Direct Swell Pressure Measurement by using Newly Designed Proving Ring- A Comparative Study

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Abstract: Expansive soils are perhaps the most challenging soils in the world. They are prone to swelling with variations in seasonal moisture conditions. Hence, this change in soil volume can cause significant structural damages in overlying light buildings such as highway pavements, low-story buildings and alike. A number of attempts have been made to evaluate the swelling pressures of expansive soils using different methods by oedometer test set- up with applied stress. Till date, the direct method, for measuring the swelling pressure, has not received much attention. However, in case of expansive soils stabilized using chemical binder which is involved with time depended pozzolanic reaction, a direct measure of swelling pressure in swelling phase itself would perhaps be more reliable. Hence, in this study, a direct method was employed where a proving ring, was designed and calibrated to measure the amount of swelling pressure in the swelling phase itself. Swell- consolidation tests were employed as indirect methods. Results indicated that the highest swelling pressures were measured by swell- consolidation test. The lowest measures were produced by the direct method, respectively. It could be argued that during the swell- consolidation tests the development of cementation particle might be effected to the swell pressure. In direct method swell pressure has measured in the first 24 hours, hence the impact of cementation on swell pressure might be less.

Keywords: Swell Pressure, Expansive Soil, Pozzolanic Reaction, Oedometer, Direct Method.

1 Introduction

Expansive soils bear potential for shrinkage or swelling under changing moisture conditions (Nelson and Miller, 1997). During the expansion, the upward pressure effects the foundation, and in case the pressure is greater than the foundation pressure, it causes damage. Thus, understanding the amount of this pressure is important in designing the structures. To predict the swelling pressure, several studies have been conducted till date. Sridharan et al. (1986) performed a study to investigate the swelling pressures using three different methods. In the first method called swell-consolidation, the sample was permitted to swell at a seating pressure while the

sample is getting saturated (full swelling), followed by subsequent loading to bring it back to its initial height. In second method, known as the restricted swell test, three or more specimens were loaded to different pressures (around the estimated swell pressure), followed by inundation with water. In the third method, called as the constant volume, the sample was imbibed in water, and with applying the stress the volume keeping zero. In these methods, the swelling pressure is equal to the stress applied to the specimens, where the deformation curve crosses the stress axis for swelling consolidation test and restrain test. In case of the constant method, stress applied to keep the change in the specimen volume as zero, was considered as the swelling pressure. However, a wide discrepancy between the results of these tests was pointed out by literature (Sridharan et al., 1986; Nagaraj et al., 2009; Atom and Barakat, 2000; Kayabali and Demir, 2011; and Singhal et al., 2011), who stated the high degree of uncertainty in swelling pressure values obtained using various oedometer tests.
Also, it should be noted that the above investigations carried out on natural expansive soil, whereas the key question is the validity of those procedures for expansive soil stabilized with using chemical additives, resulted in modification and pozzolanic reaction that introduces a cementite specimen. The pozzolanic reaction might influenced on actual swell pressure during the loading process in swell- consolidation tests when the sample returns to its initial height. Hence, it is essential to introduce a test method, where the swelling pressure measure in the swelling phase itself.

In our study, the swelling pressure of expansive soil has been measured by a direct method with the help of newly designed proving ring. This method is a kind of constant method test, do not allow vertical displacement; so, the advantage to conventional constant method is not require to control the load in the zero swell test to achieve absolutely zero swell since there will always be some amount of compression after a zero reading (Kayabali and Demir, 2011). Therefore, a methodology similar to direct measurement of swelling pressure employed by Kayabali and Demir (2011) has been applied. The indirect methods used for comparison in this study included the swell- consolidation and restricted swelling tests. It should be noted that all tests have been carried out on natural expansive soil and treated soil using Calcium carbide (CaC2). For this experimental work, a proving ring was designed, fabricated and calibrated which involves the structural and geo- technical knowledge. Since Libii (2006) created a successful design based upon the Whittmore- Petrenko proving ring, a similar methodology was applied for our investigation.

