THE BEHAVIOR OF FREE FLOWING GRANULAR DRAINS

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ABSTRACT
Granular drains are one of the most effective tools for controlling the migration of contaminants. In most cases these drains are used for relatively short term applications extending over a few years. More recently, however, these drains are being used for long-term decommissioning in the mining industry. In these situations, clogging becomes a more important issue. This paper presents the preliminary results of a laboratory test program to evaluate nature of permeability reduction and head loss within drains used for environmental applications. A laboratory test program was conducted with three types of sand: Coarse sand, Uniform sand and French drain sand under low gradient conditions. In order to simulate time effects, various suspensions of kaolinite, Battleford till and bentonite fines have been used to permeate different drains. The result of this research suggested that coarser drains can be used effectively for long-term environmental containment.

RESUME
Les drains granulaires sont un des outils les plus efficaces pour contrôler la migration des contaminants. Dans la plupart des cas, ces drains sont utilisés pour des applications à court terme qui durent quelques années. Plus récemment par contre, ces drains sont implémentés dans des ouvrages qui seront affectés par la fermeture/restauration de site miniers, conséquemment à long terme. Pour ces situations, l'obstruction du drain devient un sujet très important. Cet article présente les résultats préliminaires du programme d'essais en laboratoire qui consiste à évaluer la nature de la réduction de la perméabilité et la perte de charge dans les drains utilisés pour des applications environnementales. Le programme d'essais en laboratoire a été réalisé avec trois types de sables, un sable grossier, un sable Uniforme et un sable pour drain français sous des conditions de gradient hydraulique faible Pour simuler l'effet du temps, diverses suspensions de kaolinite, de Battleford Tillite (moraine) et de bentonite granulé ont été utilisé pour infiltrer les différents drains. Les résultats de cette recherche suggèrent que les drains constitués de matériaux grossiers peuvent être utilisé efficacement dans des ouvrages de confinement environnementaux à long terme.

1. INTRODUCTION

This paper presents the preliminary findings of the laboratory program to evaluate the hydraulic nature of free flowing sand drains. Sand drains are an important tool for remediation and control of contaminant migration. The design of these drains has typically been based on filter criteria developed for earth dams, where piping failures are a major concern. More recently, these drains are being designed for long-term environmental applications, where clogging is the primary concern. The objective of this laboratory test program is to examine the performance of different drainage materials when permeated with fines of different characteristics. The goal was to determine the nature of clogging within these drainage materials. It was also to determine whether or not the current filter design criteria can be modified for long-term environmental applications.

2. BACKGROUND

The classical approach to drain design has focused on filtration criteria, as it relates to the design of dams. Terzaghi (1922) recommended the ratio $D_{15}/d_{85} < 4$ for retention criterion and $D_{15}/d_{15} > 4$ for permeability criterion (Figure 1). Kenney et al. (1984) also suggested a relationship for retention criterion but using other particle sizes: $D_5/d_{50} < 4$. Later, in 1989, Sherard et al. argued that Terzaghi's criteria were too conservative and disproved the use of other relationships between other particle sizes such as D_{50}/d_{50} or D_{15}/d_{15} since they could be too large or too small for some clays to determine. Most of the test results in their study gave a failure boundary of $D_{15}/d_{85} > 9$. This study also distinguished two categories of downstream filters in a central core dam: "critical" and "non-critical". Where a concentrated leak can not occur, the filter can be termed "non-critical". Fine filters may not be needed in non-critical locations. For dam core applications, leak avoidance is important because piping can lead to failure.

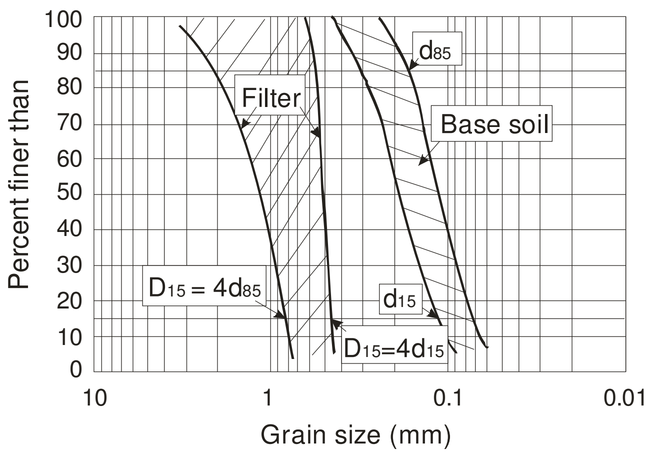

Figure 1: Diagram illustrating original Terzaghi specifications for grain size of material suitable for filter (after Terzaghi, Peck and Mesri, 1996).

