Piled wall displacements at East Arm wharf extension

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ABSTRACT

The extension to the common user wharf at the East Arm Port, Darwin was carried out in 2003. During construction, displacements of the piled wall and the deadman were measured. Lateral displacements at the later stages of construction exceeded those expected, and the relative movements of the piled wall and the deadman showed an unexpected pattern. The results of finite element analyses of the system were only partly successful in explaining the magnitude of the displacements. It was necessary to include the effects of sag in the tie rods resulting from the backfill settlement in order to explain the observed behaviour.

1.0 DESIGN AND CONSTRUCTION

The extension comprises a 110 m long piled wall, supported by tie rods attached to a continuous deadman and backfilled with granular material. The design seabed level is at about RL –18 m and the finished design surface level is at RL 5.5 m.

A section through the wharf showing the main elements and the construction stages considered here is shown in Figure 1. The main section of the wall is made up of 1500 mm diameter steel tube piles driven to toe levels of about RL –29 m in variably weathered phyllite. The piles are spaced at 2.160 m centres with single sheet piles between. Two tie rods (upper and lower) are attached to each pile and extend to the deadman. The deadman comprises a segmented concrete wall 3000 mm high and 750 mm thick founded at about RL -1 m.

The construction sequence may be simplified as:

1. Trim the existing bund and install the soldier piles and sheet piles.
2. Place loose backfill to RL –10 m against the piled wall extending to RL –1 m on the landward side and place compacted backfill to RL 0 m.
3. Install deadman founded at RL –1 m.
4. Install lower tie rods, using temporary beams to support them over the gap in front of the piled wall.
5. Place compacted rockfill to RL 3 m, extending 13 m in front of the deadman, and tension the tie rods.
6. Place backfill behind the deadman and place rockfill to RL 0 m against the piled wall.
7. Remove the tie rod supports and place backfill to RL 4 m.

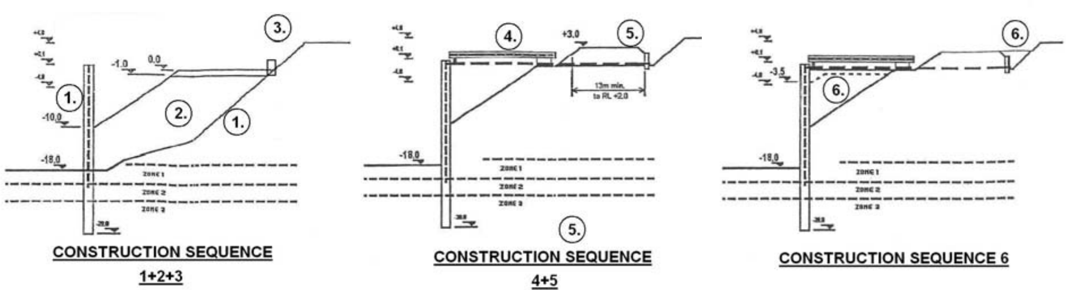

Figure 1 - Construction sequence of piled wall

The granular backfill placed up to RL 0 m was dumped under water, but because of concerns about the low densities achieved, vibroflotation was carried out. Following this compaction, up to 2 m settlement was observed. Activities subsequent to Stage 7 to complete the wharf (including installation of the upper tie rods) are not considered in this paper.

2.0 DISPLACEMENTS OF PILE WALL

Figure 2 shows a history of lateral displacement with time for Piles P14 to P16 and the adjacent deadman. Similar results were obtained along the length of the wall. Also shown on Figure 2 are the timing of key construction events: backfilling to RL –10 m behind the wall (Stage 2); tensioning of the tie rods (Stage 5): vibroflotation (Stage 7). In all the figures, a negative value of displacement indicates seaward movement and a positive value landward (toward the deadman).

