Apparatus compliance in oedometer testing at high pressures

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ABSTRACT
Characterizing soil behaviour using samples obtained from deep below the surface requires specialized testing equipment and interpretation. At these depths, material behaviour borders between soil and rock. Therefore, traditional soil testing apparatuses may need to be modified and issues such as apparatus compliance take on a larger aspect when interpreting results. Oedometer tests have been completed on clay shale samples of the Bearpaw Formation, taken from depths between 32 and 92 m. The Bearpaw Shale is a very stiff soil with preconsolidation pressures on the order of 10,000 kPa. In this paper, investigation into machine compliance on compressibility parameters (such as C_c, C_s, σ_p') is reported. At low stresses the effect of apparatus compliance is minimal however at high stresses the influence on these parameters becomes more significant. Failure to correct for machine compliance generally results in an overestimate of the compression indices and an underestimation of the preconsolidation pressure. For example the initial C_s on unloading is particularly susceptible if compliance is ignored. This can have a significant effect on design in these materials.

RÉSUMÉ
Caractériser le comportement des sols à l'aide d'échantillons prélevés à grande profondeur requiert des équipements et des analyses spéciaux. À ces profondeurs le comportement chevauche celui du sol et du roc. Les appareils courants doivent donc être modifiés et les enjeux tels que la déformation des appareils prennent une importance accrue lors de l'analyse des données. Des essais oedométriques ont été réalisés sur des échantillons de shale argileux extraits de la formation Bearpaw à des profondeurs allant de 32 m à 92 m. Le shale de Bearpaw est un sol très rigide ayant des pressions de préconsolidation de l'ordre de 10,000 kPa. Cet article rapporte les résultats d'une étude sur l'effet de la déformation des appareils sur les paramètres de compressibilité (tels que C_c, C_s, c_v, σ_p'). Sous contraintes faibles, la déformation de l'appareil a peu d'effet, par contre à hautes contraintes l'influence sur ces paramètres devient significative. En absence de corrections pour la déformation de l'appareil, les paramètres de compressibilité sont surestimés et la pression de préconsolidation est sous-estimée. Par exemple, la valeur initiale du C_s lors du déchargement est particulièrement susceptible si les déformations de l'appareil sont ignorées. Ceci aura un effet appréciable sur le design dans ces matériaux.

1 INTRODUCTION

Stiff, clay shales exhibit behaviour that lies on the boundary between rock and soil, posing many unique and interesting challenges when measuring and predicting their mechanical behaviour. In many cases, standard soil testing equipment is not adequate for characterising such a stiff material and conventional rock testing methods do not yield the constitutive parameters required in many investigations. Therefore, traditional soil testing apparatuses may need to be modified and issues such as apparatus compliance take on a greater role when interpreting results.

Clay shale core samples, collected from the Bearpaw Formation at depths up to 92 m below ground surface, were tested in an oedometer apparatus to assess the mechanical behaviour of the material. With preconsolidation pressures on the order of 100,000 kPa, the Bearpaw Shale is a very stiff soil that provides unique challenges in conventional laboratory testing.

Apparatus compliance is an important correction within many laboratory investigations however in working with a stiff soils and subsequently high pressures, the influence of apparatus compliance becomes more significant and influential on the results. Generally, failing to account for apparatus compliance results in higher compression and swelling indices (C_c and C_s), making the soil appear more compressible than it is. Additionally, ignoring the effects of compliance reduces the calculated preconsolidation pressure of the soil. In the case of very stiff soils a slight shift in the compression curve, may result in a change in preconsolidation on the order of 100's to 1000's of kPa where as the same shift in a soft soil translates to roughly 1 or 10 kPa. This highlights the significance in accounting for apparatus compressibility when working with stiff soils. In this paper, the investigation into apparatus compliance on compressibility parameters (such as C_c, C_s, σ_p') in a very stiff soil is reported.

