Testing of Expansive Clays in a Centrifuge Permeameter

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ABSTRACT: A research project was conducted on the use of centrifuge technology to characterize the expansive properties of a highly plastic clay. Direct quantification of the swelling of clays is impractical for geotechnical design because of the significant testing times involved. The research focuses on the development of a testing procedure using a simple centrifuge equipment that can provide direct, expeditious measurement of swelling. The testing procedure was found to produce highly repeatable results with testing duration of a few days. The results of the experimental program indicate that centrifuge testing can be used to quickly and directly characterize the expansive properties of clays rather than relying on questionable correlations with index properties to determine swelling potential.

RESUMEN: Un proyecto de investigación fue realizado sobre el uso de la tecnología de centrifuga para caracterizar las propiedades expansivas de una arcilla de alta plasticidad. Cuantificación directa de la expansión de arcillas es poco práctica para proyectos de diseño geotécnico debido a los tiempos extensos necesarios para conducir los ensayos. Esta investigación se centra en el desarrollo de un procedimiento utilizando una centrífuga simple que posibilita la medición directa y rápida de la expansión. El procedimiento de ensayo resulta en datos altamente repetibles con duración de unos pocos días. Los resultados del programa experimental indican que la centrífuga pruebas puede utilizarse para caracterizar rápidamente y directamente las propiedades expansivas de arcillas, en lugar de utilizar correlaciones cuestionables que usan propiedades índices para determinar el potencial de expansión.

1 INTRODUCTION

A research project was conducted with the objective of characterizing the swelling of highly plastic clays using a centrifuge permeameter. The new test aims at improving the current practice, which involve the use of conventional free swell tests, by decreasing testing time and also by providing a clear termination stage (steady state) for swell tests. This study, conducted using a comparatively simple, non-instrumented centrifuge device complements ongoing research at the University of Texas at Austin involving the use of a sophisticated centrifuge permeameter that incorporates the use of in-flight data acquisition and flow control under comparatively high g-levels (Zornberg & McCartney 2010).

Conventional free swell tests (ASTM D 4546-08) are performed in consolidation frames. Samples are compacted in consolidations cells and an overburden pressure is applied through the consolidation frame. Water is then poured to submerge the sample and deflections are measured as the sample swells. There is no clear termination point and tests often run for months until the sample height appears to come to equilibrium. The long duration of conventional tests has led to the use of questionable correlations based on soil index properties rather than on direct measurements of the actual soil swelling. The objective of this study is to develop a centrifuge testing procedure to provide a quick and inexpensive method for direct measurement of the swelling properties of clays.

Previous research of expansive clays using centrifuge technology (Frydman & Weisberg 1991; Gadre & Chandrasekaran 1994) involved instrumented centrifuges that are suitable for research studies rather than for soil characterization. Instead, this investigation explores the use of a non-instrumented centrifuge with the goal of developing an inexpensive, implementable test for quickly determining the expansive properties of highly plastic clays.

2 TESTING EQUIPMENT

The centrifuge used in this research study is a Damon / IEC centrifuge. This model is the "IEC EXD," which is a floor-mounted centrifuge used for a variety of industrial purposes. It contains four hangers that hold freely swinging aluminum centrifuge cups. The setup of the centrifuge is fairly customizable, as the contents of the centrifuge cups can be altered to fit requirements of different tests. Plastic permeameter cups that fit inside the centrifuge cups were designed and manufactured specifically for this research project. The main components of the

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centrifuge are discussed individually in the following sub-sections. The centrifuge can be observed in Figure 1. The centrifuge speed is controlled by a power setting knob. The power setting ranges from 0-100 and correlate with a power level for the electric motor.

The testing conducted in this study involves ponding water on top of a compacted soil sample and spinning the sample at comparatively high g levels (ranging from 25 to 400 g). The increased g level leads to an increased hydraulic gradient that forces the water through the samples at an increased rate that promotes expeditious swelling of the clay. A simplified diagram of the test setup is shown in Fig. 2.

