Characterisation of landfill steel mill sludge waste in terms of shear strength, pore water pressure dissipation and liquefaction potential

Caractérisation de la résistance au cisaillement, de l'évolution des pressions d'eau interstitielle et du potentiel de liquéfaction des boues d'aciérie dans un centre de stockage.

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ABSTRACT: The unique method of iron sands mining undertaken at the New Zealand (NZ) Steel Mill, produces an inert waste sludge comprised primarily of clay and iron-sands/grit. This wet sludge waste is landfilled in cells to heights up to 25m. The purpose of this paper is to characterise the sludge waste and to investigate its potential for liquefaction. This paper presents an investigation of the sludge in the existing landfill based on in situ and laboratory testing. Design parameters such as shear strength, and pore water pressure are developed and confirmed for the sludge material. Liquefaction potential of the sludge due to earthquake shaking is investigated using a CPT-based assessment and Atterberg limits test results. The paper concludes with a discussion of liquefaction potential and recommended total stress and effective stress parameters for detailed design of a new landfill development.

RÉSUMÉ : La méthode unique pour l'extraction de minerai de fer utilisée par New Zealand (NZ) Steel Mill produit une boue inerte résiduelle composée principalement d'argile et de sable ferreux. Cette boue liquide est stockée dans des casiers sur une hauteur pouvant atteindre 25m. L'objectif de cet article est de caractériser la boue résiduelle et d'évaluer son potentiel de liquéfaction. Cet article présente les résultats des essais in-situ et en laboratoire, réalisés sur la boue présente dans le centre de stockage existant. Les caractéristiques telles que la résistance au cisaillement et l'évolution des pressions d'eau interstitielle sont développées et confirmées pour cette boue. Le potentiel de liquéfaction de la boue lors d'un tremblement de terre est évalué par des essais réalisés au moyen de pénétromètres coniques ainsi que par la détermination des limites d'Atterberg. L'article conclut par une discussion sur le potentiel de liquéfaction et sur les valeurs de contrainte totale et contrainte efficace recommandées pour la conception et le développement d'un nouveau centre de stockage.

KEYWORDS: sludge, landfill, liquefaction, shear strength, pore water pressure

1 INTRODUCTION

The objectives of this paper are to characterise landfilled sludge waste in situ and to investigate the potential for liquefaction of the sludge. Various in situ test results are presented and parameters for detailed design of a proposed landfill are recommended. The potential for liquefaction of the sludge due to earthquake shaking is investigated.

2.1 *New Zealand Steel Mill*

The NZ Steel Mill is located approximately 60 km Southeast of Auckland and is the only mill in the world to manufacture iron and steel from titanomagnetite iron sands. The iron sands are found along the western coast of New Zealand's North Island and are the remains of rocks which once formed the flanking volcanoes of Mount Taranaki (located about 250 km south of the mill). They are the largest reserves of metal ore in New Zealand.

2.2 *Waste streams*

As a result of the unique nature of the NZ Steel sand mining and iron/steel making processes, a number of waste streams are produced and landfilled onsite. These wastes include: wet sludge, slag, reduced primary concentrate and char (RPCC), ironbearing dusts and general works debris.

The sludge waste is a mixture of clay slimes that result from the slurry pumping operation and the byproducts of pollution control operations. It is generated at a rate of approximately 80,000m^3/year and forms approximately half of the waste deposited in the landfill. The sludge waste is a mud-like fine grained material with a solids content of 15 to 20% by weight when it is carted to the landfill. It is comprised of clay, coal ash, ironbearing dusts and carbon.

2.3 *Landfill history*

For over 20 years, the sludge (and other wastes) have been deposited into the existing West Landfill facility in a series of cells. A new East Landfill facility has recently been designed to replace the existing West Landfill which is nearing its capacity. The East Landfill has an expected life of 30 years and a final fill volume of 4.7 million m^3. It will accept approximately 160,000m^3/year of waste.

The materials to be stored in the East Landfill are the same materials that have been landfilled in the West Landfill. As this existing facility has been in operation since 1992, it offers an ideal means for testing and characterising the sludge materials in situ for the design of the new East Landfill.

