Impact of surcharge loading on VSD performance in dewatering oil sands tailings

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ABSTRACT
A two and a half year-long laboratory test column study was conducted to evaluate the impact of surcharge loading on increasing the effectiveness of vertical strip drains (VSD's) in dewatering mature fine tailings (MFT). A 1.5 m long VSD was installed up the center of a 4 m high, 0.52 m diameter test column. The test column was instrumented with pressure transducers and manometers to measure fluid pressures adjacent the VSD and at the edge of the test column. The test column was loaded utilizing a pressurized water cap. A pressure of 40 kPa was applied to the surface of the MFT for approximately 330 days. This pressure was then increased to 60 kPa for the duration of the 1178 day long test. The results of this test program found that the elevated pressure on the surface of the MFT significantly enhanced VSD assisted settlement and increase in solids content.

RÉSUMÉ
Une étude de deux ans et demi sur une colonne d'essai en laboratoire a été menée pour évaluer l'impact de la surcharge sur l'augmentation de l'efficacité des drains à bandes verticales (VSD) dans l'assèchement des résidus fins matures (MFT). Un VSD de 1,5 m de long a été installé au centre d'une colonne d'essai de 0,5 m de diamètre et de 4 m de haut. La colonne d'essai a été instrumentée avec des transducteurs de pression et des manomètres pour mesurer les pressions de fluide à proximité du VSD et au bord de la colonne d'essai. La colonne d'essai a été chargée en utilisant un bouchon d'eau sous pression. Une pression de 40 kPa a été appliquée sur la surface de la MFT pendant environ 330 jours. Cette pression a ensuite été portée à 60 kPa pendant la durée de l'essai de 1178 jours. Les résultats de ce programme d'essai ont révélé que la pression élevée sur la surface de la MFT augmentait significativement le tassement assisté par VSD et augmentait la teneur en solides.

1 INTRODUCTION

A laboratory study was conducted to evaluate the impact of surcharge loading on increasing the effectiveness of vertical strip drains (VSD's) in dewatering mature fine tailings (MFT). This study and its previous self-weight study (Haug, et al., 2018) bring together over 5 years of investigation, laboratory testing and analysis.

The objective of this study, was to investigate the effectiveness of surcharge loading on the rate of effective stress build-up and associated settlement. The test column used for this test was identical to the one used for the self-weight test, with the exception that it used a pressurized water cap to apply the surcharge loads of 40 and 60 kPa. Due to the large scale and configuration of the test column, it was difficult and awkward to apply dead load to the MFT. This selected approach was similar to that used for seepage consolidation testing. The applied pressure distributions were not uniform. In the 40 kPa testing phase, the increase in total applied stress ranged from 0 to 40 kPa. When air pressure was increased to 60 kPa, the increase in total stress ranged from 0 to 60 kPa.

The test column was instrumented with a system of pressure transducers and manometers to monitor pore pressure along the central VSD, and at points of similar elevation inside the test column wall. Both in flow and out flow from the test column were recorded.

The study found that seepage surcharge loading in combination with a VSD significantly enhanced the rate of mature fine tailings (MFT) effective stress development and settlement over self-weight consolidation.

2 BACKGROUND

The initial self-weight study (Haug, loc. cit.) found that VSD's are effective in developing effective stress within the MFT, and increasing the dewatering rate. The degree of self-weight dewatering was found to be a function of the unit weight of the MFT, the depth of the VSDs and time. MFT consolidation ranged from zero at the surface to a maximum at the base of the VSD. This study and the associated large-strain consolidation testing showed that surcharge loading of approximately 50 kPa would be required to lower the water content to below the liquid limit and increase the solids content to above 70% higher solids content correlates with higher MFT strength.

3 MATERIAL CHARACTERIZATION

The MFT used for this project was obtained from near the surface of an oil sands pond. This saturated material had been in-place for some time, and had lightly “drained” under self-weight loading and evaporation. Table 1 presents a summary of the MFT characterization. The initial water and solids content were 114.4% and 47.3% respectively. The bulk density of this 0.2 sand to fines ratio (SFR) MFT was 1.35 Mg/m^3. The average plastic and liquid limits were 13.4% and 43.7% respectively. The average liquidity index was 2.2, indicating that this material had the consistency similar to “wet” mud.