The behavior of granular drains has been studied previously by observing their permeability reduction under flow condition. According to Reddi et al. (2005), both tap water and fines suspension can cause a decrease in permeability. When tap water is introduced, it results in rearrangement of the porous medium which involves the increase of upstream pore sizes due to particle detachment, and decrease of downstream pore sizes due to particle deposition. This process is termed "self-filtration". Along with the relocation of particles, flow rate usually reduces and that causes permeability reduction. Reddi et al. (2005) found that self-filtration in concrete sand resulted in 70% permeability reduction after 200 pore volumes of flow. The rate of permeability reduction could be faster with coarser sand. Bergerman and Haug (2007) reported reduction rates of 50%, 65% and 80% after 250 pore volumes of concrete sand, French Drain sand and Uniform sand, respectively.

When a granular filter is permeated with suspension, fine particles are injected into pores and cause faster permeability reduction (clogging) than tap water can. Baghdikian et al. (1989) found that this permeability reduction can be caused by two different mechanisms: particles larger in size than pore sizes become trapped or particles much smaller than the pore sizes inject uniformly in pores. The second mechanism is dominant when an attractive surface potential energy exists between the sand and the fines. It was then found by Sen et al. (2004) that multi-particle bridging is a third mechanism of particle retention. Regarding the rate at which particles accumulate in a given pore, Reddi et al. (2005) addressed that it is governed by three factors: (i) particle concentration in pore fluid; (ii) flow rate in the pore; and (iii) probability of particle capture in the pore. Higher concentrations of particles in the influent cause faster permeability reduction. Pore flow rates decrease with time under constant head testing due to permeability reductions. The probability of capture is progressively increased due to a reduction in pore size and pore velocity. This results in different rates of permeability reduction of porous media over time.

The clogging of particles in granular drains is also dependent on the properties of fine particles in the influent. Baghdlklan et al. (1989) showed suspensions with bentonite can reduce the permeability faster than kaolinite. With the same concentration and experimental conditions, bentonite caused a faster permeability reduction due to its "bridging capability and, therefore, the formation of aggregates." The ratio between final permeability and initial permeability (k/k_o) of test with bentonite was 0.28 while the same ratio with kaolinite was 0.85.

3. EXPERIMENTAL MATERIALS AND SETUP

Materials used in this program included French drain sand (Bergerman and Haug, 2007), Uniform sand and Coarse graded sand. The gradation curves of these drain sands are shown in Figure 2. The D_{15} sizes were 0.25 mm, 0.7 mm, and 0.9 mm for the French drain, Uniform, and Coarse graded sand, respectively. Sand samples were lightly compacted into a vertical column (268 mm high, 101 mm diameter) at porosities of 29%, 36%, and 33% for the French drain sand, Uniform sand, and Coarse graded sand, respectively.

Three different suspensions of fine were used to permeate the drainage materials in order to simulate the infiltration of fine particles from the surrounding base soil. They were sodium bentonite, kaolinite and Battleford till. These fines had specific surface areas of approximately 800 m^2/g, 0.67 m^2/g, and 0.44 m^2/g respectively. Their average particle sizes were 80 μm, 18.1 μm, and 27.3 μm, respectively.

