Reference: Evans, J.C., Huang, H. and Ruffing, D. G. (2016) "Evaluation of Soil-Bentonite Backfill Consolidation Properties" *Proceedings of the DFI International Conference on Deep Foundations, Seepage Control and Remediation, NY, NY*, pp. 169-178.

EVALUATION OF SOIL-BENTONITE BACKFILL CONSOLIDATION PROPERTIES

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ABSTRACT

Soil-bentonite slurry trench cutoff walls are the most common type of vertical cutoff wall used in the US for seepage control and for passive control of contaminant migration at environmental sites. Design considerations are often limited to constructability considerations and a target hydraulic conductivity. With design-build contracts common, the backfill design is often left to the contractor. As a barrier soil, the hydraulic conductivity of bentonite slurry wall backfill is typically required to be equal to or below $1x10^{-7}$cm/s. The importance of stress state upon the hydraulic conductivity as well as the expected stresses are both established in the literature. Grain size distribution of the base soil and bentonite content both affect compressibility and hydraulic conductivity. This paper describes the results of studies undertaken to evaluate the interrelationships between compressibility, hydraulic conductivity, grain size distribution, and bentonite content. Three base soils were used representing a range of soils found on typical construction projects. Using these base soils, mixtures containing a range of dry bentonite contents from 0% to 5% were prepared to a slump consistent with field practice. The compressibility and hydraulic conductivity were measured in consolidometers adapted for falling head permeability tests at the end of each load increment. These experiments yielded the relationship between effective stress and hydraulic conductivity as well as consolidation characteristics including time rate of consolidation and coefficients of compressibility. The experimental results are then used to indirectly evaluate stress development and to assess the time needed for consolidation. The findings show a substantial decrease in hydraulic conductivity as effective stress increases, regardless of base soil type and dry bentonite content, a relative insensitivity of stress development to backfill compressibility, and a wide range of values for coefficient of consolidation depending upon backfill mixture and stress level.

KEYWORDS

slurry wall, bentonite, cutoff wall, slurry trench

INTRODUCTION

Soil-bentonite (SB) slurry trench cutoff walls have long been used to control seepage through dams and levees and into excavations beneath the water table (Evans 1993). For SB cutoff walls, a trench is first excavated under a head of bentonite-water slurry (the slurry trench). The slurry is then replaced with the soil-bentonite backfill comprising soils, usually those excavated from the trench, blended with bentonite-water slurry and, if needed, additional dry bentonite. Calculations for trench stability are common, but SB backfill "design" has historically been largely empirical. For seepage control applications, the principle performance criterion has been hydraulic conductivity. Depending upon project needs, upper limits of $1x10^{-5}$ to $1x10^{-7}$ cm/s are commonly specified. To achieve the necessary hydraulic conductivity, designer and contractor experience has been employed to decide upon bentonite content to great success. Often, preconstruction laboratory studies of several mixtures are conducted to validate the contractor and/or designer experience.

Studies have shown a strong correlation between stress state and hydraulic conductivity (Ruffing and Evans 2010, Evans and Huang 2016) which makes understanding the effects of soil-mixture variations upon stress state important. The results of laboratory studies are presented to show how the compressibility, time rate of consolidation and hydraulic conductivity vary with effective stress and backfill composition. The laboratory results are then used with a closed form model of stress in SB cutoff walls to predict the range of stresses expected over a range of backfill mixtures.

PREVIOUS STUDIES

Given the soft, compressible nature of SB backfill and the dependence of hydraulic conductivity on void ratio, it is no surprise that the hydraulic conductivity is highly stress dependent. Previous studies, e.g. Evans 1994, Filz et al. 2001, Yeo et al. 2005, and Ruffing and Evans 2010, present the stress dependency of SB backfill. The data plotted in Fig. 1 reinforces this known relationship.