Table 1. Characteristics of MFT tested (from Haug et al. 2018).

Property	Value
Initial water content (%)	114.4
Initial solids content	47.3
Bulk density (Mg/m^3)	1.35
Solids specific Gravity	2.12
Mineral content (Mass solids) %	43.0
Mass water (%)	52.0
Mass bitumen (%)	4.50
Sand to fines ratio (SFR)	0.2
Initial clay-water ratio (CWR)	0.43
Liquid Limit (%)	47.7
Plastic Limit (%)	17.7
MBI (meq/100g)	7.60

4 TEST COLUMN

4.1 Design considerations

The initial concept was to use a similar test column of similar diameter and VSD setup as used for the self-weight loading test (Haug et al. 2018). The objective was to eliminate as many variables between the two test programs as possible. The biggest challenge for this test was to determine the loading method. The first option considered was to use a large piston to apply a “dead load” to the MFT inside the test column. This would have the advantage of applying a uniform surcharge load on the MFT. The piston could be loaded with water (or sand), however, a 6 m plus high piston would be required to provide the load. The logistics of using 10 m in combined piston and test column height, concerns about the piston binding and the challenges in providing an adequate seal above the MFT made this approach challenging.

A pipe piston was designed and constructed with a loading cap sized to fit just inside the test, however, this option was rejected in favor of using a seepage loading stress approach. This approach uses a pressurized water cap to provide loading to the MFT. The approach eliminates the need for an excessively tall test column, piston binding concerns, as well as internal sealing concerns. The downside is that increase in total stress varies along the length of the VSD.

4.2 Design

The test column was fabricated from 525 mm diameter ribbed plastic pipe (Gan et al, 2014). A drawing of the test column and instrumentation locations is shown in Figure 1. The column had a total height of 3433 mm. The length of the VSD was 1537 mm, similar to the length of VSD used in the self-weight test. A small diameter thin-walled aluminium down-hole pipe was built into the column. This pipe was to enable the lowering of a down-hole nuclear densometer, with the objective of evaluating density changes with consolidation.

The VSD was held in vertical position by a frame fabricated from 6 mm diameter stainless steel rod. The frame was welded to the base of the column. The top end of the VSD was folded over and was sealed off to prevent MFT from entering the VSD. The perimeter of the bottom end of the VSD was sealed to the base of the column so that only water permeating into the VSD could drain through the bottom. The base of the VSD was connected via a shutoff valve to a drain discharge-tube that was open to drain into an outflow collection container located on the mezzanine floor. This arrangement set the elevation of the drainage outlet at 3841 mm. Elevation zero was set at the base of the column.

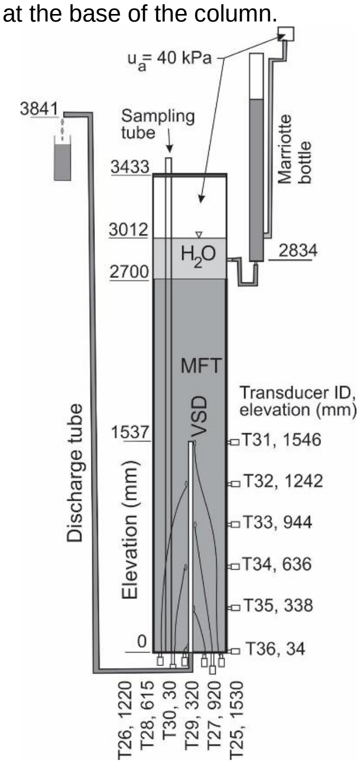

Figure 1: MFT test column design

Six pore-pressure measurement devices, each comprising of a small ceramic cup attached to an external pressure transducer located below the base of the column, were attached to the steel frame supporting the VSD. These pore-pressure measuring devices were spaced at approximately 300 mm roughly equal intervals along the full-length of the VSD.

