Settlement of Precast Culverts Under High Fills; The Influence of Construction Sequence and Structural Effects of Longitudinal Strains

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Synopsis: The Morwell River in Victoria was diverted as part of a project associated with the Morwell Power Station. The diversion required the construction of four conveyor tunnels under high fills (up to 45 metres above base level), with varying foundation conditions.

Detailed finite element analyses of each conveyor were carried out before construction, to predict upper and lower bounds for the expected settlement, and maximum differential settlement. These analyses were used to preset the vertical alignment of the culverts, so that the conveyors would have close to a constant grade in the finished structures. The differential settlement predictions were also used to assess the effect of longitudinal strains on the culvert structure, and to size movement joints between culverts, and in the foundation raft slabs.

In this paper the predicted settlements are compared with actual measured values, and reasons for discrepancies between these values are investigated, including three dimensional effects. The effect of longitudinal differential settlement on the maximum stresses and joint movements calculated at design time are also compared with those due to the measured settlement.

Keywords: arch, culvert, settlement analysis, longitudinal strains, construction sequence

Introduction

The Morwell River in Victoria's Latrobe Valley was diverted to allow access to brown coal deposits to fuel the Morwell power station. Joint venture partners, Roche, Thiess and Linfox (RTL), won the tender for this project in October 2001, with an alternative design that significantly reduced the length of the diversion, but which carried the river over four coal conveyors on an embankment over 45 metres high. The main design requirements for the culverts required to carry the conveyors under the embankment were as follows:

- The maximum fill height was over 45 metres, over deep brown coal deposits, resulting in very large differential settlement over the length of the culvert.
- One end of the culvert was constructed over an area of uncompacted fill, potentially resulting in large rotations at the boundary of this zone.
- The maximum culvert length was 365 metres, with a total length over the four culverts of 1100 metres.
- Culvert erection was required to be possible with minimum disruption to the operation of the conveyors.
- The design and supply package included the design and supply of the pre-cast concrete arch and waterproofing system, and design of the in-situ concrete foundations.
- The design life is 50 years, with the possibility of zones of acid generating material in the backfill.

Detailed finite element analyses of the embankment at the conveyor locations were carried out to assess the effect of vertical and longitudinal ground strains on the culvert structures, and to ensure that joints had sufficient room for movement. It was also necessary to preset the conveyor vertical alignment, so that after all settlement the alignment was within specified limits.

Foundation Conditions

Figure 1 is a long section showing typical foundation conditions under the conveyors, consisting of over 200 metres depth of alternating brown coal and interseam layers, overlain by fill of variable compaction. At the west end of the project the toe of the embankment is supported by about 30 metres of poorly compacted fill, which transitions rapidly to a brown coal layer. Upper and lower bound stiffness parameters were considered in the design, based on geotechnical testing and the performance of trial embankments.

The soil stiffness and strength parameters used in the analyses are summarised in Table 1:

Table 1: Soil Strength and Stiffness Parameters

Material	*Internal Friction Angle*	*Cohesion*	*Density*	*Youngs Modulus (kPa)*		*Poissons Ratio*
	deg	*kPa*	*Tonne/m3*	*Min*	*Max*	
Embankment Fill	28	5	2.0	20	60	0.3
Select fill	36	0	2.0	*	*	*
Engineered fill	28	5	2.0	20	60	0.3
Dense fill	36	0	2.1	50	100	0.3
Cement treated base	0	500	2.2	1000	1000	0.3
In-situ fill - Upper	28	5	1.9	10	30	0.3
In-situ fill – Middle	28	0	1.8	4	10	0.1
In-situ fill - Lower	28	5	1.9	10	40	0.3
Coal	29	150	1.1	15	45	0.2
Interseam	23	16	1.9	30	90	0.2

