

# Granular Column Stabilisation of a Variable Fill Reclamation

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**ABSTRACT:** A Bulk Handling and Storage Facility has been constructed on a foundation of variable rock and clay fill, which formed an existing reclamation at Lascelles Wharf in Geelong, Victoria. Granular columns of compacted rock were used to improve the settlement and strength properties of the fill. It was demonstrated that this stabilisation was mainly achieved by densification of the existing fill rather than by the granular columns behaving like piles. Construction monitoring and testing was adopted, which enabled identification and additional stabilisation of the poorest areas of fill. The method proved to be successful and warrants consideration on other projects as means of stabilising variable fill.

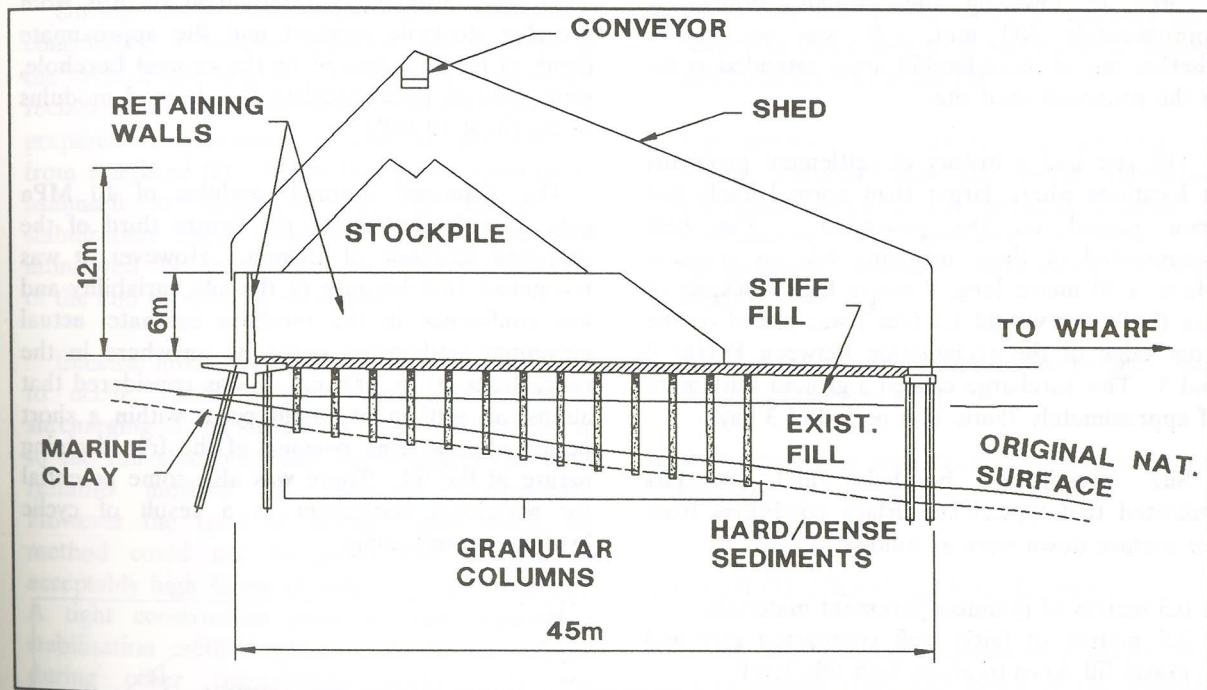


FIGURE 1 - GENERAL ARRANGEMENT

## INTRODUCTION

As part of the design and documentation of a Bulk Handling Facility at Lascelles Wharf for the Port of Geelong Authority, Maunsell utilised granular columns as a means of stabilising poor ground conditions to the extent where almost all of the foundation loads could be supported on high level spread footings. As a result of an alternative design submitted by the successful construction tenderer, most of the structural foundations were altered to be supported by concrete piles. The role of the granular columns was therefore reduced to stabilisation of pavement areas to support the ground loadings from stockpiles of materials.

