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Studies into the reinforcing effect of stone columns in soft clay

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ABSTRACT : A proposed major extension to an iron ore handling yard was located in an area underlain by soft alluvial clay. Stone columns were proposed to limit settlement of rails supporting the stacking/reclaiming machines. As part of the investigation for the project, a series of centrifuge model tests were undertaken to examine various aspects of the project, and to test some of the design assumptions. Some of the results of these model tests are presented and discussed in the light of current design methods for stone columns.

1 INTRODUCTION

Port Hedland on the north-west coast of Western Australia is one of the world's major iron ore exporting ports. As illustrated in Figure 1, ore handling yards at Port Hedland typically comprise large stacking/reclaiming machines which run on rails on top of 3 m high embankments adjacent to the ore stockpiles. With stockpiles of up to 20 m in height having a bulk unit weight of around 26 kN/m^3, the stockpiles exert a vertical stress of up to 500 kPa on the subgrade.

A major new ore handling yard was proposed in an area underlain by about 3 m of hydraulic fill over soft alluvial clay of up to 3 m thickness. It was proposed to install stone columns beneath the stacker/reclaimer embankments to limit differential vertical and horizontal movements of the rails for the stacking/reclaiming machines. A further benefit of the proposed work was the increase in stability of the stockpiles against gross failure.

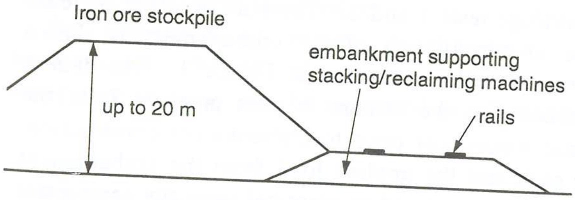

Figure 1 : Schematic cross-section through a typical ore stockpile

As part of the investigation for the project, a series of centrifuge model tests were carried out at the University of Western Australia to examine various aspects of the project, and to test some of the design assumptions. The aspect of the work described in this paper was aimed at assessing the likely magnitude of vertical and horizontal movements of the stacker/reclaimer embankment, and what reductions could be expected due to installation of stone columns. The experimental work is described in this paper, with the results presented and discussed in the light of current design methods for stone columns.

2 TESTING PROGRAM

Centrifuge model testing was performed on the 40 g-tonne Acutronic model 661 geotechnical centrifuge at the University of Western Australia (Randolph et al, 1991). Internal dimensions of the strongboxes used for the testing were 650 x 390 mm in plan view and 325 mm in height. The principles of geotechnical centrifuge modelling are well established (see Schofield, 1980 for example) and will not be described here. The models were tested at a gravity level of 100 g, and therefore the field dimensions were scaled down by a factor (N) of 100.

A total of four centrifuge models were tested as shown in Table 1, to examine both the influence of the stacker/reclaimer embankment and the effect of stone columns on deformations resulting from construction of the ore stockpile. The layout of each test was similar to that illustrated in Figure 2, although the positions of instrumentation varied slightly between tests.

A disturbed bulk sample of clay from the field site was obtained to conduct the centrifuge testing. Reconstituted samples of this material were found to have a coefficient of consolidation, $c_v = 0.45$ m^2/yr, and a compression index, $C_c = 1.08$. All other soils were chosen to be approximately representative of the field materials. Fine graded silica sand was used for the embankment and the sand layers indicated on Figure 2. Fine cast iron shot was used to represent the iron ore in the stockpile. This material has a mean particle size of about 0.35 mm, and a bulk unit weight of 40 kN/m^3. This high density meant that the loading from a 20 m high ore stockpile could be represented by a 12 cm high stockpile of iron shot at 100 g.

The centrifuge samples were prepared by mixing the clay at a water content of twice the liquid limit (w_l = 106). Salt was added to the water to

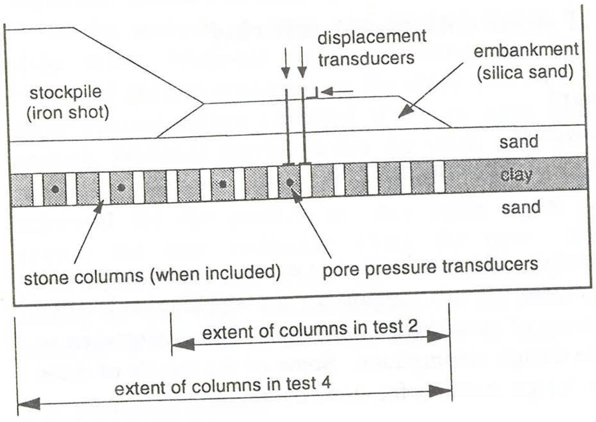

Figure 2 : General layout of centrifuge models. Position of instrumentation and precise layout varied between tests.