2 Test materials

Model soil material is selected in such a way that represents high expansion and high swell pressure. Natural soil was collected from Nanded city which are located in Sinhagad road in Pune city, Calcium carbide (CaC_2) was collected from High Purity Laboratory Chemicals Pvt. Ltd., and stainless steel (SS316). The index properties of the soil, its classification, and chemical composition are shown in Tables 1 and 2 respectively. Table 2 revealed that clay soil had about 70% silica oxide and aluminum oxide (natural pozzolans). In addition, the Calcium carbide had about 65% calcium oxide. Therefore, it was considered that aluminum silicates from the clay together with calcium from Calcium carbide would form cementitious materials of CSH and CASH, in the presence of water. The ring was made in a circular- shape. Two strain gauges (Tokyo sokki kenkyujo Co., Ltd., Japan) were also utilized in the design of the proving ring.

Table 1. T Basic physical properties of soil and Calcium carbide used for the investigation

Index	Soil	Calcium Carbide
Hygroscopic water content , w_h(%) [a]	13.35	---
Specific gravity, G_s	2.685	2.24
Liquid limit, w_L (%)	92	---
Plastic limit, w_P (%)	45	---
Shrinkage limit (%)	15.27	---
Free swell index (%)	135	---
Maximum dry unit weight, ρ_{dmax} (kN/m^3)	12.66	---
Optimum moisture content, w_{opt} (%)	35.5	---
Particle size distribution (%):		
Clay (<0.002 mm)	66	12
Silt (0.002 to 0.075 mm)	26	64
Sand (0.074 to 4.75 mm)	7	24
Gravel (>4.75 mm)	1	---
Unified soil classification symbol[b]	CH-MH	---
Degree of expansion	High to very high	---
pH	8.14	12.6

[a] determined by an air- drying method
[b] CH, high plasticity clay; MH, high plasticity silt

3 Experimental procedure

3.1 Proving ring

In order to measure the swelling pressure during the swelling process, a force sensor was used. This force sensor is a variation of Whittmore- petrenko proving ring (Libii, 2006). It was revised based on the design method used by Libii (2006) with maximum capacity of 1 kN. Two strain gauges were attached on the inner surface of the ring, and another two were mounted on its outer surface, exactly at the opposite of the ones inside. All four were connected as Wheatstone bridge, which is an electrical circuit. To measure an unknown electrical resistance, the ring becomes a load cell that measures strain. Figure 1 shows the fabricated proving ring. Before starting the tests, proving ring was calibrated for loading. It was calibrated using the oedometer set- up. The proving ring was placed between the rigid solid mass and the supporting beam as shown in Figure 2. The incremental load applied for the purpose of calibration, in our direct method, was similar to the amount of load used in oedometer tests (0- 80 kg). Each step load was kept for two minutes, and the output voltages were read by HBM-MX1615 data logger (Hottinger Baldwin Messtechink, GmbH, Germany).

Table 2. Major chemical composition of the soil and Calcium carbide

Chemical composition (%)	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	K_2O	CaO	MgO	MnO	TiO_2	P_2O_5	BaO	SrO	SO3
Soil	49.8	17.2	13.85	2.56	2.41	7.93	2.12	0.86	1.70	0.1	0.19	0.02	0.3
Calcium carbide	12.77	15.48	1.28	0.35	0.47	64.97	0.26	0.01	0.36	0.06	0.47	0.01	0.11

- Inside diameter: d_i = 50 mm;
- Thickness: t = 3.0 *mm*;
- Width of the ring: w = 10 *mm*;

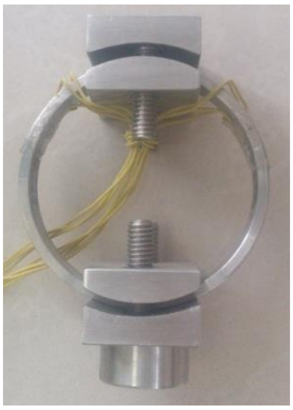

Fig. 1. View of proving ring, The fabricated ring used in the laboratory.

3.2 Specimen preparation

The specimens were prepared as described below. The required amount of oven-dried soil (size < 4·75 mm) was manually mixed with the required amount of water to obtain a homogenous soil- water mix. In case of treated soil, soil was mixed by Calcium carbide in dry state (6% of dry soil- by weight). After attaining the homogeneous admixture of soil and binder, the desire amount of water was added. Before placing the soil, the inner surface of the ring was lubricated with grease to reduce side- wall friction. The soil was then placed in the oedometer rings (75 mm in diameter and 25 mm in height), and compacted its maximum dry density (MDD) and optimum moisture content (OMC) in three layers. Prior to the tests, several samples were prepared to check the final density. After air- drying of the porous stone, it was positioned at the bottom of a dry oedometer. Subsequently, a filter paper was placed on top of the porous stone. A ring containing the soil specimen was then placed on top of the bottom porous stone and filter paper. Another air- dried filter paper was placed on top of the specimen, on top of which another porous stone and the loading pad was placed. The test specimen was then mounted in the oedometer, and positioned on the loading frame (see Fig. 2).