## DESCRIPTION OF FACILITY

The Bulk Handling Facility is housed within a shed 150 metres long, 45 metres wide and 20 metres high at the ridge. A tripper conveyor runs under the ridge along the length of the building. This conveyor enables bulk materials including coal, urea and limestone to be unloaded from ships and deposited in stockpiles on the block paver floor of the shed. Three separate stockpiles are each retained on three sides by six metre high retaining walls. Stockpiles of materials weighing up to  $2.2 \text{ t/m}^3$  can be placed to heights of up to 12 metres. The resulting surcharge loads range from 0 to 250 kPa at various locations and times. The stockpiled material is loaded onto trucks by front end loaders and the pavements are cleaned

down prior to placing different types of material.

## SITE CONDITIONS

The Bulk Handling Facility was constructed on a section of existing, asphalt paved reclamation forming Berths 2 and 3 of Lascelles Wharf. The reclamation was constructed in at least two stages with the Berth 2 reclamation constructed first, followed by the Berth 3 reclamation at a later date. Parts of the reclamation to the immediate north west of the proposed shed site were known to have been used as landfill. Falling weight dynamic compaction of one of these landfill areas resulted in lowering the ground surface by approximately 400 mm. It was not known whether any of these landfill areas extended as far as the proposed shed site.

The site had a history of settlement problems at locations where larger than normal loads had been placed on the pavement. The best documented of these incidents was an occasion where a 50 metre long, 9 metre high stockpile of slag (bulk unit weight  $1.1 \text{ t/m}^3$ ) was placed on the front edge of the reclamation between Berths 2 and 3. This surcharge caused a ground settlement of approximately 75mm in a period of 3 days.

Site investigation boreholes and test pits indicated that typical subsurface conditions from the surface down were as follows:

1. 0.5 metres of granular pavement materials;
2. 2.5 metres of fairly well compacted clay and gravel fill down to about high tide level;
3. 0 to 6 metres of very loose rock and rubble fill with approximately 20% soft clay;
4. 1 metre of firm marine clay;
5. interbedded hard/dense clays and cemented sands to a depth of at least 30 metres.

One notable exception to the typical profile was at the southern end of the site where one test pit encountered firm clayey silt to a depth of 4.5 metres. It was suspected that this poorer quality fill was associated with the older Berth 2 reclamation. The overall depth of fill varied from as little as 1 metre in the south west corner of the site, to up to 9 metres of fill behind the berth face on the eastern side of the site. It is significant to note that in all but one test pit, all of the material excavated from the test pits could be replaced in the hole without compaction. This suggested that the lower fill was in a very loose state.

## DESIGN PARAMETERS AND CRITERIA

To avoid the greatest depths of fill, the site of the shed was moved as far towards the back of the wharf as possible. However up to seven metres of fill was still expected beneath the stockpile area.

Because of the very coarse fill size, any insitu testing in boreholes was meaningless for determining strength and modulus parameters of the fill. Ideally, large scale monitored surcharge testing would have been the best way to determine the settlement properties of the fill, but the design period and budget was insufficient to allow this. Instead, the settlement records from the slag stockpile incident and the approximate depth of fill as indicated by the nearest borehole, were used to back-calculate the drained modulus of the fill at 10 MPa.

The estimated drained modulus of 10 MPa gave a settlement under the centre third of the proposed stockpile of 150mm. However, it was recognised that because of the site variability and low confidence in the modulus estimate, actual maximum settlements could be anywhere in the range from 70 to 300mm. It was considered that almost all settlement would occur within a short period after loading because of the free draining nature of the fill. There was also some potential for additional settlement as a result of cyclic loading and unloading.

