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Experimental evaluation of time effect on swelling pressure in high plasticity clay

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Abstract. Søvind Marl, a high plasticity overconsolidated Danish Paleogene clay, is a stiff clay known to exhibit swelling potential. The dependency of its swelling pressure on time is investigated by performing constant volume (CV) tests. Long periods of swelling are applied to the samples. Two samples are allowed to swell for 19 weeks, the other two only for 24 hours. The long-lasting tests show that the swelling pressure reaches the maximum value (σ'_{cv}) after 13 weeks of testing, and the change between the σ'_{cv} and the swelling pressure after 24 hours reaches 38%. In order to correct the underestimation of σ'_{cv} due to the sampling, a graphical correction of the consolidation curve is made. Due to the characteristic smooth yielding of the Søvind Marl, the graphical correction can be affected by personal interpretation.

1. Introduction

Understanding the swelling behaviour allows the prediction of potential ground heaves and structural movements of the expansive soil, which can potentially damage structures and pavements. The fluctuation of shallow groundwater and seasonal alternation of dry and wet cycles are two phenomena that also could cause volumetric changes in the swelling soils. This characteristic behaviour is due to the presence of swelling clay minerals such as montmorillonite [1]. As they get wet, the clay minerals absorb water and expand; on the other hand, as they get dry they shrink, leaving cracks in the soil. Cracks in pavements, foundations, basement floors and walls are types of damages caused by swelling soils. Typically, highly plastic clays are among the soils that exhibit swell potential [2].

The oedometer equipment can be used to quantify the swelling, and the test is performed by soaking a sample of the expansive soil and registering the tendency to expand. The two most common procedures in an oedometer test are the Constant Volume (CV) test and the Consolidation-Swell (CS) test. During a CS test, the sample is first allowed to swell under defined pressure and the vertical swell strain is recorded. After completion of the swelling, a sequence of loads is applied and the original sample height is reached again. The stress that permits going back to this height is the consolidation swell pressure σ'_{cs}. In a CV test, the sample height is kept constant under a vertical load that prevents the sample to swell. The maximum pressure required to maintain constant volume is called constant volume swelling pressure σ'_{cv}. It is assumed, neglecting secondary effects, that a sample soaked under a pressure equal to σ'_{cv} does not swell. A drawback of the CV swelling test is that the swell strain is not monitored. It is commonly found that the σ'_{cs} value, determined in the CS test, is significantly higher than σ'_{cv}, e.g. [3]. Another study [4] shows good agreement between the heave calculated by using σ'_{cv} and the heave in field tests, instead, σ'_{cs} leads to an overestimation.

For both CV and CS tests, the time to develop the full swelling potential is unknown, and in the engineering practice, oedometer tests lasting too long are not realistic. Early research showed the effect of time on the swelling pressure [5]. In some cases, the swelling needs 40 days to take place [6]. This paper investigates the dependency of swelling pressure on time. Four CV tests are performed on Søvind Marl, a Danish plastic clay. Two samples are allowed to swell for 24 hours, the other two for a period equal to almost 19 weeks. After the swelling phase, a standard incremental loading oedometer test (ILO) is performed, and the resulting consolidation curve is employed to perform a graphical correction of the swell pressure. Due to the peculiar behaviour of Søvind Marl, some difficulties are encountered in the correction.

Different σ'_{cv} are found for every sample. The value of σ'_{cv} seems to be stable after 24 hours, but the tests with the long-lasting CV phases show that σ'_{cv} stabilizes after about five weeks.

2. Material tested and methods

The Søvind Marl is a high plasticity overconsolidated Danish Paleogene clay. The high plasticity is due to the high smectite content, and its characteristic high level of overconsolidation originates from erosion due to decreases and increases in the global sea level. A peculiarity of this soil is the remarkable swelling potential.

The specimen was collected at Aarhus Harbour in a 72 mm rotary tube and hand-trimmed afterwards to guarantee the best fit to the oedometer ring. The first two samples, Test01 and Test02, originate from a depth of 63 meters below the ground. The total vertical stress acting at this point was equal to about 1150 kPa. The liquid and plastic limits for these samples are w_L = 198% and w_P = 44%. The other two samples, Test03 and Test04, were collected at a depth equal to 35 meters with effective stress equal to about 640 kPa. Test03 and Test 04 have a lower plasticity (w_L = 156% and w_P = 46%). The index of plasticity I_p of Søvind Marl was found to increase with the depth also in previous research, see e.g. [7].

