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Test column study into VSD aided self-weight consolidation of oil sands tailings

Moir Haug and Julian Gan
SNC-Lavalin Inc., Center for Advanced Materials Testing and Research
Saskatoon, Saskatchewan, Canada

ABSTRACT

A laboratory test column study was conducted to examine the effectiveness of vertical strip drains (VSDs) in enhancing dewatering of mature fine oil sands tailings (MFT), under self-weight conditions. A 1.5 m long VSD was installed up the center of an instrumented 4 m high test column. The pore water pressures within test column were measured with 10 manometers along the sides of the column and three across the base. The surface elevation of the MFT was recorded on a daily basis. The results of this study found that self-weight consolidation increased the solids content from an average 46.7% to a maximum of 58% at the base and minimum of 48% at the top of the VSD Post-test sampling of the test column showed that the MFT near the VSD had almost fully consolidated, however, samples taken further from the VSD had not reached their theoretical maximum consolidation. The results of the large strain consolidation test closely matched the test column results.

RÉSUMÉ

Une étude en laboratoire sur les colonnes d'essai a été menée pour examiner l'efficacité des drains à bandes verticales (VSD) dans l'amélioration de la déshydratation des résidus de sables bitumineux matures (MFT), dans des conditions de poids propre. Un VSD de 1,5 m de long a été installé au centre d'une colonne d'essai instrumentée de 4 m de haut. Les pressions d'eau interstitielle dans la colonne d'essai ont été mesurées avec 10 manomètres le long des côtés de la colonne et trois à travers la base. L'élévation de surface de la MFT a été enregistrée quotidiennement. Les résultats de cette étude ont montré que la consolidation de poids propre augmentait la teneur en solides de 46,7% en moyenne à 58% maximum à la base et au minimum de 48% au sommet du VSD. L'échantillonnage post-test de la colonne d'essai a montré que la MFT près du VSD était presque entièrement consolidée, cependant, les échantillons prélevés plus loin du VSD n'avaient pas atteint leur consolidation maximale théorique. Les résultats de l'essai de consolidation à grande contrainte correspondent étroitement aux résultats de la colonne d'essai.

1 INTRODUCTION

A laboratory research program was conducted to evaluate the performance of vertical strip drains (VSDs) for dewatering Mature Fine Tailings (MFT). The oil sands industry has tailings ponds in excess of 1 square km near Fort McMurray filled with slurried MFT. Settlement of these soft tailings and associated strength gain is required to support a trafficable surface on which reclamation activities can ultimately lead to the closure of the Ponds. A key component of this approach is that the surface of tailings be strengthened sufficiently to support reclamation activities (Wells and Caldwell, 2009). The objective of this research program was to evaluate the effectiveness of VSDs in dewatering MFT under self-weight conditions. The program was also intended to provide baseline data on which future studies on the effectiveness of adding surcharge load, changing VSD depths, and spacing could be evaluated. The self-weight conditions, for this study, were simulated in a large, fully instrumented test column where sedimentation and consolidation of the MFT could be assisted with the aid of a central VSD.

Tailings consolidation and effective stress build-up under self-weight loading increased from zero, at the surface, to a maximum at the base of the VSD. Post column testing confirmed that little or no MFT segregation of the tailings took place during the six and a half month long test.

2 BACKGROUND

Figure 1 shows the location of MFT in a typical oil sand pond. Immature fine tailing are spigotted into ponds where they slowly settle out. Initially tailings settling is by the process of sedimentation which causes the heavier sand particles to settle out first. Over time the fine tailings eventually transition into mature fine tailings. And, once particle to particle contact is reached within the MFT it settles by the process of consolidation. The length of time for consolidation and resulting strength build-up to take place, is a challenge in tailing reclamation

