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Strength and Permeability of a Deep Soil Bentonite Slurry Wall

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ABSTRACT: In 2006, a Soil Bentonite (SB) slurry wall was constructed at a brown-field redevelopment of a former steel mill site in Mayfield, NSW Australia. At this site, the slurry wall is designed to block groundwater flow that might contribute to the contamination of an adjacent waterway, the Hunter River. The wall was approximately 1500 m long and up to 49 m deep, constituting an apparent depth record for walls of this type.

As a part of the construction QC, there was an extensive amount of testing done, including an unusual amount of in situ strength testing using both a static cone penetrometer and field vane shear measurements. These latter measurements offer a unique opportunity to determine the strength gain of SB backfill material.

Results show a moderate stiffening of the SB material after it has been in the trench. This is consistent with field observations which show that, while SB backfill is placed in a semi-fluid condition, after some weeks it can be excavated with a vertical face. Results also show that the wall does not achieve a full static state of stress over its full depth. Rather, as the material "sets", arching occurs, in effect holding some of the weight of the backfill on the sides of the trench.

Extensive permeability testing of field-mixed SB backfill samples also provides a basis for design of future walls. In an earlier design mix program, a good correlation between percentage of fines and reduced permeability was established. It is clear that the fines content must be at a certain minimum to achieve stability in the backfill and to permit the blending of a low permeability backfill mix. Data are also presented showing the effects of permeation over an unusually long test period with contaminated groundwater.

INTRODUCTION

In 1999, operations ceased at a steelworks site on the south bank of the Hunter River in Mayfield, a suburb of Newcastle in New South Wales, Australia. The development and operation of the site over a period of approximately 85 years resulted in significant contamination, and in its declaration as a remediation site in 2001.

The original ground consisted of river channels and low lying marshlands. During the progressive development of the site as a steelworks, river sediments and by-products from the steelmaking process were used to fill much of the site. Underlying the fill there is typically a layer of marine clay, and then a thick layer of dense sand with a less pervious bedrock at a depth that varied from 25-50 meters.

The most polluted part of the site was previously occupied by coke ovens, gas holders, by-products treatment, and other processes associated with steelmaking. This area represented approximately 90% of the hazard to the environment via offsite migration of contaminated groundwater flows.

The proposed remediation strategy focused on containment rather than treatment or removal, and was arrived at following consideration of a range of technological and logistical options. It addressed the risk of onsite exposure to contaminants and offsite migration of contaminants through groundwater flows. Also, given the strategic location of the site, it made the site compatible with future industrial and port-related land-uses.

The remediation strategy had four key elements: 1) Improve drainage infrastructure, 2) Install an up-gradient subterranean barrier around the contaminated area, 3) Contour the entire site, and 4) Cap the entire site.

The effect of the proposed barrier wall is to practically eliminate upgradient groundwater flows from entering the contaminated area known as Area 1. Groundwater modeling shows that this stops the movement of contamination towards the river.

A deep barrier wall was selected as the most appropriate method of managing site groundwater after extensive investigation and review of alternatives due to its passivity and a low level of encumbrance to future site development.