Figure 3 shows the experimental setup for the constant head test. Carbon dioxide was used to flood the samples before the introduction of water, thus ensuring saturation prior to testing. Carbon dioxide is quickly dissolved in water allowing water to fill up the pores. This process helped to ensure that the measured heads were more accurate because they were unaffected by the air pressure

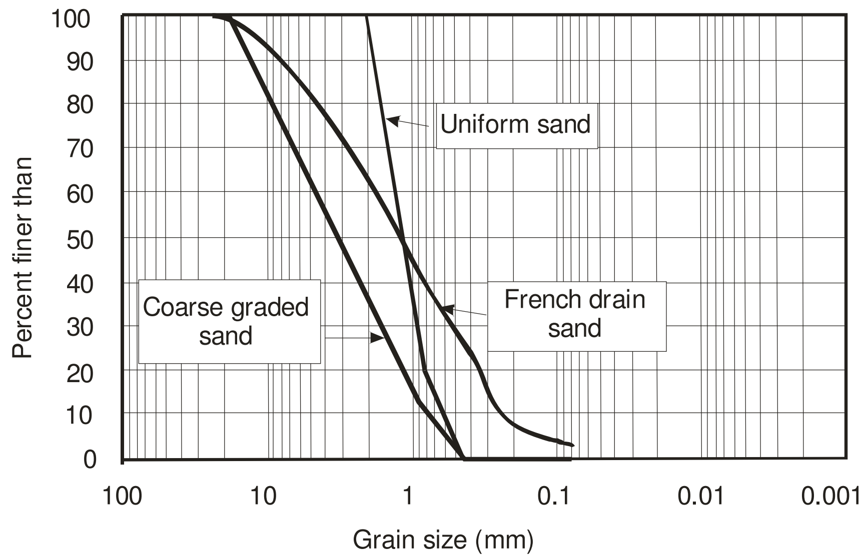

Figure 2 : Grain size distribution of 3 sand drain materials

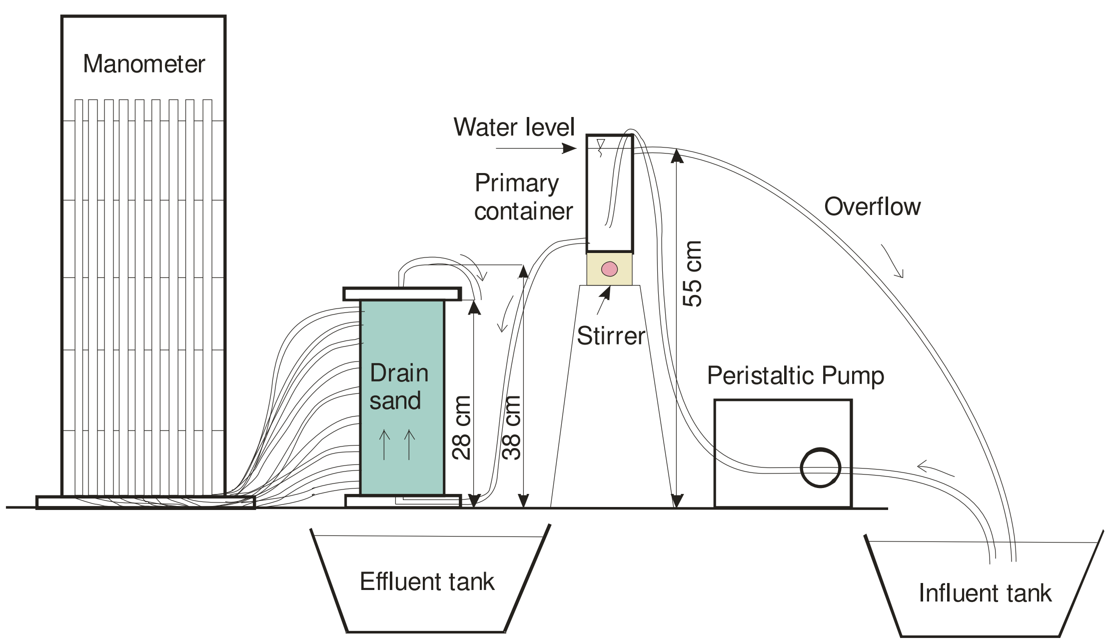

Figure 3: Experimental setup

The influent tank contained colloidal suspensions of three different fines in tap water. The suspensions were maintained by continuous mixing with a motorized stirrer during the test. The drain sand column was connected with a plastic bottle as a primary container set at 55 cm above the base of the column. Nine ports, spaced along the side of the column were attached to manometer tubes in order to measure pressure head at various elevations in the column. The primary container was fed by the influent through a peristaltic pump and placed on a magnetic stirrer to prevent particle settlement. Excess influent was returned to the influent tank through a port near the top of the bottle. The colloidal suspension was pumped into the sand column through its bottom port and exits at the top cap. The outflow tube was fixed at 38 cm to ensure the consistence from one test to the other. Tap water was passed through the column to carry out self-filtration prior to the introduction of particulate suspensions. The initial permeability of the soil filter was also established during this process. The flow rate was measured at the outlet of the soil sample and the turbidility of the effluent measured. Changes in heads were recorded to calculate permeability and evaluate clogging throughout the length of the soil column.

