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PERMEATION OF BENTONITE SUSPENSIONS THROUGH LOOSE SANDY SOIL

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Abstract: Over the past years, the levee breach flood disaster caused by underseepage has become an alarming problem in Bangladesh. The underseepage phenomenon beneath the earthen embankments may be controlled by treating the underlying granular soil with grout suspensions delivered by permeation (permeation grouting), resulting in a less permeable deposit. Drawing on this physical link, a permeameter was fabricated to investigate the permeation of bentonite suspension through the granular soil medium. The variation of injection time of stopping grout flow, injected grout weight, penetration distance with bentonite fraction for a constant pressure grout injection were studied. The time dependent effluent flow rate variation were also monitored in the laboratory. The experimental results showed that grouting operation worked efficiently for a certain range of bentonite fraction. The individual parameters like injection time, penetration distance, injected grout weight decreased with the increase of bentonite concentration. The effluent flow rate reduction became much prominent as the test proceeded towards the end that justified the effectiveness of permeation. Finally, a grout concentration was proposed considering the cost and other factors like penetration distance, injection time etc. for the sand used in this investigation.

Keywords: *Grouting; Permeation; Bentonite suspension; Sandy soil; Permeameter.*

1.0 Introduction

The construction of earthen flood control embankments is an established practice in Bangladesh for protecting people’s lives and homes, agriculture and infrastructures. Over the past years, the embankment/levee breach flood disaster has become an alarming problem that has severed and adversed the effect on national economy of Bangladesh (Islam *et al*., 1994). The major causes of breaching were seepage, overflow, erosion and sliding (Hossain & Sakai, 2008). Study showed that the seepage related erosion of the embankment soil caused major contribution of slope failure (Khan, 2009). As such, the stability of the earthen embankment is influenced by underseepage occurred during the increase and decrease of the adjacent water level in the river or reservoir.

The underseepage phenomenon beneath the earthen embankment may be controlled by treating the granular soil deposits with the grout suspension delivered by permeation (permeation grouting), resulting in a less permeable deposit. Permeation grouting does not destruct the original soil structure in the process and the grouting operation creates minimal ground disturbance and can be used for in situ remediation to existing structures. While cement suspensions and chemical solutions have been widely utilized as grouts for many decades, they may cause groundwater contamination due to long term reaction with groundwater. As an alternative, suspension of clay such as bentonite, can be a more environmentally friendly solution. Due to the greater specific area of bentonite than cement, the permeated suspensions will become more stable in the pore space over time (Yoon, 2011). In addition, when the objective of grouting is only to reduce the soil permeability, bentonite grouts can be the most economical solution (Datta & Gulhati, 2005).

To achieve the desired hydraulic performance of the grouted soil, soil behaviour during grout operation should be well understood. In this regard, the present research aims to investigate the permeation of bentonite suspension through the sandy soil deposit using a specially designed and fabricated permeameter in the laboratory. The variation of grout intake and effluent flow rate with time were monitored, and bentonite consumption for different grout suspensions was estimated as well.

2.0 Possible Mechanism of Stoppage of Grout Flow

The penetration distance and the required injection time of a grout operation largely depend on the stop mechanisms involved during the grout operation. The stoppage of grout through a soil is affected by the properties of grout (rheological blocking). If the injection pressure is equilibrated with the resistance to grout flow, the grout cannot flow any more. In this case, yield stress, which represents a resistance to flow, contributes to the stoppage of grout flow. Rheological blocking controls the stoppage of grout flow at high bentonite concentration (above 5%) which actually creates high yield stress (Yoon, 2011). In addition, the suspension flow can be limited by the physical changes in the pore space: the reduction in pore channels (deep bed filtration) and blockage of pore entrance with separated particles (pressure filtration). The deep bed filtration allows particles in the grout to settle in the pores of the sand, gradually blocking the flow path (Axelsson *et al*., 2009). Due to this phenomenon, the size of the pores gradually decreases, increasing hydrodynamic resistance and gradually causing clogging of the flow channels. This type of filtration is dominant when the relatively diluted suspensions flow through porous medium (Kim & Whittle, 2009). On the other hand, water can be separated from a liquid grout when a pressure grouting is used, accumulating particles in front of a filter medium (referred as to pressure filtration). The suspensions will then behave as thick slurry with a rapid increase in viscosity, reducing the penetration of grout through small pores (Landry *et al*., 2000). This type of filtration causes the formation of filter cakes close to the injection point. Well dispersed (i.e. low bentonite concentration) grouts have lower risk of stoppage due to this type of mechanism.