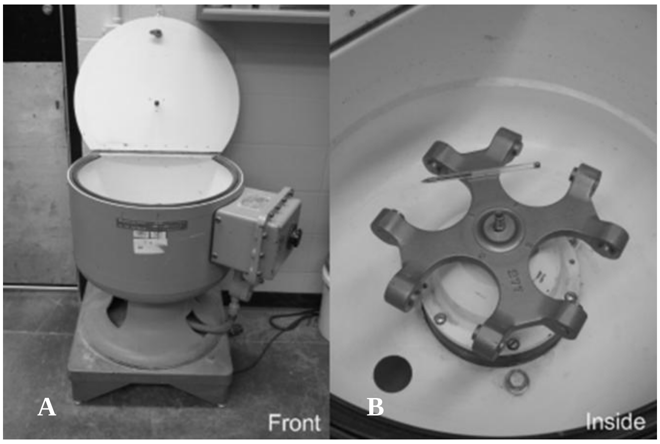

Figure 1. IED EXD Centrifuge: a) Front view b) Inside view of hangers.

2.1 *Centrifuge cup*

The centrifuge cups (Figure 3a) hang from the spinning centrifuge arms. The holders have an inner diameter of 6.35 cm and a usable inside depth of 11.43 cm. The base of the specimen holder includes a small vent hole to allow air and water outflow. When in flight the distance from the base of a sample to the center of rotation in the small centrifuge is 16.5 cm.

2.2 *Permeameter cup*

The permeameter cups (Figure 3b) fit inside the centrifuge cups and have an outside diameter of 6.33 cm and a depth of 11.43 cm. The cups have an inside diameter of 5.72 cm at the top, which is reduced to 4.71 cm approximately 2.5 cm from the base of the cups. This reduction was adopted to form a ledge that allows a porous plate to support soil samples. The base of the cup is removable and is used as a liquid collection system. Outflow can be measured accurately by measuring the increase in weight of the collection cup. A small air vent (visible in Figure 3b) connects the collection cup to the area above the sample to allow equalization of air pressure between the chambers located above the ponded water and at the bottom of the sample.

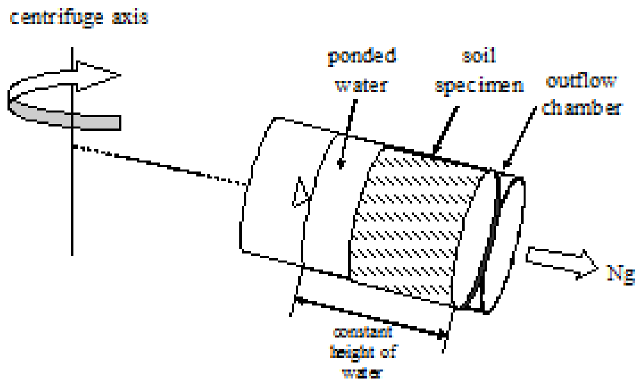

Figure 2. Centrifuge test setup.

2.3 *Porous supporting plate*

The porous supporting plate (Figure 3c) sits on top of the ledge in the permeameter cup and creates a firm yet pervious surface to place specimens. The plate contains 0.8 mm-diameter holes that allow water to flow freely from the base of the specimen. To avoid migration of soil particles, a filter paper is placed between the porous plate and the soil specimen.

2.4 *Permeameter cap*

A rubber permeameter cap fits inside the top of the permeameter cup in order to prevent excessive evaporation during testing. The rubber cap provides an airtight seal once the centrifuge is in flight.

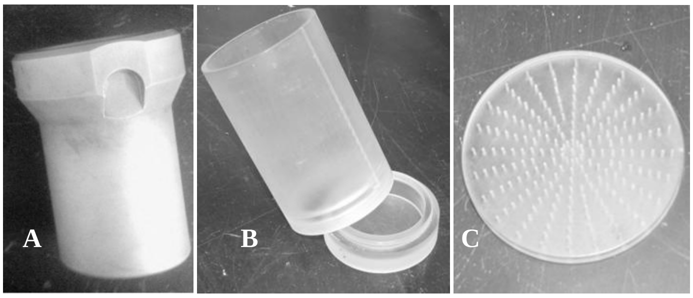

Figure 3. Centrifuge components: a) Centrifuge cup b) Permeameter cup c) Porous disc.

3 SOIL CHARACTERISTICS

The expansive soil used in this research study is a highly plastic clay from the Eagle Ford formation in Round Rock, Texas. The characterization of the clay has been reported previously (Kuhn 2005) and a summary of soil properties is included as Table 1.