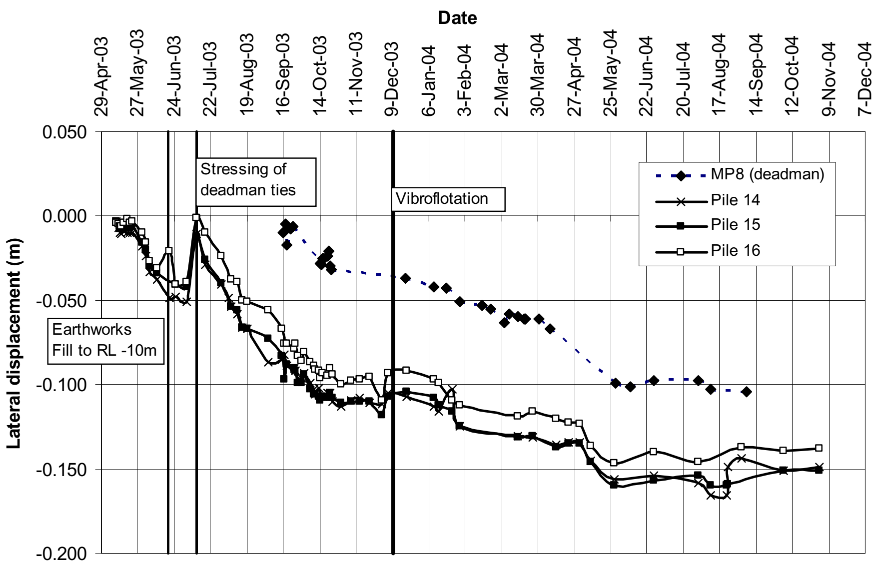

Figure 2 – Lateral displacement at top of piles P14 to P16 and at adjacent deadman

The data such as shown in Figure 2 have been used to calculate the change in lateral displacement of the piled wall in relation to the key construction events, some of which are discussed here.

Figure 3 show the variation in lateral displacement of the tops of the piles measured prior to tensioning of the tie rods. All values show seaward movement generally between –30 mm and –50 mm. Using published values (Long, 2001), lateral displacement of about 0.5% of the retained height (about –40 mm with a range from say – 20 mm to – 60 mm) At this stage, the measured displacements were within the expected range.

Following tensioning of the tie rods, all the piles showed positive (landward) movement, in the ranges 20 mm to 40 mm (piles P1 to P28) or 40 mm to 60 mm (P33 to P50). The differences probably arose from variations in the actual value of prestress (between 90 kN and 140 kN per pile), bund wall batter profile and backfill density (and hence deformation properties).

Figure 4 shows lateral displacements measured in the period between tensioning of the tie rods and compaction of the backfill by vibroflotation. The values all show seaward movement, decreasing regularly from about –100 mm at piles P5 to P15 to about –40 mm at piles P34 to P50. During this period, construction activities included filling from RL –10 m to RL 0 m, removal of vertical support to the tie rods, and possibly some surcharging above RL 0 m.

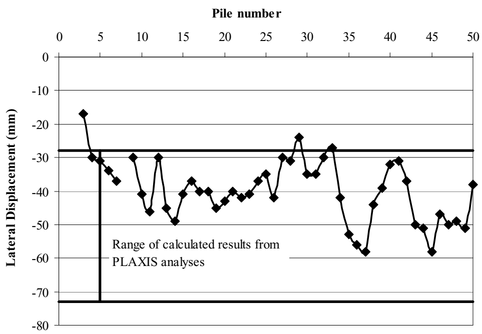

Figure 3 – Measured and calculated lateral displacements at top of piles prior to tensioning of tie rods

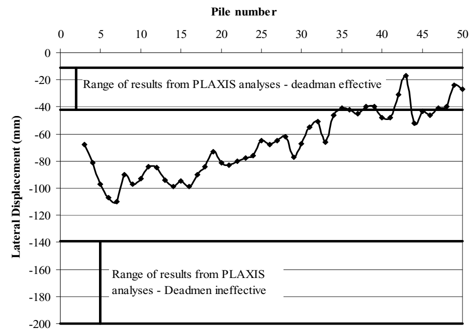

Figure 4 – Measured and calculated lateral displacement at top of piles from post tensioning of ties to vibroflotation

3.0 DISPLACEMENTS OF DEADMAN

Displacements of the deadman were not measured until sometime after stressing of the tie rods. Nevertheless Figure 2 clearly indicates that the trend of lateral displacements of the piled wall and deadman are similar which indicates the piled wall lateral displacements may be linked to the lateral displacements of the deadman.

