Time dependence of swelling in oedometer tests on expansive soil

John D. Nelson

1) Professor Emeritus, Colorado State University, President, J.D. Nelson Engineering Inc., Principal, Engineering Analytics, Inc 1600 Specht Point Rd., Fort Collins, Colorado 80525, USA

ABSTRACT

The manner in which oedometer tests are performed will influence the test results greatly. One important factor is the time allowed for each phase of the test to be completed. Not uncommonly, after inundation of the sample, the next load, and all subsequent increments of loading, are applied after a period of 24 hours. This may not be adequate for the heave to be fully developed. The results of oedometer tests are presented in which the times required for the various phases of the test to be completed were measured. After adding water, there is a period of time before swelling begins. This time period is influenced by the inundation stress. The amount of time over which swelling occurred varied significantly with applied stress. It was also shown that the manner by which the specimens in the oedometer were wetted influenced the time over which swelling occurred. When the specimens were wetted from the bottom of the sample with the top left open, swelling occurred for a longer period of time, and in greater amount, than when the entire sample was submerged.

Keywords: oedometer tests, expansive soil, crystalline swelling, osmotic swelling, inundation time dependency

1 INTRODUCTION

The appropriate protocol for oedometer tests on expansive soil should consider the time for swelling to occur after the sample has been wetted. That time will be influenced by a number of factors including the soil type, hydraulic conductivity of the soil, the inundation stress, the physical chemistry of the micelle, and the manner in which the sample is wetted. This paper reports on the results of several different experiments to investigate at least some of those factors. These results should be taken into account when interpreting oedometer test results. Also, they demonstrate that appropriate test methods cannot be strictly prescriptive and engineering judgment must be used when conducting laboratory tests.

2 NATURE OF SWELLING

The swelling of expansive soil occurs when the sample imbibes water into its structure. The mechanism of swelling relates to chemical changes in the micelle of the clay soil particle and osmotic forces that tend to cause water to be drawn into the spaces between the particles. Norrish (1954) observed that the swelling of montmorillonite took place in two different phases. At close spacings, his experiments indicated that the amount of water that was imbibed was related to the chemical nature of the adsorbed cations. At larger spacings the swelling was related to the osmotic process in developing the micelles. The initial phase of swelling is commonly termed “crystalline” swelling and the second phase is termed “osmotic” swelling (Slade, Quirk, and Norrish 1991).

The initial phase of swelling is the result of an increase in the size of the adsorbed cation as it becomes wetted. Because the hydration energy of the cations is very high the first water that enters the soil goes into the mechanism of crystalline swelling. Additional water enters the micelles by osmotic forces. As swelling progresses over time there most likely is not a distinct change from the crystalline phase to the osmotic phase. The osmotic phase comprises both completion of the outer shell of the water of hydration and osmotic flow of water into the water between cations in the micelle (Nelson et al. 2015).

The time for heave to occur will be a function of the mechanism of the particular phase that is taking place, as well as the ability of water to migrate within the soil. The migration of the water within the soil most likely takes place as both molecular flow, particularly in the crystalline phase, and viscous flow in the osmotic phase. These differences in mechanisms will influence the time that is required for swelling to be completed in an oedometer test.

3 OEDOMETER TEST EXPERIMENTS

3.1 Test procedures

Reichler (1997) performed a series of experiments based on oedometer tests on laboratory compacted samples. Samples of clay shale from the Pierre Formation in Colorado, USA were compacted under controlled conditions. Samples were taken from the expansive soil field test site at Colorado State University. The samples consisted of cuttings taken during drilling of an exploratory test hole. The
Atterberg limits taken from three depths ranged from a liquid limit of 55% to 57%, with a plastic limit ranging from 21% to 23%. The natural water content ranged from 12.9% to 13.4%. The samples were classified as CH according to the USCS.

The cuttings were mixed and allowed to air-dry. Samples were compacted directly into an oedometer ring to a void ratio of 0.61 (a density of 1700 kg/m³). Experiments were conducted in conventional cantilever-type fixed-ring oedometers with porous stones and filter paper on the top and bottom.