3.3 Test methods

The direct method consisted of an oedometer set- up, a proving ring, oedometer cell, and a digital read- out unit. This technique is called the direct method because of its ability to provide the swelling pressure directly. To start the tests, after placing the cell in the oedometer set- up, the seating load of 6.25 kPa was applied, followed by fixing of the reaction beam (top of the frame) as shown in Figure 2. There was no gap between the metal bar connected to the proving ring and the upper cap on the soil sample. Then, the soil sample was inundated and left to swell. The swell force was recorded. It should be mentioned that while most of the swelling takes place in 24 h, swelling may continue for days. Thus, 24 h period was selected only for practical purposes and comparison of results. The remaining net force is divided by the cross-sectional area of the soil sample, and recorded as the swelling pressure for the direct method. In swell- consolidation tests, the cell was placed in the oedometer test set- up and further inundated, and allowed to swell freely under a seating load of 6.25 kPa.

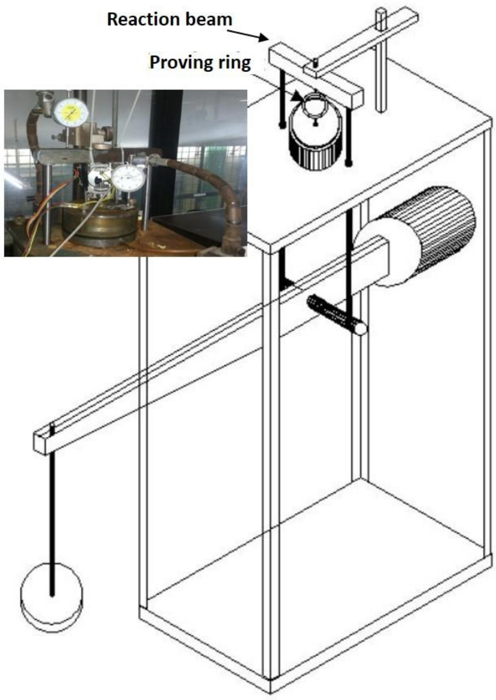

Fig. 2. The schematic diagram of oedometere test set- up with proving ring.

The amount of free swelling and axial deformation was recorded for different time intervals until 7 days. Thereafter, the test specimen was subjected to consolidation under various vertical stress for a period not less than 24h and/or until the deformation attained a steady state for each load applied over the specimen. The consolidation loads were applied until the specimen attained its original height. The swelling pressure exerted by the soil specimen under zero swelling conditions, and expressed in kN/m^2 (kPa). Restricted swelling test was carried out using four samples, and they were prepared in a similar manner as samples for the swell- consolidation tests. The cell was mounted in the oedometer set- up, and the seating load of 6.25 kPa was applied. The dial gauge was further adjusted for the initial value of dial gauge. The range of the vertical stress was carefully selected to cover the range of the expected swelling pressure. The specimen was then inundated with water. The results were plotted as percent swelling versus vertical stress. The point on the horizontal stress axis, where the zero deformation is crossed, was considered as the swelling pressure.