Six pore-pressure transducers were also installed along the wall of the column at approximately the same elevations as the pore-pressure transducers installed along the VSD. The transducers were each installed behind a corundum stone filter. Transducer readings were collected using a datalogger. The digital outputs from the transducers were found early on in the test program to be of inadequate resolution, resulting in “step-wise” readings. Manometers were later added to complement the transducers with the objective of providing “smooth” direct readings. The manometers were referenced to the applied air pressure to the water cap at the top of the column to keep the manometer columns within manageable heights. This was accomplished by venting the manometers into the pressurized air space above the water cap.

The column was filled with MFT to elevation 2700 mm. A filter was placed onto the surface of the MFT to separate it from the overlying water. The filter was supported near its perimeter by a ring fabricated from a 6 mm diameter stainless rod. A rare-earth magnet was attached to the stainless steel ring. The magnet was free to swivel such that it would stay in contact with column wall as the filter settled with the MFT. The ribs on the exterior section of the column were removed to allow for a washer to track the location of the magnet.

The region above the MFT was filled in with water to elevation 3012 mm. The water level in the test column was maintained at elevation 3012 mm throughout the test. This was accomplished with the use of a constant head Marriotte bottle device. The constant head device was designed so that it could be replenished at intervals during the test while ensuring that a constant head was maintained with water from the reservoir tank.

Figure 2 shows the stress distribution in the column prior to test initiation (Day 0). The discharge tube was filled with water and the pressure distribution was hydrostatic, resulting in a pressure of 37.67 kPa in the outflow tube at the base column elevation (0 m).

Inside the test column the water cap exerted hydrostatic pressure on the MFT, and the MFT adds an additional self-weight stress; with the total stress at the base of the VSD of 38.78 kPa. The available stresses for potential self-weight consolidation are shown shaded in this figure.

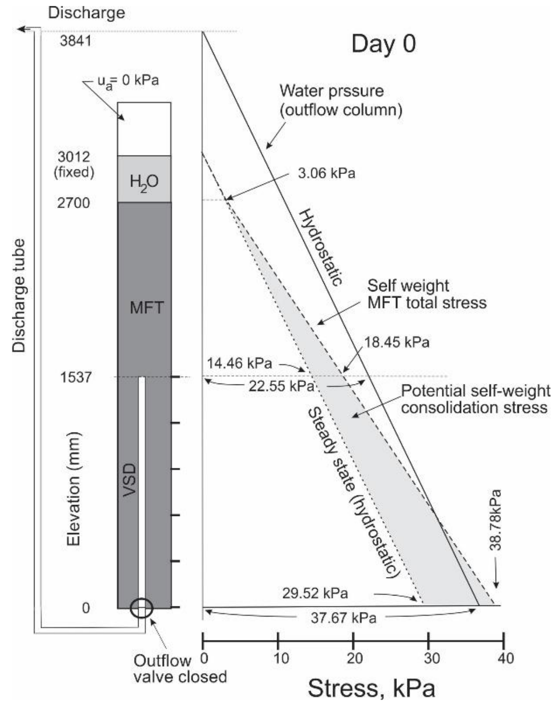

Figure 2: Stress distributions in the test column at Day 0, prior to testing.

5 40 kPa SURCHARGE LOADING

The 40 kPa test was initiated by increasing the air pressure in the space above the water to 40 kPa. As soon as this was accomplished the VSD outlet valve at the base of the column was opened to allow outflow from the VSD.

Figure 3 shows the assembled column in operation. In this photograph the laboratory technician is recording the surface elevation of the tailings. The location of the water reservoir on the mezzanine behind the test column, and Marriotte bottle are also shown in this photograph.