3.0 Materials

River sand procured from Meghna (an important river of Bangladesh that forms the Ganges Delta) dredged fill was used in this investigation. Standard physical and grain size distribution tests were performed as per ASTM standards. Grain size distribution of the sand is shown in Figure 1. The properties of the sand are also presented Table 1. In the present study, sodium bentonite was used as grouting material. The properties of the bentonite were determined using ASTM procedures and are given in Table 2. Bentonite grout can get washed away with time due to seepage through the grouted zone. Therefore, small amount of ordinary portland cement was added with bentonite to improve its permanence.

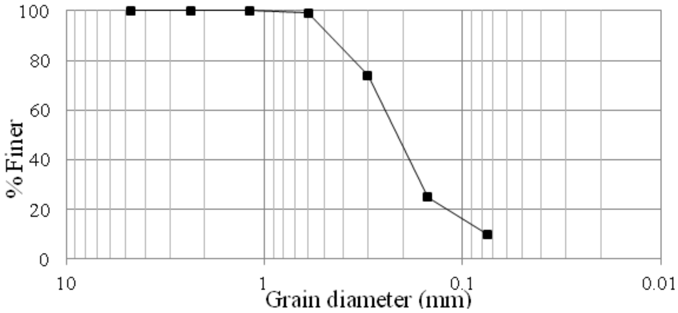

Figure1: Grain size distribution of sand used in this study

Table 1: Properties of the sand used in this study

Sl. No.	Property	Characteristic Value
1	Particle Specific Gravity, G_s	2.69
2	Uniformity Coefficient, C_U	3.33
3	Coefficient of Curvature, C_Z	1.54
4	Fineness Modulus, F.M.	1.02
5	Effective Size, D_{10}	0.075 mm
6	Maximum Density	1.65 gm/cc
7	Minimum Density	1.36 gm/cc
8	Relative Density, D_r	20 %
9	Permeability at 20 ^oC	2.45×10^{-3} cm/s

Table 2: Properties of the bentonite used in this study.

Sl. No.	Property	Characteristic Value
1	Particle Specific Gravity, G_s	2.65
2	Moisture Content	14%
3	Liquid Limit	420%
4	Plastic Limit	40%
5	Plasticity Index	380%
6	Swelling Potential	High
7	Composition	Sodium
8	Origin	China

4.0 Experimental Program

The experimental setup used in this investigation is mainly consisted of permeameter and soil mixture machine. Bentonite suspensions were prepared using the electrically operated Hobart Mixture Machine, and were injected at a constant pressure through the soil specimen in the permeation cell. The schematic line diagram of the 1-D constant pressure injection testing setup is presented in Figure 2. A 1500 mm long vertical stand was provided to clamp the grout tank. The height of the tank can be varied to induce different pressures at the soil specimen. A stirrer was provided in the tank that facilitated manual stirring operation to keep the bentonite at suspension condition. Bentonite suspension passed through a flexible chord from the tank to the permeation cell. The permeation cell was made of transparent cylinder and had a 100 mm outside diameter and 95 mm inside diameter. The height of the permeation cell was 300 mm. A graduated glass beaker was provided at the outlet to receive the effluents during testing. Bentonite suspensions were injected from the bottom of the soil specimen to expel the entrapped air bubbles from the specimen. Two screens (aperture size 0.1 mm) were placed at the top and bottom of the sand column to help in providing uniform distribution of suspension throughout cross-section of the sand column and prevent sand washing into the tubes. Each of the screens was supported by a metal plate having many circular slits. Above the top screen a 150 mm long and 90 mm diameter spring was placed that exerted pressure on sand column to keep it stable condition during the testing.