The samples were given different swelling phase durations. Test01 and Test 02 were allowed to swell at a constant volume for 24 hours. Test03 and Test04 were subjected to a constant volume swelling phase almost 19 weeks long.

After the CV swelling phase, a standard incremental loading oedometer (ILO) test was run. Each load step lasted 24 hours in Test01 and Test02, and two weeks in Test03 and Test04. The scope of performing this kind of long-lasting load step was to get a more complete evaluation of the creep strain. The maximum stress applied was 10,000 kPa, and the load path was the same for all the tests.

Table 1, table 2 and figure 1 summarize the test program, the natural water content *w* and the Atterberg limits described before. All the oedometer samples have a diameter and a radius equal to 35mm.

The tests were carried out in an automatic oedometer and the procedure during the swelling phase was identical between the different tests. Each sample was prepared and set up in the oedometer. The cell was filled with water, so the sample with natural *w* was wetted. The CV swelling started with the piston applying increasing pressure to prevent the sample to swell. The maximum pressure required to prevent the swelling is defined as the constant volume swelling pressure σ'_{cv}.

The advantage of using an automatic oedometer is that the measurement of pressure increases or decreases is more precise than adjusting the pressure manually.

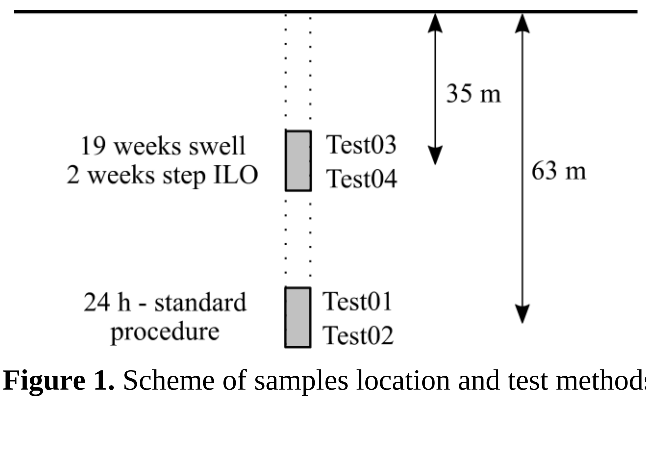

Figure 1. Scheme of samples location and test methods.

Table 1. Test program

Test	CV step duration	ILO step duration
01	24 h	24 h
02	24 h	24 h
03	19 w	2 weeks
04	19 w	2 weeks

Table 2. Samples properties

Test	Depth [m]	e_0 [-]	w [%]	w_L [%]	w_P [%]	I_P [%]
01	63	1.17	41.2	198	44	154
02	63	1.14	40.1			
03	35	1.10	42.8	156	46	110
04	35	1.08	44.6			

3. Constant volume swelling pressure

The maximum pressure required to maintain the sample volume constant is defined as the volume swelling pressure σ'_{cv}. A noticeable variability is found in σ'_{cv} of Test01 and Test02, even though both samples are from the same depth. During the first 24 hours of testing, the swelling pressure reached by these two samples is lower compared to the ones of Test03 and Test04, but all the four curves seem to be stable (see figure 2).

Figure 2 shows σ'_{cv} for Test01 and Test02, lasting only 24 hours, compared with the first day of swelling for Test03 and Test04. The value of σ'_{cv} is equal to 31 kPa and 84 kPa for Test01 and Test02, respectively. After 24 hours, Test03 and Test04 reached swelling stress equal to 212 kPa and 193 kPa, lower than their respective σ'_{cv} (see table 3). The trend of the swelling for Test03 and Test04 appears stable in figure 2, and only the longer swelling phase reveals that there is still some swelling potential.