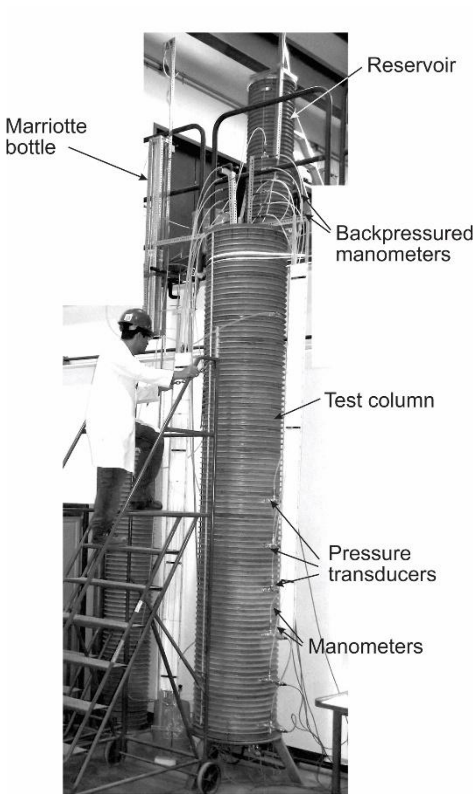

Figure 3: Test column in operation

The stress distributions within the test column and outflow column on Day 1 are shown in Figure 4. The MFT total stress was increased by 40 kPa over self-weight total stress values (Figure 2). The water pressure inside the VSD was controlled by the height of water in the discharge tube. The pore pressures in the MFT are complex and vary over the length of the VSD and horizontally between the VSD and the test column wall. They range from 43.06 kPa at the surface contact with the overlying water column, to 22.59 adjacent the top of the VSD, to 58.45 at the wall of the test column. At the elevation of the base of the VSD the total stress in the MFT is 78.78 kPa. The corresponding pore water pressure adjacent the base of the VSD is 37.67 kPa and adjacent the test column wall is 78.78. The potential self-weight and surcharge loading available consolidation stress at the start of the test is shown shaded.

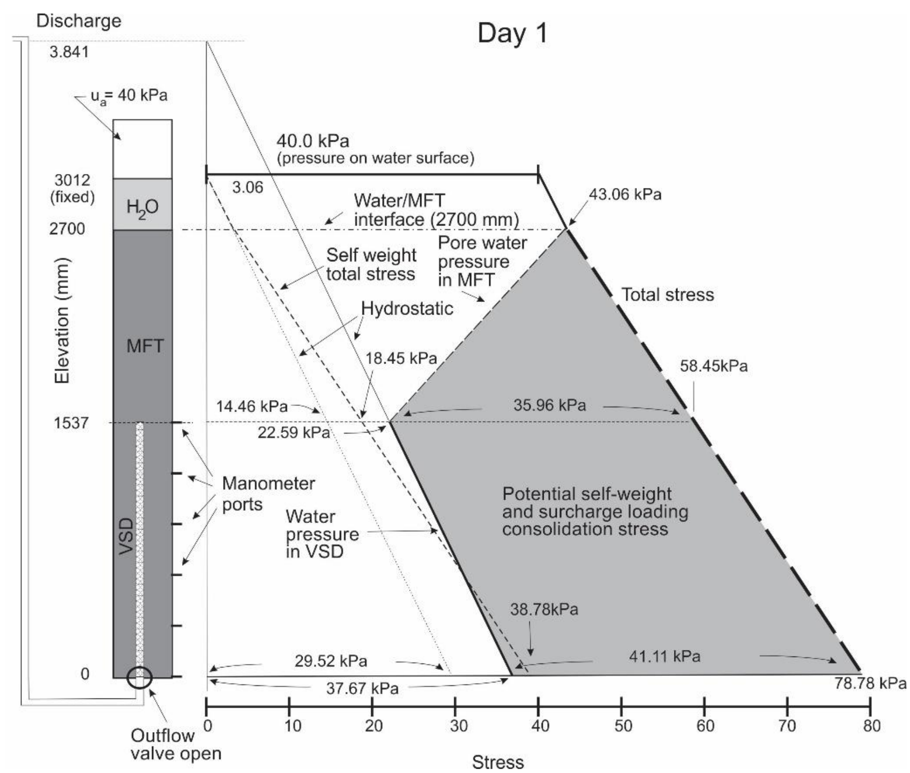

Figure 4: Stress distributions within the test column and outflow column

Figure 5 shows the stress distributions in the test column after 322 days of testing at 40 kPa stress, and just prior to increasing the stress to 60 kPa. The hydrostatic pressure inside the VSD is shown as a solid line extending from the discharge elevation (3841 mm) to the base of the VSD at elevation 0 mm. Total stress applied to the MFT is shown as a heavy dashed line. The area between these two lines represents the magnitude of potential effective stress development, as pore pressures dissipate toward hydrostatic (steady state conditions).