3 SLUDGE CHARACTERISTICS

3.1 *Prior to landfilling*

Prior to landfilling, the clay slimes and black waste are deposited into separate settling ponds to reduce the moisture content to approximately 80% to 85%. The clay slimes and black waste are then landfilled into the cells, forming a sludge waste. The sludge typically exhibits no free water, but some decant water is produced during excavation from the settling ponds. When tipped into the landfill, the sludge exhibits a degree of run-out (approximately 30 to 80m), but drains and desiccates relatively quickly.

3.2 *Operation of Landfill Cells*

The landfills are formed in a series of cells. Each cell is constructed by first constructing a containment bund of the high strength granular RPCC waste and then placing the sludge material behind it. After a sludge depth of 2.4m is achieved within the cell, the sludge is allowed to dry and desiccate for periods of 8 to 12 weeks. The next "lift" of the cell is then carried out by constructing another 2.4m high bund of RPCC on top of the previous one, and continuing the filling process with sludge in the same way as before. Because each new bund is half on the old bund and half on the sludge, the overall crest of the cell tends to move generally up the valley and is commonly termed "upstream" construction.

3.3 *In situ sludge characteristics*

3.3.1 *General*

Once the sludge has been deposited into the landfill, it gains strength relatively quickly. The surfaces of the sludge cells rarely pond rainwater and testing has shown the sludge mass does drain and consolidate over time.

To investigate the nature of the sludge within the landfill, boreholes and cone penetration tests (CPTs) were drilled through three different completed cells. Locations were chosen to represent the characteristics of both older and younger sludge materials. A variety of tests were completed in situ and on tube samples. The sludge was found to have the following typical properties:

- Bulk density: 1.4t/m^3
- Undrained shear strength (after initial settling, desiccation and consolidation): 30kPa and increasing to greater than 100kPa at depth
- Liquid limit (LL): 60% to 100%
- Plasticity index (PI): 10 to 53
- Effective angle of internal friction: 36° – 39°

3.3.2 *Shear strength*

The in situ undrained shear strength (s_u) was assessed using Geonor vane, hand-held vane, CPT and triaxial CUP tests and short term stability back analyses. The resultant shear strength data from all approaches is summarized in a single plot in Figure 1. Discussion about each method follows.

Geonor Vane: This is the most direct in situ test method and is given the highest weighting. Results show a clear indication of strength increase with depth.

Hand-held Vane: Measurements were taken with a small blade vane at the end of the open borehole barrel. Results show significantly lower values than the Geonor vane and triaxial CUP data and a generally slightly decreasing trend with depth. Such trends indicate a strong influence of sample disturbance and this data should therefore be disregarded.