During the preparation of bentonite suspension, the desired amount of bentonite was placed into the mixing bowl which was 96% of the total amount of grout materials. Small amount of cement (4% of the grout materials) was added with the bentonite powder. Then desired amount of water (approximately 8 kg) needed for the preparation of grout slurry was poured into the mixing bowl. The mixing bowl was then fixed at proper position and the mixture machine was operated for 10 minutes. The rotation of the blade helped to get a uniform grout suspension.The contents of each ingredient were calculated based on the weight ratios. For example, 5% grout suspension corresponds to water/grout ratio of 20 by weight. The prepared grout suspensions were injected into the sand column from the bottom of the permeation cell at a constant pressure of 12 kPa. To ensure this pressure the grout tank were kept 1200 mm above the inlet of the permeation cell. Different proportion of grout suspensions like 0.5, 1, 1.5, 2, 2.5, 3, 4 and 5% were injected into the various sand columns. The volume of the effluent accumulated in the graduated glass beaker was measured at different times using two stopwatches. This data were used to calculate the discharge rate at different times through outlet. The volume of the effluent was monitored with time until there were no more effluents (for 5 minutes) to confirm completion of the permeation. The time was recorded when the permeation process just stopped. This was the required time to make the sand column impervious. If the permeation process stopped before draining out through the outlet i.e. grout penetrated into the sand column within the permeation cell, the penetration distances were measured (Figure 3). The final penetration distances were measured visually by taking an average of three measurements on different sides of the sand column.

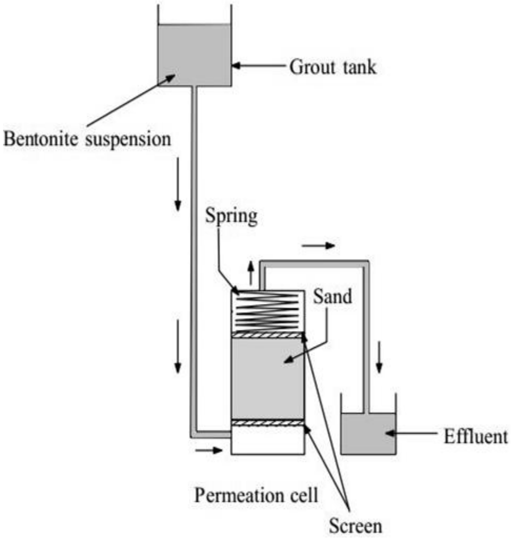

Figure 2: Schematic diagram of permeameter

Figure 3: Penetration distance (wet portion of the sand column)

5.0 Results and Discussions

The test results are summarized in Table 3, that depicts the effect of grout suspension on different parameters of grouting operation for the injection pressure of 12 kPa.

Table 3: The variation of individual parameters with grout concentration

Grout suspension (%)	Injection time (hr)	Injected grout weight per unit area (kg/m^2)	Penetration distance (cm)	Cost per unit area (USD/m^2)
1	10.1	1010	>30	3.75
1.5	8.2	803	>30	4.45
2	4.5	521	>30	3.83
2.5	3.7	320	>30	2.93
3	2.1	169	29	1.85
4	1.0	138	18	1.99
5	0.8	112	11	2.00

Table 3 also presents the injection time for which the permeation through the sand column just stopped i.e. at this moment sand column had zero permeability. Total amount of grout suspension to be injected per unit cross sectional area of the sand column are presented, Table 3. Figure 4 shows the response of injection time for different grout suspensions. It is observed from Figure 4 that the injection time decreases with the increase of percentage of grout suspension. This may probably be due to the deposition of particles and gradual pore filling until the grout flow is completely stopped. More bentonite fraction present in the grout causes more deposition within a short period of time, and faster retardation of grout flow results. Therefore, initially the slope of the curve is high and gradually decreases with the increase of bentonite fraction.