Figure 5 shows the measured lateral displacements of deadman relative to the piled wall, with a clear trend of the deadman moving seaward relative to the piled wall. This behaviour is contrary to expectations for the piled wall performing as designed since it would be expected that during the period following tensioning of the lower tie rods the piled wall would displace seaward more than the deadman. Vibroflotation was carried out in the backfill between piles P3 to P41 early in December 2003. Prior to this date, Figure 5 indicates that the deadman moved seaward relative to the piled wall by up to about 35 mm. Following this, to about the end of February 2004, the distance between the piled wall and deadman remained relatively constant. After about the end of February 2004, the deadman once again moved seaward relative to the piled wall.

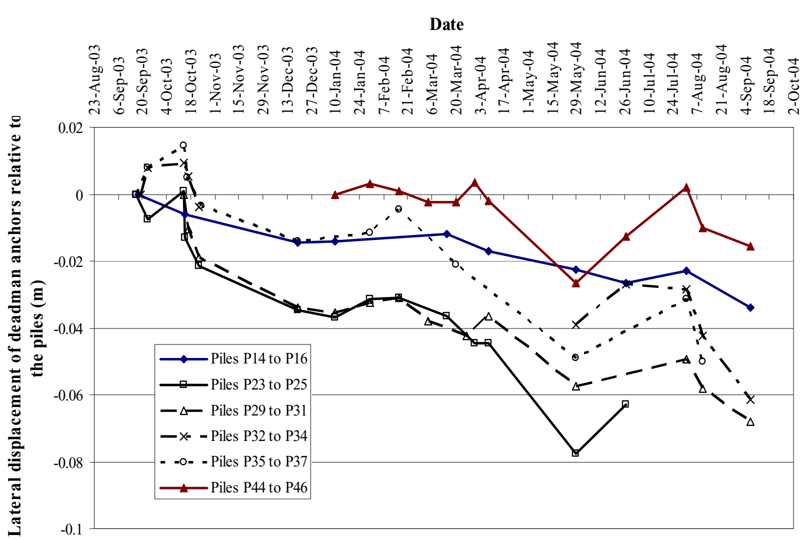

Figure 5 – Measured lateral displacement of deadman anchors relative to the piles

4.0 FINITE ELEMENT ANALYSES OF PILED WALL

4.1 Method and properties

Finite element modelling using the computer program PLAXIS was carried out to assess the expected performance of the piled wall during construction. By following the construction sequence, PLAXIS is able to provide estimates of stresses and displacements of the backfill, piled wall and deadman during construction of the wall. Analyses were performed for "As-Designed" properties and for properties "As-Constructed". The latter analyses were based on actual dredge and bund profiles and an estimate of densities and stiffness of the backfill, supported by field measurements. The significant inputs are summarised below.

(i) Loose backfill was assumed to have a bulk unit weight of 20.2 kN/m3, and a Youngs modulus in the range 10 MPa to 15 MPa.
(ii) The as-measured dredge profile of the bund wall was adopted.
(iii) High and low tide levels were considered.
(iv) The temporary support beam for the tie rods was included, although it had little influence on the results.
(v) The tie rods were stressed to 90 kN, 110 kN and 140 kN.
(vi) The vibroflotation process was modelled after filling to RL 0 m (Stage 7) by reducing the level of backfill from RL 0 m to RL -2 m and increasing the backfill unit weight to 21.35 kN/m^3. An additional 2 m of backfill with unit weight of 20.2 kN/m^3 was then added to bring the backfill level back to RL 0 m.