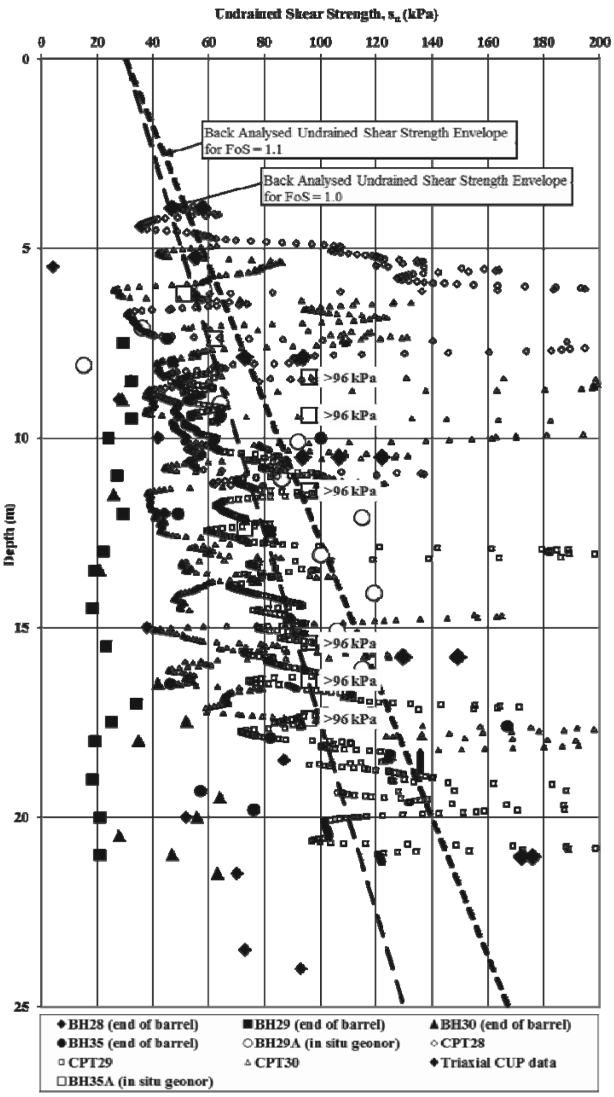

Figure 1. Undrained shear strength of sludge material with depth

CPT: A method of deriving the undrained shear strength from CPT data is given by Lunne, Robertson & Powell (1997). The data show a clear trend of increasing strength with depth and also, by comparing the different test locations, a clear indication of strength increase with the length of time the sludge has been in place.

Triaxial Tests: The consolidated undrained triaxial tests with pore pressure measurement (CUP tests) give a measure of undrained strength (s_u) with consolidation pressure (p´) and also a s_u/p´ relationship. This relationship gives an indication of the expected increase in strength with depth after full consolidation. The CUP data depth plotted on Figure 1 is based on the effective consolidation stress applied to the sample for each test, to represent a comparable overburden stress.

Back analysis: Based on historical annual survey data, the maximum free-standing slope face height for an operating cell was 24.5m with a slope of 1.2H: 1V. A back-analysis of this maximum free standing slope has been carried out using equilibrium software (Slope/W). An undrained shear strength profile for the sludge material of 30kPa at the surface, increasing at 4kPa per meter with depth is required for a safety factor of unity. Similarly, an undrained shear strength profile for the sludge material of 30kPa at the surface, increasing at 5.5kPa per meter with depth is required for a safety factor of 1.1.

Bund failure has never occurred at the site. Therefore, it can be inferred that the undrained shear strength of the sludge material is higher than the back-analysed undrained shear strength envelope (assuming a safety factor of unity). The back-analysed shear strength envelopes (refer Figure 1) show that the Geonor vane and triaxial undrained shear strength data closely fit the back analysed shear strength envelope for a safety factor of 1.1 and is therefore more representative of the sludge undrained shear strength characteristics.

3.3.3 *Pore pressure monitoring*

Six pore water pressure transducers were installed in two boreholes at various depths below the ground surface. Pore water pressures were measured over a period of one month.

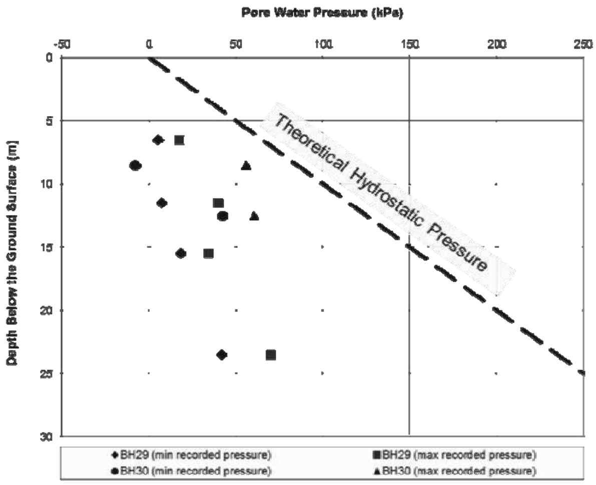

Figure 2. Pore water pressure distribution in sludge with depth

The sludge pore water pressure monitoring results are presented in Figure 2. The maximum and minimum ground water pressures measured by the transducers are presented as a function of depth below the ground surface. The results indicate that the pore water pressures in the sludge material range from 10kPa to 60kPa and are significantly lower than the theoretical pore water pressures for hydrostatic conditions with the water table at the ground surface. These results demonstrate the sludge mass is able to dry out and desiccate prior to subsequent placement of the above sludge layers and that the sludge mass is able to drain within the landfill cells.

4 LIQUEFACTION

The assessment of liquefaction potential of the sludge waste has been approached using CPT data and Atterberg Limits.

4.1 *CPT-based liquefaction assessment*

Liquefaction analyses using the CPT data have been undertaken using the assessment methods developed from the 1998 NCEER/NSF Workshop, supplemented and updated with the more recent recommendations for liquefaction assessment including the works of Zhang et al. (2002), Cetin et al. (2004), Moss et al (2006a), and Moss et al. (2006b).

