Measurement of swelling pressure: direct method versus indirect methods

Kamil Kayabali and Saniye Demir

Abstract: Light structures including highways and railroads built over potentially expansive clay soils may suffer damage from swelling. Considerable research has been done in an attempt to characterize swelling properties of expansive soils. Although direct measurement of swelling pressure is relatively straightforward, it has not drawn much interest. The present study attempts to measure swelling pressure directly. We call experimental techniques for swelling pressure other than this direct method the indirect methods. Some indirect methods require more than one soil sample and that all samples be identical. However, natural soils may not always provide identical samples. Therefore, reconstructed identical soil samples produced from natural soils were used in the present study. For comparison, the restricted swell, swell-consolidation, double oedometer, and zero swell tests were employed as indirect methods. While the restricted swell test slightly underestimated swell pressure, swell-consolidation and zero swell tests overestimated it. The double oedometer test did not provide swell pressures correlatable with those found using the direct method. Free swell data correlated reasonably well with swell pressure data from the direct method, so an empirical form was established from which swell pressure can be easily estimated.

Key words: expansive soils, swelling pressure, free swell, zero swell, restricted swell, double oedometer.

Résumé : Les structures légères comme les autoroutes et les chemins de fer construits sur des sols argileux potentiellement expansifs peuvent subir des dommages en raison du gonflement. Des travaux de recherche considérables ont été réalisés dans le but de tenter de caractériser les propriétés de gonflement des sols expansifs. Même si la mesure directe de la pression de gonflement est relativement simple, celle-ci n'a pas attiré beaucoup d'intérêt. La présente étude tente de mesurer la pression de gonflement directement. Les méthodes expérimentales de mesure de la pression de gonflement, autres que la méthode directe présentée, sont appelées les méthodes indirectes. Certaines méthodes indirectes nécessitent plus d'un échantillon, et requièrent que les échantillons soient identiques. Cependant, les sols naturels ne permettent pas toujours d'obtenir des échantillons identiques. Alors, des échantillons de sol reconstruits et identiques produits à partir de sol naturel ont été utilisés dans cette étude. Les méthodes indirectes du gonflement restreint, du gonflement-consolidation, de l'odomètre double et les essais de gonflement zéro ont été utilisés à des fins de comparaison. Tandis que l'essai de gonflement restreint sous-estime légèrement la pression de gonflement, les essais de gonflement consolidation et de gonflement zéro la surestiment. L'essai de l'odomètre double n'a pas fourni de pressions de gonflement pouvant être corrélées avec celles obtenues par la méthode directe. Des données de gonflement libre sont raisonnablement bien corrélées avec les pressions de gonflement obtenues par la méthode directe, alors une formulation empirique a été développée à partir de laquelle la pression de gonflement peut être facilement estimée.

Mots-clés : sols expansifs, pression de gonflement, gonflement libre, gonflement zéro, gonflement restreint, odomètre double.

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Introduction

Expansive soils can adversely affect light civil engineering structures, such as highways, railroads, runways, canals, utility lines, and low-rise buildings. Jones and Holtz (1973) reported that damage caused by expansive soils is more than double the total damage from natural disasters, such as earthquakes, floods, hurricanes, and tornados. The cost of damage arising from expansive soil problems in the USA alone amounts to US$2.3 billion annually (Dhowian et al. 1988; Erzin and Erol 2004).

Swelling soils are those that undergo volumetric changes upon wetting and drying. The principal cause of expansion in those soils is the presence of expansive clay minerals such as montmorillonite. Swelling soil problems are usually encountered in semi-arid regions, such as the southwestern part of the USA, southern Africa, and Australia, where seasonal changes in water content of the subsoil or fluctuations of shallow ground water levels are high. These events take place mostly in the upper 6 m of soil (Bell 2005).

Swelling pressure is the pressure required to hold the soil, or restore the soil, to its initial void ratio when given access to water (Shuai 1996). Numerous studies have been published relating swelling pressure to index properties, such as dry unit weight, initial water content, clay content, consistence limits, and cation exchange capacity (e.g., Alonso et

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Table 1. Atterberg limits for 12 soil samples.

No.	LL	PL	PI
EM3	54	25	29
EM4	52	24	28
EM5	56	25	31
EM6	57	23	34
EM7	56	25	31
EM9	83	33	50
EM10	84	30	55
Z1	71	28	43
Z2	74	31	43
Z3	69	27	42
Z4	93	32	61
Z5	79	30	49

Note: LL, liquid limit; PL, plastic limit; PI, plasticity index.

Table 2. Percentage of sand, silt and clay components in 12 soil samples according to Unified Soil Classification System (USCS) (ASTM 2006).

No.	Sand (%)	Silt (%)	Clay (%)
EM3	15	40	45
EM4	17	43	40
EM5	12	40	48
EM6	24	23	53
EM7	33	25	42
EM9	5	40	55
EM10	2	28	70
Z1	10	35	55
Z2	8	46	46
Z3	10	36	54
Z4	3	38	59
Z5	7	36	57

al. 1992; Basma et al. 1995; Rao et al. 2006). There is general agreement that swelling pressure increases with increasing dry unit weight, increasing clay content and decreasing initial water content. In addition, empirical relationships have been developed between swelling pressure and some basic soil properties (e.g., Thomas et al. 2000; Erzin and Erol 2004; Rao et al. 2004). For example, Komornik and David (1969) related swelling index to liquid limit, dry unit weight, and initial water content. Vijayvergiya and Ghazzaly (1973) established a relationship between swelling pressure and liquid limit and dry unit weight. Nayak and Christiensen (1971) and Erzin and Erol (2004) proposed relationships between swelling pressure and plasticity index, initial water content, and clay content.

To predict swelling pressure, numerous laboratory tests have been proposed. Laboratory tests currently used to evaluate the swelling pressure of expansive soils are the free swell, zero swell, loaded swell, restricted swell, constant volume, swell-consolidation, and double oedometer tests, all of which are essentially modifications to the one-dimensional simple oedometer test. The most commonly used tests amongst those listed are the free swell, constant volume, zero swell, and swell-consolidation tests (Petry et al. 1992; Basma et al. 1995; Shuai 1996; Attom and Barakat 2000).