The experiments reported in this paper consisted of consolidation-swell tests following general procedures outlined in ASTM D4546 Standard Method of Test. Each specimen was subjected to an initial inundation stress for a period of approximately 24 hours. One sample was allowed to consolidate for about 4 days, but the length of the pre-inundation time period appeared to have no correlation to the total consolidation strain during the period.

Depending on the test to be performed the inundation stress, \( \sigma'_i \), varied from 31 to 378 kPa. At the end of that time the sample was inundated and kept submerged for a period of 72 hours. The swelling strain was measured at various time increments during this period.

### 3.2 Oedometer test results

Figure 1 shows the consolidation and swelling strain as a function of time for a typical test (test A). Figure 1.1 shows the consolidation that occurred during the pre-inundation phase. Figure 1.2 shows the strain during the period after inundation. For convenience in discussing the results, the notation for various points in time and the corresponding strain is shown in Figure 2. The test results using the notation defined in Figure 2 are listed in Table 1.

In Figure 1 it is seen that after inundation, settlement continued for a period of time, \( t_2 \). In Table 1 it is shown that \( t_2 \) ranged from 2 to 15 minutes. In these experiments Reichler used dry filter paper on both the top and the bottom of the specimen. Unpublished data from experiments that were conducted at the author’s former firm showed that compression of the filter paper in amounts that would translate to a strain of about 0.01 occurred during the inundation period. This value is of the same magnitude as the settlement recorded initially.

![Fig. 1.1. Consolidation prior to inundation.](image1)

![Fig. 1.2. Settlement and swelling after inundation.](image2)

#### Table 1. Time and strain for oedometer tests.

| Test ID | \( \sigma'_i \) (kPa) | \( T_1 \) (min) | \( t_2 \) (min) | \( t_3 \) (min) | \( t_4 \) (min) | \( \varepsilon_1 \) | \( \varepsilon_2 \) | \( \varepsilon_3 \) | \( \varepsilon_4 \) |
|---------|-----------------|----------------|---------------|---------------|---------------|--------------|--------------|--------------|--------------|
| A       | 31              | 1783           | 2             | 5             | 250           | -0.010       | -0.011       | 0.024        | 0.004        |
| B       | 187             | 1791           | 3.5           | 13            | *             | -0.010       | -0.011       | -0.011       | 0.000        |
| C       | 220             | 1309           | 12            | 14            | 300           | -0.003       | -0.009       | -0.009       | 0.000        |
| D       | 249             | 1355           | 10            | 15            | 100           | -0.004       | -0.013       | -0.014       | -0.001       |
| E       | 282             | 1395           | 15            | 17            | 200           | -0.001       | -0.010       | -0.007       | 0.000        |
| F       | 378             | 5684           | 10            | 29            | 140           | -0.003       | -0.012       | -0.014       | -0.001       |

* denotes time data not available
(i.e., $\varepsilon_2$) in the oedometer test. Calibration of the equipment for this deflection was not done in these experiments. It is believed that the strain $\varepsilon_2$ is primarily due to compression of the filter paper and not the soil.

Nevertheless, it is interesting that heave does not begin until some period of time, $t_3$, that ranged from 5 up to 29 minutes. As shown in Figure 3 the time for swelling to begin increases as the inundation stress increases. This may reflect a tighter spacing of the particles under the higher stress which could hinder migration of water into the micelles and slow the hydration of the cations.

At the time, $t_3$, swelling of the sample began. The swelling progressed relatively rapidly at first after which there was a marked reduction in the rate of swelling. The time at which the rate of swelling decreased is noted as the time, $t_4$. Figure 4 shows the effect of inundation stress on the time, $t_4$. At high stresses this time period is reduced significantly. If the inundation stress that is placed on the sample is equal to the constant volume swelling pressure, no heave will occur and $t_4$ would be equal to zero. This point will be discussed more fully in Section 4 of this paper.

