Swelling pressures of clay rocks from laboratory tests: experience and improvements

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ABSTRACT: Swelling in underground works can cause severe problems during and after construction. Consequently, swelling potential must be identified and quantified prior to construction. ISRM recommendations exist but not all interpretations are included and not all applied testing procedures follow these recommendations. Swelling pressures are not only influenced by the testing procedure, but also by the sampling technique and the conservation, transportation, and protection procedure of the samples, as well as the lab equipment. The construction of the test apparatus and the testing procedure both influence the test results. Swelling pressures can be determined by confined swelling tests. However, for incremental loading and unloading tests, often called Huder-Amberg tests, the procedure to determine swelling pressures are not well defined and the authors noted large deviations to the results of swelling pressure tests. A different technique to determine the swelling pressure from the incremental test is presented.

Keywords: swelling, clay rocks, shale, laboratory tests, tunnels, heave.

1 SCOPE

This paper describes basic factors to determine the swelling pressures and behaviour of argillaceous rock and hard soil from samples in the laboratory. In soil mechanics the deformational behaviour of soil with vertical confined uniaxial loading and unloading is determined by oedometer tests (EN-ISO 17892-5; ASTM D4546-3). Swelling also occurs in shales, like hard soils, in the prairies of Canada (Hardy, 1965) or in the mid-western states of the USA. In Europe, laboratory testing of swelling rocks started with the construction of the Belchen Motorway tunnel in Switzerland in the 1960s (Grob, 1972). Huder & Amberg (1969) proposed a testing procedure in oedometer devices and a method for determining the swelling pressures. The effect of mineralogy on swelling was investigated later at ETH Zürich (Madsen, 1979; Madsen & Müller-Vonmoos, 1985 &1989; Madsen & Nüesch, 1989 &1990). Suggested methods have been published by ISRM (1989) and an improved version a decade later (Madsen, 1999). The tests for pure argillaceous rocks are discussed, but not tests on rocks with clay-sulfate mixtures.

2 FUNDAMENTALS OF SWELLING

2.1 Mechanical (elastic) deformation versus swelling

Samples are mostly taken from core borings. In the ground the samples were loaded or stressed by the in-situ stresses, which are released by the drilling process and bringing the core to the surface. Deformations due to mechanical unloading will occur. This unloading process could also be called mechanical swelling The sample is kept together by negative pore pressures and osmotic stresses. To avoid release of the osmotic stresses by changes of water content, the samples must be sealed by packing them in aluminum foil after retrieval and sealing the sample with paraffin and wax. During drilling the boring will be flushed and water may penetrate the core and the sample, to reduce the water intake additives such as "Antisol", a product based on cellulose or polymers, must be used.

2.2 Fundamentals of osmotic swelling

The swelling of clay as it manifests itself in tunnel construction is referred to as osmotic swelling. This type of swelling occurs when clayey sediments are unloaded and enabled to take up water.

The driving force for the osmotic swelling is the large difference in concentration of the ions electrostatically held close to the clay surface and the ions in the pore water (Figure 1). Irregularities in the crystal lattice are manifested by an excess negative charge that must be compensated by cations (positively charged ions) close to the clay surface (Madsen & Müller-Vonmoos, 1985 & 1989).