Table 1 : Centrifuge model configurations

Test no.	Stacker/reclaimer embankment	Stone columns
1	yes	none
2	yes	beneath stack/reclaim embankment only
3	no	none
4	no	beneath and beyond toe of ore stockpile

approximate the salinity of sea water since the clay was originally deposited alluvially in a coastal environment. The slurry was then consolidated in a centrifuge strongbox under a uniform vertical pressure approximately equivalent to the expected overburden stress at the mid-depth of the model clay layer. After full consolidation, "stone" columns, if required, were installed by inserting a 12 mm (1.2 m) diameter thin-walled tube into the clay through a guiding template. The tube was then extracted to remove a cylinder of clay, and the hole backfilled with fine sand, lightly tamped into place. The columns were placed on a 35 mm (3.5 m) square grid, resulting in a replacement ratio of 9 %. After placing the upper sand layer and mounting various transducers and equipment, the model was placed on the centrifuge and allowed to consolidate under 100 g.

In tests 1 and 2, the stacker/reclaimer embankment was then formed in-flight by pouring sand in one increment from a sand hopper (Randolph et al, 1991). Full consolidation of the clay under the embankment was allowed before the centrifuge was stopped and the hopper moved, filled with iron shot and the centrifuge restarted. After allowing for reconsolidation of the clay, the ore stockpile was constructed in six equal increments with 30 second (3½ day) delays between each stage. In tests 3 and 4, the stacker/reclaimer embankment was not included, and so the ore stockpile was constructed as above without stopping to move the sand hopper.

Instrumentation of the model included miniature pore pressure transducers installed in the soft clay, and displacement transducers to measure vertical and horizontal movement of the soil surface. In the two tests with stone columns, attempts were made to measure settlement directly on top of a stone column and also midway between the columns by using small upstands.

3 TEST RESULTS

The results of the centrifuge model testing are presented here in terms of prototype units only. Model lengths and displacements have been scaled up by a factor of 100 (N), while model time has been scaled up by a factor of 10 000 (N^2).

3.1 Stress Concentration

Where stone columns are installed into a soft clay stratum, any surface loading of the soft clay will be partially carried by the stiffer columns. This results in less stress being transferred to the soft clay, and therefore leads to smaller surface settlements. By comparing the results of the tests described above, an estimate of the proportion of load carried by the columns can be made.

Pore pressures were measured in the soft clay stratum beneath the stacker/reclaimer embankment in centrifuge tests 1 and 2. The pore pressure increase due to construction of the embankment is shown versus time for both tests in Figure 3. The data is presented as the change in pore pressure from the static values just prior to embankment construction. In each test the applied load from the embankment could be considered as identical since the same mass of sand was deposited in each case.

In test 1, a pore pressure rise of 48 kPa was recorded. This is in close agreement with the calculated embankment loading of 49 kPa, allowing for the variation of g-level with height in the model. If it is assumed that the reduction in maximum pore water pressure from test 1 to test 2 reflects the reduction in total stress imposed on the clay, it is possible to estimate how much extra stress the stone columns attract. Assuming that each column influences a total area of 3.5 x 3.5 m^2, a vertical stress of about 48 kPa from the embankment is equivalent to a load of 588 kN. In the second test, a stress of 37 kPa (the rise in pore pressure) is assumed to act on the clay area, equivalent to a load of 411 kN. This implies that the difference in load (177 kN) is taken by the stone column, equivalent to a stress of 157 kPa over the area of the stone column. Thus the stress concentration factor (n = stress on the stone column/average stress on the clay) can be calculated as 157/37 = 4.2.

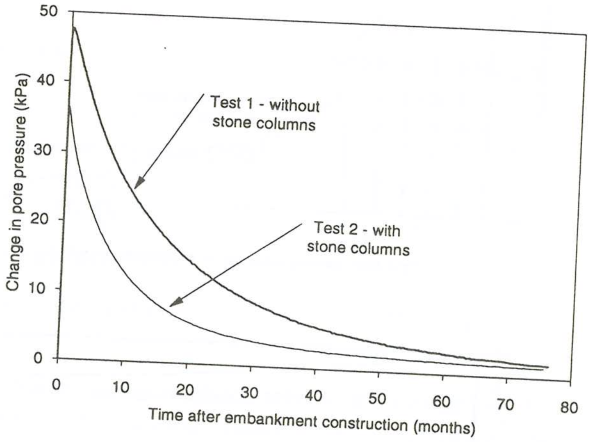

Figure 3 : Pore pressure response in clay stratum after construction of embankment.