The pore pressures within the MFT were known at seven levels within the test column. The first was at the MFT surface and the remaining six at elevations (for both wall and VSD) of the test column monitoring ports. The pore pressure at the surface of the MFT was 40 kPa. Immediately adjacent the top of the VSD (distinct from "near VSD" locations) the pore pressure was hydrostatic 22.59 kPa (controlled by the head in the discharge tube). The path of pore water pressure change between the top of the VSD and the surface of the MFT is undefined.

The monitored pore water pressures within the MFT are also shown on this figure. Dashed lines approximate the change in pore pressure with depth for near wall and near VSD locations. The piezometers and manometers pore pressure values near the wall are approximately 58 kPa. The corresponding build-up in effective stress ranges from approximately 5 kPa across from the top of the VSD to approximately 20 kPa across from the bottom of the VSD. In the case of the near VSD locations, those in the middle section of the VSD have fallen below 50 kPa, representing an effective stress build-up of approximately 25 kPa.

Figure 5 also shows the surface elevation of the MFT was 2092 mm after 322 Days of testing. This is a decrease of 608 mm from the initial 2700 mm at the start of the test; and represents a drop of approximately 23 %.

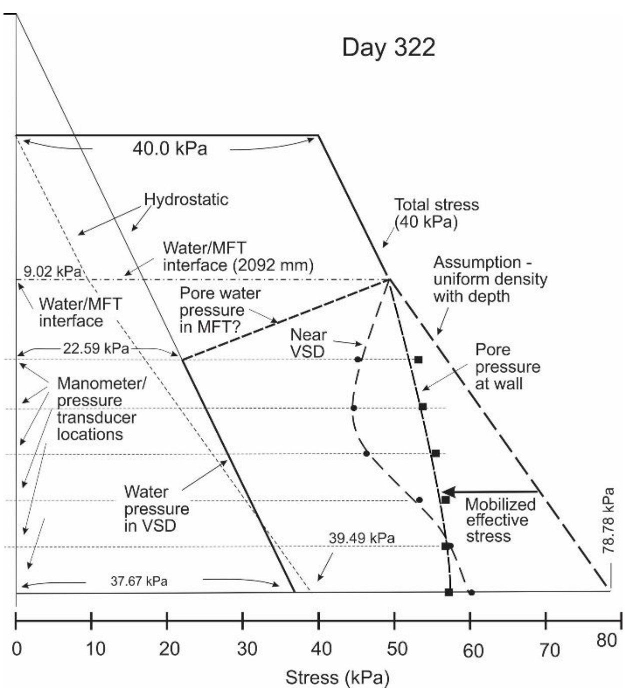

Figure 5: Stress distributions after 322 days of testing

6 60 kPa SURCHARGE LOADING

Figure 6 show a plot of the end of test (Day 1178) test column pore pressure and MFT surface elevation monitoring. The surface elevation of the MFT had dropped an additional 420 mm (to elevation 1672 mm) during the 852 days of testing at this stress level. The total settlement of the surface of the MFT was 1.028 m, or 38%.

This figure also shows the pore pressure distributions with depth for the near VSD and near wall locations. After 1178 days of testing the MFT had settled to 130 mm from the top of the VSD. As a result, high pore pressures were present within the upper portion of the test column. Further down in the test column, significant increases in effective stress occurred. Near the base of the VSD 40 kPa of effective stress had developed near the wall and over 50 kPa of effective stress had developed near the VSD.