3.3 Effect of method of inundation

The manner in which the sample is inundated will also have an influence on the time required for swelling to be completed. Normally, inundation is accomplished by covering the sample completely with water. During a project at the author’s firm oedometer tests were being conducted on undisturbed samples of highly plastic claystone that had been sampled using a driven ring sampler. The samples continued to swell after inundation for very long periods of time. Therefore, a revised method of inundation was initiated. Water was added to fill the oedometer ring only to the top of the soil sample, leaving the top open to the air. Thin plastic was placed over the sample to minimize drying of the sample. It was thought that by allowing a pathway for the air in the soil to flow out, more complete and faster wetting of the sample would occur. The results of these tests are presented in Table 2.

| Test ID | Method of Inundation | Duration of Test | $\sigma'_i$ (kPa) | Percent Swell (%) | Swelling Pressure (kPa) |
|---------|----------------------|------------------|-------------------|------------------|------------------------|
| AA      | Submergence          | 30 hours         | 174               | 3.9              | 409                    |
| BB      | Submergence          | 40 days          | 135               | 4.3              | 395                    |
| CC      | Immersion to top of sample for 31 days followed by submergence for 9 days | 185 | 5.2 | 443 |

The method of inundation was the same for tests AA and BB. Notwithstanding the difference in inundation stress, $\sigma'_i$, allowing the sample to swell for many days resulted in a significantly higher percent swell. The swelling pressure for both tests was nearly the same. In test CC the top of the sample was left open for the first 31 days after which it was submerged. This resulted in a 33% increase in the percent swell relative to the sample that was inundated in the conventional way for a normally used test period. The swelling pressure increased by less than 10%.

In test BB in which the sample was allowed to swell for 40 days the percent swell was 10% greater than that for test AA which was allowed to swell for about one day.
4 DISCUSSION AND CONCLUSIONS

The process of swelling begins when water has migrated into the sample sufficiently to cause changes in the clay micelle. Because of the strong forces developed by the hydration energy of the cations, it is expected that the first water introduced to a dry soil goes into completing the hydration shells of the cations (Nelson et al. 2015). Subsequent water enters the spacing between particles by osmotic processes. The strain, $\varepsilon_i$, shown in Table 1 did not vary greatly with applied stress. Since all samples had the same initial void ratio initially the void ratios at the beginning of swelling were also about the same also. Thus, the interparticle spacing would have been about the same. Consequently, the larger time, $t_i$, at higher stresses cannot be explained by differences in permeability. It must be concluded that the applied stress inhibits the initiation of cation hydration as well as osmotic flow of water.

The time over which swelling occurred decreased with applied stress as shown in Figure 4. It was noted that if the inundation stress was equal to the swelling pressure the time, $t_i$, would equal zero. This, however, does not mean that physical chemical processes are not occurring within the sample. Constant volume oedometer tests have shown that swelling pressure takes time to develop. Thus, even though volume change does not take place, hydration of cations will continue. For water to develop and expand the clay micelle, air in the soil must be compressed and dissolved. Also some air must be forced out. These processes will depend on the initial state of the soil and the initial degree of saturation. The effect that air movement has on the rate and extent of swelling was shown by the effect of leaving the top of the soil sample open to the air, as shown by the test results in Table 2.

After the initial phase of swelling has been completed at time $t_4$, swelling will continue. This was shown in Table 2 by the continued swelling for time periods as high as 40 days. In engineering practice it is not practical to conduct oedometer tests for such extended periods of time. However, it is important that the tests be performed at least until the time $t_4$ has been reached. In the use of the test results to predict heave it must be recognized that some additional heave may occur beyond that time.

ACKNOWLEDGEMENTS

Laboratory test results were obtained by D.K. Reichler at Colorado State University and the author’s firm Engineering Analytics, Inc.

REFERENCES

1) Nelson, J. D., Chao, K C., Overton, D. D., and Nelson, E. J. (2015): Foundation Engineering for Expansive Soils, John Wiley & Sons, Inc., Hoboken, NJ, USA.

2) Norrish, K. (1954): The Swelling of Montmorillonite, Discussions of the Faraday Society, 18, 120-134.

3) Reichler, D. K. (1997): Investigation of Variation in Swelling Pressure Values for an Expansive Soil, Master’s thesis, Colorado State University, Fort Collins, CO, USA.

4) Slade, P. G., Quirk, J. P., and Norrish, K. (1991): Crystalline Swelling of Smectite Samples in Concentrated NaC1 Solutions in Relation to Layer Charge, Clays and Clay Materials, 39(3), 234-238.