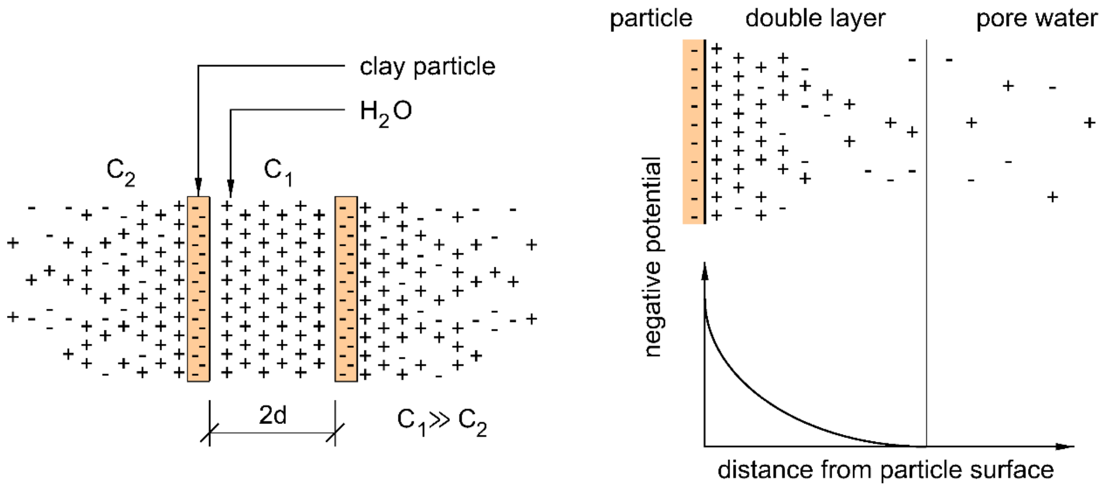

Figure 1. Schematic through two negatively charged clay particles within water with ions. The concentration C_1 of cations (positively charged ion) is much higher between the clay layers than in the porewater C_2. The interlayer cations are fixed electrostatically to the clay surface by the negative charge. The ion concentration may be changed by water penetrating in the space between clay particles. On the right side the potential indicated between the clay particle and the pore water with the diffuse double layer. The half spacing d is normally in the range of one to two nanometers (nm) or 10^{-9} m (Madsen & Müller-Vonmoos, 1985).

The swelling pressure σ (Madsen & Müller-Vonmoos, 1985; Madsen, 1979; Madsen & Nüesch, 1990) of a clay is thus dependent on a constant K describing the material, the distance 2d between the clay surfaces, the valency ν of the cations (positively charged ions) at the clay surface and pore water. Small variations in the distance d will have a great influence on the swelling pressure.

$$\sigma = \frac{K}{(d \times \nu)^2} \quad (1)$$

The half distance d between the surfaces of the clay minerals is in the order of one to two nanometer, nm or equivalent to 10^{-9} m. Rock with single valency cations (sodium) in the pore fluid will have higher swelling pressures than dual valency cations (calcium, magnesium). These relations help to explain the osmotic swelling. However, the direct determination of the parameters governing above equation (1) is for practical purposes very difficult and elaborate. For technical applications, the swelling pressure is mostly determined by testing in the laboratory. It is evident that the swelling pressures of a sample will be influenced by all the possible modifications a sample undergoes during sampling, transport, storage, preparation, and testing in the laboratory.

3 SWELLING TESTS

The recommendations by ISRM (ISRM, 1989 & Madsen, 1999) provide guidelines how swelling tests should be carried out. Comparing to soil mechanics tests, the greatest difference are the loads, for soil mechanics tests they are in the order several hundred kPa while the loads for rock swelling tests are in the order of 1 to 3 MPa, thus one to two magnitudes larger. Therefore, the apparatus must be stronger for rock tests.

3.1 Confined swelling stress test

The test is described in the ISRM recommendations (Madsen, 1999) under the title "determining axial stress" and describes the apparatus, the procedure, and the reporting of the results. The stiffness of the ring should be high so that radial strains are less than 10^{-4}, meaning that a 100 mm diameter ring should deform less than 0.01 mm. The stainless rings used at EPFL have a 60 mm interior diameter and are 15 mm thick. During swelling the loading frame deforms in the vertical direction, this deformation must be compensated that the sample does not deform (expand) vertically, and the correct loads are measured. The test provides a result of a swelling pressure, there is no interpretation of the measurements necessary.

3.2 Incremental loading tests to determine swelling pressures and strain

In the ISRM suggested method (Madsen, 1999) the method is described under the title: Method for determining axial swelling stress as a function of axial swelling strain. It is also described in the Swiss standard (SN 670 356). In soil mechanics this method is called incremental loading oedometer test (EN-ISO 17892-5). Following the soil mechanics nomenclature, we chose the title above.