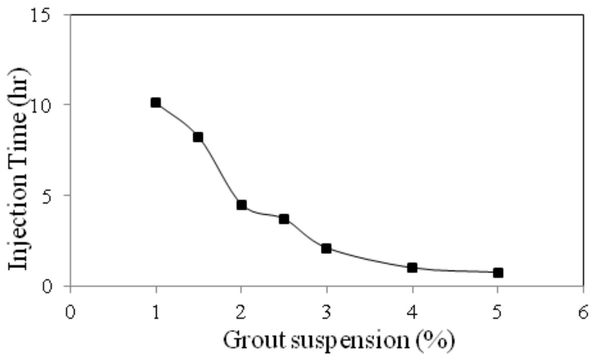

Figure 4: Variation of the injection time with grout suspension

Figure 5 represents the variation of injected grout weight per unit cross sectional area of sand column with the grout suspension. It is observed from this figure that the injected grout weight also decreases with the increase of percentage of grout suspension at a similar fashion shown in Figure 4. This is probably due to the faster retardation of grout flow at higher percentage of grout suspension. The slope of the curve also gradually decreases for higher value of grout suspensions.

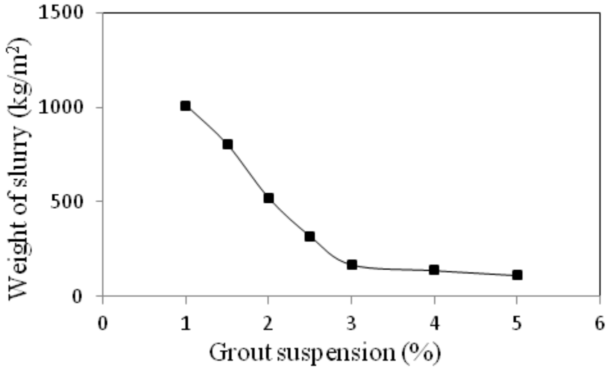

Figure 5: Variation of injected grout weight with grout suspension

The final penetration distances measured by taking an average of three measurements on different sides of the sand column (at impervious condition) are presented in Table 3. Figure 6 shows the penetration distance versus bentonite fraction curve. It is observed from the figure that the penetration distance decreases with the increase of percentage of grout suspension. This might be due to the fact that, when bentonite fraction increased the void space of the sand were filled up with the grout within short period of time. Yoon (2011) also observed the similar behaviour; he performed a series of injection tests with bentonite suspension and observed that the bentonite grouts with Sodium Pyrophosphate solution produced better penetrability.

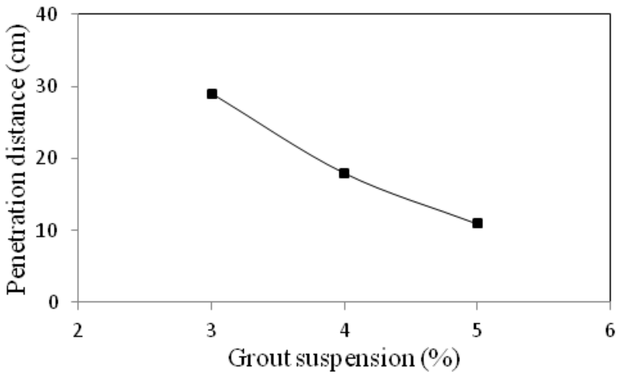

Figure 6: Variation of penetration distance with grout suspension

The probable estimated cost of bentonite per unit cross sectional area of sand column is presented in Table 3. Figure 7 shows the bar diagram of the bentonite cost for different percentage of grout suspensions. It is observed from the bar diagram that minimum cost (considering only bentonite consumption) can be achieved when 3% grout suspension is used. Cost was higher when the percentage of grout suspension and the weight of injected grout were higher that eventually called for more bentonite consumption. In the present study 3% grout suspension is the value that optimized these two factors and resulted in minimum bentonite consumption. Generally, bentonite is available in the market as a 25 kg unit bag and present market price is 9.4 USD (September 2012). The small amount of cement fraction present in the grout suspension was neglected during this cost estimation. For example the cost for 3% suspension was calculated as follow:

$$\frac{3}{(100+3)} \times 169 \times \frac{9.4}{25} = 1.85\ USD \qquad (1)$$

The left hand side of Eq. 1 contains three terms indicating the desired grout suspension, injected grout weight for the grout suspension and price rate of bentonite respectively.