There is an ample amount of literature related to more specific aspects of the swelling behavior of soils. For instance, different from the most common analysis technique of examining swelling behavior in one direction, Hawlader et al. (2003) examined the three-dimensional stress effects on time-dependent swelling behavior of Queenston shale and proposed a model capable of predicting the swelling behavior of shales under multiaxial stresses. Hawlader et al. (2005) developed a numerical model to analyze the case histories of two tunnels in Canada from the standpoint of the effects of swelling on underground structures in three dimensions. Vu and Fredlund (2004) investigated the one-, two-, and three-dimensional heave in expansive soils. They showed that the prediction of heave, based on the general theory of unsaturated soil, provides a practical means of estimating multidimensional heave in unsaturated expansive soils. Erzin (2007) attempted to investigate swell pressure versus soil suction using artificial neural networks (ANNs) and concluded that the ANNs model for predicting the swell pressures from easily determined soil properties exhibited considerably high correlations.

Two important issues with the various single oedometer tests used to determine swell pressure should be emphasized. The first is the wide discrepancy between the results of the various one-dimensional oedometer tests. In a specific instance, Sridharan et al. (1986) showed that swelling pressure obtained from the constant volume test for a soil sample was 380 kPa, while the free swell test for the same soil gave a value of 1300 kPa. This simple example illustrates that the discrepancy between the different tests can be as high as several hundred percent. The second point to draw attention to is the extreme values (as high as 3400 kPa) reported by Shuai (1996). These issues seem to indicate that the swelling pressure values obtained using various simple oedometer tests bear high degrees of uncertainty. Obviously, it is imperative to introduce a test method with a smaller degree of uncertainty for swelling pressure, by which the reliability of the other test methods can be assessed.

The goal of this investigation is to compare direct and indirect swelling tests and to show the degree of discrepancy that indirect methods introduce. We call our specific design the direct method, in which swelling pressure is measured via a load cell under constant volume. The indirect methods used for comparison are the zero swell, swell-consolidation, restricted swell, and double oedometer tests.

Materials

Twelve high-plasticity soils were selected for the investigation. Natural soil samples collected from different parts of the formation locally known as Ankara clay were first oven-dried and then sieved through No. 40 mesh. Several kilograms of each soil were reserved to conduct all types of swell tests. The Atterberg limits of soils used in the investigation are presented in Table 1 as supplementary data. In addition, sieve analyses were performed on minus No. 40 material for each sample; the percentages of different grain sizes are given in Table 2. To show the dominant mineral types in each soil, X-ray diffraction analyses were conducted (Table 3).

Table 3. Types and ratios (approximate, %) of common minerals in soil samples.

	Ratio (%)											
Type	EM3	EM4	EM5	EM6	EM7	EM9	EM10	Z1	Z2	Z3	Z4	Z5
Aragonite	31	69	28	36	25	33	34	36	27	32	52	33
Chlorite	—	—	42	9	29	37	36	15	30	36	19	37
Magnetite	17	2	15	2	14	18	17	—	15	18	3	18
Quartz	12	22	10	12	8	11	12	—	1	3	18	11
Kaolinite	—	7	5	41	24	1	1	—	27	11	8	1
Polygorskyte	20	—	—	—	—	—	—	31	—	—	—	—
Albite	7	—	—	—	—	—	—	17	—	—	—	—
Muscovite	13	—	—	—	—	—	—	—	—	—	—	—
Vermiculite	—	—	—	—	—	—	—	1	—	—	—	—

Fig. 1. Swell pressure measurement apparatus devised for this study.

To prepare identical samples from the natural soil samples, the following procedure was employed.

Because water content strongly influences swell pressure, the first step was to set up the identical water content for all 12 samples so that the results of the swell tests using different techniques would have a common basis for comparison. Although there is not a specific rationale behind the choice, the plastic limit was considered to be the appropriate water content to conduct the swell tests. The majority of the soil plastic limits used in the investigation were around 25, so this water content was selected for the preparation of identical samples.

Considering that some amount of water evaporates during sample preparation, a water mass corresponding to 26% (so that the ultimate water content was reduced to about 25%) of dry mass was added to the minus No. 40 material and mixed until a homogeneous mixture was obtained. Ninety grams of wet soil (which, based on experience, is approximately the mass required to create a wet density of 2.0 Mg/m^3 or so) was poured in two portions into a 50 mm diameter cylindrical container. Each portion was tapped gently using a metal piston. Next, the cylinder containing the lightly compressed soil was placed in a loading frame where one end was capped and a compressive load was applied from the other end via a 49.5 mm diameter ram. Compression continued until an ultimate load of 10 kN (equivalent to about one metric ton) at a constant speed was attained. For practical purposes only and for no apparent valid reason, a ram speed of 0.5 mm/min was applied. The compressed sample was then transferred to a consolidation ring with a diameter of 50 mm and a height of 20 mm,

Table 4. Water content (w), soil density (ρ), swell pressures (SP), and average swell pressure for 12 soil samples as found using the direct method.

No.	w (%)	ρ (Mg/m^3)	SP (kPa)	SP (kPa) Mean
EM3	24.9	2.01	79	70
	24.9	2.03	63	
	24.8	2.01	72	
EM4	25.3	2.01	71	70
	24.6	2.00	65	
	25.0	2.00	74	
EM5	25.2	2.00	132	150
	25.2	2.00	161	
	24.2	2.03	147	
EM6	25.3	1.99	80	80
	25.5	1.99	80	
	25.1	1.99	84	
EM7	25.1	2.00	75	80
	25.9	1.99	89	
	24.6	1.99	83	
EM9	25.8	2.00	915	930
	25.6	2.00	956	
	24.9	1.98	930	
EM10	25.3	2.03	729	700
	25.2	2.03	712	
	26.2	2.01	672	
Z1	25.5	2.06	377	370
	26.1	2.04	345	
	25.7	2.03	383	
Z2	24.3	2.03	709	690
	25.0	2.03	623	
	24.8	2.02	729	
Z3	25.5	2.06	264	270
	26.0	2.04	272	
	25.7	2.03	281	
Z4	24.4	2.00	1064	1040
	24.5	2.02	1031	
	24.3	2.01	1024	
Z5	25.3	2.00	672	655
	25.7	2.00	637	
	25.5	2.00	656	

Fig. 2. Swell pressures for 40 specimens of soil sample Z5 recorded at different water contents.