2 GEOLOGICAL SETTING

The Cretaceous Bearpaw Formation forms the bedrock surface over most of southern Saskatchewan. The Bearpaw, the youngest formation of the Montana Group (71-72 Ma), is a westward thinning wedge of predominately marine silty clays and sands. It was deposited during the Campanian to early Maastrichtian during last major transgression and regression of the Cretaceous Bearpaw Sea.

The Bearpaw Formation was deposited at a slow rate in relatively quiet waters. Volcanic activity in south-western Montana occurred at various times during the deposition of the Bearpaw Formation resulting in layers of volcanic ash within the sedimentary sequence (Scott & Brooker 1968). Deposition continued through the early Tertiary until the sediments reach a maximum elevation, speculated at being upwards of 1000 m (Dawson et al.,1994). Subsequent tectonic uplift and isostatic rebound began a period of significant erosion and minor deposition throughout the remainder of the Tertiary. In southern Saskatchewan, Pliocene sediments of the Empress group, comprised of lower preglacial and an upper proglacial unit, are one of the few Tertiary deposits still present today. Glaciation within the region began around 1.8 million years ago (Fenton et al, 1994) depositing thick successions, from at least six glaciations, of glacial tills throughout the region.

3 SITE DESCRIPTION

A field site, located roughly 160 km south of Saskatoon, Saskatchewan, was selected for the following investigation (Figure 1). The site consists of 30 m of glacial till overlying approximately 90 m of the Snakebite Member of the Bearpaw Formation. Drilling was conducted using a hydraulic rotary drill. Three 0.6 m long Shelby tubes were collected near the till/clay contact. Following this, nine 1.5 m Denison core barrel samples were collected every 5 m between 42 and 92 m within the Bearpaw Formation. The Denison core barrel was chosen to sample this material as it has been specifically designed for very stiff soil and/or weak rock. In these brittle materials the presence of a non-rotating inter core barrel (Figure 2) has been shown to improve the quality of sample that could be retrieved. The depth of each sample taken is indicated in Figure 3. Washed cuttings were taken during the entire length of the borehole and the hole was cased to the till/clay contact to facilitate sampling over multiple days. Evidence of bentonite lenses, shell fragments and large concentration layers were also found during the investigation. A photograph of a section of this retrieved core is presented in Figure 4.

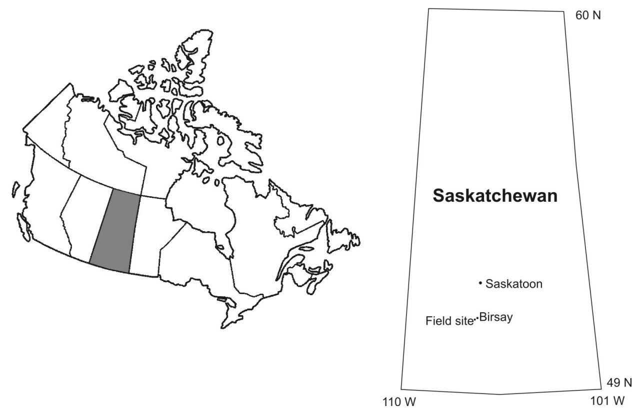


Figure 1. Location of field site in southern Saskatchewan

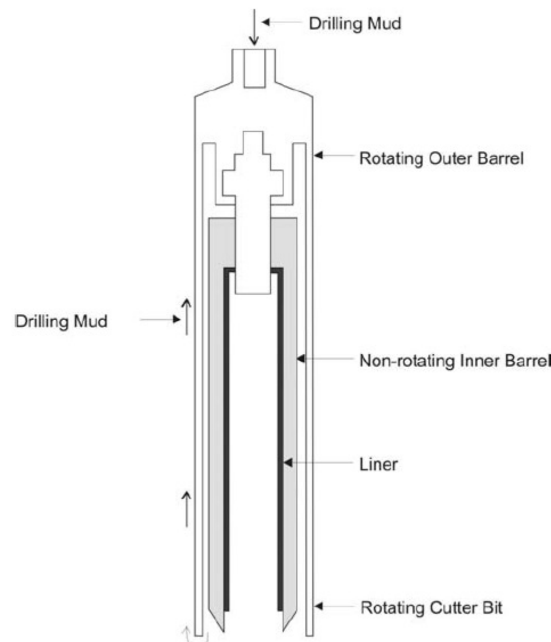


Figure 2. Schematic of Denison core barrel (modified from Terzaghi et al., 1996).