The Eagle Ford clay is among the most expansive clays found in Texas. As indicated in Table 1, this clay has a very low saturated hydraulic conductivity (8.9×10^{-8} cm/s), high liquid and plastic limits (88 and 39 respectively), and a comparatively high optimum water content at standard proctor compaction (24%). The Eagle Ford clay is composed by approximately 75% clay minerals of which 50% have been reported to be smectites (Hsu & Nelson 2002). Standard one-dimensional swell tests were performed in consolidation frames with overburden pressures ranging from 6 kPa (standard overburden pressure for free swell testing) up to 200 kPa. The results of the free swell tests can be observed in Figure 4. A best fit logarithmic relation is also shown in the figure.

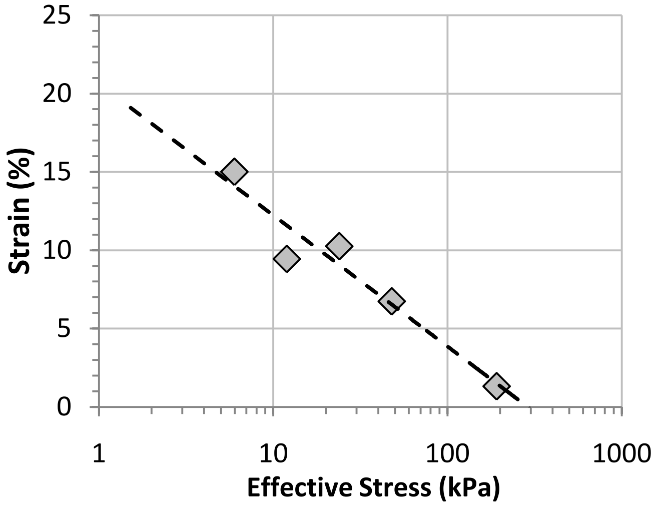

Figure 4. Standard free swell test results.

Table 1. Properties of Eagle Ford Clay

Property	Value	ASTM Standard
Specific Gravity	2.74	D 845-02
Liquid Limit	88	D 4318
Plastic Limit	39	D 4318
Shrinkage Limit	18	D 4943
Particle Size:		
Passing 0.075mm	97%	D 422-63
Passing 0.002mm	76%	D 422-63
Standard Proctor:		
Optimum water content	24%	D 1557
Maximum dry unit weight	15.2 kN/m^3	D 1557
Modified Proctor:		
Optimum water content	14%	D 695
Maximum dry unit weight	17.8 kN/m^3	D 698
Hydraulic conductivity	8.9x10^{-8} cm/s	D 5084

The free swell tests resulted in high swell values, with approximately 15% swell obtained at a confinement of 6 kPa. Based on the relationship defined by five tests performed, the swell pressure was determined to be approximately 300 kPa.

4 TESTING PROCEDURE

Soil was compacted in one centimeter lifts in the permeameter cups at optimum water content and standard proctor density using kneading compaction. A view of the kneading compactor used in this investigation is shown in Figure 5a. The kneading compactor applies a constant pressure to the soil surface during compaction. Sample heights of one, two, and three centimeters were tested as part of the feasibility study. A height of two centimeters was eventually selected as the standard height for testing based on the good repeatability of test results and the comparatively small test duration. The selected standard testing procedure also involved use of two centimeters of water ponded on top of the compacted samples and of approximately 12 grams of washers placed on top of the porous disc to apply an overburden in flight. The setup of washers on top of the samples is shown as Figure 5b.