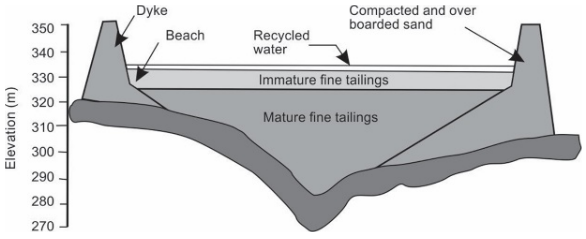


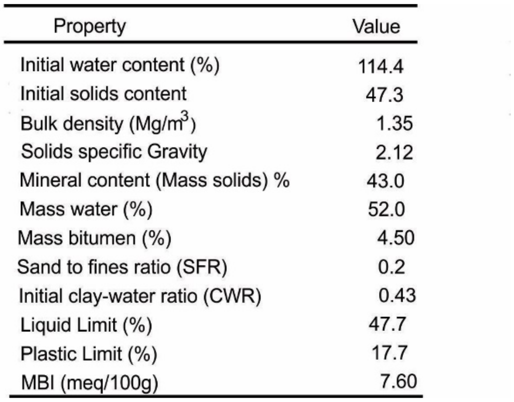
Figure 1: Typical oil sands tailings pond redrawn after MacKinnon, et al., 1989

Jeeravipoolvarn et al. 2009. reported on the results of long-term 10-m tall, 0.91 m diameter standpipe test conducted on oil sands tailings at the University of Alberta. These test columns did not contain VSD's. The initial solids content in test column 1 with a sand to fines ratio (SFR) of 0.12 increased from 30.6 to 41.8 in 25.7 years. In test column 2, with a SFR of 0.92 the solids content increased from 45 to 48.3 % in two years.

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 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



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 LARGE STRAIN CONSOLIDATION TESTING

4.1 Test Apparatus

A large-strain consolidation tests was carried out on the MFT slurry. This long duration test was conducted on a 150 mm diameter test sample. A photograph of one of the test apparatus is shown in Figure 2. This equipment was specially designed for use on soft tailings to measure consolidation and hydraulic conductivity during consolidation testing. The test apparatus consists of a mechanical loading system and stainless steel consolidometer cell. The unique feature of this apparatus is its ability to precisely apply low loads, which are required to accurately characterize soft tailings. These test apparatus are capable of accurately applying loads from as low as 0.2 kPa and as high as 500 kPa. MFT tailings do not have significant rebound, thus, the consolidometer cell and measuring devices can be transferred to one of four high pressure consolidometers, where the load can be increased from 500 kPa to just less than 5000 kPa (Gan el al., 2011). Typical length of time for testing on clay rich MFT type material can exceed five months.

The mechanical loading system is composed of a counterweight device, direct loading yoke and a mechanical arm to provide leverage for high loads. The stainless steel loading cap is of significant dimension and weight. It is balanced by an adjustable counterweight system to enable the application of small loads necessary for testing slurry materials.

The consolidometer cells are 150 mm in diameter and 165 mm high. The cells are designed for two-way drainage through the top and bottom. Drainage through the bottom can be closed off for one-way drainage through the top only. Ports for manometers are distributed over the height of the cell for monitoring pore water pressures during consolidation and heads during hydraulic conductivity measurements. The lower porous stone is sealed into the base of the cell to allow for hydraulic conductivity measurement of the consolidated slurry during or at any selected stages in a consolidation test. The cell is also connected to a constant head system. The constant head system is used for maintaining constant back-pressure during consolidation testing and to provide flow for hydraulic conductivity measurement. Maintaining a constant back-pressure ensures that there is no disturbance to the equilibrium of the system at any time whether during consolidation or hydraulic conductivity testing.

Figure 2: Large-strain consolidation test apparatus

4.2 LSC Test Results

The results of the large strain consolidation test are shown in Figure 3. This plot shows a void ratio versus log effective stress. The maximum stress applied during this load-stepped consolidation test was 500 kPa. A linear primary consolidation line relationship was produced based on an initial water content of 114.4%. The Compression index c_c obtained from this line was 0.56. This value is approximately double the predicted value based on the relationship described by Nagaraj and Murty (1985) for "normal" clays, and suggests that consolidation of the tailings may be partially under the impact of chemical or biological processes. The unloading portion of the test produced a relatively flat rebound curve.

Constant head hydraulic conductivity tests were conducted on the MFT in the consolidometer on attainment of a consolidated state at selected stress levels. The hydraulic conductivity ranged from 2 x 10^{-8} m/s to 2 x 10^{-9} m/s, corresponding to void ratios of 1.92 and 0.66 respectively (Haug et al., 2017). The maximum hydraulic gradients during the continuous hydraulic conductivity testing were less than 0.5. These gradients produced a small seepage stress. The "adjusted" points on the e-log P plot reflect the increased total stress caused by this low flow. At higher loads the seepage stress was insignificant. The combined slurry consolidometer and hydraulic conductivity test took in excess of five months to complete.