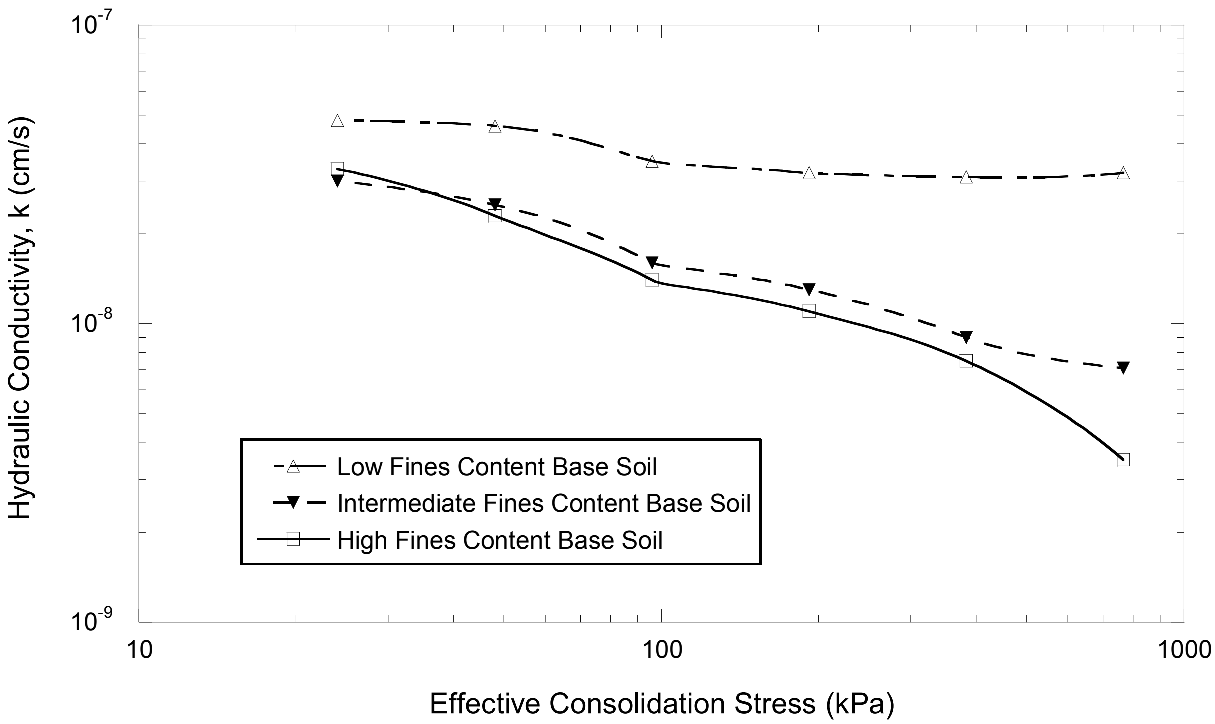

Fig. 1. Effective stress vs. *k* for SB backfill (plotted from data in Evans and Huang 2016)

The primary question is how do the grain size distribution, specifically the fines content, and the bentonite content impact the hydraulic conductivity? The current study investigated this relationship using model SB backfills created from three base soils with varying fines contents and a varying bentonite content (Evans and Huang 2016). The grain size distributions of the three base soils are presented in Fig. 2 against a recommended grain size distribution for SB base soils from an earlier design guidance document (Lagrega, et al. 1996). For the purposes of the discussions herein, the soils are identified as high, intermediate, and low fines content soils with fines contents of 77%, 42% and 6% respectively. Notice that only the intermediate fines content soil falls within the recommended fines content and all soils lack sufficient coarse materials to meet the recommended gradation.

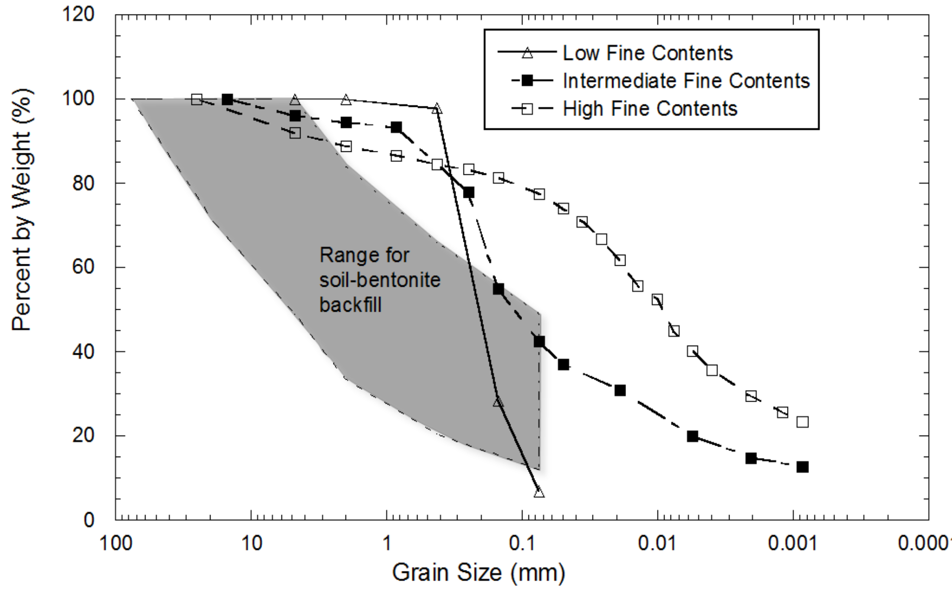

Fig. 2. Grain Size of SB Soils and Recommended Range (from Evans and Huang 2016)

The hydraulic conductivity measured at one effective stress (96 kPa) is presented in Fig. 3 as a function of base soil fines content (6% to 77%) and bentonite content (0% to 5%). Two findings of note are clear from a review of Fig. 3. First, increasing the natural fines content results in a decrease in the hydraulic conductivity of about one-half an order of magnitude for the mixtures containing dry bentonite. The hydraulic conductivity reduction, more than an order of magnitude, is greater for the mixture with no dry bentonite (slurry only). Second, the addition of dry bentonite has a significant effect as the dry bentonite content goes from 0% to 5%.