Figure 3 shows how σ'_{cv} for Test03 and Test04 is reached after almost 13 weeks of swelling. The values of σ'_{cv}, marked by a dot, are equal to 276 kPa and 267 kPa for Test03 and Test04, respectively. The change between σ'_{cv} and the swelling pressure after 24 hours of Test03 and Test04 is 30% and 38%, respectively. The values of σ'_{cv} are peaks, but the swelling pressure for each test is more stable after five weeks of swelling. While in the first five weeks the swelling pressure increases for both tests, hereafter it tends to be more constant.

Table 3. Constant volume swelling pressure σ'_{cv}

Test	CV step duration	σ'_{cv} [kPa]	σ'_{cv} [kPa] after 24h
01	24 h	31	-
02	24 h	84	-
03	19 w	276	212
04	19 w	267	193

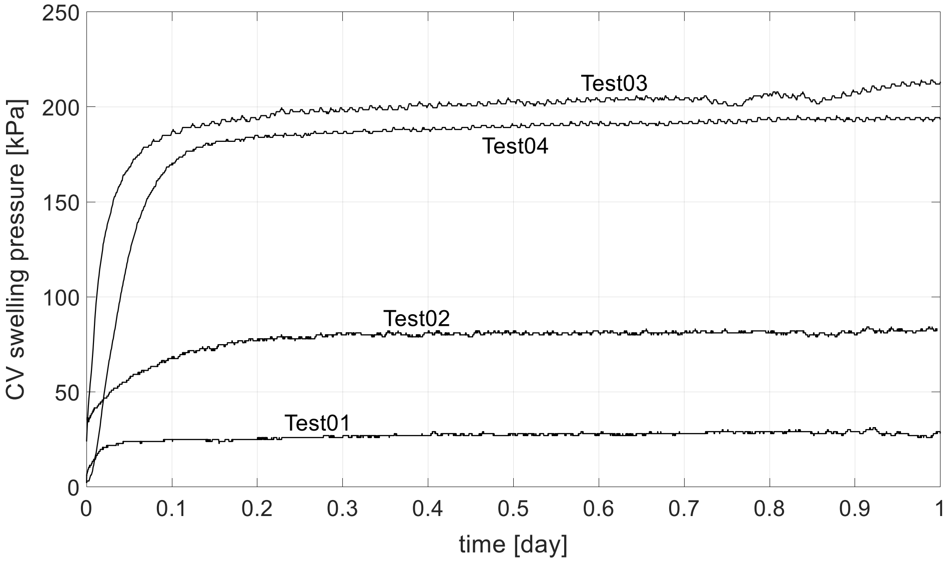

Figure 2. Swelling pressure for Test01 and Test02 (one day long) in comparison with Test03 and Test04 within the same period.

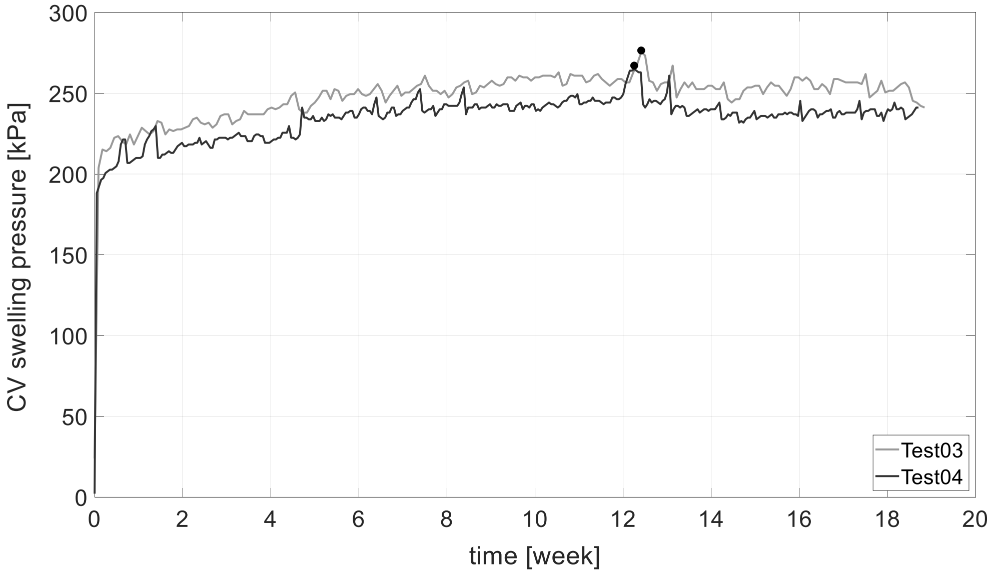

Figure 3. Swelling pressure for Test03 and Test04 (19 weeks long).