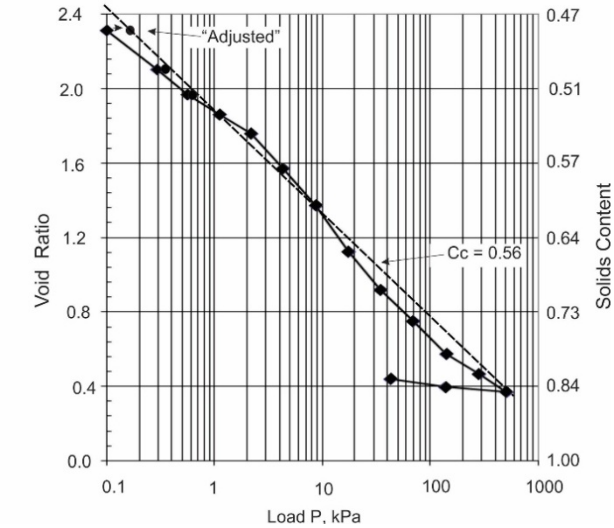


Figure 3: Large-strain consolidation Void ratio and Solids content versus log P plot.

5 TEST COLUMN

A schematic of the test column set-up and pressure distribution prior to testing is shown in Figure 4. Liquid collected by the VSD was drained to an outlet with an overflow at the same level as the MFT surface. Total stress and pore water pressure at the start of the test are equal. As the pore water pressure moves toward the long-term hydrostatic line that is maintained in the VSD, effective stress gradually builds up in the MFT.

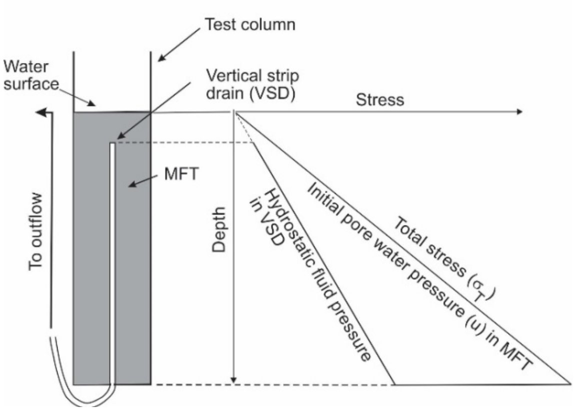


Figure 4: Initial test column and VSD stress distributions

5.1 Design

Gan et al. (2014) described the set-up of the test column and initial test results. The test column was fabricated from a commercial PVC ultra-rib pipe. The pipe had an internal diameter of 525 mm and came in 4 m lengths

The test column instrumentation consisted of 13 manometers. Ten manometers were approximately equally spaced along the outside wall of the test column. Three manometers were evenly spaced from the VSD to the test column wall. One large borehole piezometer typically used for borehole installations was placed on the inside bottom of the test column, and a plate load-cell was added at the base of the column as a late addition to the monitoring.

The location of 10 side column manometers (A to J) and 3 base manometers (K to M) are shown in Figure 5. Each manometer was equipped with a bleed screw to facilitate air removal. Figure 6 shows the location of the base load-cell, single vibrating wire piezometer, and base manometers evenly spaced from the VSD to the wall of the test column.

5.2 Instrumentation

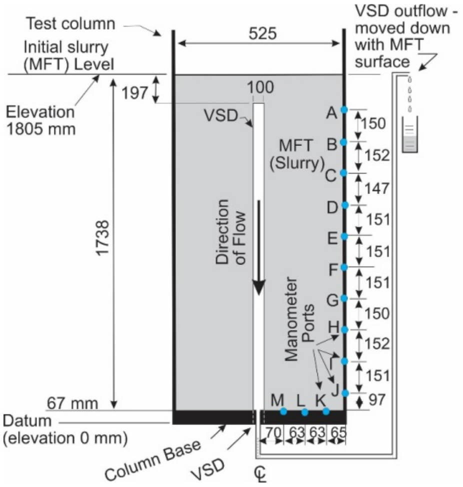


Figure 5: Schematic illustration of test column instrumentation, revised after Gan et. al, 2014.