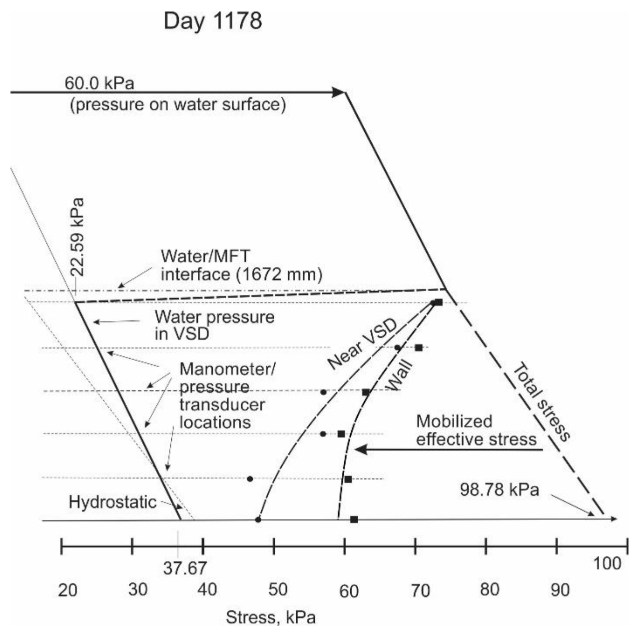

Figure 6: Stress distributions after 1178 days of testing

7 TEST COLUMN DECOMMISSIONING, SAMPLING AND TESTING

The column was dismantled by die grinder cutting the column into 10 vertical segments, from top to the bottom (Figure 7). Each of the layers along the VSD were approximately 170 mm in thickness. The selection and location of these "layers" is separate from the location of the pressure transducers placed vertically along the VSD and wall of the test column. The spatial layout of the sampling and testing "cells" pertaining to each layer is shown in Figure 8. There were a total of 22 sampling locations for water content in each layer. Section 2-8-13 shows the location of cells used in the analysis.

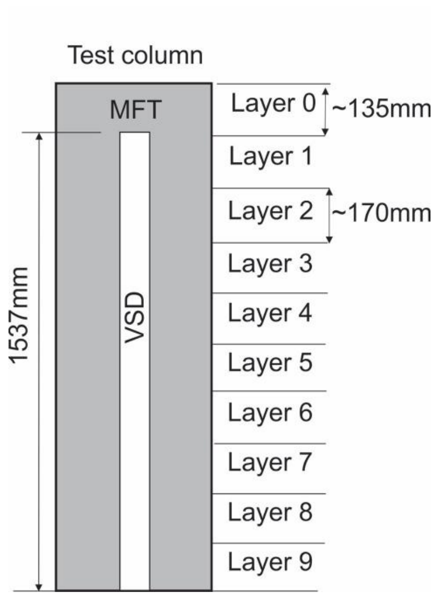

Figure 7: Sampled layers

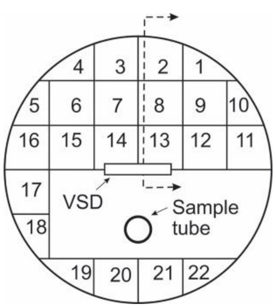

Figure 8: Sampling cell locations

Figure 8 also shows the location of the VSD along with the sampling tube. No reliable geophysical reading were obtained from the sampling tube, due to the relatively small diameter of the test column.

The soft unconsolidated MFT at the surface was removed down to elevation 1537 mm, prior to sampling and testing. The material above the top elevation of the VSD was designated as Layer "0".

Cutting and removal of segments of the test column exposed "undisturbed" surface of MFT. The MFT was then trowelled level and the metal template was pressed into MFT surface (Figure 9). Metal template was retrieved and all material pertaining to the layer just tested and sampled were removed to create a flat level surface in readiness for the next cut to the column. The column was then cut to expose the fresh MFT surface. Testing and sampling procedures were repeated for each ensuing layer.

The highest water contents were obtained for the upper most layer, and for samples nearest the test column wall. These values were in the mid 70% range. Water contents in the top layers near the VSD were in the upper 60% range. The lowest water contents were found at the base of the column (low to mid-40% range) and immediately adjacent the VSD (mid to upper 30% range).