4 LABORTATORY INVESTIGATION

4.1 Material Properties

The Bearpaw Shale is a highly plastic clayey silt. Liquid and plastic limits range from 99 to 149% and 23 to 29%, respectively, over the sampled interval. Average water content and degree of saturation range from 19 to 30% and 90 to 98%, respectively. The average grain-size distribution over the entire sampled interval is 7% sand, 54% silt and 39% clay however, local variation in the individual cores samples was observed. Preconsolidation pressures were interpreted using the Butterfield (1979) method. Measured preconsolidation pressures for the Bearpaw Shale range from 4 to 10 MPa and are seen to increase with depth. The above results are consistent to other studies conducted in the region (Sauer & Misfeldt 1994; Shaw & Hendry 1998).

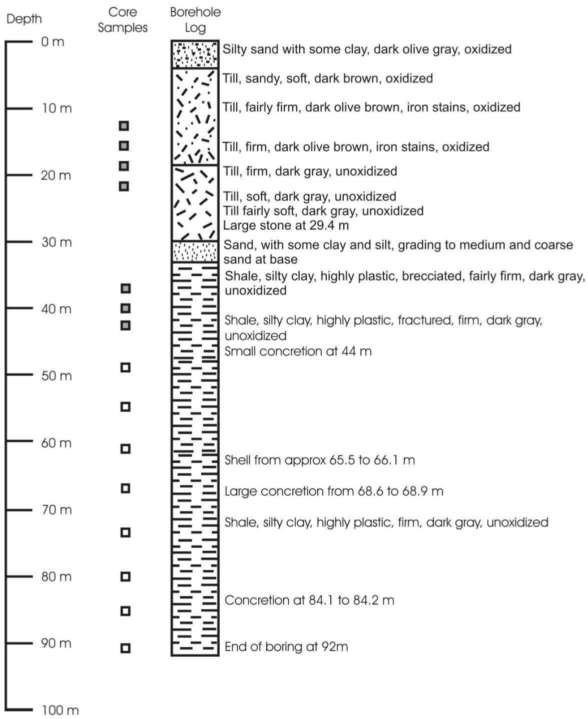


Figure 3. Stratigraphic log and collected core samples. Shaded squares are Shelby tubes, open squares are Denison core barrels.

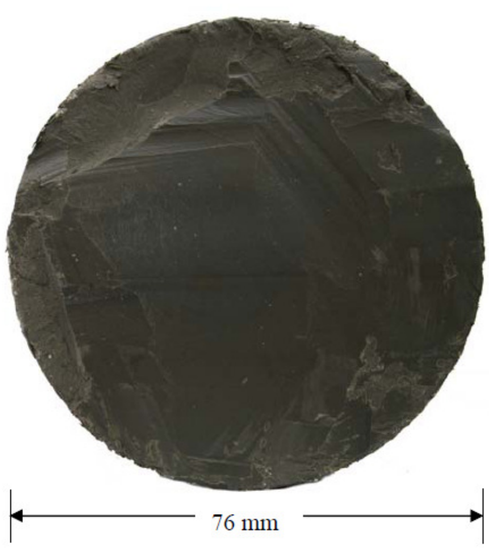


Figure 4. Photograph of a typical core sample extruded from Denison core barrel.