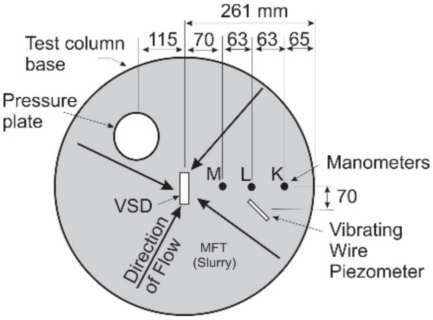


Figure 6: Instrumented base of test column

5.3 Test initiation and monitoring

A tremie system was used to fill the test column with MFT, from the bottom upwards. The lower end of the tremie pipe was maintained below the surface of the tailings during deposition to prevent segregation and air entrapment. The final surface elevation of the MFT was 1.805 m. The manometers were filled with tap water to the 1.805 m level prior to the start of testing.

Monitoring commenced immediately upon completion of MFT placement. The test was initiated by opening the manometer valves followed by opening the VSD outlet valve. The test column instrumentation was monitored closely for the first 48 hours. Test column monitoring then continued on a regular basis for the next 6.5 plus months. At the end of that time, the test column was dismantled in sections from top down to obtain samples for testing.

6 PRESENTATION OF TEST RESULTS

6.1 Drainage and settlement

The cumulative volume of water collected from the VSD during the test is shown in Figure 7. This data provides a measure of the performance of the VSE. The figure also shows for comparison purposes a “smooth” outflow curve based on a projection of the flow over the first 100 days.

Initially the rate of outflow was high, but gradually slowed with time. There was a noticeable reduction in the slope in cumulative outflow at around 2500 hrs (approximately 100 days). Initially the outflow rate dropped steeply then gradually levelled off. At the end of the test the outflow rate was 0.5 ml/hr. Total outflow collected during the test was approximately 32 L. At the end of the test a layer of water was present on the surface of the MFT slurry, and surface water was lost to evaporation during testing.

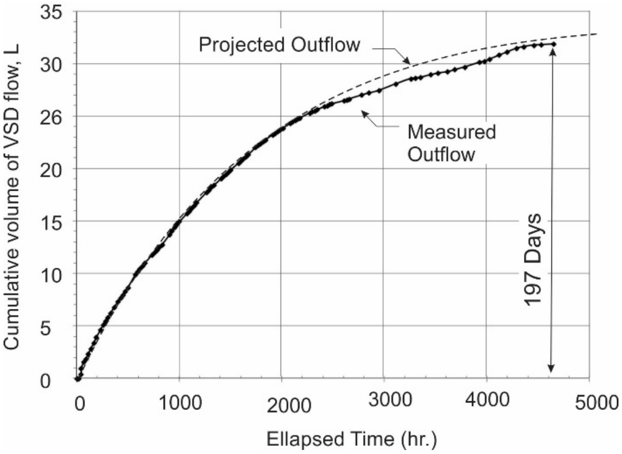


Figure 7: Cumulative volume of water discharged through the VSD.

Figure 8 shows the measured elevation of the surface of the MFT slurry along with the calculated subsidence. The MFT surface dropped from an initial elevation of 1.805 m to a final elevation of approximately 1.580 m, which represents a total subsidence of approximately 0.23 m (approximately 13%). Unfortunately, complete measurements of outflow volume were not obtained during the test.

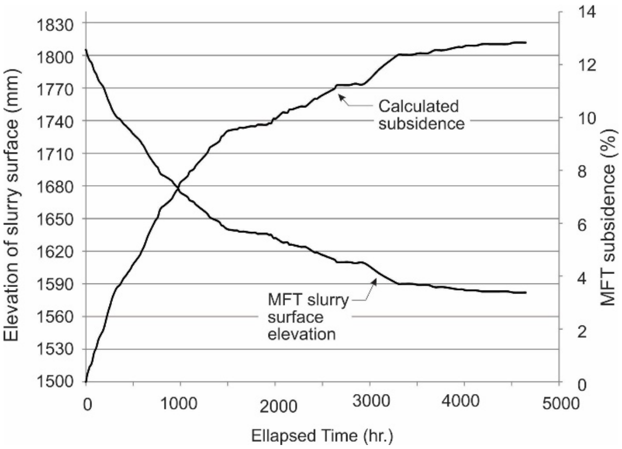


Figure 8: Change in MFT level within the test column and corresponding settlement.