The effect of the sagging tie rods on wall performance could not be assessed using the finite element models. However, an approach to assess the impact of sag of the tie rods on the displacement of the piled wall and deadman is given in Section 6.

4.2 Results

The results of the analyses for a range of properties and inputs are indicated in Figure 3 (typical) and Figure 4 (the exception).

Figure 3 indicates that reasonable agreement between estimated and measured displacements of the pile wall is obtained prior to tensioning of tie rods (and both after tensioning of tie rods and after vibroflotation; in results not included here).

Figure 4 shows no agreement for the period following tensioning of the tie rods up to vibroflotation. The measured displacements of the piled wall at the eastern end during this period are more than twice those estimated using the range of assumed backfill properties (from loose to dense) and other conditions. This applies whether the deadman is considered as fully effective or totally ineffective (no restraint).

The calculated load in the tie rods for the "As-Constructed" analyses at the end of model construction Stage 7 range from 148 kN/m to 193 kN/m at high tide and from 191 kN/m and 235 kN/m at low tide. The higher values were obtained for an initial prestress of 140 kN per tie rod, and the lower values for an initial prestress of 90 kN per tie rod.

5.0 FINITE ELEMENT ANALYSES OF DEADMAN

PLAXIS was also used to calculate the load versus displacement performance of the deadman at the end of model construction Stage 7 for a range of backfill and geometric properties. The results are shown in Figure 6. Depending on the properties of the backfill in front of the deadman, the calculated capacity of the deadman at Stage 7 varies between about 350 kN/m and 550 kN/m. All values are quoted for a 2.16 m length of deadman, the tie rod spacing. Deadman capacity is achieved at lateral displacements varying from about 50 mm to about 100 mm. These values agree with the capacities estimated using conventional methods of analysis.

The above analyses are only appropriate for conditions at high tide for the period following stressing of the tie rods and before vibroflotation. During this period, displacements of the piled wall of up to 110 mm were measured. Hence by comparing the results from finite element analyses with actual performance, it would appear that the deadman must have been close to or at yield during this period of construction on the basis of the measured displacements. It implies also that the load applied to the deadman must have approached or exceeded the calculated values of 350 kN/m to 550 kN/m. This is a significantly higher tie rod tension than the 148 kN/m to 188 kN/m calculated by the finite element model for the end of construction Stage 7.

The deadman capacity of 350 kN/m to 550 kN/m assumes backfill in front of the deadman had been completed to the design level of RL 3m. However there are indications that in some areas the backfill in front of the deadman was lower, reducing its capacity.

In conjunction with the earlier analyses, it was concluded that settlement of the backfill which led to sagging of the tie rods provided a plausible mechanism by which the load in the tie rods could increase from around 150 kN/m to in excess of 350 kN/m and as a consequence cause yield of the deadman and increased lateral displacement of the piled wall. Sagging of the tie rods also explains the observed seaward displacement of the deadman relative to the piled wall which conflicts with the results of the PLAXIS modelling.