4.2 Oedometer Testing

Over 35 oedometer tests, including both multi-staged (MSL) and constant rate of strain (CRS) tests, were conducted on core samples of the Bearpaw. One of the unique challenges of working in this type of stiff material is being able to achieve adequate load magnitudes in the oedometer apparatus. Rarely is it feasible in stiff clays to achieve loads of 4 times the preconsolidation pressure as outlined in ASTM (1996) however pressures ranging from 22-100 MPa were achieved during this work. Modifications, including increasing the hanger length to accommodate more physical weight (up to a maximum of 200 kg) and the design of new sample cutters, collars and top caps to reduce the overall cross-section of the sample, were made to achieve these increased pressures. This reduction in size provided a unique opportunity to investigate the sample size effect across four different sample sizes ranging from 17 to 70 mm in diameter when testing very stiff clays. A photograph of the testing apparatus is given in Figure 5.

Figure 5. Photograph of oedometer apparatus.

4.3 Apparatus Compressibility

To assess the apparatus compressibility, loading sequences were conducted using steel specimens. The steel specimens, of similar dimension to the actual soil specimens tested, were placed in the oedometer cells and loaded incrementally until the maximum load of 200 kg was applied, followed by unloading. Similar methods for determining apparatus compliance have been used and found to be successful by Kalidindi et al., 1997 and Cotecchia, 1996.

To ensure consistency and repeatability, each compliance test was duplicated. This was done by completely disassembling the oedometer cell then reassembling and performing an additional compliance test. Each compliance test conducted corresponded to an equivalent oedometer test where the porous stones used in the compliance test corresponded to the stones used in the soil test. Load increments were applied sequentially, once equilibrium of the dial gauge was achieved.

A typical result of an apparatus compressibility test and its duplicate are shown in Figure 6. As seen, the shape of the curve resembles that of a standard oedometer curve for a soil, with hysteresis observed between the loading and unloading curves. The maximum deformation observed during loading is approximately 0.38 mm. Although slight deviation is shown between the two curves, the deviation only occurs at lower pressures where the resultant effect on the data is minimal. In high stress regions where the correction is more significant, the original and duplicate compliance curves are judged to be of equivalent quality.

To apply the compliance correction, a polynomial function was fitted to the compliance loading curve which was then used to correct the oedometer readings at each stress interval. This was done by calculating the apparatus compressibility using the derived function, at each stress interval within the oedometer test and subtracting it from the measured data to remove the effect of machine compressibility.

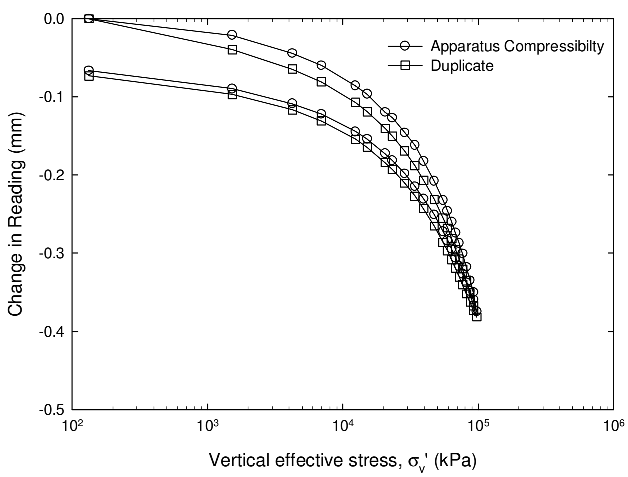
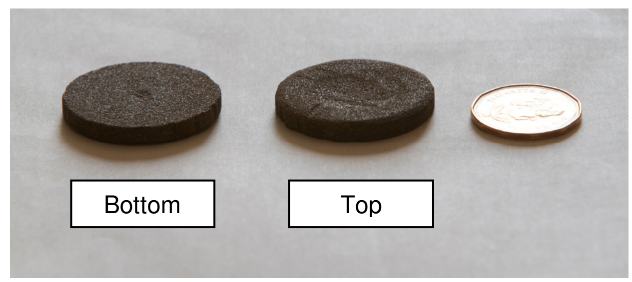


Figure 6. Compressibility of oedometer apparatus.