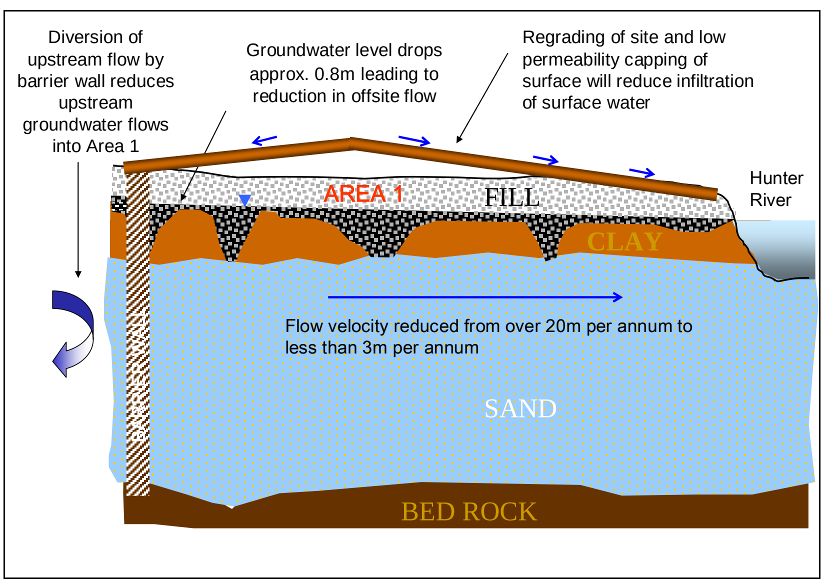

FIG. 1. Design Concept of Containment System

The wall was constructed using a long reach excavator to a depth of approximately 24 m, followed by a special slurry clamshell that excavated to the bedrock. The final depths varied from 23 m to 49 m, with the 49 m depth being an apparent new record depth for SB slurry walls. Stability of the trench was maintained with bentonite slurry during excavation. Once final depth was attained, the trench was backfilled with a blend of excavated spoils, select imported soils, and bentonite slurry. The permeability specification was a maximum of 1 x 10^{-8} m/sec. Additional information on the project can be found in Jones et al. (2007).

An unusual aspect of this project was that there were numerous static cone readings taken for the full depth of the wall. Since these types of readings can be used to infer shear strengths and since there are relatively few measurements of shear strength in situ in SB walls, this was a significant contribution to the state of knowledge. For additional information on in situ strengths, a deep vane shear test was run. The cone and vane data were correlated to each other and to in-situ measurements from other projects.

STRENGTH OF SOIL-BENTONITE BACKFILL

SB backfill is initially placed in a semi-fluid state with essentially zero shear strength. In the field, it has been observed that the backfill gains strength to the point where vertical cuts can be made through it. SB slurry walls generally do not consolidate vertically. Settlement plates installed at this site on top of the backfill, over a period of 4 months after construction, only settled from 0-10mm. The authors believe that the strength gain is actually due to thixotropic behavior of the backfill materials.

On this project, the strength of the in-situ SB backfill was measured with a series of 24 piezocone (CPTu) tests performed through the full depth of the wall. In addition, a vane test was performed to a depth of 18m at one of the cone locations. The CPTu tests were performed 4 to 67 days after backfill placement, with an average of 35 days. A review of the cone resistance corrected for pore pressure and area ratio, q_t, averaged over depth showed that consolidation time before testing had no measurable influence on measured q_t resistance.