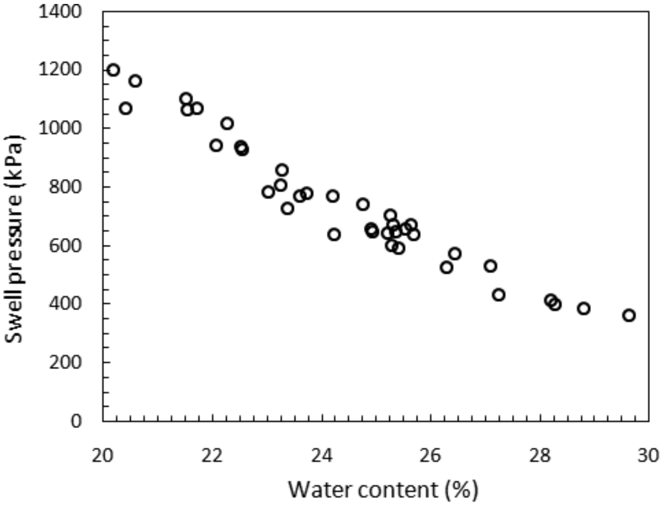


Fig. 3. Sample plot for determination of swell pressure using the restricted swell test on soil sample EM9.

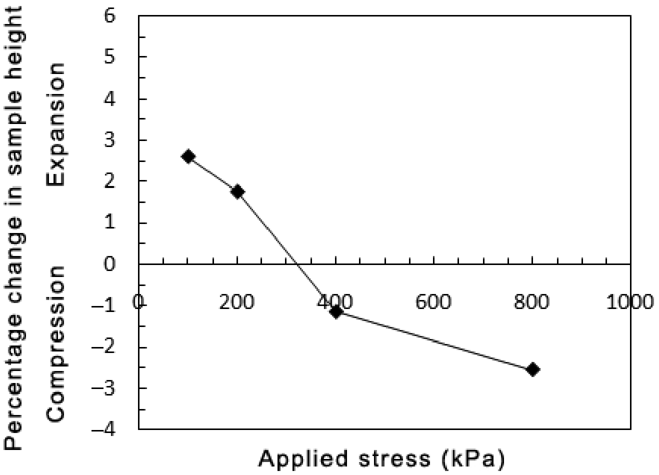


Table 5. Water content (w), soil density (ρ), consolidation stress (σ'), strain (ε), and swell pressure (SP) values for 12 soil samples as found using the restricted swell test.

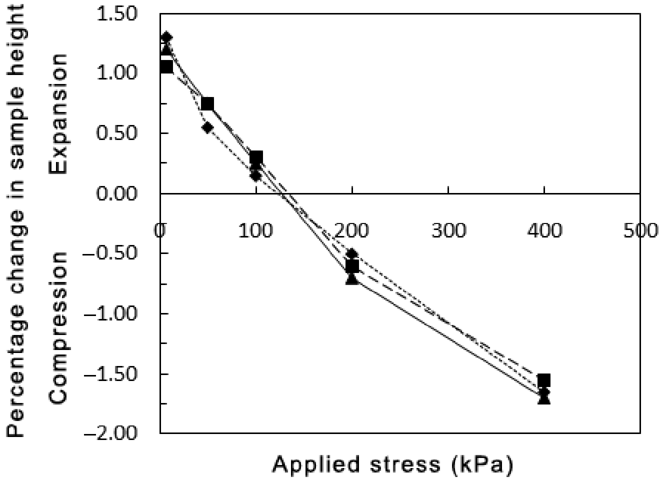
No.	w (%)	ρ (Mg/m^3)	σ' (kPa)	ε (%)	SP (kPa)
EM-3	24.1	2.03	50	0.3	70
	25.5	2.00	100	–0.3	
	25.5	1.97	200	–1.7	
	25.7	1.98	400	–2.3	
	25.5	2.00	800	–4.6	
EM-4	25.5	1.97	100	–0.1	95
	25.7	2.00	200	–1.4	
	25.6	2.00	400	–2.0	
	25.7	1.98	800	–4.0	
EM-5	24.3	2.03	50	0.4	85
	25.6	1.98	100	–0.2	
	25.8	2.02	200	–1.5	
	25.7	1.94	400	–2.3	
	25.7	2.01	800	–4.1	
EM-6	25.9	1.98	50	0	50
	25.6	1.99	100	–0.8	
	25.4	2.00	200	–1.6	
	25.8	2.00	400	–2.8	
EM-7	25.8	1.98	100	0.6	140
	25.4	1.99	200	–0.8	
	25.6	2.00	400	–2.5	
	25.9	1.99	800	–3.5	
EM-9	24.9	1.97	100	5.6	650
	24.8	1.98	200	5.3	
	25.6	1.90	400	2.2	
	25.0	1.98	800	–1.3	
EM-10	25.6	2.04	100	4.1	600
	25.8	2.01	200	1.8	
	25.8	2.02	400	0.7	
	25.6	2.04	800	–0.7	
Z-1	24.9	2.02	100	2.7	320
	25.3	2.03	200	1.4	
	25.5	2.04	400	–0.7	
	25.4	2.03	800	–1.5	
Z-2	25.6	2.00	100	4.2	470
	25.5	1.99	200	1.5	
	25.3	1.97	400	0.3	
	25.4	2.04	800	–1.4	
Z-3	25.2	2.04	100	1.5	220
	25.2	2.04	200	0.2	
	24.9	2.06	400	–1.5	
	25.3	2.06	800	–2.3	
Z-4	25.0	2.00	100	5.5	850
	25.5	1.96	200	4.7	
	24.9	2.03	400	1.9	
	24.9	1.99	800	0.3	
	24.5	2.03	1200	–1.6	
Z-5	25.3	2.02	100	2.6	400
	25.3	2.05	200	1.8	
	25.2	2.04	400	–1.2	
	25.9	2.02	800	–2.6	

and the upper and lower surfaces of the soil were leveled using a steel straightedge. The mass of the ring plus the wet soil was recorded and the sample was subjected to the swell test. Three samples were prepared for each method except in the case of the restricted swell test where four samples were used.