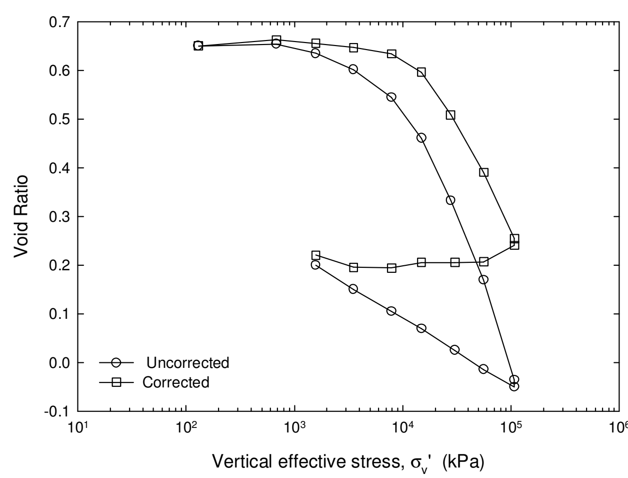
4.4 Compliance Example

Compliance correction is normally assumed to account for elastic deformation of the apparatus as well as seating of the loading mechanism with the soil specimen. During the course of oedometer testing of Bearpaw Shale samples, plastic deformations of the filter stones was observed in a small number of cases. Although this was a very rare occurrence, this example provides a valuable illustration of the effects of not accounting for compliance. An example of filter stone deformation is illustrated in Figure 7a and the consequence of not accounting for these plastic deformations is plotted as void ratio versus vertical effective stress in Figure 7b. The filter stone in Figure 7a was placed below the soil sample in the oedometer apparatus. The top of the filter stone shows a small depression where the cutter and soil specimen compressed the filter material. The dial gauge measuring deformation of the loading cap would measure the sum of the compression of the soil, the ‘normal’ apparatus compression as well as plastic deformations of the filter stone. The result is a high overestimation of the compression of the soil specimen.

The effect on the test data for this extreme example of apparatus compliance is plotted in Figure 7b. The result is a calculation of a negative void ratio at the maximum applied pressure. In addition, the uncorrected loading curve continues to increase in slope despite approaching and passing void ratio equal to zero. The corrected curve shows a more reasonable loading pattern with a stiff response at pressures less than the preconsolidation pressure followed by compression along the normally consolidated line. Some issues remain with the unloading curve in the corrected data as a result of the relatively high compliance within the apparatus and the difficulty of measuring an accurate compliance curve after plastic deformations have occurred.



a.



b.

Figure 7. Photograph of a permanently deformed filter stone and example of uncorrected data.

4.5 Data Correction

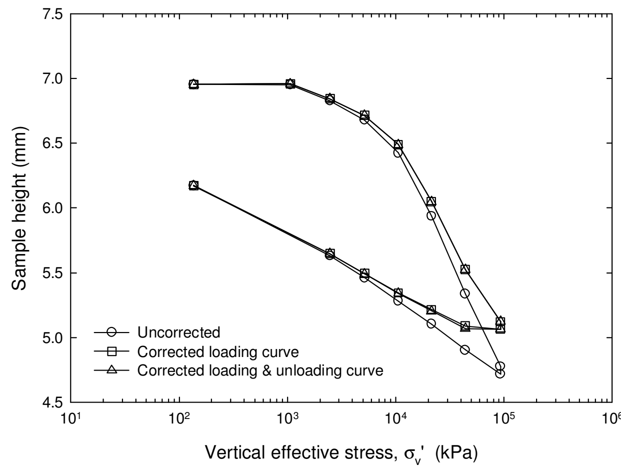
The results of a typical oedometer test on Bearpaw Shale are shown in Figure 8 in terms of both sample height and void ratio. The consolidation tests were conducted in accordance with ASTM D4546-96 (ASTM, 1996) using the Constant Volume approach for determining swell pressure as reflected by the straight line connecting the first two data points. The specimen was loaded incrementally to a maximum stress of 93 MPa. As part of the oedometer test, creep or secondary compression behaviour was assessed during the final loading increment prior to unloading. This was achieved by maintaining the maximum stress of 93 MPa for a period of approximately 30 days and recording subsequent changes in specimen height. This behaviour is shown by the vertical line at the end of loading in Figure 8. Following the creep test, the specimen was unloaded to the seating pressure.