4 Results and Discussion

A highly expansive soil was used to compare the swelling pressure, which was measured by different methods. The tests have been repeated four times for each method. Details and data regarding the oedometer swelling pressure test are presented in Table 3 and Table 4 for the virgin soil and treated soil respectively. The results of the direct method test are summarized in Table 5 for the virgin soil and treated soil respectively. To run the restricted swell test, four specimens were used for four different tests. The results of the swell pressure tests along with applied pressure versus stress, are presented in in Table 6 for the virgin soil and treated soil respectively. Data from Tables 3, 5, and 6 revealed the average of the swelling pressures for the virgin soil for swell-consolidation, the direct method, and restricted swell tests measure as 199.7 kPa, 56.4 kPa, and 72.5kPa respectively. Data from Tables 4, 5, and 6 depicted the average of the swelling pressures for the soil in treated sate for swell-consolidation, the direct method, and restricted swell tests measure as 65.2 kPa, 14 kPa, and 18.7 kPa, respectively. The results indicated that the highest swelling pressure in case swell- consolidation test, and the lowest for the direct method. Results are observed to be in agreement with Basma et al. (1995), who mentioned that the most likely reason for the higher swelling pressures, registered during the swell-consolidation test, is due to the high pressure needed to expel the pore water from the voids. However, Kayabali and Demir (2011) pointed out that the swell- consolidation test overestimates swelling pressures. In our results, the restricted swell test showed close values observed for the direct swell test. The disadvantage of restricted swell test is that it requires several specimens for a test, if it is to be applied to a field specimen is to get at least three undisturbed specimens at identical initial conditions which becomes difficult. Moreover, as described above, in swell- consolidation tests, the swelling pressure is derived through stress applied over the sample after full swelling. In case of clay soils treated with using chemical additives (calcium), results in a complex soil matrix behaviour.

Adding chemical additive to the soil leading to modification and pozzolanic reaction of the soil which has already been reported by Abiodun and Nalbantoglu (2014), Rogers et al. (2000), and Tonoz et al. (2003). The pozzolanic reaction might be act as a resistance force while bring back the sample height to its initial height. Since in direct method the swell pressure was measured in swelling phase itself, swell pressure might not be effected with a complex soil matrix behavior due to pozzolanic reaction. To argue the existence of cementitious material, typical SEM (Scanning Electron Microscopic) of the virgin soil and treated soil after direct swell test and oedometer test presented in Figures 3a-d. The micrographs show that the clay platelets flocculated and found flaky pattern after treatment (Figures 3b and 3d). The flocculated and flaky patterned of Fig. 3b (after 24h in direct method) to be further developed in Fig.3d in oedometer test after about 14 days on treated soil. Figure 3d shows the fine reticulated network of grey patches that might be related to formation of cementitious compounds. These compounds filled the void space and covered the clay clusters. Similar observation reported by Juneja and Shinde (2019). Considering the facts above, the direct method would be more reliable to measure the actual swelling pressure in the swelling phase itself. Moreover, the calculated Standard Deviation (SD) of swell pressure of untreated soil which measured by oedometer, restricted, and direct method tests have been obtained 8.57, 8.22, 9.09 respectively. Likewise, the calculated standard deviation (SD) of swell pressure of treated soil measured by oedometer, restricted, and direct method tests have been obtained 15.22, 6.7, 3.65 respectively.

. **Table 3.** Swell Pressure (kPa) values as found using the swell- consolidation test on Virgin, strain (ε), and consolidation stress (σ, in kPa**)**

soil	Test No.	Recorded strains (%)										Swell Pressure (kPa)
		σ =0	σ =10	σ =30	σ =50	σ =70	σ =100	σ =140	σ =190	σ =250	σ =270	
Virgin soil	T1	12.8	10.8	8.256	6.496	5.256	3.624	1.928	0.84	-0.82	-0.98	210
	T2	8.56	8.20	7.00	5.88	4.76	2.80	1.24	0.01	-1.00	-1.20	200
	T3	10.52	9.36	8.56	7.12	5.16	3.12	1.032	-0.80	-2.01	-2.35	189
	T4	10.40	8.92	7.36	6.80	6.08	4.40	3.20	0.04	-0.96	-0.98	200

Table 4. Swell Pressure (kPa) values as found using the swell- consolidation test on Treated soil, strain (ε), and consolidation stress (σ, in kPa)

soil	Test-No.	Recorded strains (%)						Swell Pressure(kPa)
		σ =0	σ =10	σ =30	σ =50	σ =100	σ =200	
Treated soil	T1	6.39	4.75	2.12	-1.4	-6.24	-11.96	46
	T2	6.24	5.06	3.42	0.92	-4.32	-9.11	62
	T3	7.50	6.23	4.56	1.91	-2.90	-8.98	71
	T4	8.08	6.62	5.08	2.46	-2.11	-15.42	82

Table 5. Swell Pressure (kPa) values as found using the direct method test on Virgin and treated soil

Virgin soil	Test No.	Swell Pressure (kPa)	Treated soil	Test No.	Swell Pressure (kPa)
	T1	62.86		T1	10
	T2	42.99		T2	16
	T3	58.86		T3	18
	T4	60.93		T4	12