Methods

The direct method consists of a main frame, a load cell of 5 kN capacity, a floating ring–type conventional oedometer cell, and a digital read-out unit (Fig. 1). This technique is called the direct method because of its ability to provide the swelling force directly. A better nomenclature than the direct swell test would perhaps be a constant volume or zero strain swell test; however, there are some constraints on the stiffness of the load cell that prevent us from naming the test in this way. To run this test, the soil sample in the consolidation ring is first placed into the oedometer cell or the consolidometer. It is then placed in the loading device and a seating load of 10 N is applied, so that there is no gap between the metal bar connected to the load cell and the upper cap on the soil sample. Finally, the soil sample is inundated and left to swell. The swell force is recorded at the end of 24 h and the initial seating force is deducted. The remaining net force is divided by the cross-sectional area of the soil

Fig. 4. Sample plot for determination of swell pressure using the swell-consolidation test on soil sample EM3.



sample and recorded as the swelling pressure for the direct method. It should be mentioned that, while a great portion of swelling takes place in 24 h, swelling may continue for days — particularly for high plastic clays. The 24 h period has been selected only for practical comparison purposes.

The double oedometer test was first described by Jennings and Knight (1957). It was originally proposed for use with collapsible soils and has, with some modifications, become a widely used test. In this test, two samples are subjected to oedometer tests. One is the simple swell test, in which the soil sample is first inundated and the percent change in the sample height (i.e., free swell) is recorded at the end of 24 h. The second sample is tested at its natural water content and is subjected to a vertical stress generally in the range of 25 to 100 kPa. Loading continues until the amount of expansion experienced with the free swell test is passed. The results are plotted as the percent change (i.e., compression) in the sample height versus vertical stress. The vertical stress corresponding to the decimal value of the percent of expansion change (from the free swell test) in the vertical axis is determined to be the swelling pressure.

In the swell-consolidation test, the sample in the consolidometer is inundated and allowed to swell freely. The amount of free swell is recorded at the end of 24 h. Next, the sample is subjected to a vertical stress, usually starting at 25 kPa. Loading continues at a load increment ratio of 1 until the amount of free swell under vertical stress is totally eliminated. The results are then transferred to a graph of the percent change in sample height versus vertical stress. The graph has both expansion and compression on the vertical axis; the point where the curve crosses the horizontal zero percent change line is the swelling pressure.

In the zero swell test, the sample is first placed in a consolidometer, an initial seating load of 7 kPa (1 psi) is applied, and the extensometer deformation device is adjusted to read zero. The specimen is then inundated and increments of vertical stress are applied to prevent swelling. Variations from the deformation reading at the time the specimen is inundated are preferably kept between 0.005 and 0.010 mm. The specimen is kept under pressure until there is no tendency to swell. The vertical stress at this point is recorded as the swelling pressure.

For the restricted swell test, four to six identical specimens are needed. The specimens are placed in consolidometer cells, and deformation extensometers are adjusted for the starting value. The range of vertical stresses to be applied to the specimens is selected so that the expected swelling pressure remains within the range. The specimens are inundated immediately after loading. Following inundation, the specimens tend to swell. The specimens loaded at less than the swelling pressure expand, while those loaded at more than the swelling pressure compress. The results are plotted as the percent change in specimen height versus vertical stress. The point on the vertical stress axis where the zero deformation line crosses the experimental curve is designated as the swelling pressure.

Experimental work and results

Twelve high-plasticity soils were used to compare swell pressures as reported via the different methods. The first series of tests included determination of swell pressures using the direct method. For this series, three samples were prepared for each soil as defined previously. The results are given in Table 4. To check whether there is any difference between the swell pressures reported for the same soil as well as to verify the repeatability of the direct method, 40 Z5 soil specimens were tested. The results are plotted in Fig. 2. While there is some scatter, the deviations from the mean line are negligibly small, indicating that the repeatability of the proposed direct method is reasonably good.

Four specimens of each soil sample were used to run the restricted swell tests. The test data obtained from each soil type were evaluated using charts such as the one shown in Fig. 3. The resulting swell pressures are presented in Table 5 along with water content, total density, and applied pressure versus strain data.

Experimental data from the swell-consolidation tests using three specimens for each soil sample were first evaluated using a graph such as that shown in Fig. 4. Swell pressures for all soils are listed in Table 6 along with the associated data.

Figure 5 is a sample plot demonstrating the results of the double oedometer tests on three specimens of one soil type only. The data pertaining to this test are presented in Table 7 along with the swell pressures for each soil type.

Results obtained from the zero swell test using three specimens of each soil are plotted in Fig. 6. Swell pressures obtained this way are given in Table 8 along with the pertinent data.

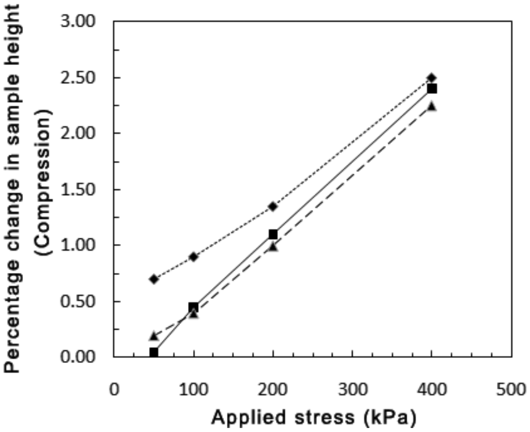
Swell pressures obtained using the direct method are correlated with those of the restricted swell, swell-consolidation, double oedometer, and zero swell tests in Figs. 7 through 10, respectively. While there appears to be a good correlation, R^2, between the swell pressures reported using the direct method and the restricted swell test ($R^2 = 0.96$), the restricted swell test slightly underestimates swell pressure if swell pressures derived using the direct method are accepted to be true and valid.

When the direct method is compared with the swell-consolidation test, there is a very high correlation ($R^2 = 0.98$); however, the swell-consolidation test overestimates swell pressure. The difference between the results of the

Table 6. Water content (*w*), soil density (*ρ*), and recorded strains for various levels of consolidation stress (*σ*′, in kPa) along with the resulting swell pressure as found using the swell-consolidation test.