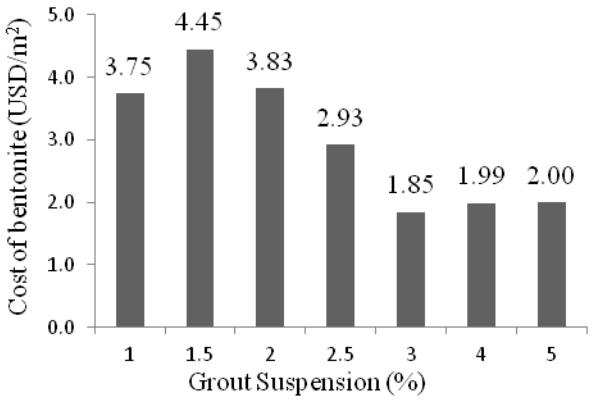

Figure 7: Variation of cost of bentonite with grout suspension

The draining of effluent through toutlet was not stopped even after 24 hours when 0.5% grout suspension was used. As the percentage of grout suspension increased, draining of effluent also stopped rapidly. When the grout suspensions were more than 5%, a thick grout cake formed at the entry of the sand column that retarded the grout flow (Figure 8). This type of stoppage mechanism is called pressure filtration (Kim & Whittle, 2009). Therefore, 5% grout concentration formed the higher limit of appropriate grout able range for this particular sand. Rheological blocking controls the stoppage of grout flow at high bentonite concentration (above 5%) which actually creates high yield stress. In the present study, stoppage of grout flow probably governed by the deep bed filtration filtration rather than rheological blocking as deep bed filtration is dominant when relatively diluted suspensions flow through porous medium (Yoon, 2011). Gulhati and Datta (2005) recommended to use 10% to 25% bentonite suspension for a sand that has

$D_{10} \geq 0.2$ mm. Fine sand with $D_{10} = 0.075$ mm that was used in this investigation, appropriate groutable range was found to be in the range of 1% to 5% indicating a requirement of more diluted suspension with finer sand fraction.

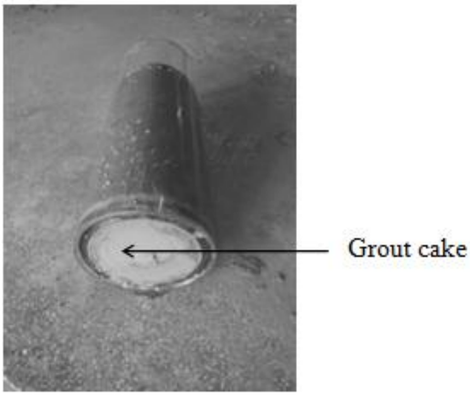

Figure 8: Formation of grout cake at the entry of sand column (for 8% bentonite concentration)

The reduction of effluent flow rate or drain rate through the outlet for 2% grout suspension with time was monitored, and presented in Figure 9. It is observed from the figure that that 90% of the initial flow rate (corresponding value 0.067 mL/s) isreduced within the initial 50% of the injection time (corresponding value 120 minutes). This means that flow rate reduction became much prominent as the test proceeded towards the end. This is probably due to the change of properties of the porous medium. The suspension flow can be limited by the physical changes in the pore space: the reduction in pore channels and blockage of pore entrance with separated particles.