Similar calculations can be performed using data from test 3, where columns were not present, and test 4, where columns were included beneath the ore stockpile. At full height of the stockpile, a pore pressure rise of 425 kPa was measured without the stone columns, compared to the calculated maximum load of 435 kPa. In the test without stone columns, a rise of only 320 kPa was measured. Using the same logic as before, a stress concentration factor of 4.6 may be deduced from these values.

By inspection of Figure 3, the time for approximately 50 % of excess pore pressure dissipation to occur can be estimated as 10 months for the test without stone columns, and 6 months with stone columns. This apparent reduction in consolidation time is primarily due to (i) a reduction in total stress on the clay with time, since consolidation settlement of the clay results in the shedding of more load to the stone columns; and (ii) an increase in the rate of pore pressure dissipation due to the draining effect of the stone columns. It is believed that the latter effect is dominant in the tests described here.

3.2 Deformation

The deformations measured during each centrifuge test are summarised in Table 2. Examining these data, it is apparent that the inclusion of stone columns beneath the stacker/reclaimer embankment has a number of benefits in terms of displacement. Settlement under the weight of the embankment itself was reduced markedly, while the vertical and horizontal displacements that were measured after forming the ore stockpile were approximately halved by inclusion of stone columns.

By comparing tests 1 and 3, the stacking/reclaiming embankment itself had a very significant effect on the magnitude of heave due to construction of the adjacent stockpile. This is partly due to the physical weight of the embankment, and partly due to strength gain in the soft clay under the embankment's load. By contrast to the reduction in heave, lateral deformations at the surface were reduced by a much smaller proportion. Similar observations can be made comparing tests 3 and 4, where stone columns beneath the stockpile reduced heave markedly, but had relatively little effect on reducing lateral movement beyond the toe. In this test series, stone columns resulted in a marked reduction in lateral deformations only when overlain by the stacker/reclaimer embankment. It is believed that this is because the columns are stiffer when carrying greater axial load, and therefore provided

Table 2 : Summary of deformations measured in centrifuge tests (prototype scale).

Test No.	Settlement due to embankment construction (mm)	Heave at toe due to stockpile construction (mm)	Lateral displacement at toe due to stockpile construction (mm)	
			After one month	Long term
1	170	15	70	-
2	100	8	30	85
3	-	65	115	160
4	-	7	90	130 to 140

more restraint to movement when the embankment was present.

In centrifuge test 2, an attempt was made to measure settlements at the top of a stone column, and at the top of the clay midway between columns via small settlement plates, as indicated on Figure 1. Unfortunately, one of the displacement transducers malfunctioned part way though the test, and therefore a sensible comparison of the two settlement values could not be made. However, the maximum settlement determined from the instrumentation in test 2 is plotted on Figure 4, together with settlement data from centrifuge test 1. From this Figure, it is apparent that the stone columns substantially reduced the total settlement, as well as accelerating the rate of settlement. The settlement reduction factor due to the stone columns (as defined by Balaam and Booker, 1985) is found to be about 0.6.

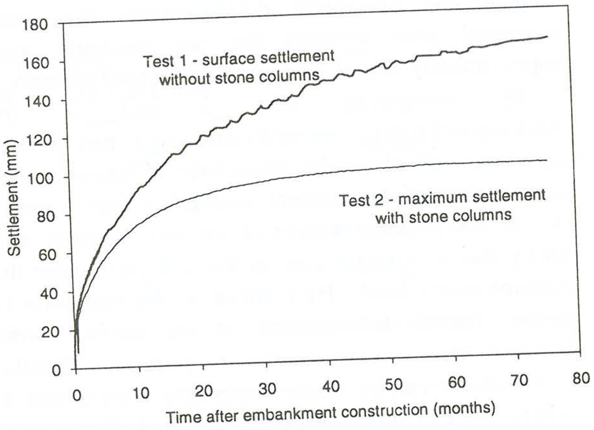

Figure 4 : Settlement due to embankment construction in centrifuge tests 1 and 2.

Typical data illustrating the heave and lateral displacement measured at the centre of the embankment during stockpile construction are shown on Figure 5. The lateral displacement data clearly show the stockpile construction increments, since the laser displacement transducer measuring lateral movements was temporarily "blinded" by dust from the iron shot used to construct the stockpile. A consistent feature of the data is that a small lateral movement towards the stockpile was recorded initially, with movement away from the stockpile in later stages. This response is probably due to slight overconsolidation of the clay, and is consistent with the "drained" and "undrained" responses described by Tavenas et al (1979) from field data on lateral displacements adjacent to embankments on soft clay. It is obvious that lateral and vertical displacements generated by the stockpile are strongly time dependent, with a small amount of movement still occurring some 5 years after construction of the stockpile.