The CPT data show that the sludge materials are very cohesive (i.e. they have Ic values greater than 2.6) and therefore, in theory, are not susceptible to liquefaction. The calculated liquefaction factor of safety (derived from $CRR_{7.5}$) for the majority of the CPT data was above 1.0 for a peak ground acceleration of 0.17g (10% probability of exceedance for a 30 year period).

4.2 *Liquefaction Susceptibility using Atterberg limits*

Over the past few decades it has been assumed that fine-grained soils (silts and clays) do not liquefy. Recent research has shown that, under some circumstances, fine grained soils (such as sludge) may be susceptible to liquefaction and there have been various suggested criteria for defining the limits.

Seed et al. (2003) recommended an area on the Casagrande Plasticity Chart within which soils should be classified as "potentially liquefiable". Out of nine, eight results are all well outside the potentially liquefiable region. Therefore the waste mass as a whole is not susceptible to liquefaction according to these criteria. Some small pockets or zones may be more susceptible than others, but will not govern the behaviour of the overall material mass.

Bray & Sancio (2006) suggested criteria based on PI and the ratio of natural water content to the liquid limit (w/LL). Again, only one result out of nine plots within the "Susceptible" region.

Boulanger & Idriss (2006) suggested that materials can be expected to exhibit clay-like behaviour (i.e. non liquefiable) if they have PI value of greater than 7 and that fine-grained soils with PI values less than 7 should be considered as potentially exhibiting "sand-like" behaviour (i.e. liquefiable). The PI data for the sludge range from 10 to 53 and fall into the "clay-like" category, indicating the material is not susceptible to liquefaction.

4.3 *Liquefaction conclusion*

It is concluded that the landfill materials are not susceptible to liquefaction under any credible level of shaking. In addition to this, however, it should be noted that the level of shaking under operating conditions (10% probability of exceedance in 5 years) is only 0.06g, and this is unlikely to exceed the strain threshold for liquefaction to occur for any type of material, except very loose sands.

In the long term the final landfill geometry will have a maximum slope of 5H: 1V and will be made up of consolidated sludge in many separated cells with numerous effective RPCC "chimney drains" extending up full-height through the fill. Even if liquefaction could occur, it would be localised and confined within the cells, with little risk of significant displacement.

5 DESIGN

Based on in situ and laboratory testing at the West Landfill, the sludge design parameters that have been selected for the cell design of the East Landfill are summarised in Table 1.

A seismic reduction factor was adopted for the sludge shear strength envelope to account for potential cyclic strain softening that may occur within the sludge during seismic loading. For a 7.5 magnitude earthquake, Boulanger and Idriss (2007) recommend a ratio of cyclic undrained to static strength for natural clays/silts is 0.8. Therefore the static strength was reduced by 20%.

Table 1. Sludge design parameters used for design of East Landfill

Test Method	Undrained	Drained	
	s_u (kPa)	c' (kPa)	ϕ' (deg)
Back Analysis (FOS=1.1)	30+5.5z[1]	0	35
Triaxial (CUP)	N/A	0	36-39
Geonor vane	15 to 120 with depth	N/A	N/A
CPT	25 to > 200 with depth	N/A	N/A
Design (static)	0 (for z < 2.5m depth) 30 + 4z (for z > 2.5m depth)	0	0 (for z<2.5m depth) 32 (for z>2.5m depth)
Design (seismic)	0 (z<2.5m depth) 24+3.2z (z>2.5mdepth)	0	27

[1] Most likely lower bound, assuming a factor of safety of 1.1

6 CONCLUSIONS

The design of a new landfill has been based on the properties and performance of an existing landfill that has been operating for 20 years. The landfills are operated in cells, with facing bunds retaining sludge, constructed in lifts using "upstream" construction. The characteristics of the sludge in situ are governed both by the nature of the material and the operation procedures. Key to the process is the limited height of each lift, together with the period of desiccation between lifts.

To investigate the properties of the sludge for design input, boreholes and CPT's were put down through completed landfill cells of different ages. The tests showed the in situ sludge to have significant strength increase with time and depth, with pore pressures well below hydrostatic conditions. The need to check liquefaction potential is self-evident. The sludge was assessed to be non-liquefiable by a number of methods.

7 ACKNOWLEDGEMENTS

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