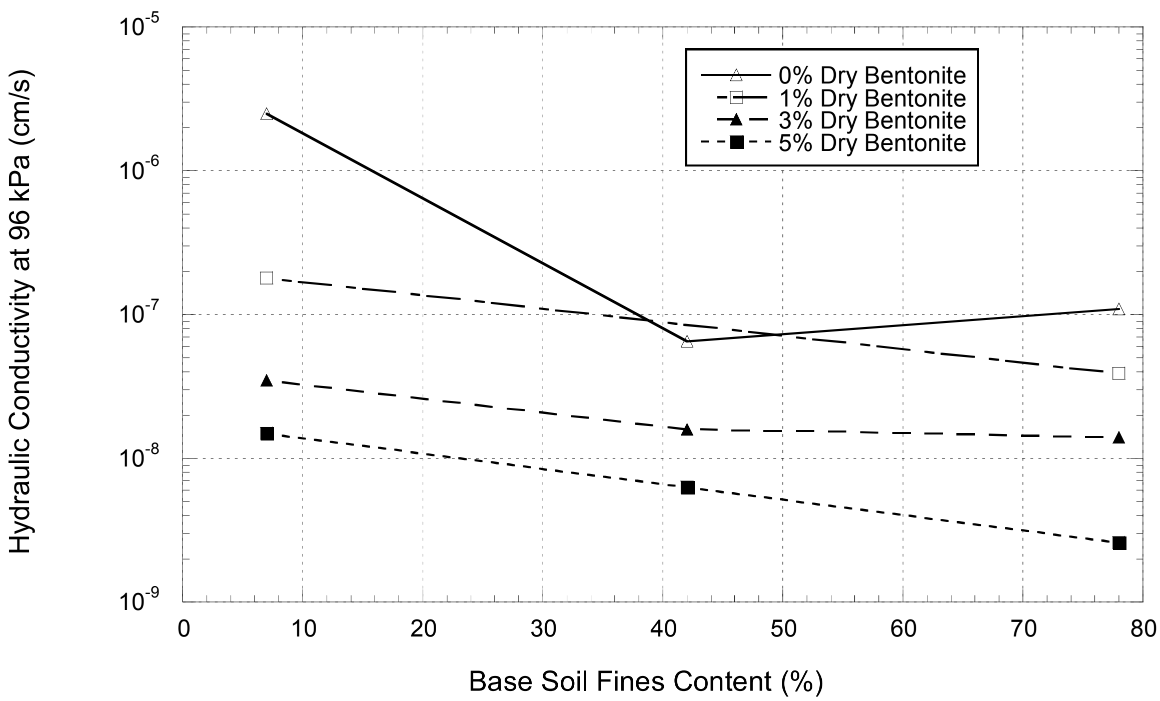

Fig. 3. Base soil fines and dry bentonite vs. *k* of SB (from Evans and Huang 2016)

LABORATORY INVESTIGATIONS AND DISCUSSION OF RESULTS

Bentonite-water slurry was prepared using 5% bentonite and 95% tap water, by mass. Tap water properties included a temperature of 25 ℃, pH value of 7.75, and conductivity of 170 μs/cm. The average viscosity of the slurry after 24 hours of hydration was 40.7s although the slurry viscosity decreased to 35.4s after remixing in the high-speed colloidal shear mixer for 5 minutes demonstrating the thixotropic behavior of bentonite slurry.

After a minimum of 24 hours of hydration, the slurry was mixed with the three base soils (low, medium, and high fines content). Dry bentonite was added at rates of 0% (slurry only), 1%, 3% and 5% dry bentonite resulting in a total of twelve backfill mixtures. The base soils started at their natural moisture contents of 8%, 16%, and 24% for the low, medium and high fines content soils, respectively. Slump tests were conducted after mixing the backfill in order to ensure the slump was in the appropriate design range of 100 mm to 150 mm (4-6 in) using a laboratory scale slump cone (Malusis et al, 2008). The moisture content for each backfill mixture was measured. The prepared backfill mixtures were stored in sealed containers for a minimum of two days prior to testing to allow for equilibration of moisture throughout the sample.

Fixed-ring consolidometer/permeability cells with lever-arm loading were used for falling-head permeability tests at varying states of effective stress and to determine time rate of consolidation and one-dimensional stress-strain parameters (ASTM D2435-04 and Yeo et al. 2005). The hydraulic conductivity results are reported in Evans and Huang 2016.

LABORATORY TEST RESULTS

The time rate of consolidation data was interpreted using Taylor's T_{90} method and the resulting coefficient of consolidation, c_v, values for the twelve backfill mixtures are shown on Figs. 4, 5 and 6. These data show a range of c_v, values from $4x10^{-5}$ to $7x10^{-8}$ m^2/s for the range of fine contents, bentonite contents, and stress shown indicating a nearly three order of magnitude difference in time to consolidation of the SB backfill. The impact on consolidation time for representative SB cutoff walls is explored in the analysis section.