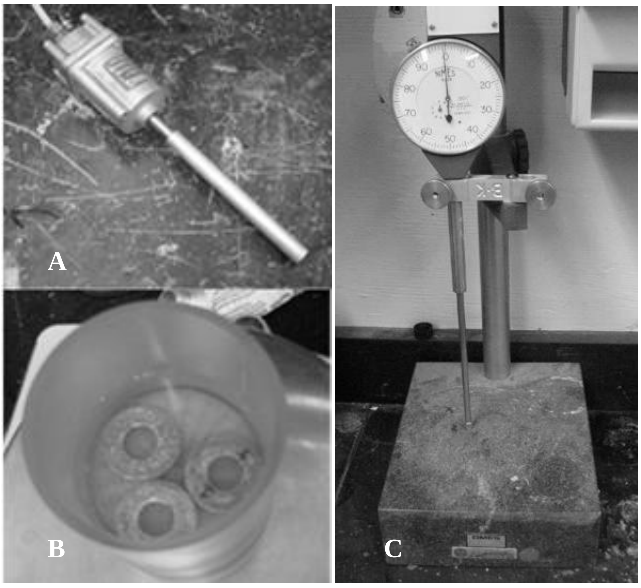

Figure 5. Measurement and preparation devices: a) Kneading compactor b) Overburden washers c) Mounted caliper

Samples were then spun in the centrifuge and removed approximately every 12 hours to measure sample height and outflow. A vertically mounted caliper (Figure 5c) was utilized to expeditiously measure the variation in specimen height. Two samples were tested simultaneously in each test. The process of turning off the centrifuge, removing and measuring samples, and spinning up the centrifuge again typically took approximately 5 minutes for both samples.

Testing length was dependent on several factors including sample height, g-level, and water head and ranged between one and five days. During the preliminary testing program, it was found that the sample height was the major factor effecting testing duration. This was due to water front requiring additional time to reach the base of the sample when the sample height was increased. Generally, one centimeter samples reached their ultimate swelling value after two days, two centimeter samples completed swell after four days. Three centimeter samples took over a week to reach equilibrium. The selected g-level and the water head were found to have a comparatively smaller effect on the overall test duration.

A typical result illustrating the swelling over time of a centrifuge test is shown in Figure 6. The results shown in the figure correspond to a two cm-tall sample flown at a g-level of 100 g. These results are typical of those obtained in the rest of the tested specimens. Once the time for swelling to complete was determined from a test with incremental readings, additional tests were completed with readings taken only at the initial compaction condition and the final reading.

Additional information on the testing procedure along with a complete analysis of the test results can be found in Plaisted (2009).

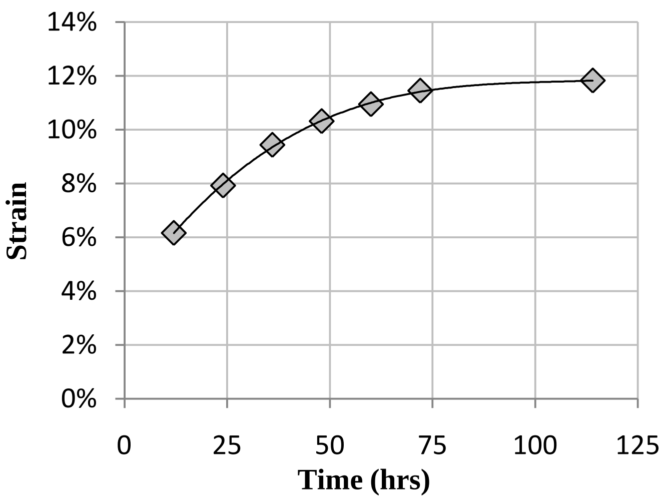

Figure 6. Swell over time of centrifuge sample.

5 RESULTS

Table 2. Centrifuge Test Results

100g Target		200g Target	
γ_d (g/cc)	Final Swell	γ_d (g/cc)	Final Swell
1.51	13.4%	1.52	9.5%
1.51	12.5%	1.52	9.6%
1.51	12.9%	1.54	10.4%
1.52	12.9%	1.52	9.8%
		1.54	10.4%
		1.53	9.8%

Testing was performed at g-levels of 100 and 200. The 100 g-level test set consisted of 4 tests and the 200 g-level set consisted of 6 tests. In all of the tests samples were two centimeters tall and an overburden mass of 21 grams was included. The overburden mass resulted in overburden pressures of approximately 6.5 kPa at a g-level of 100 and 13 kPa at a g-level of 200. Standard proctor density and optimum water content was targeted (1.55 g/cc dry density at 24% wc). The soil used in testing was found to be wet of optimum and samples ranged from 24.7% to 25.5%. This resulted in compaction dry densities lower than target (ranging from 1.51 g/cc to 1.54 g/cc). Measured swells in each test set were consistent with a standard deviation of 0.36% and 0.38% for 100g and 200g samples respectively.