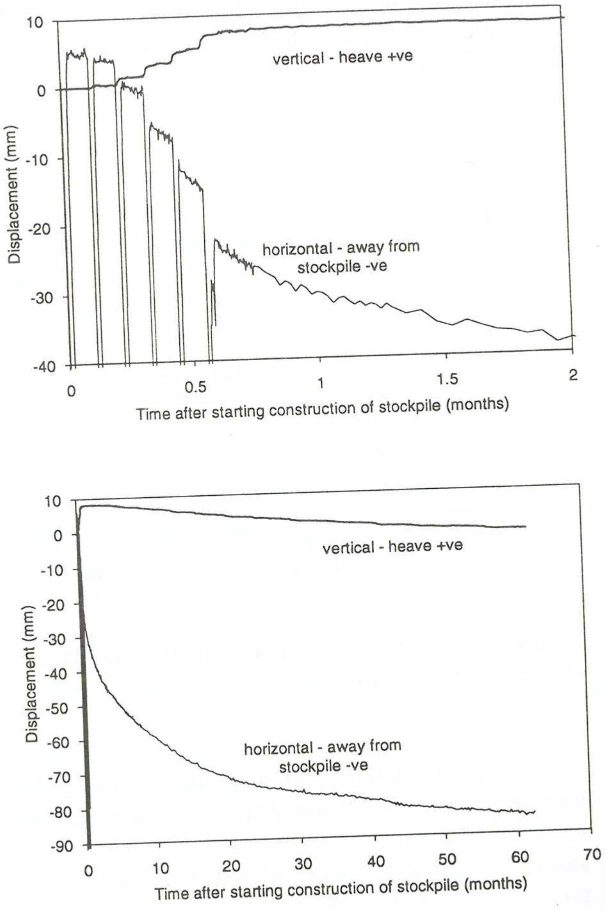

Figure 5 : Displacement of embankment after construction of stockpile during centrifuge test 2.

4 COMPARISON WITH DESIGN METHODS

The test data described here may be compared with various design approaches that have been proposed. Balaam and Booker (1985) describe a numerical analysis of stone column-clay interaction and present charts enabling the settlement reduction due to inclusion of columns to be calculated for elastic conditions and also allowing for plastic yield of the column. A range of ratios of column stiffness (E_p) to clay stiffness (E_s) are covered. Using these charts, a settlement reduction factor of about 0.7 may be found for the column configuration described here, for E_p/E_s between 20 and 40 and allowing for yield of the column. If yield is not allowed for, a settlement reduction factor of between 0.3 and 0.45 may be calculated.

The results of estimates of settlement reduction by the above method, and alternative approaches by Greenwood (1970) and Van Impe (1989) are summarised in Table 3. The approaches are relatively consistent for the case examined here, and all yielded slightly conservative predictions compared to the reduction factor of about 0.6 derived from the centrifuge testing program.

Table 3 : Estimates of settlement reduction due to stone columns.

Method	Settlement reduction factor
Balaam and Booker (1985)	
- elastic	0.3 to 0.45
- plastic	0.7
Greenwood (1970)	0.75
Van Impe (1989)	0.75 to 0.85

Some design methods rely on the estimation of a stress concentration factor (n) to calculate the settlement of a stone column-clay system. Such methods are described by Mitchell (1981), who quotes values of n between 2 and 6, although values of 3 or 4 are stated to be more usual. These figures compare well with the stress concentration factors of 4.2 and 4.6 estimated from the experimental work described here.

5 CONCLUSIONS

A number of centrifuge tests were conducted to examine the influence of stone columns in reducing surface deformations due to construction of an iron ore stockpile. The stockpile was estimated to impose a surface load of up to 500 kPa. The findings of the work reported in this paper can be summarised as follows :

- Stress concentration factors between 4 and 5 were estimated from the centrifuge tests. The values compare well with typical values reported in the literature from field observations.
- A settlement reduction factor of about 0.6 was found from the centrifuge testing program. Various design methods predicted reduction factors in the range of 0.7 to 0.8, and thus were slightly conservative in this instance.
- Installation of stone columns in the model tests was found to substantially reduce vertical surface deformations due to construction of the ore stockpile. Lateral deformations were only reduced markedly when the columns carried sufficient axial load from higher overburden stress.

ACKNOWLEDGMENTS

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