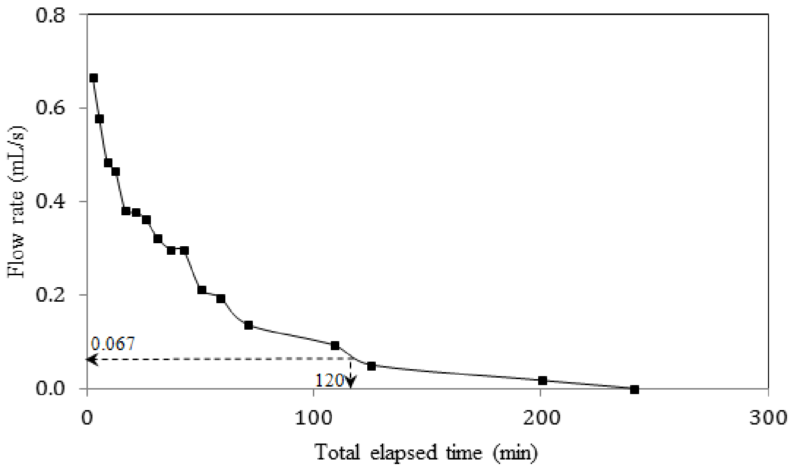

Figure 9: Variation of effluent flow rate with time for 2% grout suspension

The variation of grout intake with time is an indicator of the morphological changes in pore channels as particles are deposited (Schwarz & Chirumalla, 2007). This is presented graphically in Figure 10. It is observed from the figure that initially the grout suspension penetrated through the sand column with very high flow rate, and then suspension flow rate started to decrease as the penetration proceeds through the sand column. This may be due to the deposition of particles and gradual pore filling until the grouting is completely stopped (Axelsson *et al*., 2009). As the particle fraction increased, a faster retardation of the suspension flow was observed. Yoon (2011) also found similar result and he performed a series of injection tests with 5, 7.5 and 10% bentonite suspensions under 35 kPa constant pressure injected through a clean sand at a relative density of 30%. The behavior observed by Dupla *et al*. (2004) was also similar; they performed injection tests with microfine cement and observed that the cement grouts with high W/C ratio produced better injectability (larger injected volume).

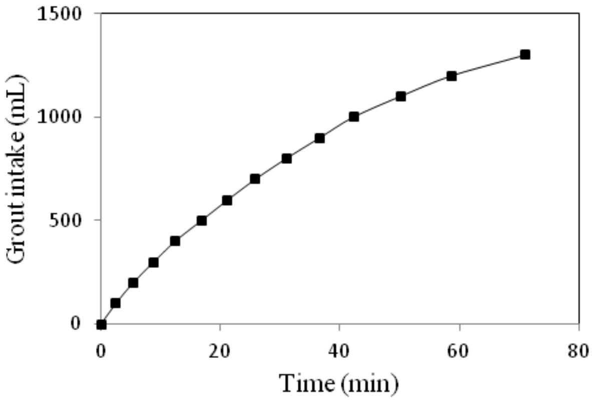

Figure 10: Variation of grout intake with time for 2% grout suspension

6.0 Conclusions

This investigation examines the scope of improving the hydraulic behaviour of granular soil with bentonite suspension. Based on the experimental investigations and test results, the following conclusions are made.

i. The appropriate range of grout suspension for the soil tested was found to be in the range of 1% to 5%. The required injection time to create effective imperviousness of soil becomes very large (greater than 24 hours) when the grout suspension is below 1%, resulting in an inefficient grouting operation. Above 5% grout suspension, a thick bentonite cake was found to be formed at the entry of the soil column that prevented the grout flow.

ii. The required injection time to stop the grout flow decreases with the increase of bentonite concentration. The decrease is more pronounced for the higher value of bentonite concentrations. As such, valuable time can be saved during field operation using relatively higher bentonite concentrations.

iii. The variation of injected grout weight with bentonite fraction (or concentration) is almost similar to the variation of injection time i.e. injected grout weight also decreases with the increase of bentonite fraction. The penetration distance was also found to decrease with the increase of bentonite concentration indicating negative effect of the use of higher bentonite concentration. However, higher grout pressure or chemical may be used to increase the penetration distance.

iv. Bentonite consumption was found to be the minimum while used a 3% grout. Based on the present market price, the estimated probable cost per unit area of sand column (for bentonite consumption only) is 1.85 USD. This indicates that an intermediate value of grout concentration (3% for this study) may be preferable considering cost and other factors like penetration distance, injection time etc.

v. The time dependent grout flow behaviour analysis reveals that greater portion of the grout flow reduces within the initial period of injection time. In the present study, 90% of the effluent rate was reduced within the initial 50% of the total injection time (for 2% grout suspension monitored in this study). Thus, it can be concluded that significant amount of grout flow may be reduced within the initial 50% percent of clogging time.

7.0 Acknowledgements

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