			Recorded strains								
No.	*w* (%)	ρ (Mg/m^3)	$\sigma' = 7$	$\sigma' =$ 50	$\sigma' =$ 100	$\sigma' =$ 200	$\sigma' =$ 400	$\sigma' =$ 800	$\sigma' =$ 1200	$\sigma' =$ 1600	SP (kPa)
EM-3	25.9	2.00	1.05	0.75	0.30	–0.60	–1.55	—	—	—	150
	26.0	1.94	1.30	0.55	0.15	–0.50	–1.65	—	—	—	
	25.9	2.03	1.20	0.75	0.25	–0.70	–1.70	—	—	—	
EM-4	26.2	1.97	1.50	0.10	–0.60	–1.90	–2.95	—	—	—	90
	26.5	1.98	0.75	0.50	0.20	–0.55	–2.15	—	—	—	
	26.4	2.00	0.25	0.20	0.05	–1.15	–2.85	—	—	—	
EM-5	26.2	1.98	1.15	0.75	0.30	–0.20	–1.10	—	—	—	160
	26.3	2.00	1.35	1.10	0.70	0.00	–1.35	—	—	—	
	26.0	1.94	0.90	0.45	0.15	–0.55	–1.95	—	—	—	
EM-6	26.4	1.97	2.20	1.95	1.40	0.15	–1.75	—	—	—	240
	26.4	1.96	1.60	1.60	1.25	0.70	–1.25	—	—	—	
	26.5	1.98	0.90	0.80	0.60	0.20	–1.65	—	—	—	
EM-7	26.2	1.94	1.10	1.00	0.70	–0.20	–1.80	—	—	—	200
	25.6	1.99	2.50	1.50	1.00	0.00	–1.60	—	—	—	
	25.8	1.97	1.55	1.30	1.05	0.30	–1.20	—	—	—	
EM-9	25.5	1.98	9.15	—	—	8.25	7.50	5.50	3.60	2.05	1800
	24.7	1.97	9.50	—	—	4.50	4.05	2.80	1.55	0.30	
	25.3	1.98	8.35	—	—	7.45	6.70	4.75	2.50	1.40	
EM-10	25.0	1.99	8.15	—	—	7.15	5.80	3.10	0.90	–0.80	1400
	25.1	2.04	9.00	—	—	7.65	6.45	3.75	1.50	–0.10	
	24.7	2.03	9.15	—	—	7.20	5.90	3.20	0.95	–0.80	
Z-1	25.8	2.04	4.55	4.80	4.60	3.90	2.45	–0.25	—	—	750
	26.0	2.03	4.45	4.40	4.35	4.15	3.30	1.20	—	—	
	25.0	2.02	4.90	—	4.30	3.85	2.60	0.20	–1.60	—	
Z-2	26.3	2.01	7.40	—	—	—	4.70	2.20	0.45	–1.25	1600
	24.8	1.97	9.65	—	—	—	5.35	3.10	1.35	–0.05	
	24.3	2.03	7.00	—	—	—	4.75	3.05	1.50	0.05	
Z-3	25.8	2.01	4.45	—	3.70	3.05	1.75	–0.50	–2.15	—	450
	25.8	2.03	3.40	—	3.05	2.75	1.60	–0.40	–2.05	—	
	25.9	2.03	2.50	—	2.10	1.60	0.45	–1.70	–3.35	—	
Z-4	24.8	2.02	11.75	—	—	10.15	8.65	5.59	3.75	1.95	1950
	24.2	1.94	11.65	—	—	9.85	8.80	6.65	4.80	3.15	
	24.8	2.01	11.85	—	—	9.90	8.30	5.75	3.80	2.20	
Z-5	26.4	2.02	7.50	—	6.95	6.40	5.10	2.55	0.60	—	1300
	26.4	2.00	7.65	—	7.00	6.45	5.15	2.45	0.45	—	
	26.5	2.02	6.95	—	6.45	5.70	4.85	1.60	–0.50	—	

Fig. 5. Sample plot for determination of swell pressure using the double oedometer test on soil sample EM6.



swell-consolidation test and the direct method seems consistent and about twofold (Fig. 8), which draws attention and deserves further investigation. Providing that this fact is validated with a broader database, the swell-consolidation test can be a convenient tool to determine swell pressure without requiring additional effort (such as employing the direct method), because it is one the most common tests used on fine soils.

A quick glimpse at Fig. 9 reveals that there is practically no reasonable relationship at all between those two methods based on the data used. Swell pressures obtained using the double oedometer test are extremely high, greater than 2000 kPa for five soil types.

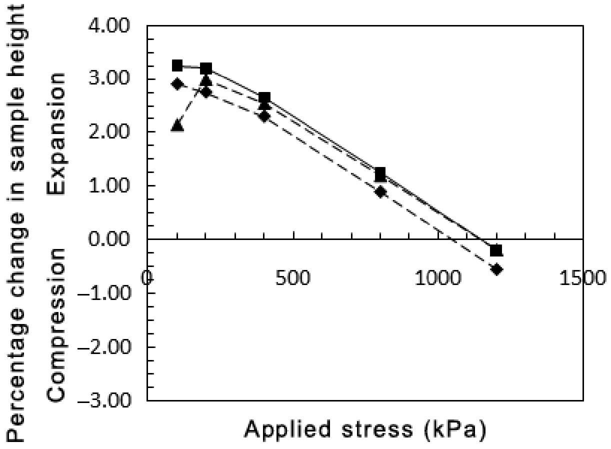
The relationship between swell pressures obtained using the direct method and the zero swell test is displayed in Fig. 10. This comparison indicates that the zero swell test overestimates swell pressure in general.

While the initial intention was not to seek a relationship

Table 7. Water content (w), soil density (ρ), and recorded strains for various levels of consolidation stress (σ', in kPa) along with the resulting swell pressure as found using the double oedometer test.