4. RESULTS AND DISCUSSION

Typical self-filtration tests results for the three sands is shown in Figure 4. According to Kenney et al. (1984), only particles smaller than the constriction size of the filter can move during this process.

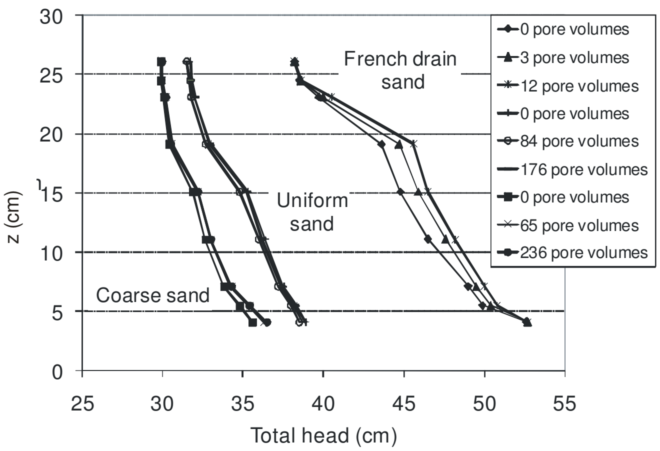

Figure 4: Self-filtration process of Coarse sand, Uniform sand and French drain sand.

It can be seen that the total head within the French Drain sand column had greater changes during self-filtration. This indicates that more movement of particles took place than for the other two sands. This was most likely due to the presence of a higher percentage of fine particles inside this sand. Fines at the bottom of the column were transported through the pores and caused clogging in the middle area. From 0 pore volume to 12 pore volumes, total heads at the mid points of the column were increasing gradually indicating clogging was occurring creating more resistance in this portion of the column. Unlike French Drain sand, the Uniform sand and Coarse sand contained few particles finer than 0.425mm. This appears to be the reason why there was a little change in position of particles inside the sands during their self-filtration process.

The degree of saturation of the sand samples prior to each test was found to be important. If a sample contained entrapped air in pores, it obstructed the flow. As the test continued to run, part of the air was released through the outflow. This produced inconsistent results from one test to the other. As a result, a full saturation of the samples was needed to ensure that consistent results were obtained.

Figure 4 also shows the resistance to flow from the beginning of test. While total heads in French drain sand test could be as high as 53 cm, those in Uniform sand and Coarse sand were significant lower (under 40 cm). This was because these two sands had a significant proportion of large pores. The calculation on permeability coefficients also reflected this porous nature, with values of: 0.0002 m/s, 0.0071 m/s and 0.0096 m/s for French drain sand, Uniform sand and Coarse sand, respectively.

The inflow was switched to one of three suspensions of fines in the second stage of testing. The introduction of fines into sand column resulted in head loss for all drain sands.

The results of constant head tests performed on French drain sand and 3 types of suspension are shown in Fig. 5 to Fig. 7. These plots show total head at the various ports along the column plotted against the height of the port on the ordinate. A scaled representation of the sand drain column is shown in the background on these figures.

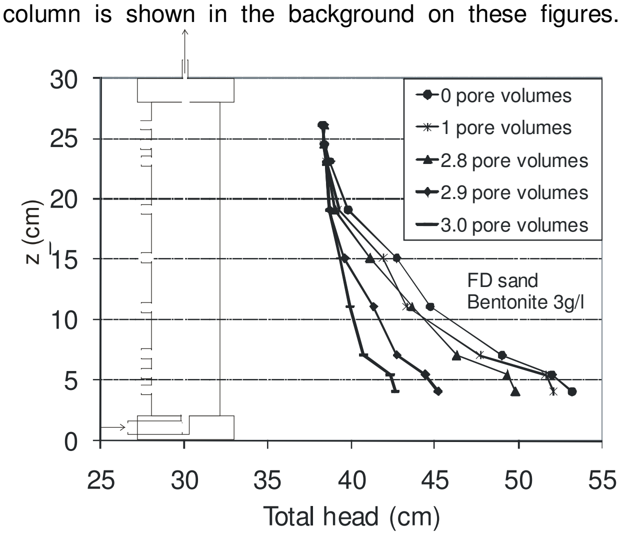

Figure 5: Total head versus elevation of French drain sand with 3g/l bentonite concentration.