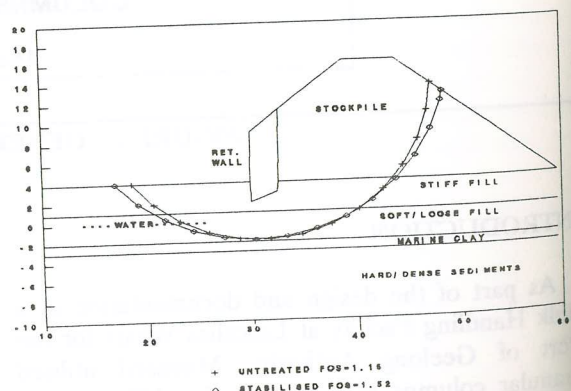


FIGURE 2 - STABILITY ANALYSIS

It was necessary to minimise settlements, to avoid distress to the raked piles beneath the stockpile, to ensure washdown water did not pond on the pavement, and to ensure smooth operation of the loaders. On the basis of these considerations, stabilisation aimed to approximately halve the settlements under stockpile loading, so that using the worst estimates of settlement, not more than 150mm of

settlement would occur at any location.

Using the worst fill profile indicated by site investigations, stability analysis under undrained conditions indicated that factors of safety for stockpile failure beneath the retaining walls without ground improvement were unacceptably low (see Figure 2). Stabilisation of the fill and the firm marine clays was therefore required to improve the stability of the stockpile to an acceptable level.

#### CHOICE OF STABILISATION TECHNIQUE

During early discussions with stabilisation contractors, it became apparent that because of the variable and largely unknown properties of the reclamation fill, contractors would not be prepared to guarantee a level of performance from stabilised fill. It was therefore important to Maunsell as designers that the method of stabilisation used should be able to be well monitored for quality, and that the performance of the end product be verifiable.

Because most of the settlements were expected to occur within a short time after loading, surcharging of the surface in progressive stages up to the full stockpile load was arguably the most reliable method of reducing settlements. However the level of strength gain using this method could not be guaranteed to give an acceptably high factor of safety against instability. A tight construction program also required a stabilisation method which could be carried out during other construction works. It was considered that this could not be practically achieved with surcharging.

Dynamic compaction (falling weight surface compaction), could have been used to densify the upper granular soils but was expected to have minimal effect on the granular soils below sea level and the clays due to damping effects. Since these were the soils which required the greatest amount of stabilisation, dynamic compaction was considered inappropriate.

Vibrocompaction (compaction of stone columns with a down hole vibrator) was a potentially acceptable method of compaction but there were doubts about whether vibrocompaction would be able to penetrate bigger cobbles and boulders in the fill. It was also considered to be relatively difficult to monitor the amount of improvement to the ground with this method. (Actually, recent developments in vibrocompaction equipment

could have addressed this second issue).

Grout injection may have improved the foundation conditions, but the highly voided fill may have required very large quantities of grout. It would also have been difficult to predict the amount of improvement which could be achieved.

Out of all the stabilisation techniques considered, down-hole hammer compacted granular columns were eventually chosen as the most suitable and economical technique for stabilising the ground at the site. The main advantages of this technique were that:

1. Down-hole hammering stood a relatively good chance of being able to penetrate large cobbles and boulders within the fill.
2. The method of installation, monitoring and testing ensured that the worst subsurface conditions received the greatest amount of stabilisation, and provided a means of extrapolating measured settlements to other locations.
3. Stabilisation could proceed concurrently with other construction work.
4. Both settlement and strength properties of the fill could be improved.

#### DESIGN OF GRANULAR COLUMNS

In the past, granular columns have mainly been used in marine clays and much of the available literature is for the design of granular column stabilisation of soft cohesive soils with a drained modulus of 1 to 2 MPa. The required modulus of the granular column materials is typically 20 times the modulus of the soil being stabilised, hence sand or poor quality rock fill are commonly used. The granular column is assumed to act both as a pile with a low axial crushing strength and as a vertical drain which increases the rate of consolidation.

In using granular columns to stabilise what is predominantly a loose rock fill, much higher modulus materials were required for the granular columns. Well graded, angular, basaltic crusher rock was eventually adopted. This was judged to have a modulus of approximately 10 times the modulus of the reclamation materials.

Because of the low ratio of moduli and the free draining nature of the reclamation fill, it was

believed that most of the benefit from the installation of granular columns would be through densification of the ground around columns rather than as a result of the columns behaving as piles. This theory was later demonstrated during construction when it was shown that the volume corresponding to surface ground heave was only 25% to 30% of the total volume of granular column rock added to the ground.