6.2 Post-test VSD Inspection

The VSD was visually inspected at the end of the test (Figure 9). A fine layer of MFT clay covered the outside of the VSD from top to bottom. The inside of the VSD was clean, as is shown in the figure 9. The thickness of the clay filter cake covering was approximately 1 mm.

Figure 9: Post-test photograph of exposed VSD

6.3 Pore pressure monitoring and analysis

Manometer readings along with estimated total stress measurements at each manometer elevation are presented together in Figures 10, 11 and 12. These values are shown in total head for the manometers and MFT total stress, expressed in equivalent mm of H_20; where 100 mm of water head equals 0.98 kPa. Total stresses were computed based on an initial solids content of 46.7% (at time of testing) and adjusted for water loss as consolidation proceeded. Base piezometer readings are also shown in Figure 12.

All of the manometers followed a similar trend of increasing total head from the primed value of 1805 mm toward the initial total stress equivalent values. The pattern of these curves then began to decrease as water drained from the MFT, and effective stress developed within the MFT. At the end of test (197 days) the pore pressure were still dropping at a decreasing rate.

The upper test column manometers (A to E) showed that no measurable effective stress developed in the MFT during testing for near surface manometer A. Further down in the test column effective stress increasingly developed within the MFT reaching 10.2 kPa at manometer E.

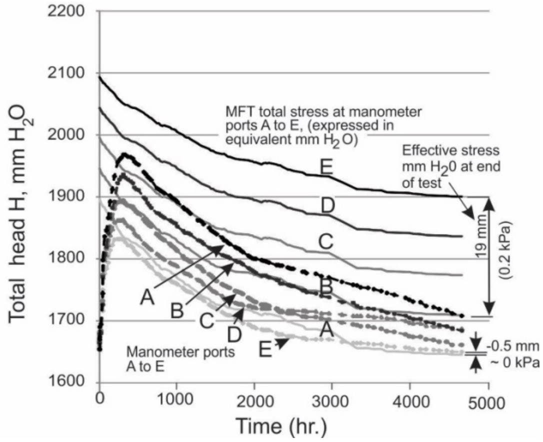


Figure 10: Change in manometers A through E total, and corresponding approximate MFT total stress with time

The lower manometers at the wall test column manometers showed relatively uniform increase in effective stress with depth of MFT. MFT at manometer F developed 1.5 kPa of effective stress and MFT at manometer J reached 4.4 kPa of effective stress.

The three manometers installed in the base all showed significant pore pressure reduction and build up in effective stress within the MFT. The greatest increase in effective stress (5.6 kPa) occurred on the base of the tests column and adjacent to the VSD. This was close to the calculated maximum of 6.4 kPa based on initial test column height and MFT density; and confirms that MFT in the test column was still settling when the test was decommissioned.

The low sensitivity piezometer showed considerable scatter, however, generally agreed with the manometer readings. These reading also closely agreed with the "projected" initial base manometer pressure, selected to show the likely manometer total head decrease had they been primed to match the MFT total stress. No reliable data was collected from the pressure plate.

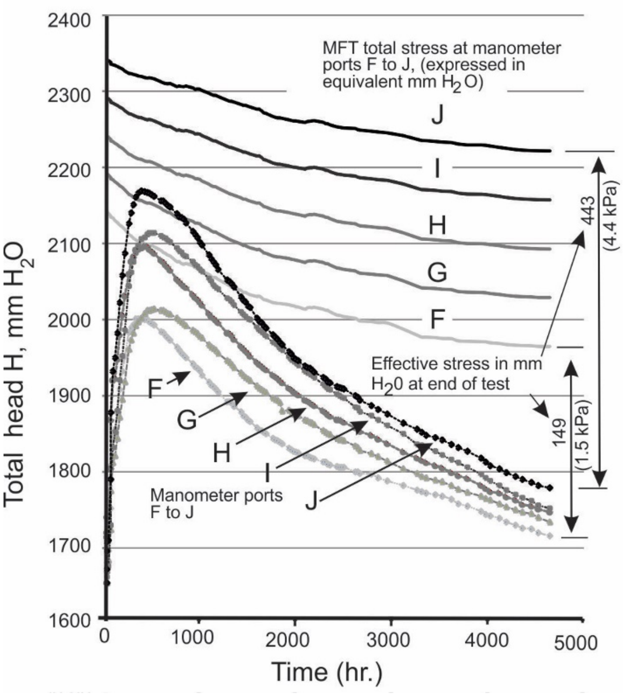


Figure 11: Change in manometers F through J total, and corresponding approximate MFT total stress with time