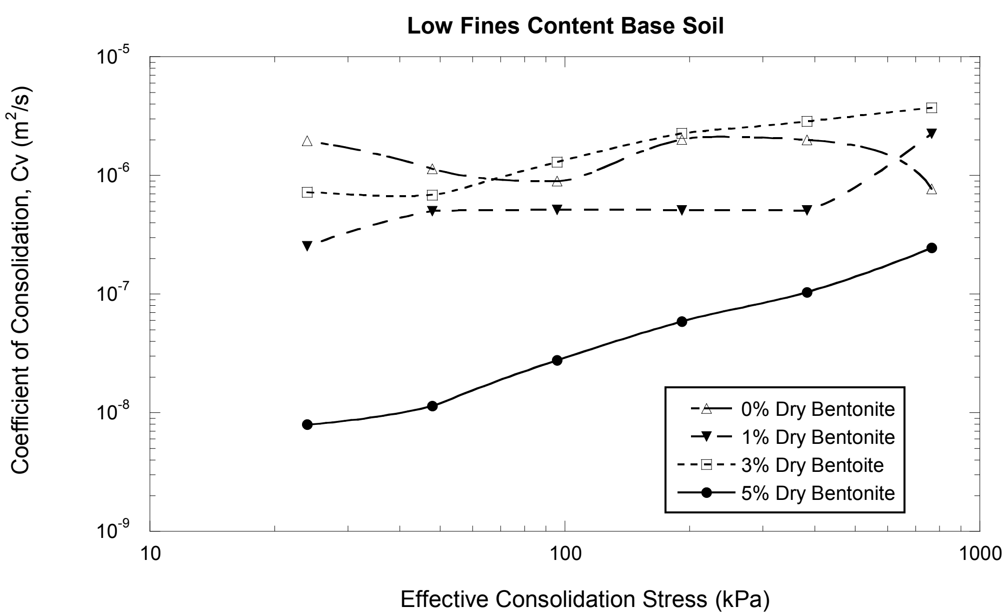

Fig. 4. Coefficient of consolidation for low fines content backfills

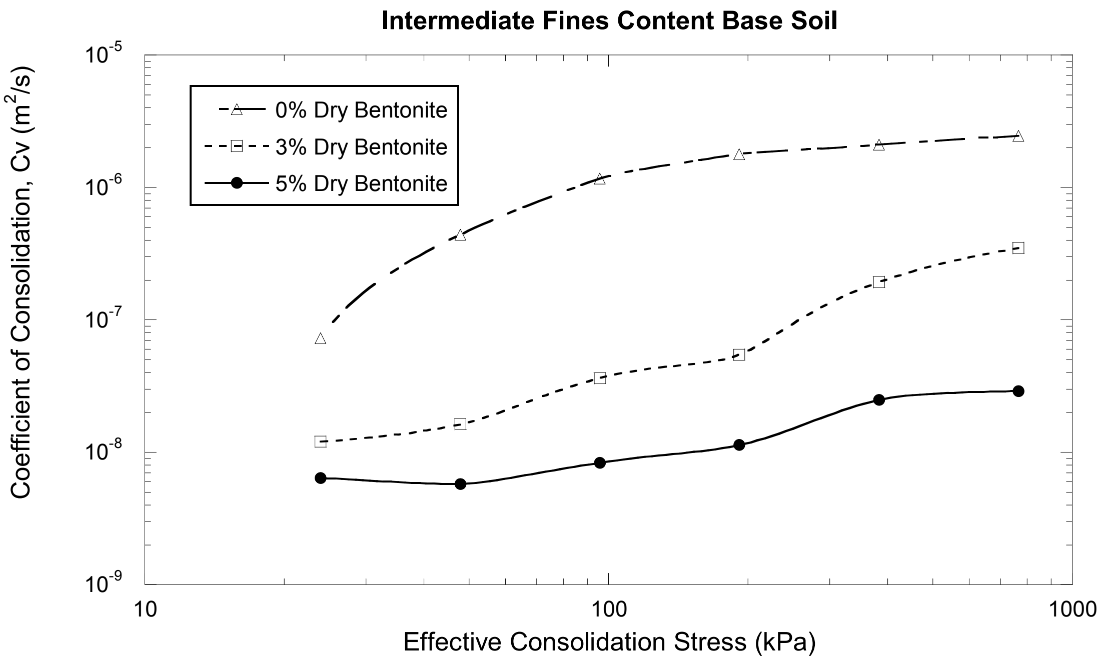

Fig. 5. Coefficient of consolidation for intermediate fines content backfills

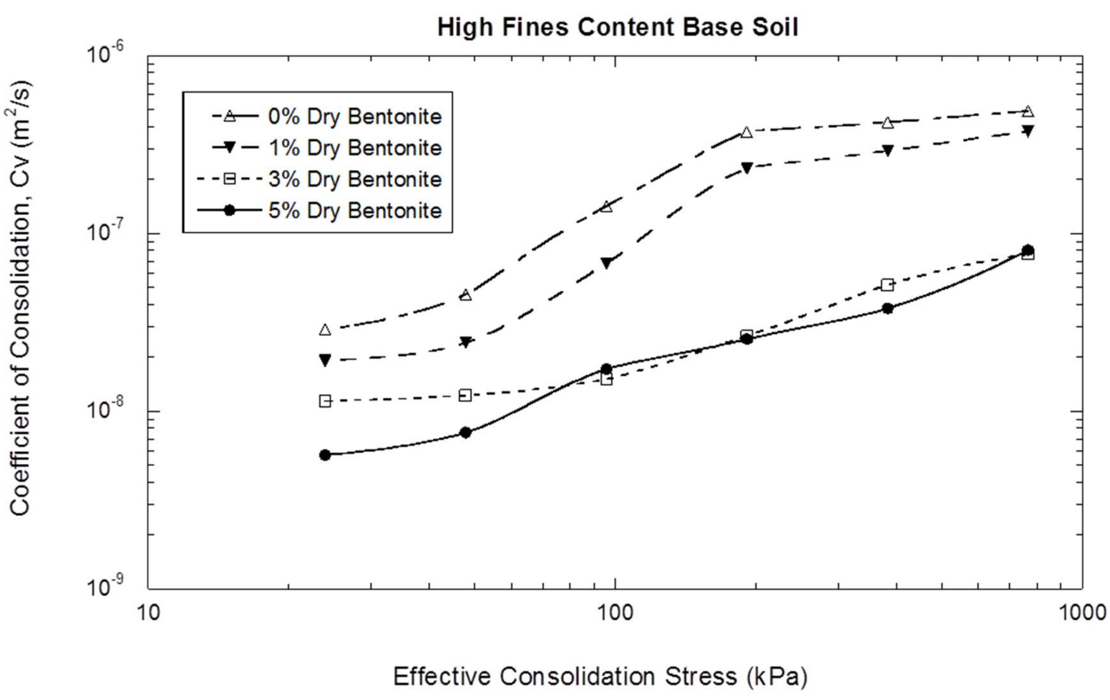

Fig. 6. Coefficient of consolidation for high fines content backfills

The relationship between void ratio and effective consolidation pressure (e log σ_v' curves) for loading and unloading was also evaluated from the consolidation tests. As the material is completely remolded, these plots can be used to determine the modified compression index, C_{c_ε}, for loading and the modified swell index, C_{s_ε}, for unloading. The modified compression index is shown in Fig. 7 as a function of base soil fines content and bentonite content. Fig. 8 presents a similar data set with the only change being that the dependent variable is the modified swell index.