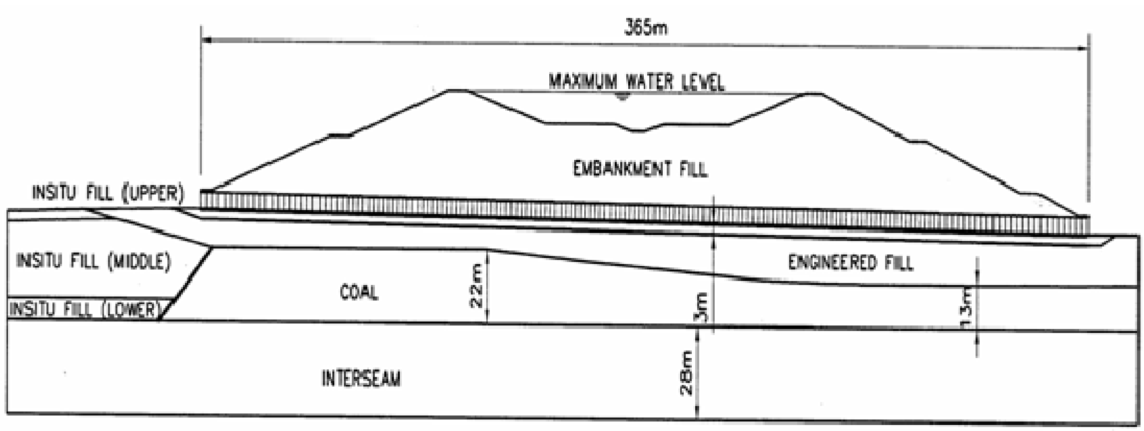

Figure 1. Geotechnical Long Section

Original Longitudinal Analysis

A detailed longitudinal analysis of the tunnels and embankment was required to assess the following effects:

- Differential settlement due to varying foundation conditions.
- Longitudinal strain of the arch and foundations due spreading of the underlying soils under the weight of the embankment.
- Longitudinal overturning loads on the arch segments due to the embankment slope.

The following design features were provided to accommodate longitudinal effects:

- Wide co-incident movement gaps in the arch and raft slabs at 12 metre intervals to allow for rotation and longitudinal strains.
- Intermediate joints in the longitudinal crown beam to the arch provided additional flexibility, whilst maintaining the stability of the arch to longitudinal forces.
- The vertical alignment of the arch was preset in the mid-range of the predicted settlements to avoid sags in the conveyor alignment after completion of settlement.

Independent 2D longitudinal analyses were carried out by Reinforced Earth, using Strand7, and by SMEC, using FLAC. Agreed lower and upper bound soil stiffness parameters were used, based on soil investigation reports, and settlement results from large trial embankments. Each section was analysed

using lower and upper bound stiffness values, to determine the likely range of settlement, and using maximum differential stiffness (i.e. maximum coal stiffness and minimum fill stiffness) to determine the maximum differential settlement. In addition Reinforced Earth carried out 3D analyses of the arch and raft slab to assess the effect of differential settlement and longitudinal strains on the structure.