4. Correction of the CV tests

Besides their characteristic high plasticity and swelling potential, the group of high plasticity Danish Paleogene clays also shows the so-called "loss of memory" [8]. In fact, instead of presenting the bilinear consolidation curve, typical of soft soils, Søvind Marl shows a progressive yielding under compression.

Moreover, it is often possible to find two yield stresses at different stress levels. The lower yield happens when stress higher than the vertical in situ stress and swell pressure is applied. The higher yield is commonly identified as the stress that anticipates the virgin compression line [9,10].

The resulting consolidation curve, represented in the log (σ')-e plane, is adopted in the process of the swelling pressure correction. During the sampling, the disturbance caused to the specimen can cause a reduction in matric suction. Due to this, the σ'_{cv} can be underestimated and it is necessary to correct the laboratory curve [11].

Different ways to perform this correction has been published. The present paper adopts the method by Nelson and Miller [12]. This graphical method finds the corrected value of CV pressure $(\sigma'_{cv})_c$ in the intersection between the horizontal line passing through the initial σ'_{cv} and the tangent to the consolidation curve.

As shown in figure 4, for Test04, the $(\sigma'_{cv})_c$ is equal to about 500 kPa, almost double the original value. The choice of points selected from the consolidation curve is affecting the $(\sigma'_{cv})_c$ value.

It has previously been experienced that a highly overconsolidated clay shows 100 percent or more in the difference between $(\sigma'_{cv})_c$ and σ'_{cv}. Moreover, the higher the swelling pressure, the higher the correction [11]. The same is experienced in Test03, where $(\sigma'_{cv})_c$, calculated by the same correction, is equal to about 560 kPa, 100 percent higher than the initial σ'_{cv}.

The four presented oedometer tests correspond to the previously described behaviour, showing a smooth yield and a not well-defined zone where the preconsolidation stress occurs.

Due to this, the definition of a clear tangent to the curve as well as a single value for the preconsolidation stress is difficult. In Test04, the tangent passes through the third and fourth points of the ILO (see figure 4). The subsequent points would return an unrealistic overestimated value, due to the higher inclination of the consolidation curve.

Both figure 5 and figure 6 show the characteristic smooth yielding for the four tests, and it is clear that the graphical correction of the σ'_{cv} is heavily affected by the selection of points in the consolidation curve.

By analysing samples of Søvind Marl within a variable depth (11.5-47m), a previous study identified the lower yield in a range between 600 kPa and 800 kPa, and the higher yield between 6300 kPa and 8900 kPa [9]. Figure 5 illustrates σ'_{cv} and the intervals of the lower yield stress σ'_{LY} and the higher yield stress σ'_{HY} for Test02. Compared to the cited values, the present tests return smaller values for the intervals for both the lower and higher yield stress.

Figure 6 illustrates the consolidation curves for the other three tests. In the two samples, Test03 and Test04, the subsequent load steps were two weeks long and therefore expected to show a higher maximum strain due to more creep. Instead, the deformation is higher for the two samples tested with the traditional 24-hour load step. Besides a much higher swelling potential, the samples taken from 35-meter depth (Test03 and Test04) show lower compressibility compared to the other specimen from 63 meters.