Granular columns of 600mm minimum diameter on an equilateral triangular grid spacing of 2.5 metres were adopted. This corresponds to a ground coverage by the columns of 5%. In fact average column diameters during construction were 700mm which is 7% of the ground area. Assuming that this additional volume of rock causes a corresponding reduction in the void ratio ( $e$ ) of the ground, an initially loose fill ( $e=0.7$ ) would be consolidated to a medium dense fill ( $e=0.6$ ). This increase in density was expected to approximately double the modulus of the reclamation fill and therefore halve settlements.

As a means of checking this predicted reduction in settlements, the method of analysis developed by Balaam et al (1977) was used. This method was developed for soft clay soils and the design charts use a modulus ratio of 20. A large degree of interpolation between design charts was therefore required. Nevertheless, this method also indicated that settlements would be approximately halved by the granular columns.

An important outcome from this method of analysis was that it could be shown that granular columns must extend to the full depth of the reclamation fill and firm marine clays to be efficient. Appropriate construction methods were therefore adopted to ensure that full penetration to a hard base was achieved in the majority of columns.

It was important that hard spots above the granular columns which may cause "mushrooming" in the block paver pavement surface were avoided. To reduce the potential for hard spots, the granular column rock fill was terminated 1.5 metres below the pavement surface, and a sand fill judged to be similar in stiffness to the upper reclamation fill was substituted in the top of the columns.

Stability analysis showed that the undrained strength of clay soils was critical to the design. By installing granular columns in these clays an angle of friction is added to the undrained strength of the clays. It was assumed that the

granular column rock fill had an angle of friction of  $45^\circ$ , occupied 5% of the area and picked up approximately 3 times the load intensity of the surrounding soil due to its higher modulus. From these assumptions it was calculated that an angle of friction of  $9^\circ$  is added to the undrained strength of the clay soils. Using this increased strength beneath the stockpile resulted in a similar critical surface to the unstabilised ground but with an acceptable factor of safety against instability (see Figure 2).

The compaction procedures adopted for installation of the granular columns were based on judgement and observation of performance during installation, since no theoretical design approach was possible or appropriate.

## CONSTRUCTION METHOD AND RECORDS

The method of granular column installation adopted is shown on Figure 3 and is summarised as follows:

1. A 500mm diameter steel tube with a plug of crusher rock is bottom driven with a drop hammer to a minimum penetration approximately corresponding to the base of the fill. Driving then continues using blows of known energy until a specified set is achieved which is calculated to result in the toe of the pile founding below the marine clays on dense/hard sediments.
2. The tube is pulled back and the plug of rock is driven to the base of the tube.
3. Charges of crusher rock with a volume of a  $0.17\text{m}^3$  are placed in the tube (equivalent to a loose lift of 900mm). The tube is then raised an amount which approximately equals the compacted height of the charge under the local ground conditions. The charge is then compacted by six blows of a drop hammer each with an energy of 9 tonne metre. This step is repeated until the column is formed. It is important during this step to raise the column level as quickly as possible so that inflow of water does not cause the hammer to become submerged.
4. 1.5 metres below the finished ground surface placement of rock is stopped, a geotextile disk is placed on the top of the column and lightly compacted sand is placed up to ground level.

