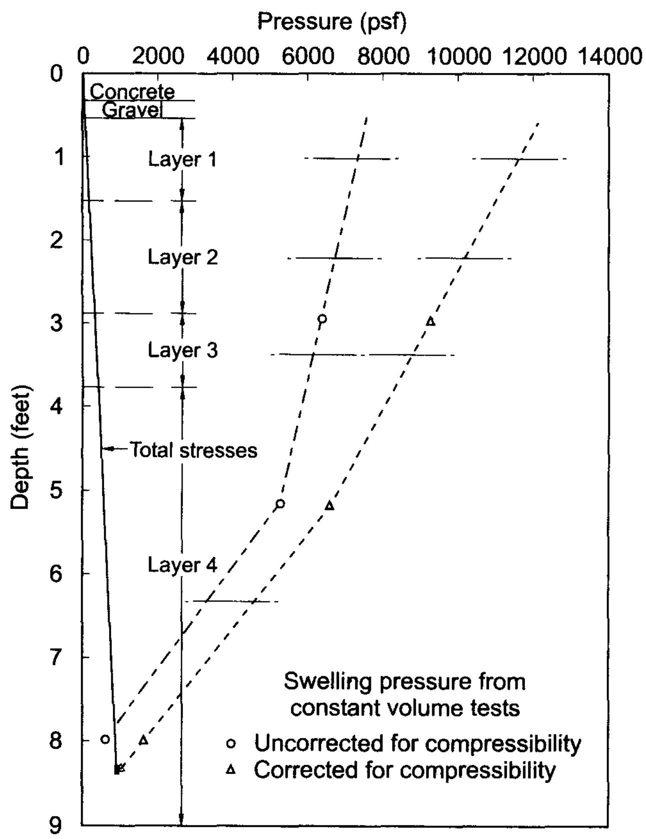


Fig. 16. Stresses below industrial building floor slab.



testing swelling soils. Compressibility corrections should then be applied to the test data to determine a corrected swelling pressure and corrected swelling index, C_s. Percentage errors without the corrections can be in excess of 100% for the swelling pressure and generally 10 to 50% for the swelling index.

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