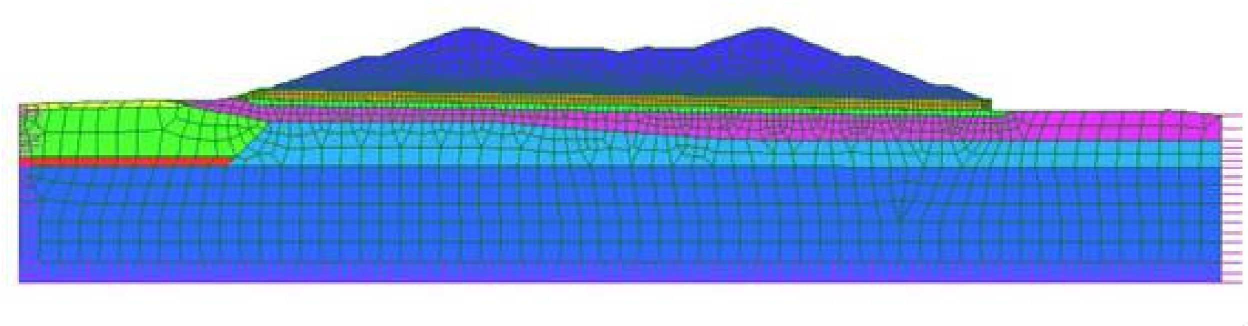

Figure 2 Original Longitudinal Finite Element Mesh

A typical finite element mesh for the longitudinal analysis is shown in Figure 2. The section analysed was adjacent to the conveyor tunnels, ignoring the stiffening effect of the structure. The soil elements at the level of the structure were modelled as rectangular elements with the same elevation dimensions as the precast arch panels. The soil strains at the corners of the elements were then extracted and used to calculate joint opening and closing, and stresses in the structure, assuming that all strains took place at the movement joints. Predicted and actual settlements are shown in Figures 3 to 6, showing the following data:

- The predicted settlement for maximum and minimum soil stiffness values.
- The mid-range predicted settlement
- The actual settlement at July 2006, approximately 4 years after the start of construction, and 2 years after completion of the embankment.

Measured Settlements

The conveyors are parallel, running approximately west-east with a spacing of 50 metres. The conveyors are designated 110 to 410 from north to south. The fill was built up in roughly horizontal layers, in effect working from south to north, since Conveyors 410 and 310 were significantly lower than the conveyors to the north (Figure 11). The vertical alignment of the four conveyors is shown in Figure 7.

The actual settlement profiles of the four conveyors, surveyed in Jul 2006, are shown in Figures 3 to 6, and the settlement of the tunnels over time under the two embankment high points is shown in Figure 8. Point 1 is under the west berm and Point 2 under the east.

Figures 3 to 6 show the conveyors from 410 to 110, in their order of backfill. It can be seen that there is good agreement between the mid-range predicted settlement and the actual settlement for Conveyor 410, but the conveyors that were constructed later have progressively reduced settlement, particularly at the eastern end.

A possible reason for the discrepancy between the predicted and measured settlements is that the filling operations for conveyors 410 and 310 caused significant settlement in the foundation layers under 210 and 110 before monitoring of these structures was started. In order to test this hypothesis a three dimensional settlement analysis of the embankment construction between all four conveyors was carried out, modelling the actual sequence of construction of the tunnels and the embankment.

Three Dimensional Settlement Analysis

Simplified 2D Analysis

In order to keep the 3D model to a manageable size it was necessary to greatly simplify the mesh. The mesh was created using the minimum number of elements that would give an acceptable representation of the embankment cross section and foundation layers. Since it was intended to use 20 node brick