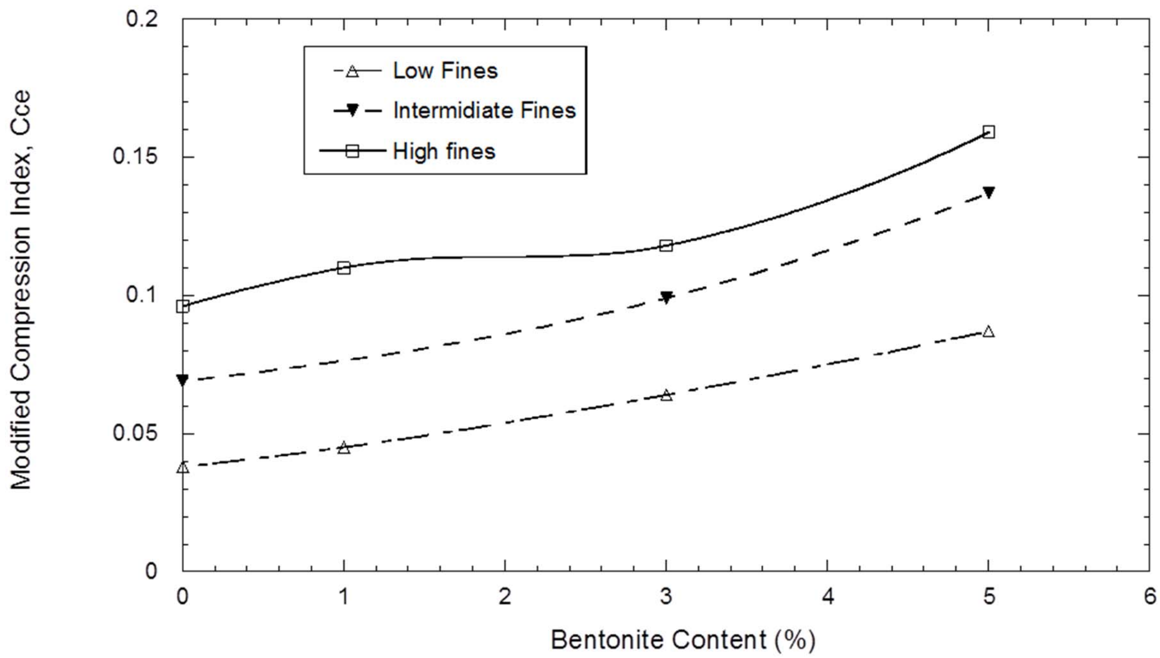

Fig. 7. Modified compression index for backfills

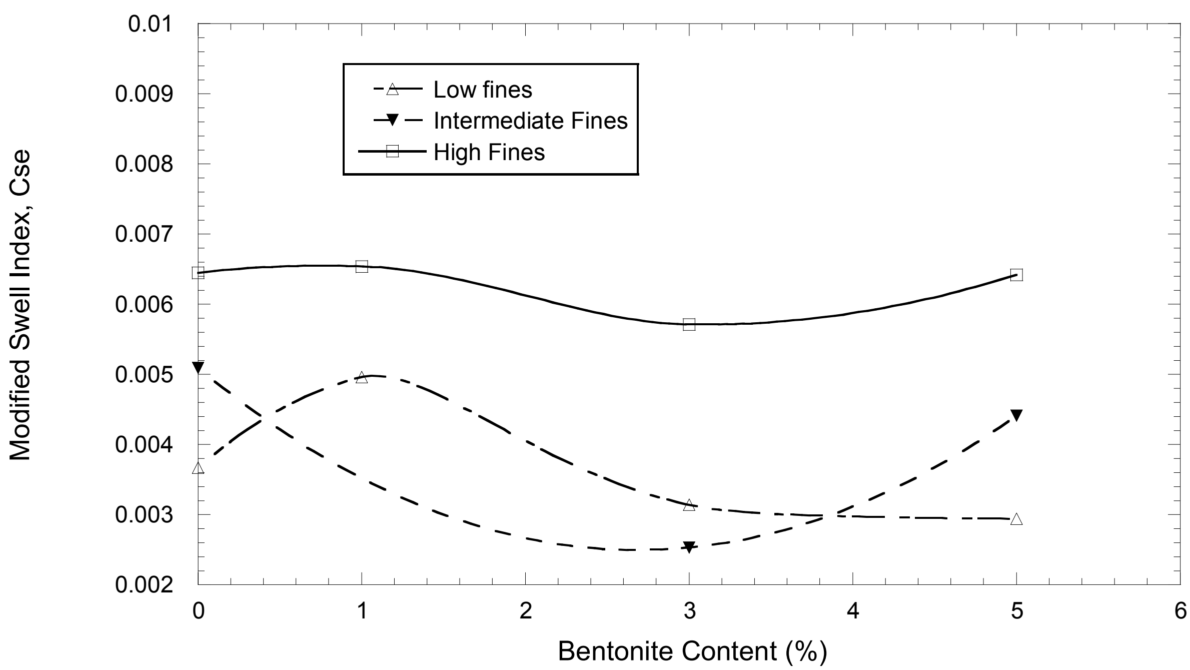

Fig. 8. Modified swell (recompression) index for backfills

As shown in Fig. 7, C_{c_ε} is sensitive to both the fines content and the bentonite content. Increasing the fines content or the bentonite content results in increasing compressibility.

ANALYTICAL INVESTIGATIONS

The hydraulic conductivity is heavily stress dependent (Figs. 1 and 3) and the stresses in the backfill are believed to depend upon the compressibility characteristics of the backfill (Filz 1996). The modified lateral squeezing model (MLSM) uses the compressibility of the backfill and the movement of the material adjacent the trench to balance the horizontal forces at the trench sidewall (Ruffing et al. 2010). The governing closed-form solution to this force system is shown as Eq. 1 (Eq. 8 in Ruffing et al. 2010).

$$\sigma'_{ho} = \gamma'_o z k_{am} = 10^{\left(\frac{2\Delta - BC_1}{BC_{c\varepsilon}}\right)} \quad [1]$$

Fig. 9 shows input data and stress prediction results from an earlier study in which the modified compression index, $C_{c\varepsilon}$, was determined from one particular SB backfill.