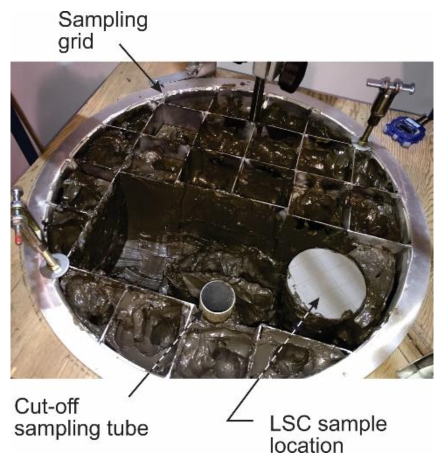

Figure 9: Photograph of sampling

The VSD was kept intact through the entire column decommissioning process. It was protected from drying by wrapping it with plastic wrap. After the VSD was removed from the column base, MFT samples were taken from both sides of the VSD for water content analysis. The condition of the VSD after it was taken down from the column is shown in Figure 10. The interior of the VSD was found to be clean. No sign of what might have been called a filter cake was observed on the surface of the VSD, rather a lower water content material consistent with changes observed across the column. A small overlap "kink" was also observed approximately ¼ from the bottom of the VSD.

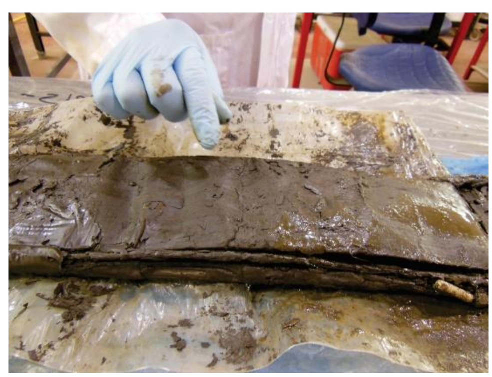

Figure 10: VSD post-test inspection

8 ANALYSIS

Approximately 200 MFT samples were collected for water content measurement during the decommissioning of the test column. Figure 11 shows how the water content varied with elevation (depth) for Cells 2, 8, and 13. The highest water contents were for Cell 2 reflecting their distance from the VSD. The lowest water contents were for Cell 13 closest to the VSD. The drop-off in water content is initially sharp, and then decreases at a somewhat consistent rate, the variation between cells narrowing with decrease in elevation. The average plastic limit, liquid limit, and liquidity index for Cell 13 were 13.4, 42.9, and 1.24 respectively.

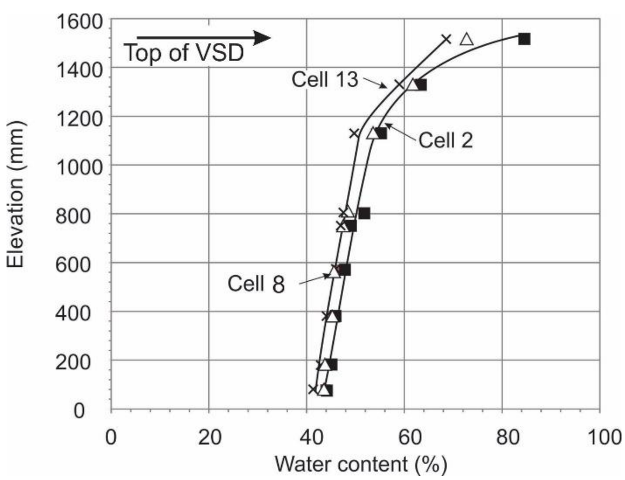

Figure 11: Post-test variation in water content with depth (elevation)

Pore water pressures within the test column were also calculated (deduced) from post-test water contents to provide a “rough” comparison with monitored pore pressure values with test column depth. This was accomplished by using the results of the large-strain consolidation (LSC) test conducted as part of the self-weight column test program (Haug et al., 2018); which showed the relationship between water content and effective stress for this MFT. The corresponding pore pressures were calculated based on the effective stress values.