Table 6. Swell Pressure (kPa) values as found using the restricted swell test on Virgin and . treated soil, strain (ε), and consolidation stress (σ)

Soil	Test No.	σ (kPa)	ε (%)	Swell Pressure (kPa)	Soil	Test No.	σ (kPa)	ε (%)	Swell Pressure(kPa)
Virgin soil	T1	30	1.65	80	Treated soil	T1	5	0.7	17
		50	0.76				10	0.2	
		70	0.20				20	-0.1	
		140	-0.82				50	-0.6	
	T2	30	0.9	70		T2	5	1.4	28
		50	0.20				10	0.8	
		70	0.01				20	0.3	
		140	-2.00				50	-0.8	
	T3	30	2.15	62		T3	5	0.5	12
		50	1.30				10	0.1	
		70	-1.2				20	-0.4	
		140	-3.02				50	-0.7	
	T4	30	1.65	78		T4	5	0.6	18
		50	0.76				10	0.3	
		70	0.2				20	-0.1	
		140	-1.15				50	-0.3	

It is known that a low SD indicates that the data points tend to be close to the mean (also called the expected value) of the set, while a high SD indicates that the data points are spread out over a wider range of values. The higher SD value is belong to swell pressure that measured by oedometer method on treated soil sample. Discrepancy between the values could be due to existence of cementitious particle in soil matrix. However, more tests are required on different expansive soils, and further on stabilized soils with different admixtures to confirm the applicability of the method.

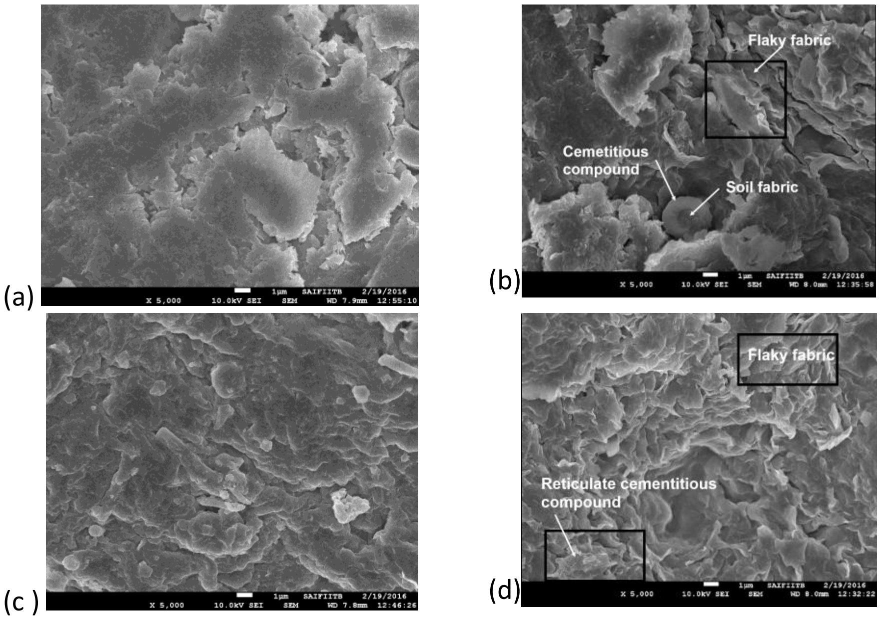

Fig. 3. Scanning electrons microscope images of (a) untreated soil after direct method test;(b) treated soil after direct method test;(c) untreated soil after oedometer test;(d) treated soil after oedometer test

5 Conclusions

In order to measure the swelling pressure directly in the swelling phase, which is more reliable particularly for the stabilized expansive soil, we utilised a direct method in our study. For the purpose of research work, a proving ring was designed, calibrated, and used to measure the amount of swelling pressure. Swell- consolidation and restricted swell tests are called as indirect methods, while measurement with the proving ring is called as the direct method.

Results showed that the highest and the lowest swelling pressures were measured by the swell- consolidation test and direct method, respectively. Stabilization of expansive soil to prevent swelling, and controlling the heave is a quite important consideration for designing infrastructure like roads and railways. Knowing the fact that some of these stabilization methods cause modifications and pozzolanic reactions, which are time dependent and make the soil matrix complex, a direct method for swelling pressure measurement could be more reliable. Further tests are required using different expansive soils. Subsequently, investigation of swelling pressures for stabilized soils would also be fundamental.

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