The decision to correct the test data using only the loading curve and not both the loading and unloading curves was made. Although, at the scale shown in Figure 6, there is noted difference between the loading and unloading curves the resultant difference on the corrected test results was minor. Figure 8 provides a comparison of the differences in correcting the data using only the loading curve and with using both the unloading and loading curves. There are negligible differences between using both the unloading and loading curves (shown by the triangles) in comparison to only using the loading curve (shown by the squares) under the stress interval tested, as the slopes of the normal compression line (C_c) and the rebound line (C_s) were similar between the two curves. This supported the decision to only use the loading curve to correct the data.

Upon examination of the effect of apparatus compliance it can be seen that when apparatus compressibility is not taken into account the stress-strain curve plots below the corrected curve. This difference is less in the low stress portion of the curve however becomes more significant in the higher stress portion of the curve, highlighting the importance of this correction when working in high stress regimes. The corrected data results in shallower slopes of the normal compression line (C_c) and the rebound line (C_s) and an increase in the calculated preconsolidation pressure. A comparison of the above parameters calculated from both the uncorrected and corrected data are presented in Table 1. Failing to correct for apparatus compressibility is seen by overestimation of C_c and C_s and a slight underestimation of σ_p'.

5 CONCLUSION

Apparatus compliance is an important correction within many laboratory investigations, however in working with stiff soils and subsequently high stresses the influence of this apparatus compliance becomes more significant and influential on the results. Failure to account and correct for machine compliance will result in an overestimation of the compression indices (C_c, C_s) and an underestimation of preconsolidation pressure (σ_p') in conventional oedometer tests. This will affect design in these materials and highlights the importance of correcting laboratory data for apparatus compliance.



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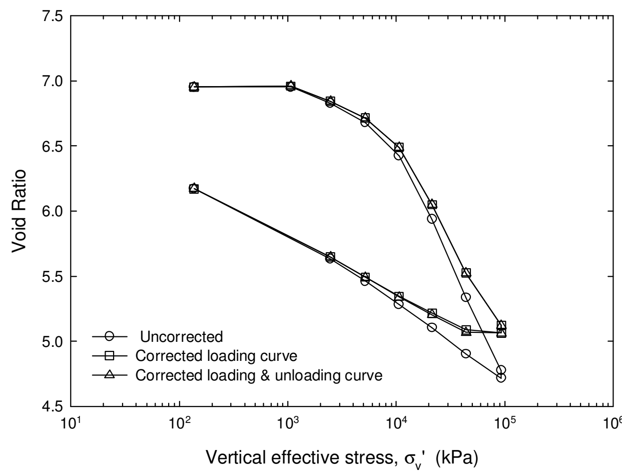

b.

Figure 8. Relationship between uncorrected and corrected oedometer test data

Table 1. Effect of apparatus compliance on compressibility parameters

Parameter	Uncorrected	Corrected
C_c	0.44	0.37
C_s	0.12	0.10
σ_p' (kPa)	11980	12130

This paper summarized the effects of compliance in two oedometer tests on stiff clay shale samples of the Bearpaw Formation. In one test not accounting for compliance resulted in calculation of a negative void ratio. In both tests the unload line was significantly affected.

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