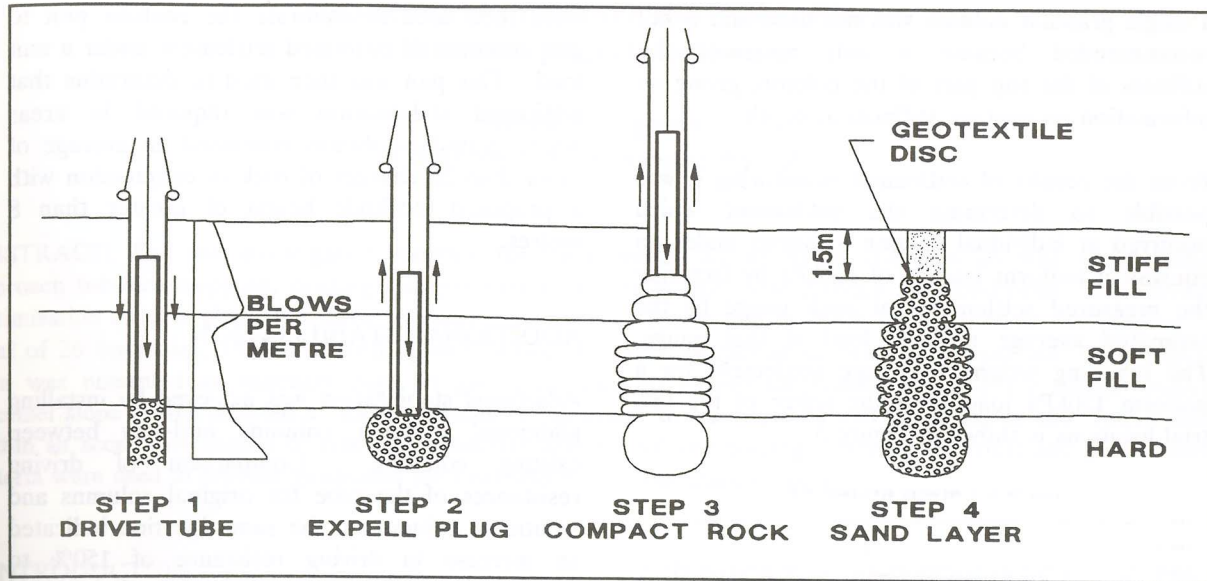


FIGURE 3 - COLUMN INSTALLATION METHOD

As a result of early monitoring of the column installation, The above procedure was modified in two ways:

1. Monitoring showed that the rate of heave in the ground surface rapidly increased towards the top of the column. To prevent unnecessary heaving of the ground surface, the amount of compactive effort was halved in the top 3 metres of the column.
2. In the softest ground conditions, applying the full specified compactive energy to the charge sometimes resulted in very large column diameters (greater than 1 metre). A practical limit corresponding to 800mm diameter (300mm lift per charge) was therefore adopted and the actual numbers of blows required to produce this lift recorded.

Installation records for each granular column included average set of the tube per blow versus depth during driving, and both the tube lift and the number of compacting blows for each charge of rock during extraction. A graphical presentation of the information available for a typical column in one of the worst areas is shown in Figure 4.

#### INTERPRETATION OF CONSTRUCTION RECORDS AND SETTLEMENT TRIALS

As part of the construction program, two large scale load trials were performed on the granular column stabilised reclamation. The load trials were positioned at locations which were expected

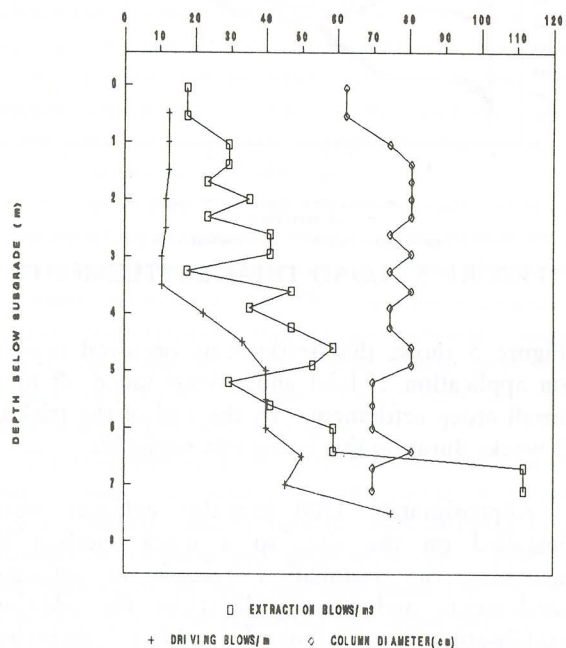


FIGURE 4 - INSTALLATION RECORDS

to correspond to the worst and best fill conditions as interpreted from the boreholes.