Parameter	Units	Value
Lateral Squeezing (LS) Model		
γ'_o	kN/m^3	11.2
D_b (min)[1]	kPa	500
D_b (max)[1]	kPa	1600
ϕ'_o	degrees	35
Arching Model and Geostatic		
γ'_b	kN/m^3	9.7
c_b	kPa	0
ϕ'_b [2]	degrees	30
k_{ob}	---	0.5
Modified Lateral Squeezing (MLS) Model		
γ'_o	kN/m^3	11.2
$C_{c\varepsilon}$ [1]	---	0.10
C_1 [1]	---	-0.09
ϕ'_o	degrees	35

[1] values based on data in Fig. 5.
[2] from Baxter et al. (2005)

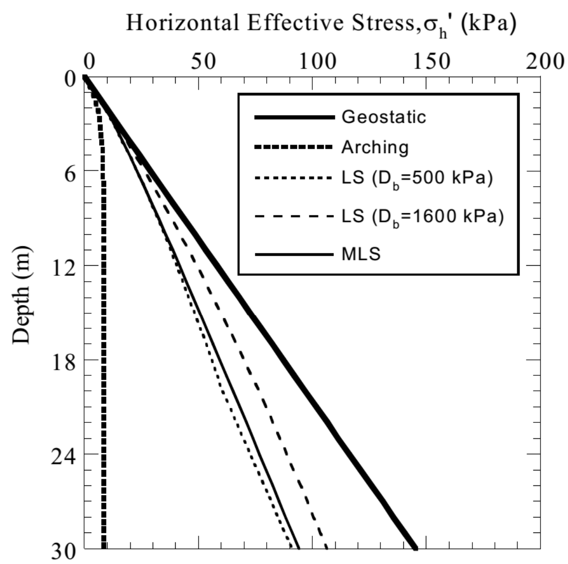

Fig. 9. Horizontal effective stress distributions in SB cutoff wall (B = 1 m) predicted by arching, lateral squeezing, and geostatic methods (from Fig. 6. in Ruffing et al. 2010)

Using the data presented on the table embedded in Fig. 9 and the compressibility information collected in this study allows for a study of lateral earth pressures over a range of base backfill soil types and bentonite contents. Equation 1 (the governing equation of the MLSM) was used along with the data presented in the embedded table in Fig. 9 to calculate effective stress across a range modified compression indices. The results of these analyses are shown on Fig. 10.