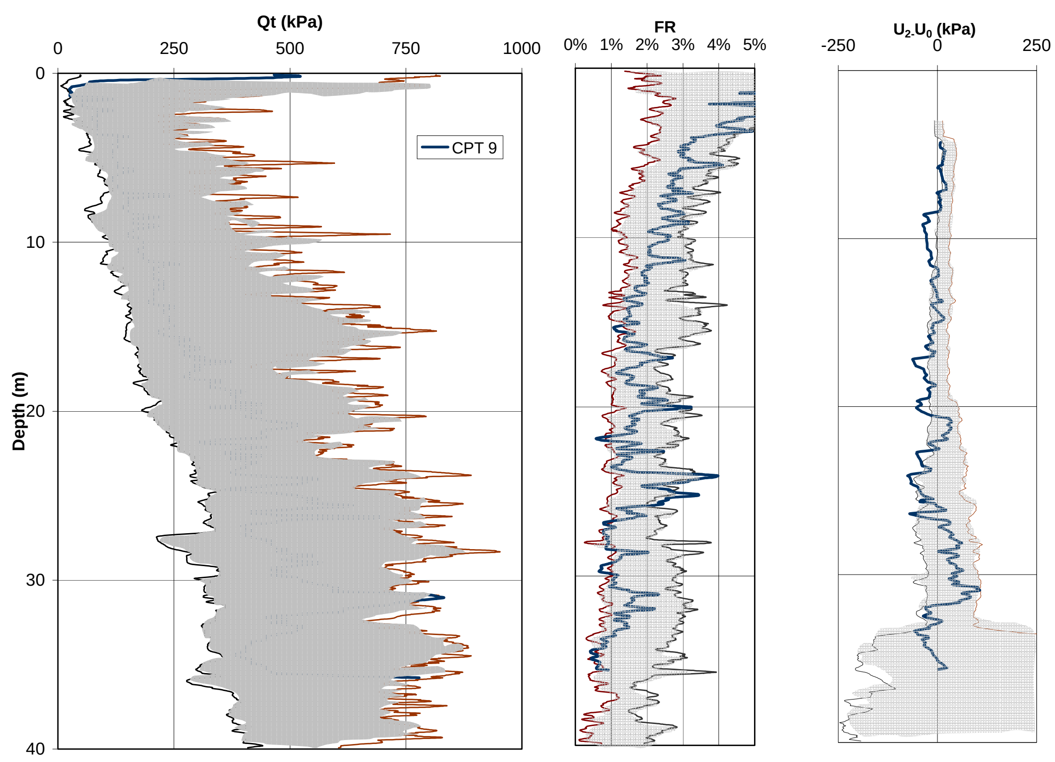

FIG. 2. Summary of CPTu results in SB wall

Figure 2 shows the minimum and maximum corrected cone resistance values, q_t, for the 24 tests. The cone resistance was first filtered to remove any set of values that exceeded 1MPa while at the same time showing a sudden increase within a depth increment of 2 or 4 cm, to eliminate the influence of small obstructions, such as gravel or unmixed clay clods left in the backfill.

The average value plus and minus one standard deviation of the Friction Ratio (ratio of cone friction to corrected cone resistance, fs/q_t) and of the pore pressure (u2) parameters are also displayed on Figure 2. In addition, one typical CPTu test, CPT-9 is also shown as an example for q_t, FR and u2 (thick blue line).

The undrained shear strength, s_u is calculated based on the corrected cone resistance and total vertical stress, σ_{vo}, as follows:

$$s_u = (q_t - \sigma_{vo}) / N_{kt} \qquad (1)$$

where N_{kt} is a correction factor; N_{kt}=15 is a recommended average, Lunne (1997)

The distribution of vertical stress in the wall is not well known since a combination of factors including arching have an influence (Evans and Ryan, 2005). However, assuming the backfill was normally consolidated at the time of the CPTu test, the following relationship would apply, p being the effective consolidation pressure, σ'_v, the effective vertical stress and u_o, the static pore pressure:

$$p = \sigma'_v = \sigma_v - u_o \qquad (2)$$

Hence, the total vertical stress, σ_{vo}, in equation (1) can be expressed as a function of u_o and p, which results in a direct expression of s_u as a function of q_t in the following formula:

$$s_u = (q_t - u_o) / (p/s_u + 15) \qquad (3)$$

In absence of site specific triaxial testing, the authors relied on values proposed by in Baxter et al. (2005) for determination of the ratio s_u/p (0.19 for a 35% plastic fines backfill) corrected to take into account the typical fines content of the wall of 25 to 30%:

$$s_u/p=0.18. \qquad (4)$$

Hence the following relationship:

$$s_u = 0.0486 * (q_t - u_o) \qquad (5)$$

This relationship could be verified by comparing s_u derived from qt with peak shear strength (PSS) values measured in-situ using a deep vane test as shown in Figure 3. The vane blades were 75mm in diameter and 75mm in height and were equipped with a coupling to measure separately the friction developed by the rotation of the rods; the calculated PSS values were not corrected for plasticity index; note also that the CPTu was performed after 36 days, while the vane test was done after 83 days. The average s_u profile v. depth derived from the 24 CPTu tests is also plotted on Figure 3, the peak q_t values having been filtered as previously explained.

The increase of s_u with depth is nearly linear in the top 15 meters and then uneven to 40 meters but with a peak at around 25m. The values of the shear strength, s_u generally vary between 5 and 15kPa, which is consistent with values at other projects Evans and Ryan (2005), Baxter et al. (2005).