			Recorded strains						
No.	w (%)	ρ (Mg/m^3)	σ' = 50	σ' = 100	σ' = 200	σ' = 400	σ' = 800	σ' = 1200	SP (kPa)
EM-3	26.1	2.00	1.10	1.30	1.90	3.00	—	—	180
	26.2	1.93	0.20	0.50	1.00	2.00	—	—	
	26.0	2.00	0.70	0.90	1.40	2.45	—	—	
EM-4	25.9	1.99	0.65	0.75	1.15	2.00	—	—	180
	25.8	2.00	0.40	0.50	0.90	1.80	—	—	
	25.8	2.00	0.25	0.35	0.70	1.55	—	—	
EM-5	25.6	1.98	0.10	0.25	0.60	1.50	—	—	250
	25.7	2.01	0.05	0.30	0.85	2.00	—	—	
	26.1	2.00	0.70	1.10	1.50	2.50	—	—	
EM-6	25.4	1.99	0.70	0.90	1.35	2.50	—	—	250
	25.4	1.99	0.05	0.45	1.10	2.40	—	—	
	25.4	2.00	0.20	0.40	1.00	2.25	—	—	
EM-7	25.4	1.95	—	1.20	1.60	2.75	3.80	4.80	150
	26.1	1.95	—	2.00	2.80	4.25	6.05	7.40	
	26.1	1.99	—	1.30	2.05	3.10	4.75	5.25	
EM-9	25.9	1.97	—	0.30	0.50	0.90	1.50	1.95	>2000
	25.5	1.98	—	0.40	0.60	1.10	1.90	2.50	
	26.2	1.97	—	0.10	0.30	0.60	1.25	1.85	
EM-10	25.5	2.02	—	0.25	0.40	0.80	1.60	2.40	>2000
	25.2	1.99	—	0.20	0.35	0.80	1.60	2.45	
	25.4	2.05	—	0.15	0.15	0.40	0.90	1.50	
Z-1	25.8	2.00	—	1.15	1.45	2.10	3.05	3.95	1700
	25.8	2.00	—	1.10	1.50	2.20	3.30	3.90	
	25.6	2.02	—	0.50	0.75	1.30	2.25	3.20	
Z-2	25.4	2.08	—	0.35	0.45	0.75	1.40	1.95	>2000
	25.6	1.97	—	0.50	0.75	1.25	2.00	2.80	
	25.2	2.04	—	0.35	0.55	0.90	1.60	2.45	
Z-3	25.5	2.02	—	0.65	0.95	1.50	2.15	2.75	1700
	25.7	2.03	—	0.25	0.30	0.45	1.15	2.15	
	25.3	2.02	—	0.60	0.90	1.35	2.20	2.80	
Z-4	25.8	2.00	—	0.85	1.25	2.05	3.20	4.20	>2000
	25.2	1.98	—	1.20	1.75	2.55	3.80	4.85	
	25.3	2.02	—	0.70	0.85	1.50	2.35	3.20	
Z-5	25.4	2.03	—	0.45	0.70	1.10	1.80	2.65	>2000
	25.8	2.04	—	0.65	0.90	1.40	2.20	2.70	
	25.3	2.03	—	0.60	0.85	1.40	2.25	2.85	

Fig. 6. Sample plot for determination of swell pressure using the zero swell test on soil sample Z5.



between swell pressure measured using the direct method and free swell, there is a reasonable match between two data pairs (Fig. 11), showing that swell pressure can be estimated easily from free swell tests. To determine whether an empirical relationship can be established between swell pressure and free swell, an additional 10 samples were tested using the direct method and free swell test. Again, three specimens were used for each of the two testing methods. The results are given in Tables 9 and 10. By using the additional swell pressure and free swell data along with those in Fig. 11, a new graph was constructed (Fig. 12). The coefficient of correlation between swell pressure and free swell is reasonably high (R^2 = 0.93). It is observed from Fig. 12 that swell pressure can be estimated from the free swell using the empirical form

$$\text{SP} = 93.3\text{FS} - 53.4 \qquad [1]$$

where SP is the swell pressure (kPa) and FS is the free swell (%).

Table 8. Water content (w), soil density (ρ), and recorded strains for various levels of consolidation stress (σ', in kPa) along with the resulting swell pressure as found using the zero swell test.

			Recorded strains							
No.	w (%)	ρ (Mg/m^3)	σ' = 50	σ' = 100	σ' = 200	σ' = 400	σ' = 800	σ' = 1200	σ' = 1600	SP (kPa)
EM-3	24.8	2.01	–0.05	–0.25	–0.65	—	—	—	—	60
	24.7	1.95	0.25	0.00	–0.40	—	—	—	—	
	24.9	2.03	0.00	–0.15	–0.60	—	—	—	—	
EM-4	25.3	1.99	–0.15	–0.20	–0.45	—	—	—	—	100
	25.3	2.01	0.00	–0.05	–0.35	—	—	—	—	
	24.6	2.00	0.10	0.05	–0.25	—	—	—	—	
EM-5	24.8	1.99	0.25	0.00	–0.65	—	—	—	—	100
	24.5	2.00	0.70	0.50	–0.15	—	—	—	—	
	24.8	2.02	–0.25	–0.40	–0.55	—	—	—	—	
EM-6	25.6	1.99	–0.10	–0.45	—	—	—	—	—	80
	25.3	1.96	0.10	–0.05	—	—	—	—	—	
	25.1	1.98	0.10	–0.05	—	—	—	—	—	
EM-7	25.5	1.99	0.05	–0.25	–1.05	—	—	—	—	110
	25.2	2.00	0.40	0.35	–0.25	—	—	—	—	
	24.9	1.98	–0.50	–0.70	–1.05	—	—	—	—	
EM-9	25.5	1.97	—	—	3.85	3.50	2.25	0.75	–0.75	1400
	25.8	2.00	—	—	2.85	1.95	1.50	0.70	–0.10	
	24.5	1.99	—	—	3.30	3.25	2.20	1.10	–0.10	
EM-10	25.7	2.01	—	3.50	3.35	2.90	1.45	0.15	–1.10	1200
	25.6	1.99	—	3.35	3.35	2.55	0.60	–1.10	–2.65	
	26.0	2.04	—	3.80	4.00	3.50	1.75	–0.15	–1.75	
Z-1	25.4	1.96	—	0.80	0.85	0.35	–0.95	–2.45	—	400
	25.9	2.02	—	0.45	0.40	0.05	–1.05	–2.35	—	
	24.8	2.03	—	0.50	0.30	–0.25	—	—	—	
Z-2	25.4	2.02	—	2.10	2.15	1.90	1.00	–0.05	—	1100
	25.2	2.03	—	3.00	3.00	2.45	1.15	–0.15	—	
	27.1	2.03	—	2.00	2.15	1.75	0.75	–0.40	—	
Z-3	25.9	2.01	—	0.70	0.50	–0.15	—	—	—	450
	25.6	2.03	—	1.00	0.75	0.00	—	—	—	
	24.5	2.03	—	1.75	1.50	0.75	—	—	—	
Z-4	24.9	1.96	—	4.40	4.50	3.75	2.00	0.40	–1.05	1300
	25.5	2.00	—	4.55	5.00	4.55	3.00	1.40	0.00	
	24.9	2.02	—	3.00	2.90	1.90	—	—	—	
Z-5	25.4	2.00	—	2.90	2.75	2.30	0.90	–0.55	—	1100
	25.7	2.00	—	3.25	3.20	2.65	1.25	–0.20	—	
	26.0	2.01	—	2.15	3.00	2.55	1.20	–0.20	—	

Fig. 7. Comparison of restricted swell test results and the direct method.