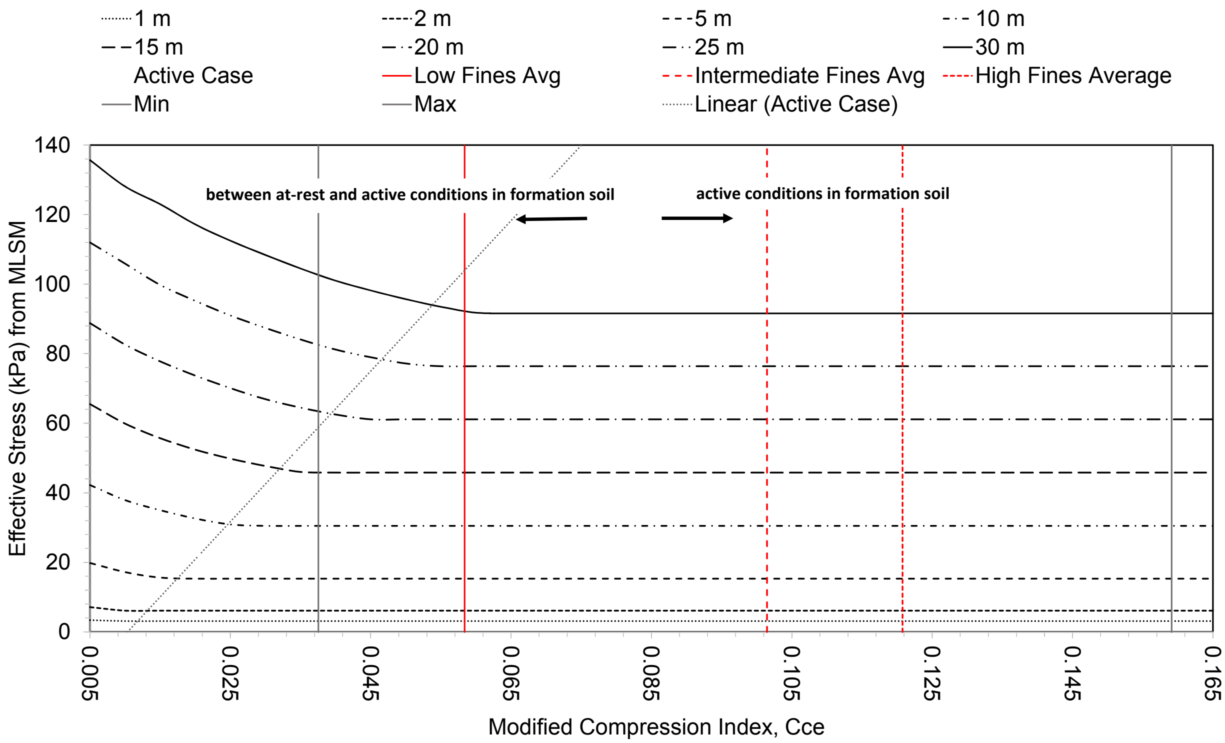

FIG. 10. Horizontal stress as a function of modified compression index and depth for a theoretical medium dense sand (Φ=35°) formation soil

Several interesting findings are clear from the information in Fig 10. First, the backfill consolidation behavior, represented by the modified compression index, only influences the state of stress prior to the active condition in the materials adjacent the trench. The diagonal dotted line shows that as the stiffness of the backfill increases, the depth required to fully mobilize active earth pressure increases. Next, above the depth where active earth pressure controls the horizontal stresses, it is found that stiffer backfills, i.e. lower modified compression indices, result in greater stresses. Finally, other than at the extremes of very low modified compression index (very stiff backfill) and deep cutoff walls, the stiffness of the backfill does not significantly influence the stress state. Notice that throughout these analyses, the controlling factor was largely the active earth pressures from the adjacent formation soils.

It is also useful to consider the effect of fines and bentonite content upon the time rate of consolidation. To do this, a wall width of 1.0 m was assumed consistent with the assumption of wall width for stress calculations. One-dimensional, double-drainage conditions were assumed with all flow laterally towards the sidewalls of the trench. Importantly, and perhaps controversially, the impact of the filter cake was ignored in these calculations. While the role of the filter cake after backfill is placed is beyond the scope of this paper, ignoring the role of the filter cake considered three factors. First, the purpose of the calculations is to examine the effect of fines and bentonite content upon the time rate of consolidation. Next, some have argued that the movement of the backfill, clearly present in the slurry filled trench, largely destroys the filter cake during backfill placement. Finally, the hydraulic conductivity of the filter cake may not be largely different than the hydraulic conductivity of the backfill rendering its inclusion in the calculations of no consequence (Ruffing et al. 2016). Note that the c_v values are stress dependent (Figs 4, 5 and 6). For this parametric study, an average c_v value was used over a stress range of 25 to 100 kPa representative of the range of stresses expected (see Fig. 10). For the purposes of studying the effect of the coefficient of consolidation, the average time for 50% and 90% consolidation was computed. The results of these computations are shown on Table 2.