The backfill density as measured before placement was quite uniform during the whole construction project with an average value of 1.95g/cm3. Using the proposed s_u/p constant, and adopting an average Water Table depth of 4m, the s_u increment between 5 and 15m depth would hence be 17kPa as compared to an increment of only 3-4kPa in average from the Fig 3 plot, confirming that a predominant part of the weight of the backfill is transferred onto the surrounding dense native sands, illustrating how the arching effect plays a significant role in the stress distribution in the backfill.

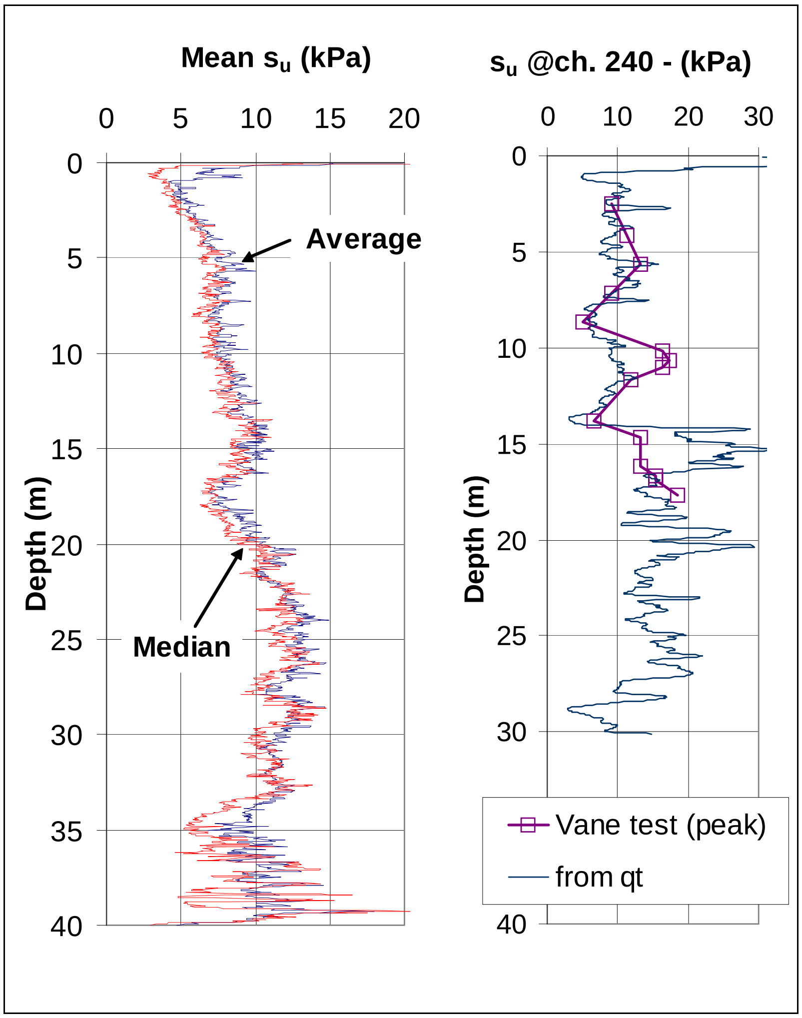

FIG. 3 – Left, Average S_u derived from CPTu using $s_u = 0.0486 * (q_t - u_o)$ and Right, Comparison of Field Vane data and S_u(CPTu)

PERMEABILITY OF SOIL-BENTONITE BACKFILL

The soil profile at this site consisted mainly of a very clean medium sand, with D_{50}=0.3mm and a Uniformity Coefficient close to 3. While there were layers of fine-grained material, it was readily apparent that there would not be enough fines to provide a backfill blend that would meet the requirements of the project (1 x 10^{-8} m/sec) with the excavated spoils alone. The option of adding additional dry bentonite was considered but was held in reserve because of the high cost and the relatively easy-to-meet performance standard. A search for sources of fines was launched and eventually encompassed sources at distances of up to 100 km away from the site.