6 ANALYSIS

In order to analyze centrifuge test results, a framework was developed to calculate the elevated stresses in centrifuge samples. It is possible to calculate soil pressures by considering that the unit weight of a soil under centrifugal acceleration is:

$$\gamma_c = \rho\omega^2 r$$

where ω is the rotational velocity of centrifuge and r is the radius from the center of rotation to the soil. The unit weight of soil changes with centrifuge radius and therefore soil pressures must be calculated by integrating across centrifuge radius such that the pressure from soil at radius r is defined as:

$$p(r) = p_t + \int_{r_t}^{r} \rho_s \omega^2 r \, dr$$

where p_t is the pressure at the top of the soil specimen due to water head or overburden and r_t is the centrifuge radius at the top of the soil sample. This relationship can be used to define the total stress in a soil specimen.

Pore water pressures in centrifuge samples were determined by assuming steady state flow, soil saturation, and Darcian flow. The fluid potential was calculated as:

$$\Phi_c = \frac{1}{2}\omega^2(r_0^2 - r^2) + \frac{P(r)}{\rho_w}$$

where r_0 is the radius of the sample base (taken as the datum). Given a centrifuge discharge velocity of:

$$v_c = -\frac{k_s}{g}\frac{\partial \phi_c}{\partial r}$$

where g is the gravitational constant, the fluid potential formula can be differentiated and the discharge velocity substituted. After integration the pore pressure was found to be:

$$P(r) = \frac{1}{2}\rho_w \omega^2 r_0^2 + C_1 r_0 + C_2$$

The two constants C_1 and C_1 were determined by imposing boundary conditions ($P(r_0) = 0$, $P(r_t) = P_1$, the applied pressure head). The full derivation can be found in Plaisted (2009).

The resulting stresses from these derivations are shown in Fig. 7 for a two centimeter tall specimen. The base of the specimen is at a centrifuge radius of 16.51 centimeters. For this specimen height and g-level the stresses are nearly identical to a linear approximation. The linear approximation assumes the entire specimen is at a g-level equal to that calculated for a radius at mid specimen height. The maximum error due to a linear approximation was less than 1% of the more accurate parabolic stress distribution determined using the more robust method accounting for a g-level varying with radius.

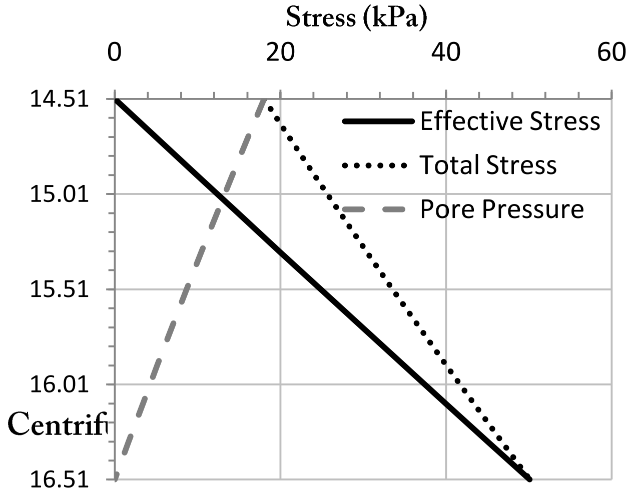

Figure 7. Stresses in a centrifuge sample

6.1 *Comparison of centrifuge results with standard free swell tests*

In order to compare the centrifuge results with the standard free swell tests performed in consolidation frames, the swell-stress relation determined by the standard tests was used to predict the total swell of the centrifuge tests. This was accomplished using a finite difference approach where centrifuge specimens were divided into 20 sections, stresses were calculated for each section, and the swell for each section was predicted from the standard swell-stress relation. This process was repeated for 10 iterations with calculations for density and strain for each section being updated each step.

The resulting predicted swells were much lower than those measured in the centrifuge. The predicted swells were approximately 4% lower than those measured (an error close to 40% for 200g specimens and 30% for 100g specimens). A comparison of measured and predicted swells in centrifuge samples is included as Fig. 8.