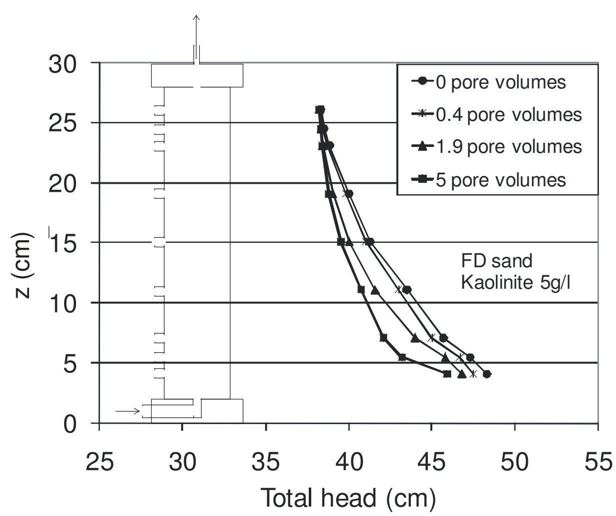

Figure 6: Total head versus elevation of French drain sand with 5g/l kaolinite concentration.

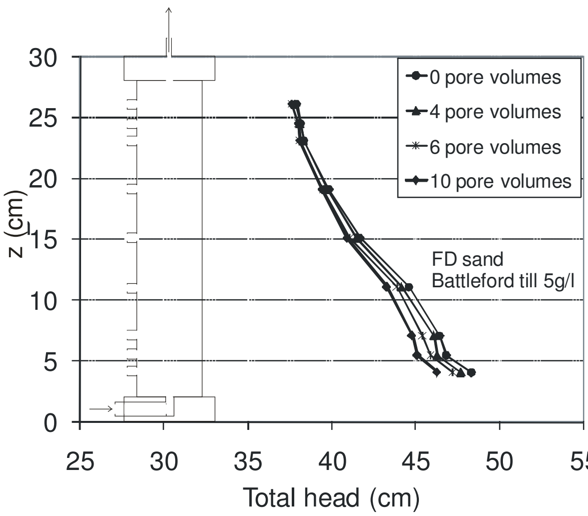

Figure 7: Total head versus elevation of French drain sand with 5g/l Battleford Till concentration

Figure 5 shows the change in total head across a column of French drain sand caused by the inflow of a suspension containing 3g/l of bentonite. This figure shows that the largest change in total head occurs at the inflow end of the sand column. This indicates that most of the clogging takes place within the first 10 to 15 mm.

Figure 6 shows the change in total head across a French drain sand column caused by the inflow of 5g/l of kaolinite. In this case, the drop in head is far less pronounced and appears to be spread throughout the lower portion of the column. This result is despite the fact that there is a higher concentration of kaolinite and that the test ran until 5 pore volumes of fluid had passed through the sample.

Figure 7 shows the change in total head across a French drain sand column caused by 5g/l Battleford till fines. The change here is quite minimal, even after 10 pore volumes of the suspension had passed through the sample.

It is obvious that bentonite made the greatest impact on head loss. In contrast, Battleford till fines made the smallest. This was because of the great swelling capacity of bentonite and its formation of aggregates. Particles from the inflow were not allowed to travel freely along the whole sample. As a result, the outflow in all tests was quite clear (maximum turbidility was 556 NTU for Battleford till). This observation agrees with test results from Reddi et al. (2005) and Bergerman and Haug (2007). Their study came to the same conclusion on the clogging of fines based on measurements of permeability reduction versus time. In all tests, heads at the effluent end were the most stable.