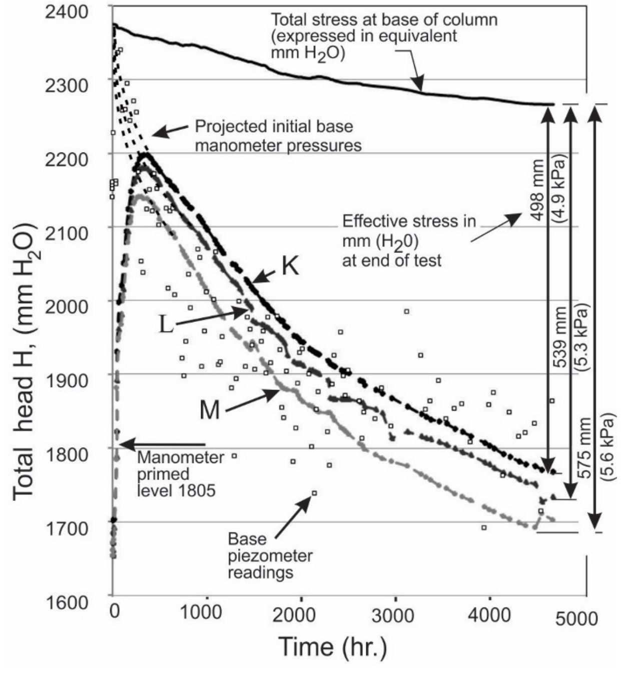


Figure 12: Change in manometers K, L, and M total, base piezometer total head, and corresponding approximate MFT total stress with time

7 SUMMARY AND CONCLUSIONS

The main conclusion of this study is that VSDs are effective in dewatering high clay content MFT near the VSD under self-weight conditions. The degree of self-weight dewatering is a function of the unit weight of the MFT, the depth of the VSDs and time. Both the test column and the large strain consolidation test show an increase in solids content from 46% at the surface to a maximum of 58% at a depth of 1.5 m. (Figure 13). This increase is significant in comparison with the values reported by Jeeravipoolvarn for 10 m tall non-VSD aided test columns. Increasing the solids content of the MFT to 70% would require that the effective stress increased to approximately 50 kPa. Figure 13 also shows the location of post-test near VSD and post-test near wall MFT samples. This data was calculated from water contents and overlying thickness of MFT. Considering that MFT inside the test column had not reached "full" consolidation, these samples show general agreement with the laboratory consolidation test results.

Self-weight consolidation was also found to be a relatively slow process, with only the zone nearest of the VSD consolidated after 6 ½ months of testing.

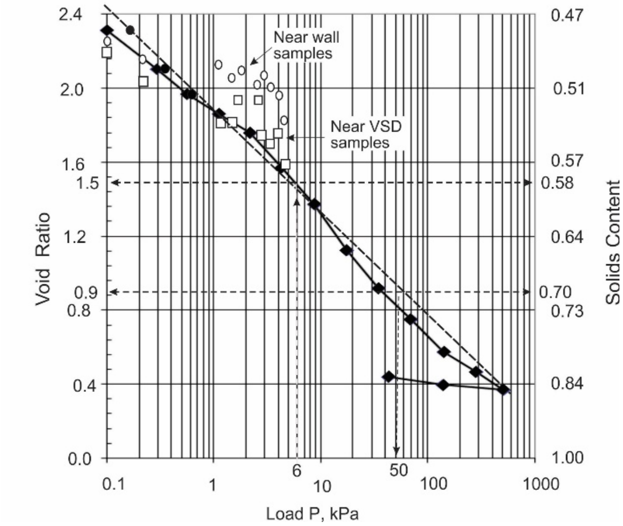


Figure 13: Change in solids content and comparison of test column and post-test stress state.

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