6.2 *Determining the swell-stress curve from centrifuge results*

A method was developed to calculate the relation between swell percent and effective stress directly from centrifuge test results. A logarithmic swell-stress relation was assumed such that:

$$S\% = A ln(\sigma') + B$$

where S% is the percent swell expected at an effective stress σ', and A and B are unknown constants. Assuming a linear approximation of effective stresses in centrifuge samples the total swell of a centrifuge sample is defined as:

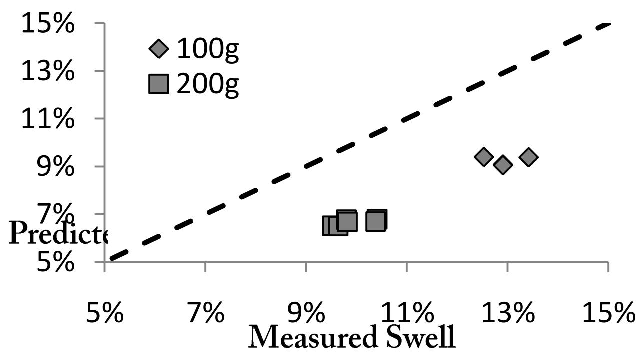

Figure 8. Comparison measured and predicted swells

$$S\%_{total} = \frac{\int_{\sigma_t'}^{\sigma_b'} S(\sigma)}{\sigma_b' - \sigma_t'}$$

where $S(\sigma)$ is the swell-stress relation and σ_t' and σ_b' are the effective stresses at the top and base of the specimen. After evaluating the integral the total swell of a sample is found to be:

$$S\%_{total} = \frac{A\sigma_b'\left(\ln(\sigma_b') + B'\right) - A\sigma_t'\left(\ln(\sigma_t') + B'\right)}{\sigma_b' - \sigma_t'}$$

where $B' = \frac{B}{A} - 1$. The two unknowns, A and B, can be defined if two test results for the same soil are known. The complete derivation can be found in Plaisted (2009).

Using this method the swell-stress relation was predicted based on two tests conducted at different g-levels. The total swell, effective stresses at the top and base of the specimens, and resulting swell-stress function coefficients are listed in Table 3.

Table 3. Data for determining centrifuge swell-stress curve.

Test #	Swell (%)	σ'_t(kPa)	σ'_b(kPa)
1	12.9	6.81	45.22
2	10.4	13.11	86.60
Resulting Coefficients			
A	-3.87	B	25.08

The swell-stress function determined from centrifuge tests is plotted against the function defined from standard free swell tests. The centrifuge curve is approximately 5% higher than the standard curve which is in agreement with the findings in Section 6.1 of higher than expected swelling in the centrifuge.

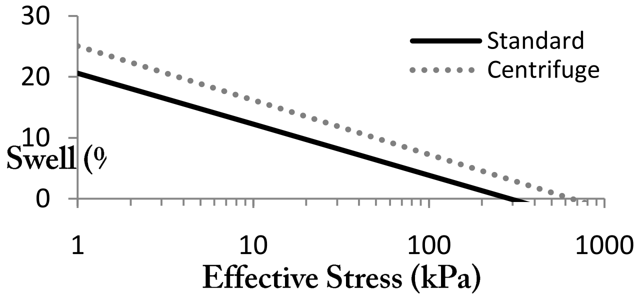

Figure 9. Swell-stress curve comparison

6.3 *Accounting for the additional swell observed in centrifuge tests*

One possibility for the difference in swelling seen between centrifuge and standard tests was a miscalculation of pore water pressures in the centrifuge. In order to determine the effect of an under estimation of pore water pressures in centrifuge samples, an analysis was performed assuming a constant pore pressure equal to the applied pressure head at the top of the specimens. This was meant to be representative of an increase in pore pressure in samples due to a clogged lower drainage boundary or a capillary barrier effect.

The swell-stress curve was recalculated with the constant pore pressure distribution using the method discussed in Section 6.2. The updated pore pressures resulted in lower effective stresses at the base of the specimens and the calculated swell-stress curve shifted downward. The shift made the disparity between the standard swell-stress curve and centrifuge curve lower however there was still a significant difference. The swell-stress curve determined assuming constant pore pressures throughout the samples is shown in Fig. 10.