The sample is tightly placed in the ring in the natural ("dry") state and incrementally loaded to overburden stress (Figure 2), then unloaded in steps to 15 kPa and incrementally reloaded to the overburden stress with the strains recorded. The sample is then submerged with water (wetted). The sample starts to swell, the instantaneous and time-dependent deformations are recorded. The sample is then unloaded in steps and the deformations recorded. The interpretation is not given in the ISRM recommendations. Many features postulated by Pimentel (2015) are already implemented in the test.

3.3 Interpretation of the incremental loading test by the method of Huder-Amberg (1969)

The incremental swelling test (Figure 2) is in general practice mostly interpreted with the method suggested by Huder-Amberg (1969). The swelling pressure [HA] corresponds to the axial stress that must be applied to the specimen that during hydration no axial swelling develops and is obtained as the intersection of the extrapolated swelling line with the reloading curve (Figure 2). The authors have noted that the method gives higher swelling pressures than the direct confined swelling tests and started to compare the results with overburden and swelling stress from confined tests (Table 1). Our findings indicate that the determination with the method Huder & Amberg (1969) gives swelling pressures that are in a few cases (10%), like the swelling pressure determined with the confined swelling test, but in the other cases much higher, sometimes by a factor of two or even larger up to 5, often these swelling stresses exceed the overburden stress and are thus not considered reliable.

3.4 *Interpretation of the incremental test by compensation of the mechanical deformation.*

A co-author (Mathier, 2007) proposes a method that determines the swelling strain by deducting the mechanical (elastic) deformation [E] of the sample determined by unloading the wetted sample to 15 kPa (Figure 2). The swelling pressure is read at the intersection [B] with the swelling line.

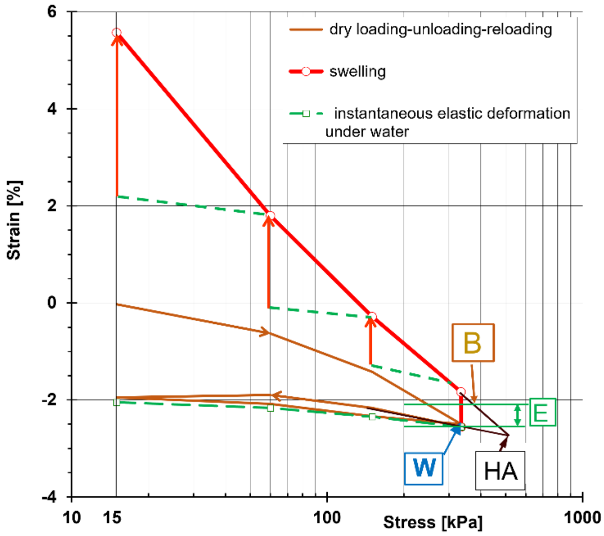

Figure 2. Incremental swelling test with loading, un- and reloading phases and wetting of sample (W) followed by stepwise unloading and swelling. Interpretation after Huder & Amberg (1969): Intersection of swelling line and of reloading-unloading curve (HA). The method proposed by the authors with compensation of mechanical axial deformation (E) is point B: intersection of swelling line with the horizontal from the unloading line at 15 kPa.

Table 1. Compilation of swelling pressures for different sites determined with different methods.

Case	Number	Over burden [m]	Pre-load [kPa]	Over-burden Stress [kPa]	Swelling pressure Huder-Amberg [kPa]	Swelling pres., with compens-ation of elastic deformation [kPa]	Swelling test confined [kPa]
Road	RB2 - 11	15.1	340	340	460	335	290
	RB2 - 12	15.1	150	340	720	400	--
	RB2 - 13	15.1	720	340	450	360	--
Metro	C24	27.1	--	637	600	300	100
	C28	13.3	--	299	900	500	250
	C29	29.1	--	529	700	250	40
	C31	17.1	--	380	2000	900	70
Tunnel	GM173.2	15.0	--	327	560	250	80
	GM173.5	15.0	--	333	500	300	60
Tunnel	Dech7	49.7	--	1260	2000	400	110
River crossing	R1 - 40	4.00 – 4.30		100	-	-	129.4
	R2 - 52	5.20 – 5.50		126	260	97	224.4
	R3 - 68	6.75 – 7.05		165	420	112	273.0
	R5 - 117	11.65 - 11.95		283	620	98	---
Railway tunnel	#39239	47.90 – 48.20		1250	600	700	900
	#39252	73.60 – 74.00		1920	1900	800	700
	#39252a	73.90		1925	2000	950	---
	#39255	79.10 – 79.60		2070	600	450	400
	#39279	104.7 – 105.0		2730	10000	2500	2100