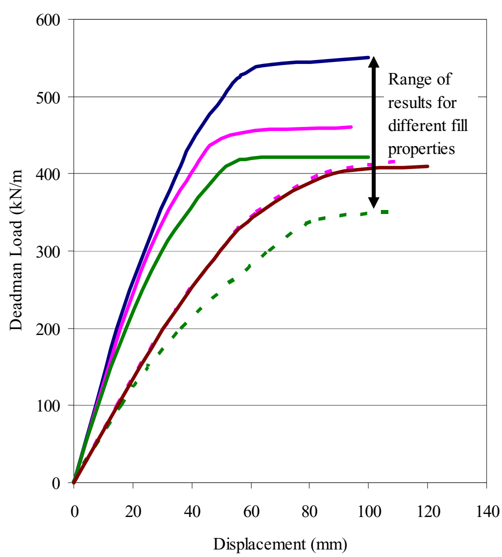

Figure 6 – Calculated deadman load versus displacement performance

6.0 EFFECT OF SAG IN TIE RODS

Consider the wall at construction Stage 7 following completion of backfilling to RL 0 m, but prior to removal of the tie rod supports. At this stage, the PLAXIS modelling indicates a tension in the tie rods at high tide of between 148 kN/m and 188 kN/m. At the same stage, and for the same material properties, the deadman capacity is calculated to be 415 kN/m (one of the cases in Figure 6). Following the removal of the tie rod supports (after completion of filling to RL 0 m), settlement of the backfill occurred which resulted in observed sagging of the tie rods in the order of 500 mm.

It is possible to calculate the lateral displacement of the piled wall and deadman as a function of sag of the tie rods. The load deformation response of the deadman and of the piled wall was calculated from the PLAXIS analysis. The forces imparted into cables by sag under uniformly distributed loading were calculated from published equations (Megson, 1996). The results are shown in Figure 7 for the lateral displacement of the piled wall and deadman as a function of the tie rod sag. Figure 8 shows the calculated relative displacement of the deadman with respect to the piled wall as a function of tie rod sag.

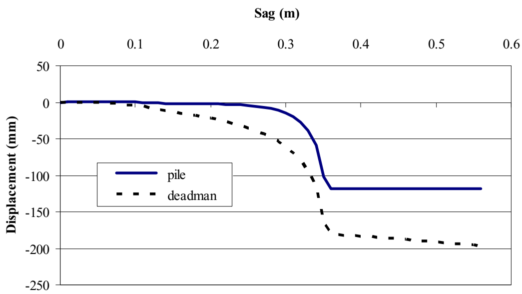

Figure 7 – Calculated displacement of piles and deadman anchors with sag

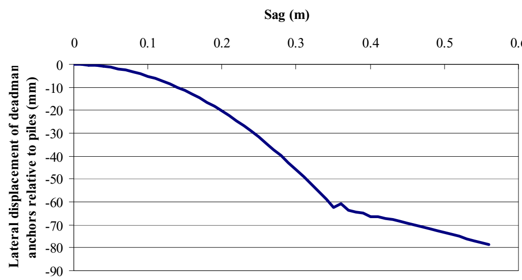

Figure 8 – Calculated relative displacement of piles and deadman achors with sag

Figure 7 indicates that for the range of potential properties of the backfill, to achieve the observed lateral displacements of the piled wall (80 mm to 100 mm for the period between tensioning of the tie rods to vibroflotation), would require the tie rods to sag about 325 mm to 420 mm over the same period which is well within the range of observed displacements.

The calculated displacements of the deadman relative to the piled wall shown in Figure 8 appear to be reasonably consistent with the measured values shown in Figure 5. Monitoring of the deadman displacements at the eastern end of the wharf (opposite Piles P5 to P30) did not occur until about 2 months after stressing of the tie rods. The relative displacements shown in Figure 5 are therefore likely to be lower than actual total relative displacements of the deadman and piled wall.

7.0 CONCLUSIONS

Displacements of the piled wall during most stages of construction were generally as expected from experience and published results. These displacements were also in the range of those calculated by the PLAXIS finite element program using a range of input data.

The lateral displacements at the later stages of construction exceeded those expected, and also showed the piled wall and the deadman moved toward each other, an unexpected result. This result could not be modelled by the PLAXIS software. Calculations based on the forces induced by sag in the tie rods resulting from backfill settlement were able to explain the observed behaviour.

8.0 REFERENCES

Long, M. (2001). Database for retaining wall and ground displacements due to deep excavations. Journal of Geotechnical and Geoenvironmental; Engineering, ASCE, Vol.127 (3), pp 203-224.

Megson, T.H.G. (1996). Structural and Stress Analysis. Arnold, London.