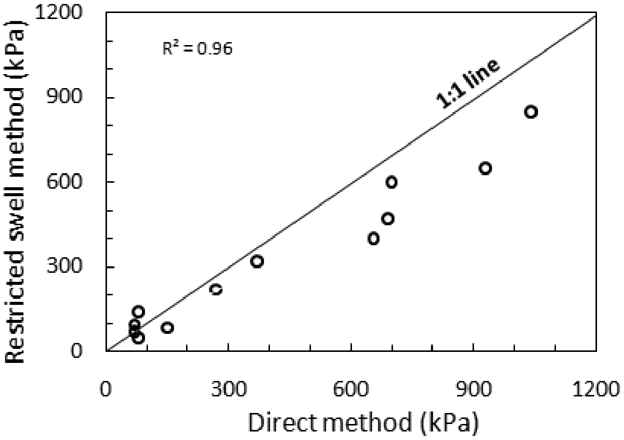


Fig. 8. Comparison of swell-consolidation test results and the direct method.

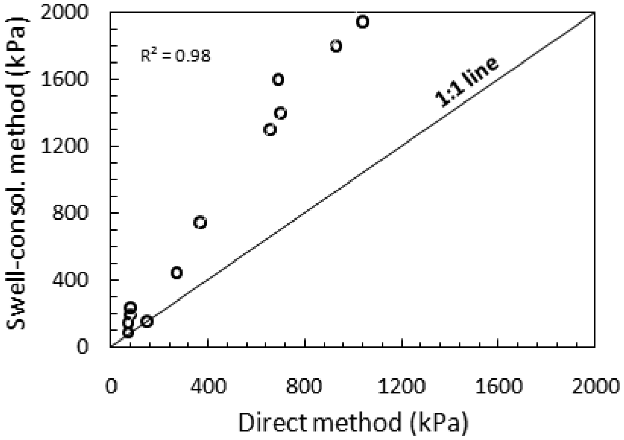


Fig. 9. Comparison of double oedometer test results and the direct method.

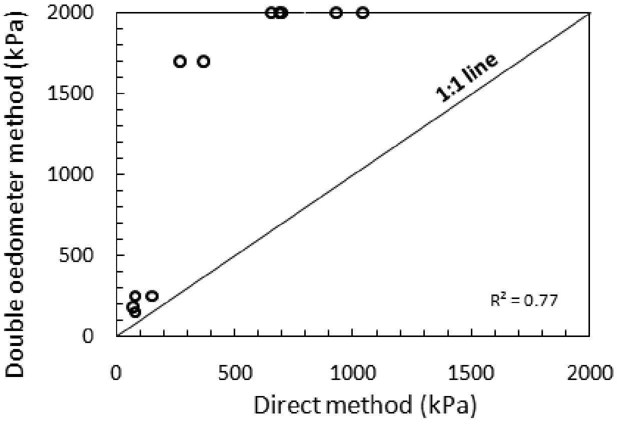


Fig. 10. Comparison of zero swell method results and the direct method.

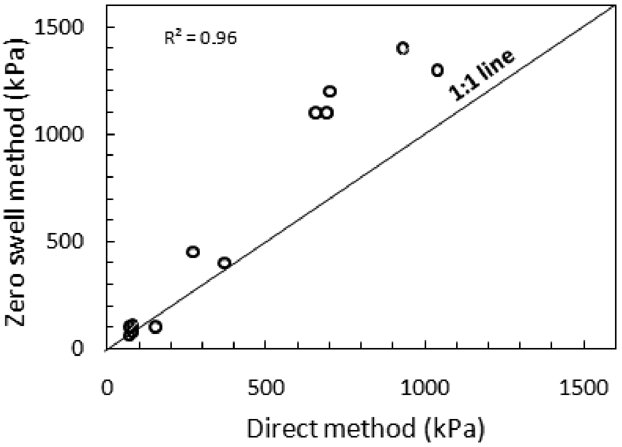


Fig. 11. Comparison of free swell data and swell pressure data for 12 samples only.

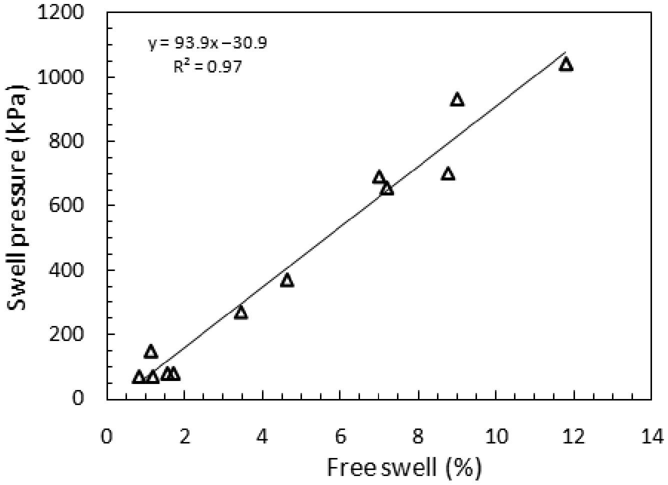


Table 9. Water content (w), soil density (ρ), swell pressures (SP), and average swell pressure for the additional 10 soil samples as found using the direct method.