The samples were preloaded to the overburden stress, except for the first case where a second sample was loaded less and a third higher than overburden. The method by compensating the mechanical deformation provides swelling pressures that are comparable to the confined swelling pressure test.

The testing apparatus used at EPFL (Mathier, 2007) is automated. It controls and records the loading and the displacement automatically. The confined swelling test and the incremental swelling test can be carried out in the same apparatus. The time-dependent behaviour i.e., consolidation and swelling, during the stages is also recorded and allows the determination of the relevant parameters.

3.5 Other methods for determining the swelling pressure

A comparison of the methods used at the Norwegian University of Science and Technology (NTNU) and the Karlsruhe Institute of Technology was carried out by Selen et al. (2018). The procedures deviate from the suggested method by ISRM. For both methods intact rock specimens and ground rock (powder tests) were carried out. The NTNU test use a preloading of 2 MPa on the samples, without considering past pressures of the samples. With the KIT procedure the samples are cyclically loading and undergo also drying cycles. The differences in obtained "swelling pressures" between the intact samples and the powder samples are huge. There were no samples tested with the suggested ISRM procedure. Because of the overloading (prestressing) the original rock structure will be changed and over-consolidated. In addition, due to drying, the sample will be changed further. Consequently, these tests are considered non representative for the in-situ swelling pressures.

3.6 Drilling and sampling, transport and storage procedures and laboratory preparation

The drill core should be relatively large. A triple core barrel (dual core barrel with in-liner) should be used with a core diameter of 85 mm (PQ). The damage to the core is substantially smaller than with HQ and 65 mm core diameter. During drilling an organic additive "Antisol" should be used with the drilling fluid, which substantially reduces the swelling of samples (Madsen & Nüesch, 1989) during the drilling.

During their investigations Madsen & Nüesch (1989) found swelling pressures that were extremely high. The samples had been exposed to free air, with relative humidity below 40%, for one day or longer. Furthermore, additional tests were carried out by exposing some samples to dry air. The dried samples gave on average swelling pressures p = 4.5 MPa, whereas samples taken fresh from the rock without delay and carefully sealed with aluminum foil and a mixture of paraffin (2/3) and wax (1/3) gave swelling pressures of 1.5 MPa.

More detailed studies on the effects on samples exposed to air or liquid (water or brine) were researched by Ewy (2015, 2018) that give similar results and recommendations.

3.7 Horizontal (lateral) stresses in the incremental swelling test

During the incremental loading and unloading the lateral stresses will change (Steiner, 1993), once the unloading is sufficiently large, vertical deformations may not only be from swelling but rather plastic deformations, as the shear strength of the clay can be exceeded. Three-dimensional behaviour of swelling rocks had been studied by Bellwald (1990).

4 CONCLUSIONS

The comparison of swelling pressures determined by different methods shows that the confined swelling pressure tests appear to give the most reliable results, as demonstrated by parallel tests, this was also found by Serratrice & Soyez (1996), Robert & Fabro (1987) et Sridharan et al. (1986). The evaluation with the Huder-Amberg test gives mostly substantially higher swelling pressures and should be substituted by the method that compensates the elastic (mechanical) deformation of the tested sample. It may be advisable to update the recommendations of ISRM on swelling tests.

To achieve good results for swelling tests the whole chain of operation must be considered: from retrieving samples in the field, transporting from to field to laboratory, storage, preparing the samples in the laboratory and testing them. As an alternative to the dry preloading, unloading, and reloading cycle followed by wetting, a confined swelling test may be carried out first, followed by a stepwise unloading of the wetted sample.

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