The trial load areas measured 15x15 metres square and were loaded with a pyramid of surcharge fill equivalent to about 40% of the full design load. Hydraulic settlement gauges capable of measuring settlements from the commencement of fill placement were installed at several locations on the surface of the trial area both on top of columns and in between.

It should be noted that the method of test loading

a single granular column was not used and is not recommended because it only measures the stiffness of the top part of the column, giving no information on average stiffness at depth.

From the results of settlement monitoring it was possible to determine the settlement which occurred at individual column locations under an equivalent uniform loading of 130kPa by factoring the measured settlements at each gauge by the estimated average uniform load at that gauge. The resulting weighted average settlement for a uniform 130kPa loading at the softer of the two trial locations is shown in Figure 5.

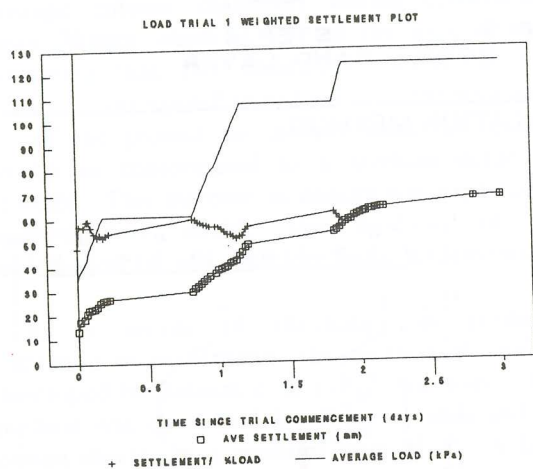


FIGURE 5 - LOAD TRIAL SETTLEMENTS

Figure 5 shows that settlements occurred rapidly on application of load and quickly tailed off to a small creep settlement. By the end of the trial at 3 weeks duration this creep was negligible.

Approximately 1200 granular columns were installed on the site, so a quick method of assessing the installation records to estimate settlements and identify locations for addition stabilisation was required. After comparing several analysis methods with the measured settlements from the load trials, it was concluded that the quantity rock fill added to individual granular columns was the best indicator of the relative magnitudes of total settlement at a column location. The reason why this correlation works is that greater depths of fill require more rock fill and result in higher settlements for the same fill modulus, while lower modulus ground results in a larger diameter granular column which also requires more rock fill.

To assist in interpretation of the granular column data, a contour plot of number of charges of rock fill added at each column was produced. Observed settlements from the settlement trials

were then used to calibrate the contour plot to give contours of estimated settlement under a unit load. This plot was then used to determine that additional stabilisation was required in areas where granular columns contained an average of more than 20 charges of rock in conjunction with a proposed stockpile height of greater than 8 metres.

#### ADDITIONAL STABILISATION

Additional stabilisation was achieved by installing additional granular columns mid-way between existing columns. Comparison of driving resistances of the tube for original columns and additional columns at the same location indicated an increase in driving resistance of 150% to 200%. This tends to confirm that the ground between the granular columns was substantially densified by the granular columns.

#### IN SERVICE PERFORMANCE

Since being commissioned in March 1993, the Bulk Handling Facility has been filled to capacity twice. There has been no apparent mushrooming of the pavement, and drainage slopes have been maintained. Survey of the pavement to determine the maximum settlements which have occurred has not yet been carried out.

#### CONCLUSION

Even in relatively high modulus materials such as loose rock fill, granular columns provide a useful method of densifying, and thus stabilising the soil. It is important to note that the key to successful design of granular column stabilisation of a variable site, where design parameters can largely only be estimated, lies not in rigorous analysis but in a well thought out method of construction monitoring, field trials and interpretation of results.

The Port of Geelong Authority is gratefully acknowledged for giving their permission for publication of this paper.

#### REFERENCES

- Balaam Poulos & Brown (1977), "Settlement Analysis of Soft Clays Reinforced with Granular Piles", Proc. 5th S.E.Asian Conference on Soil Engineering, Bangkok, pp 81-92.