All of the potential fines sources were tested in various additive ratios to the site base soils. The results, summarized on Fig 5 below, show that a minimum fines content of 20% in the backfill blend was required to reliably achieve the required permeability.

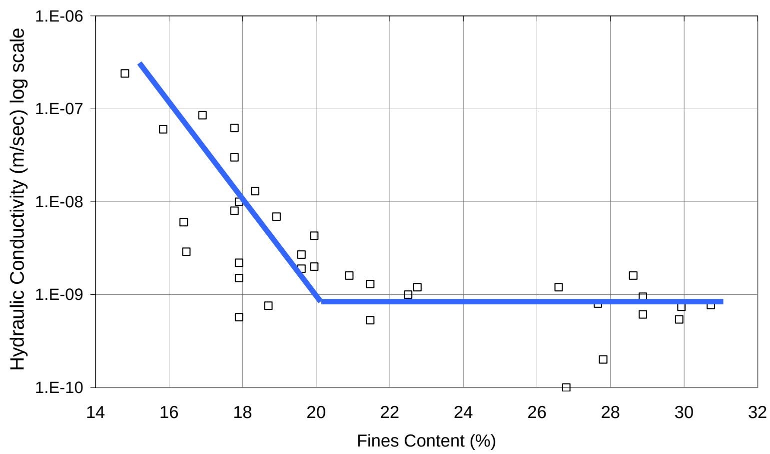

FIG. 4. Design Mix Summary Plot

An unusual aspect of this project was that there were several samples exposed for a very long term, up to six months, to the most contaminated water found at the site. Figure 6, shows a test, in which a volume of contaminants corresponding to 4.5 times the final pore volume was exchanged over a period of 3,100 hours, without variation of the permeability. The contaminated water was high in coal tars and had a very strong odor. The long-term exposure tests were run on the same samples and in the same triaxial test cells where the earlier permeability tests had been run. There was no significant degradation of any of the samples due to the contaminated materials.

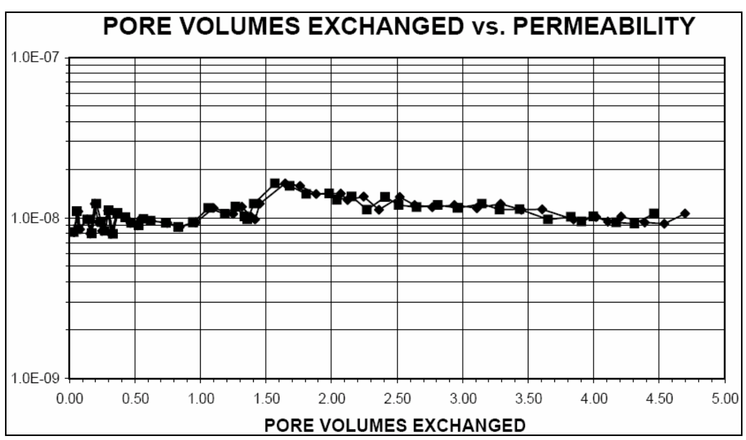

FIG. 5. Long Term Permeability Test (in cm/sec)

As a matter of practice, fines content in the field was generally higher than the minimum standard of 20% established for the site. In the figure below, the test results from grab samples taken at the surface from the backfill as it was placed are summarized. It can be seen that the results are comparable to the ones obtained in the pre-job design mix program. All results met the required permeability standards.

In an effort to understand better how the fines content of the backfill samples contributed to the impervious characteristic of the backfill, a number of backfill samples were selected for further analysis. For these samples, the fines portion of the backfill, less than 74microns in size (#200 sieve) was further analyzed with the hydrometer. As can be seen in the figure below, while there is a general correlation of decreasing permeability to increasing fines content in each size range, that correlation is very strong and clear for clay size fines. This suggests strongly that, as previously surmised, the best fines to use in an SB backfill blend are those that have good content of plastic, clay-sized fines.