Two similar tests conducted on Uniform sand and Coarse sand with bentonite exhibited unique results (Figure 8 and 9). The trend of head loss was similar for these two sands. This pattern appeared to be due to the coarse texture of the sand which allowed fines to move easily through them. Part of these fines got clogged in the pores, while a larger portion was washed through the sand with the flow. That was the reason why the outflow quickly became cloudy (turbidility greater than 1000 NTU). Pore sizes of the sands were large relative to the size of fines and it took longer to block all the pores (115 pore volumes for Uniform sand to cause 10 cm of head loss at port 1 compared to 3 pore volumes for French drain sand to cause the same amount). In addition, because of the large pore sizes, fine particles were trapped uniformly in the whole sample. This caused head loss at all ports, not only the influent end such as occurred in French drain sand. Bentonite fines resulted in the greatest clogging and fastest reduction in permeability. These tests ran for 12 to 22 hours each. For other fines like kaolinite or Battleford till at the same concentration, test duration on Uniform sand and Coarse sand could maintain flow for days or weeks.

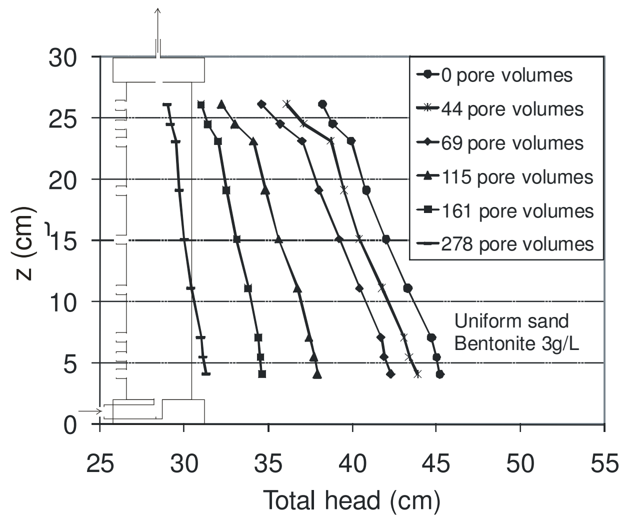

Figure 8: Total head versus elevation of Uniform sand with 3g/l bentonite concentration

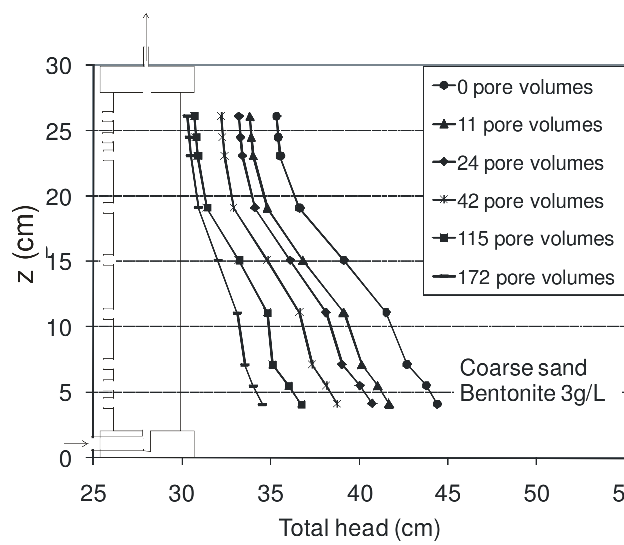

Figure 9: Total head versus elevation of Coarse sand with 3g/l bentonite concentration

5. CONCLUSION

This research program examined the behavior of 3 types of sand drain materials permeated with suspensions of 3 different fines under low gradient conditions. The results provided an insight into the self-filtration process and levels of clogging which can occur. French drain sand showed significant movement of soil particles within the sand column while Uniform sand and Coarse sand did not. The rate of head loss appeared to be fastest with a suspension of bentonite and slower with kaolinite or Battleford till fines. The study also showed that Uniform sand or Coarse sand with kaolinite or Battleford till fines requires a long exposure to the inflow suspension before significant clogging occurs. The results also showed that a more open structure is less affected by high swelling bentonite clays and that a significant proportion of these fines pass through permeable sands. As a result, a more open graded sand drainage system will have to be able to handle these fines after they pass through the granular drainage materials.

6. REFERENCES

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