No.	w (%)	ρ (Mg/m^3)	SP (kPa)	SP (kPa) Mean
CA-3	25.4	2.01	319	350
	25.1	2.02	340	
	24.8	2.02	380	
EY-1	24.8	1.96	254	290
	24.5	1.96	284	
	24.0	1.96	329	
EY-3	24.6	1.98	194	205
	24.4	1.98	211	
	23.8	2.01	213	
EY-5	24.5	1.89	806	870
	24.5	1.88	879	
	24.6	1.84	925	
EY-8	24.6	1.91	309	310
	24.8	1.91	299	
	24.3	1.92	327	
MK-1	25.2	2.04	503	525
	25.5	2.01	502	
	25.7	2.02	575	
MK-2	25.7	2.01	778	785
	25.4	2.02	790	
	25.1	2.01	789	
MK-5	24.9	2.05	739	810
	24.5	2.04	893	
	24.5	2.04	801	
YY-1	24.8	2.03	125	115
	25.2	2.02	106	
	25.0	2.02	121	
YY-2	25.0	2.01	736	675
	25.2	2.01	614	
	25.4	2.02	679	

Discussion and conclusions

Some of the important conclusions that can be drawn from this investigation are as follows:

(1) The restricted swell test slightly underestimates the swell pressure. While there is a high correlation between swell pressures obtained using this test and the direct method, this test suffers from the problem of needing several identical specimens for a single test, which is sometimes difficult.

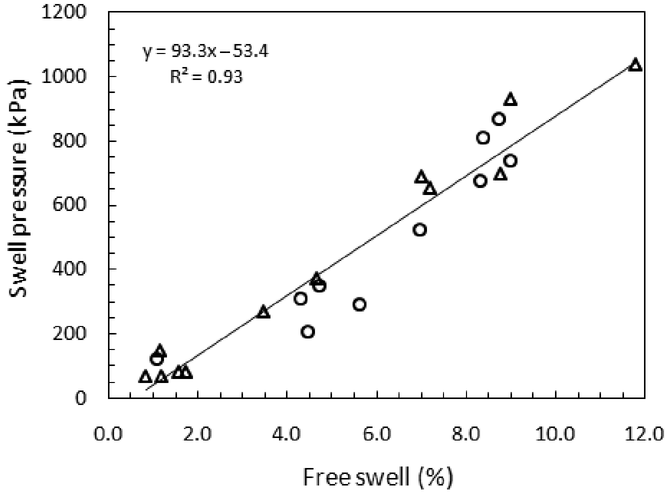
(2) The swell-consolidation test overestimates swell pressure. The degree of overestimation is about twofold and rather consistent. As discussed by Basma et al. (1995), the most likely reason for the higher swelling pressures registered during the swell-consolidation test as opposed to the direct method is the high pressure needed to expel the pore water absorbed during inundation. However, as the swell-consolidation test is a routine laboratory test conducted on fine-grained soils in most site investigation cases, this method deserves further attention. A broader database may lead to the establishment of an empirical relationship to predict swell pressure from a swell-consolidation test.

(3) There is practically no correlatable relationship between swell pressure measured with the double oedometer test and swell pressure measured using the direct method. The double oedometer test requires two identical samples, one for the free swell test and the other for the loaded oedometer test. However, samples may not

Table 10. Water content (w), soil density (ρ), free swell (FS), and average free swell for the additional 10 soil samples using the direct method and zero swell test.

No.	w (%)	ρ (Mg/m^3)	FS (%)	FS (%) Mean
CA-3	25.2	2.01	4.45	4.7
	24.8	2.01	4.95	
	24.6	1.97	4.80	
EY-1	26.1	1.97	5.40	5.6
	25.7	1.98	5.80	
	25.3	1.97	5.60	
EY-3	25.7	2.01	4.35	4.5
	25.1	1.98	4.50	
	25.3	2.02	4.55	
EY-5	25.1	1.92	9.30	8.7
	24.8	1.91	8.70	
	25.2	1.91	8.15	
EY-8	25.1	1.92	4.40	4.3
	24.9	1.85	4.15	
	25.1	1.92	4.50	
MK-1	24.4	2.04	6.45	7.0
	24.7	1.99	7.05	
	24.4	2.02	7.40	
MK-2	24.5	2.02	9.05	9.0
	25.0	2.01	8.70	
	25.0	2.02	9.25	
MK-5	24.2	2.04	8.45	8.4
	24.0	2.05	9.05	
	24.0	2.05	7.60	
YY-1	24.4	2.03	1.05	1.1
	24.7	2.02	0.85	
	25.2	2.03	1.35	
YY-2	25.2	2.00	7.75	8.3
	24.7	1.97	8.35	
	24.8	2.02	8.75	

Fig. 12. Comparison of free swell data and swell pressure data including an additional 10 samples.



always be identical. In addition, the determination of swelling pressure is erroneous in that the amount of deformation (i.e., expansion) from the free swell test is compared with the amount of deformation seen in the loaded specimen's deformation, which is in compression, and the pressure corresponding to this amount of deformation is fixed as the swelling pressure. This approach has two important drawbacks. One is the implication that the swell and shrink behavior is linear; the other is the comparison between the properties of saturated and partially saturated specimens.

(4) The zero swell test also overestimates swell pressure. Before asserting that there can be an empirical form between swell pressures reported from the zero swell test and the direct method, more tests need to be conducted. It is somewhat surprising that the results from zero swell tests do not agree with the direct method, given that the two methods basically share the same mechanism. This is perhaps because it is difficult to control the load in the zero swell test to achieve absolutely zero swell. It is unclear if the swelling has absolutely ceased when the dial gauge indicates zero heave. In fact, it is more logical to expect some amount of compression after a zero reading and it is probably the most likely reason for the zero test giving higher values than that of the direct method.

(5) The correlation between swell pressure measured using the direct method and free swell is considerably high. It is proposed that swell pressure can be predicted from free swell using the empirical form SP = 93.3FS – 53.4, which can be refined by using a broader database in further investigations.

(6) The apparatus devised for this investigation for directly measuring swell pressure is simple, robust, and gives reasonably reliable and repeatable results. It is proposed as a convenient tool for measurement of the swelling pressure of expansive soils.

(7) Swelling pressure measured using the direct method is considered to be slightly less than the true value, due to the stiffness of the load cell. The higher the stiffness of the load cell, the lower the degree of error that should be expected in swelling pressure measurements. For future studies, the compressibility of the testing apparatus needs to be taken into account to better define the swelling pressure.

We emphasize that these are all different methods involving different physical mechanisms. Each method was developed as a means for predicting swelling pressure. Our goal is not to compare those methods one versus another. Rather, we question their reliability by comparison with the presumably more reliable one.

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