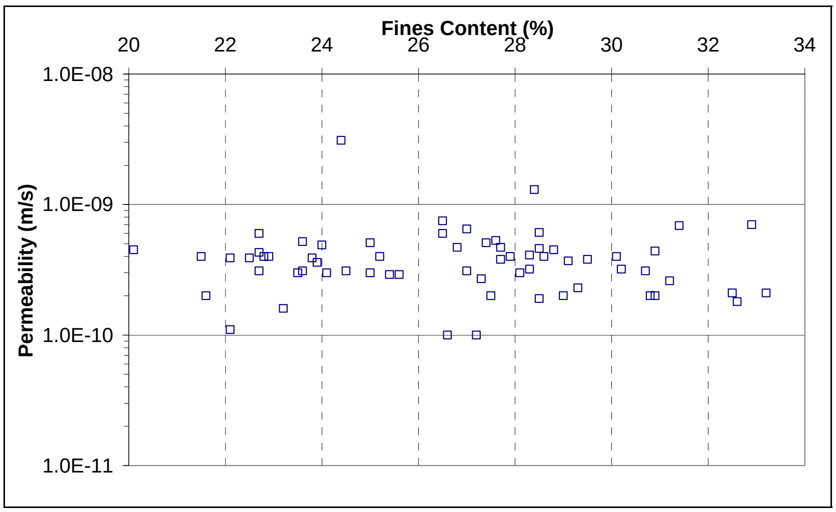

FIG. 6. Field Samples Tested for Permeability

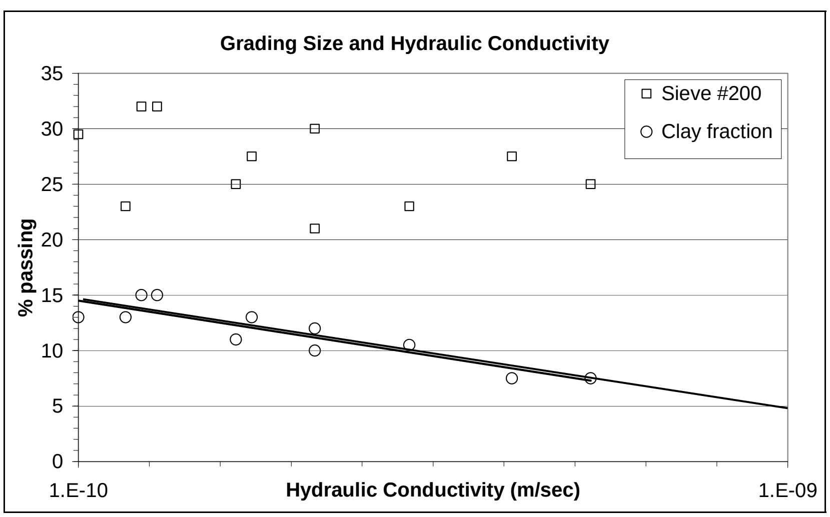

FIG. 7. Influence of Fines Size on Measured Permeability

CONCLUSIONS

The Mayfield project presented an unusual opportunity to gain a lot of performance data on an unusually deep soil bentonite slurry wall. Based on the data presented in this paper, as well as previous relevant experience, the authors conclude:

- The mechanism for strength gain in SB backfill is likely thixotropy and is not related to vertical consolidation of the backfill.
- A relationship was proposed to correlate corrected cone resistance q_t (CPTu) to the in-situ undrained shear strength of the backfill assuming a constant value for s_u/p; a good correlation was found between $s_{u\ (q_t)}$ and peak shear resistance from vane test in one test carried out to 17m depth;
- 24 CPTu tests, performed to the full extent of the SB wall, were used to obtain an average value of s_u v. depth, with mean and median values generally between 5 and 15kPa between 0 and 40m depth; these relatively low values of su illustrate the arching effect occurring in the trench through a progressive transfer of vertical loads on the native soils;
- A certain amount of fines is needed to establish an impervious matrix. In this case the criterion was set at 20%, which is a typical number for SB backfill.
- Permeabilities of field mixed samples were predicted well by the pre-job lab design mix study.
- Increasing percentages of fines, particularly clay-sized fines, have a good correlation to decreasing permeability.

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