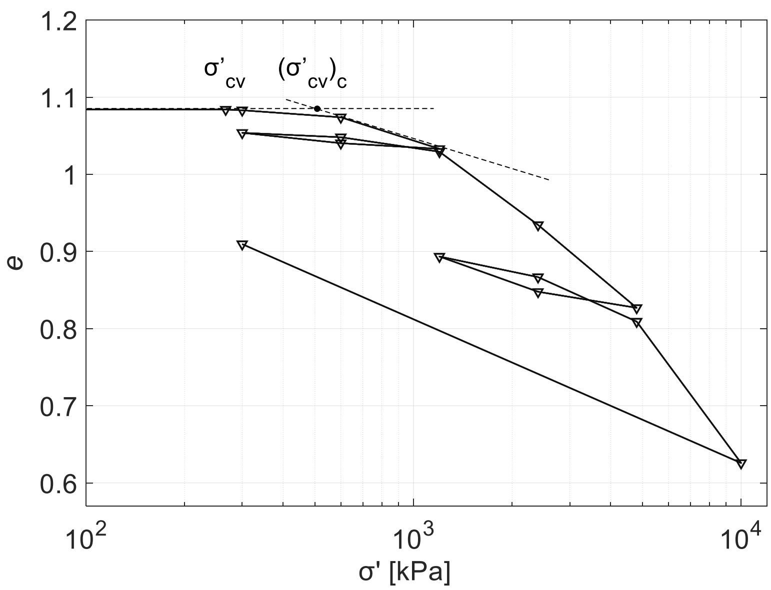

Figure 4. Initial and corrected values of swelling pressures for Test04.

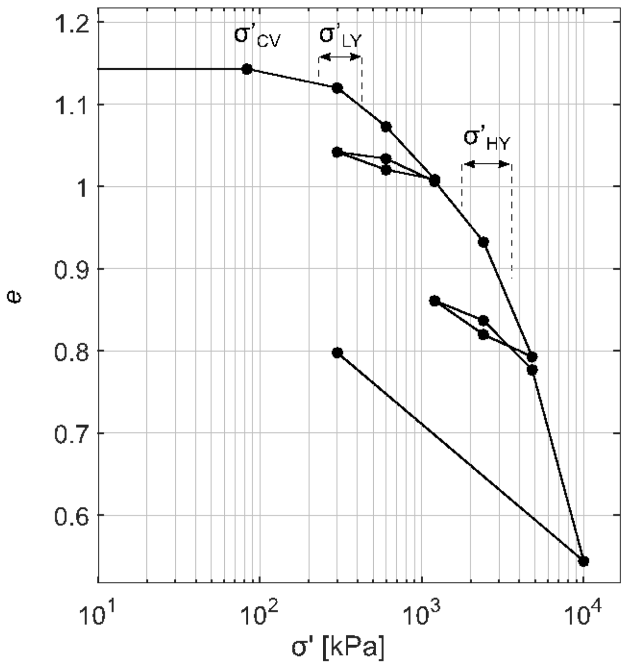

Figure 5. Consolidation curve Test02 showing the interval of lower and higher yield stresses.

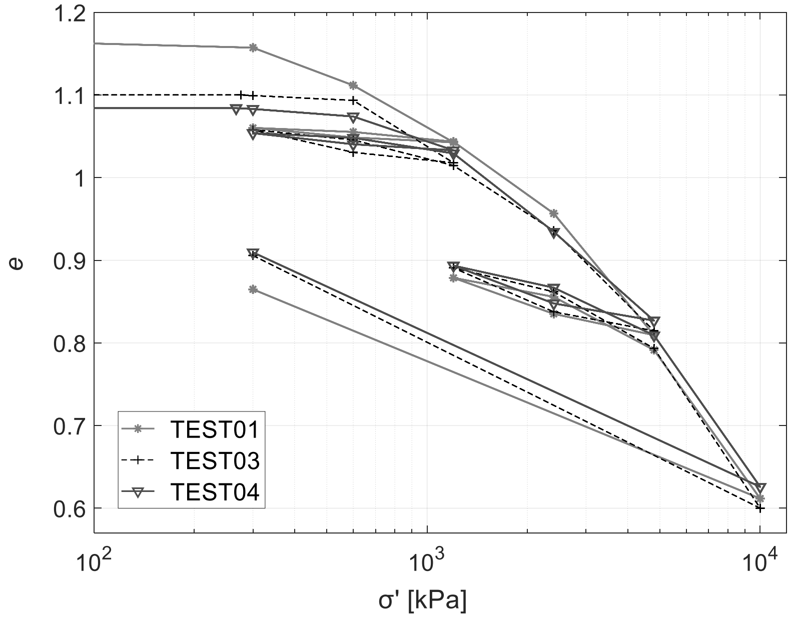

Figure 6. Consolidation curves for Test01, Test03 and Test04.