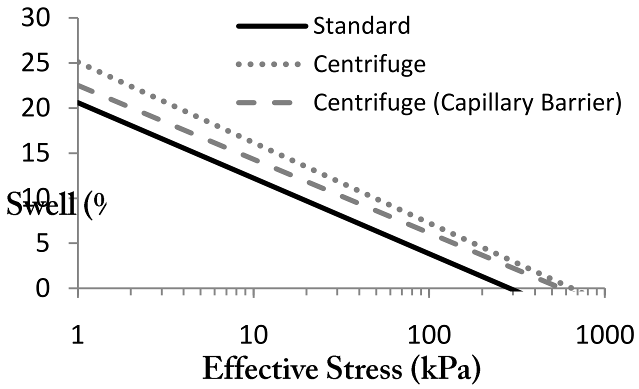

Figure 10. Swell-stress comparison with capillary barrier

A second reason for the higher swells measured in centrifuge tests could be the times at which the sample heights of centrifuge samples were measured. In standard free swell tests the initial height is taken as the height of the sample after the overburden load has been applied. The final height is taken once swelling has ended while the sample is still under load. In the centrifuge test setup, sample heights were measured before and after being spun in the centrifuge. Accordingly, the load experienced by centrifuge samples is not applied while measurements were taken.

Figure 11 is a representation of changes in sample height that standard and centrifuge samples undergo. Both samples are compacted to a specified density (1). Once the overburden and/or centrifuge stresses are applied, the sample compresses slightly (2). Water is then ponded on the samples and they swell until equilibrium (3). Once being removed from the increased stress due to overburden and/or centrifugation the samples rebound (4). Initial and final heights are taken as (1) and (4) for centrifuge samples, while the standard free swell procedure measured from (2) and (3).

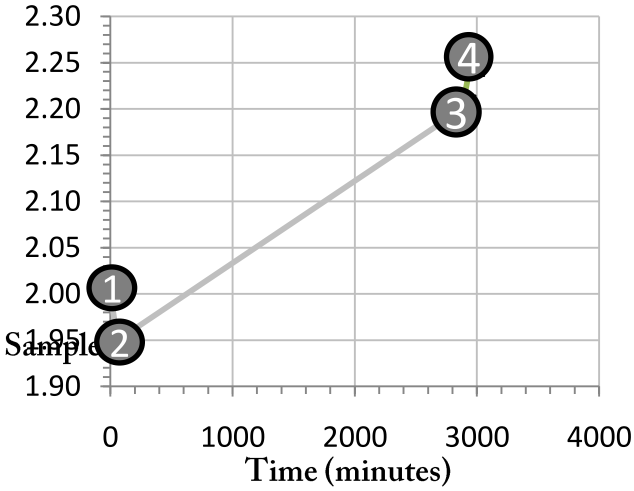

Figure 11. Representation of sample height changes

The different times at which measurements are taken will lead to a disparity in swell measured from centrifuge and standard tests. The magnitude of the disparity depends on how much compression (between points 1 and 2) and rebound (between points 3 and 4) occurs. If the compression and rebound are similar and small relative to the total swell (between 2 and 3), the disparity in measured swell would be small. This could explain all or at least a portion of the difference in swell measured in the centrifuge and standard tests. Further testing is being performed to measure the compression and rebound of samples and quantify the error caused by the difference in measurement procedure.

7 CONCLUSIONS

A procedure for the use use of a non-instrumented, inexpensive centrifuge was developed to characterize the swelling potential of a highly plastic clay. The following conclusions can be drawn from this investigation:

- The centrifuge test was shown to produce highly repeatable results of the swelling potential of the Eagle Ford clay.
- The testing procedure required test durations that were primarily a function of the selected sample height.
- The swelling potential of the Eagle Ford clay decreased with increasing g-level as a result of the increased stress level in the samples.
- A method was developed to calculate the swell-stress curve from two centrifuge tests.
- Swelling measured in the centrifuge was higher than that predicted by standard tests.
- The difference in swelling between standard and centrifuge tests can be attributed to an under-estimation of pore pressures and a different stress state when height measurements were performed.

Further research is under way in order to more accurately determine the differences between standard and centrifuge test results. Yet, the testing procedure developed in this study should be capable of inexpensively and quickly defining the entire swell-stress curve of a soil.

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