Table 2 Time for 50% and 90% consolidation of SB backfill

Backfill Fines	Bentonite Content (%)	Coefficient of Consolidation (m^2/s)	Time for 50% consolidation (days)	Time for 90% Consolidation (days)
Low	0	9.6E-07	0.6	2.6
Low	1	4.2E-07	1.3	5.8
Low	3	9.0E-07	0.6	2.7
Low	5	1.6E-08	36	156
Intermediate	0	5.6E-07	1.0	4.4
Intermediate	3	2.2E-08	26	113
Intermediate	5	6.9E-09	83	358
High	0	7.2E-08	7.9	34
High	1	3.7E-08	15	66
High	3	1.3E-08	44	190
High	5	1.0E-08	56	241

An examination of the data on Table 2 reveals the fines and bentonite content can have a large effect upon the time rate of consolidation. For example, the time for 50% consolidation can vary from less than one day to fifty-six days, depending upon the backfill mixture. The trend is illustrated in Fig. 8 showing that as the bentonite content increases, the time for consolidation increases. Figure 8 also illustrates that as the fines content increases, the time to consolidation also increases. The data at 5% bentonite for the medium and high fines content base soil shows the high fines content consolidates a bit quicker than the medium fines content. This result could be real due to differences in void ratio between the two mixtures or due to experimental error as the difference in C_v values is small.

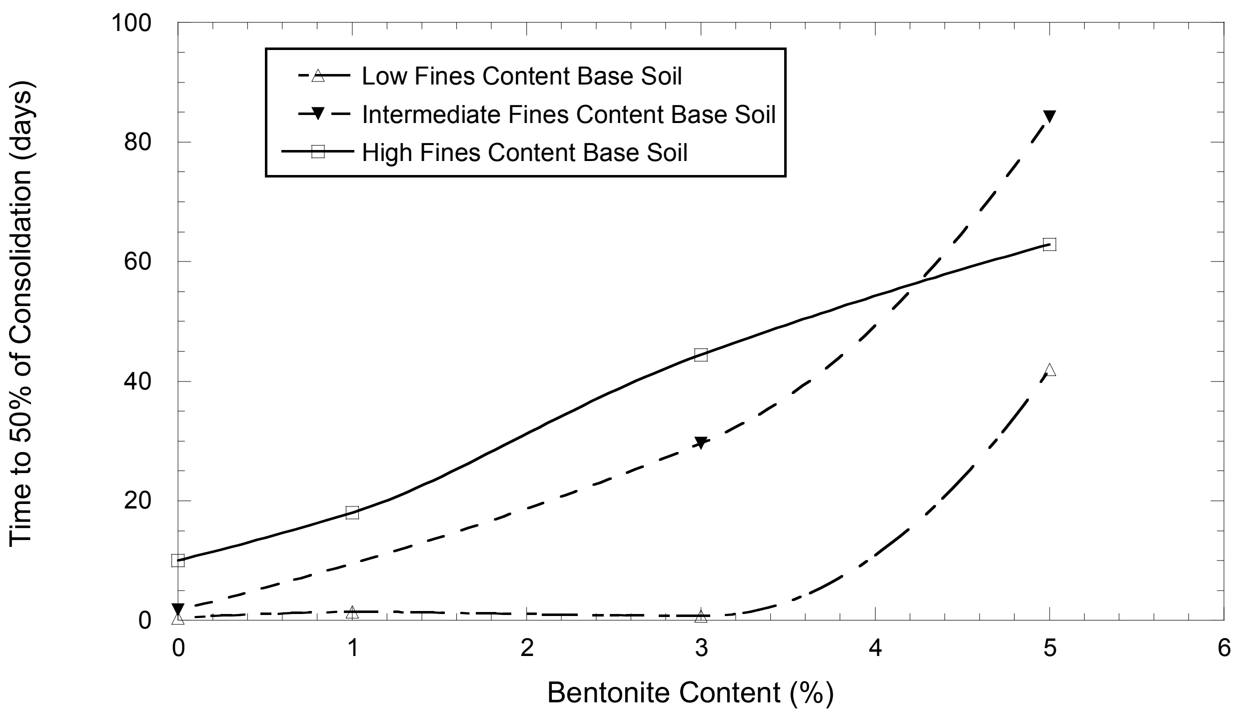

FIG. 11. Time to 50% consolidation

SUMMARY AND CONCLUSIONS

A series of consolidation tests were conducted on SB backfill mixtures created using three base soils with low, medium, and high fines content and varying dry bentonite contents from 0% to 5%. The data from these tests were used to determine the coefficient of consolidation for time rate of settlement calculations and modified compression indices for stress calculations. The analysis shows that the state of stress is largely controlled by the active earth pressure developed in the adjacent formation soils as a result of inward movement of the trench sidewalls resisted by the SB backfill. Even over a wide range of backfill stiffness, the stiffness shows little influence on the stress state.

The backfill fines content and bentonite content did, however, have a large influence on the time needed to consolidate the backfill. For all backfills tested at dry bentonite contents of 0% and 1%, the time for 50 percent consolidation was less than two weeks but additional bentonite added to the mix increased that time to as much as three months.

ACKNOWLEDGEMENTS

The authors would like to thank Bucknell University for their support of Hejintao Huang during her work on this project. The authors would like to thank Bucknell University student Melissa Replogle and Nancy Ingabire Abayo for their assistance with some of the laboratory testing. James Gutelius Bucknell University's Director of Laboratories for the Department of Civil and Environmental Engineering provided the fine-grained soil used in the experiments. The support of Hejintao Huang by Bucknell University's Program for undergraduate Research is gratefully acknowledged.

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