5. Discussion

In the light of the presented tests, some lessons can be learned. First of all, a longer CV test permits more accurate evaluation of the swelling potential; however, a swelling phase lasting months is not realistic. Good laboratory practice could be checking the test after 24 hours, and, if the sample still exhibits swelling, allowing it to have more time to swell. For example, in the case of Test04, if the swelling phase lasted one week, the σ'_{cv} would be equal to 211 kPa, closer to the σ'_{cv} reached after 19 weeks.

When an ILO test is run afterwards, in order to have a less scattered consolidation curve, it is advised to set up the first load not too much higher than the σ'_{cv}. With the same purpose, the applied loads should follow a sequence of small step increments, and not just double the load, as commonly done. In this way, it is possible to rely on more points, useful to the graphical correction.

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When analysing the swelling of highly overconsolidated clays, it is important to keep in mind the variability of soil behaviour due to the depth, plasticity index and some disturbance due to sampling. If possible, it is preferable to compare the results with previous studies.

6. Conclusion

The time effect on swelling pressure in a high plasticity overconsolidated clay is evaluated experimentally. Four CV tests were performed on Søvind Marl. Two samples from 63 meters depth were allowed to swell for 24 hours, and another two samples from 35 meters depth, for almost 19 weeks, in order to test the time influence on the swelling potential.

In the engineering practice, a swelling phase lasting months is not doable, but it is important to take into account that the swelling potential is not fully developed after 24 hours of testing. Performing a 24-hour test produces lower and unreliable measurements of swelling pressure. For Test04, a change equal to 38% is registered between the σ'_{cv} at 24 hours and the σ'_{cv} after 19 weeks of testing. When evaluating the swell in high plasticity clay, a compromise between accuracy and time available could end in a swell phase one week long and add an extra 20% to the estimated swelling pressure.

The correction of the consolidation curve reduces the underestimation of σ'_{cv} due to sampling disturbance. The correction suggested by [12] returns a $(\sigma'_{cv})_c$ equal to almost double the original value, for both Test03 and Test04. Due to the characteristic progressive smooth yielding of the Søvind Marl, it is difficult to define a clear bilinear behaviour. Furthermore, the graphical correction can be affected by personal judgement because of the variability in the inclination chosen in the construction.

References

[1] Norrish K 1954 The swelling of montmorillonite *Discuss. Faraday Soc.* **18** 120–34
[2] Peck R B, Hanson W E and Thornburn T H 1974 *Foundation Engineering* (New York: John Wiley & Sons) p 544
[3] Nelson J D, Reichler D K and Cumbers J M 2006 *4th Int. Conf. Unsaturated Soils (Carefree)* pp 951–61
[4] Abduljauwad S N, Al-Sulaimani G J, Basunbul I A and Al-Buraim I 1998 Laboratory and field studies of response of structures to heave of expansive clay *Geotechnique* **48** 103–21
[5] Seed H B, Mitchell J K and Chan C K 1961 Studies of swell and swell pressure characteristics of compacted clays *Highw. Res. Board Bull.* **313** 12–39
[6] Nelson J D 2015 *15th Asian Regional Conf. on Soil Mechanics and Geotechnical Engineering* pp 490–3
[7] Grønbech G L, Nielsen B N, Ibsen L B and Stockmarr P 2015 Geotechnical properties of Søvind Marl — a plastic Eocene clay *Can. Geotech. J.* **52** 469–78
[8] Krogsbøll A, Hededal O and Foged N 2012 *Proc. 16th Nordic Geotechnical Meeting (Copenhagen)* pp 133–40
[9] Grønbech G L, Ibsen L B and Nielsen B N 2015 Preconsolidation of Søvind Marl - a highly fissured Eocene clay *Geotech. Test. J.* **38** 501–10
[10] Okkels N and Hansen P B 2016 *Proc. 17th Nordic Geotechnical Meeting (Reykjavik)* pp 367–76
[11] Nelson J D, Chao K C, Overton D D and Nelson E J 2015 *Foundation Engineering for Expansive Soils* (New York: John Wiley & Sons) p 416
[12] Nelson J D and Miller D J 1992 *Expansive Soils: Problems and Practice in Foundation and Pavement Engineering* (New York: John Wiley & Sons) p 259