Figure 12 presents a “rough” comparison of the test column pore pressure monitoring and post-test water content sampling. The data points from six transducers located at distinct elevations along VSD or wall (Figure 6) are repeated in this figure. Also shown are the calculated pore water pressures at the VSD and test column wall. These data points represent average values for the nine vertical layers. The end-of-test calculated pore pressure values along the section 2-8-13 generally fall in the same range as the monitoring values, even though there is significant variations in water content between cells.

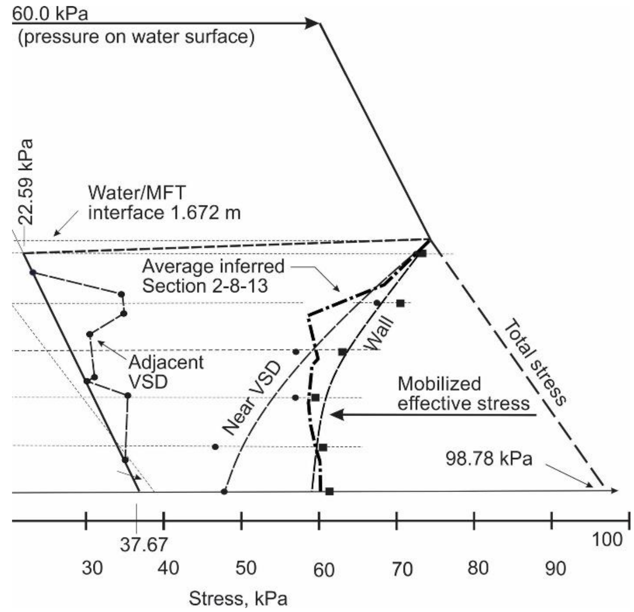

Figure 12: Comparison of monitoring and post-test sampling results.

Figure 12 also shows a similar plot for “smeared” MFT samples collected from the VSD. The impact of the high seepage gradient near the VSD is apparent in the low thirty’s water contents, which required approximately 60 kPa of effective stress to produced. Haug et al, 2016, described the relationship between void ratio and low gradient directly measure hydraulic conductivity, for the MFT used in this test program. Based on that work, the hydraulic conductivity of the “smeared” low water content MFT would be in the approximately of 3 x 10^{-9} m/s.

9 SUMMARY AND CONCLUSIONS

The test column designed and constructed for this project was found to be capable of simulating a variable total stress surcharge load. This total stress load varied from near zero at the top of the VSD to 60 kPa at the base of the VSD.

Surcharging was found to significantly increase the rate and magnitude of effective stress development. It also caused significant MFT settlement in the test column compared to self-weight consolidation. MFT in the test column settled 38% (based on original height) from its original 2.70 mm height during 2.3 years of testing. Increasing the surcharge from 40 to 60 kPa was found to provide increasingly more benefit, in terms of effective stress development and settlement. An average effective stress of approximately 35 kPa was developed at 1/3 height within the test column under the 60 kPa of surcharge (representing approximately 60% consolidation). This stress build-up occurred within approximately two years. MFT consolidation levels reached maximums of 64 % and 82 % at the test column wall and near the VSD respectively. These values are based on effective stress development, and the e-log P relationship for this material, described by Haug et al. 2018.

There was no evidence that flow through the VSD was seriously “pinched” off or hindered by the movement of the clay fines and bitumen. A gradual reduction in flow into the VSD was observed, however, that reduction can be largely explained by the decrease in hydraulic conductivity of MFT immediately adjacent the VSD.

There was no indication of the development of a filter cake adjacent the VSD. There was lower water content/higher dry density MFT near the VSD, but, this appeared due to the decrease in water content. This finding was confirmed through visual examination of the dismantled sections, which showed no sudden change in material characteristics (other than for lower water content) consistent with the build-up of a filter cake. The low water content values of the “smeared” material on the VSD was estimated to have a hydraulic conductivity in the range of 3×10^{-9} m/s.

The MFT remained in “near” liquid viscous state during the entire 60 kPa consolidation process. The measured water contents did not fall below the liquid limit.

10 REFERENCES

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