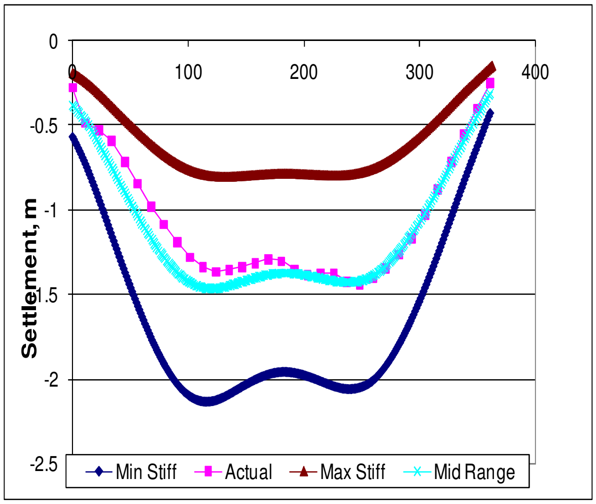

Figure 3. Conveyor 410

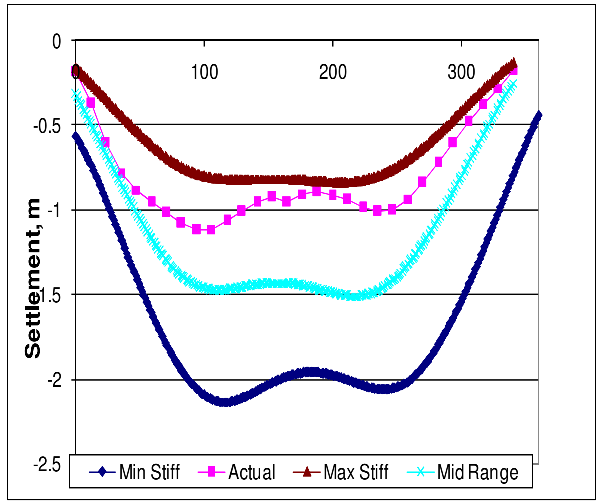

Figure 4. Conveyor 310

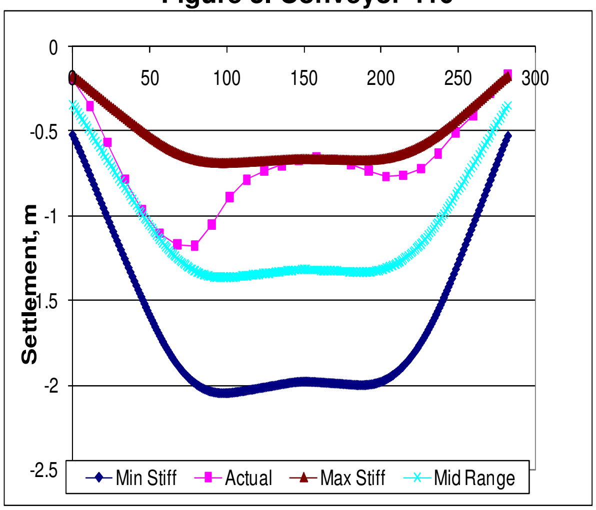

Figure 5. Conveyor 210

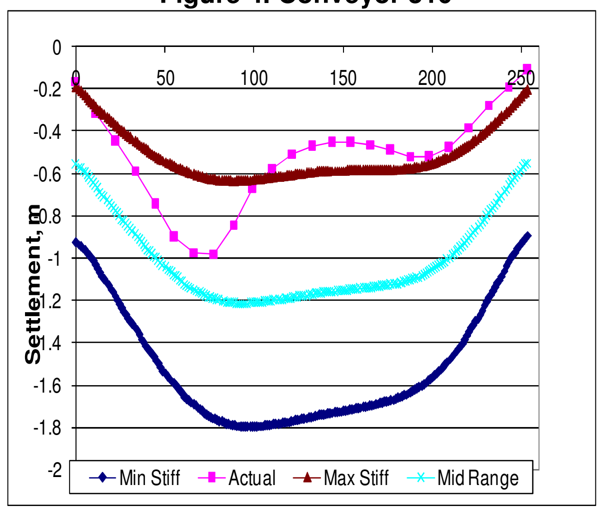

Figure 6. Conveyor 110

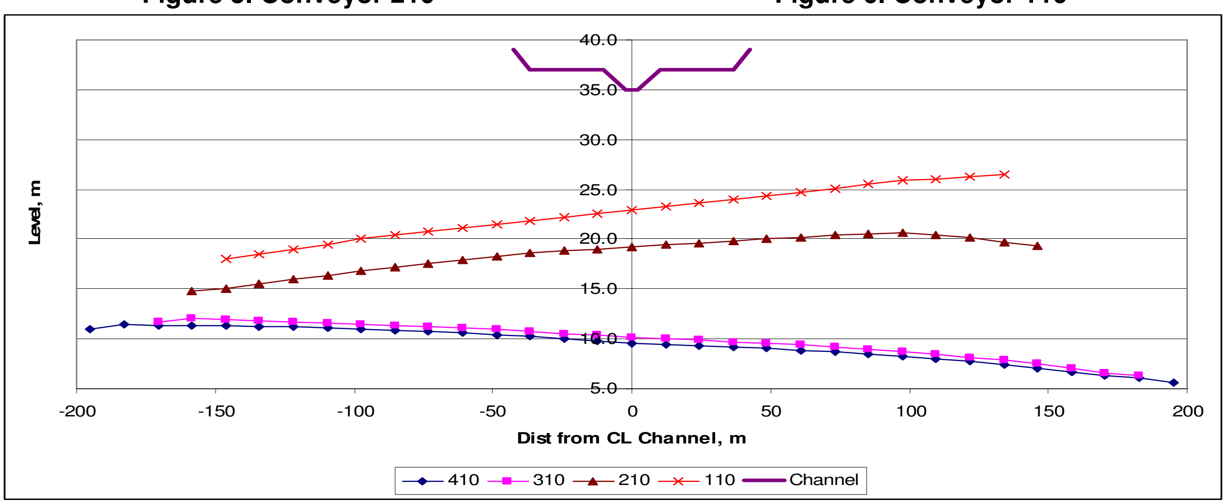

Figure 7: Conveyor Vertical Profiles

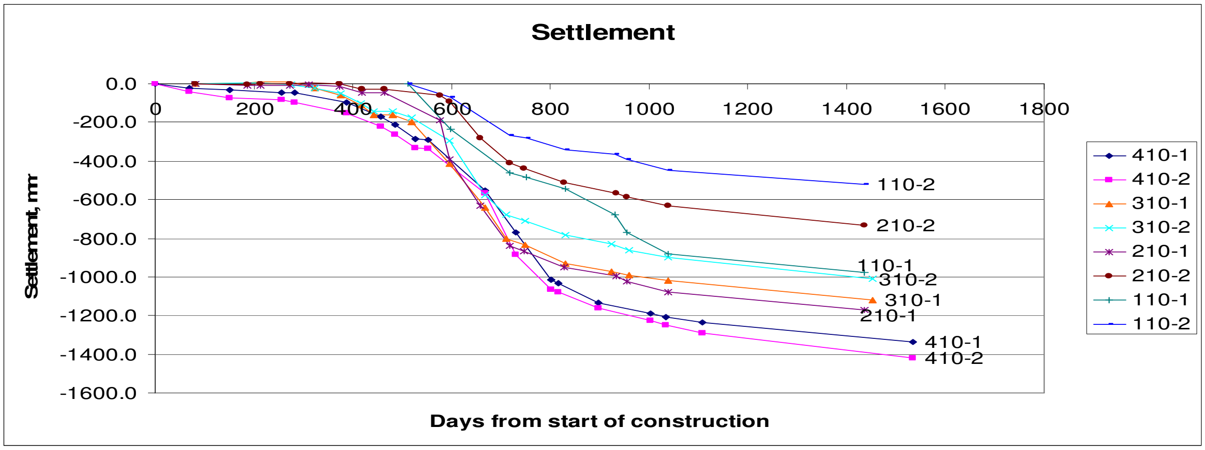

Figure 8: Measured Conveyor Settlement Over Time

elements for the 3D analysis, the four node plate elements were converted to 8 node elements in the simplified mesh. The number of nodes in the model was reduced from 6226 to 194. A 2D plane strain analysis was carried out for conveyor 410 using the simplified mesh (Figure 9), and the results compared with the original analysis (Figure 10).

The simplified mesh was found to give acceptable agreement with the original analysis, and this mesh was therefore used as the basis of the 3D analysis.

3D Analysis

Simplified 2D meshes were set up for each conveyor, and then combined in their correct positions in a 3D model. The plate elements were then used as a basis for constructing 20 node brick elements, after which the plate elements were deleted, forming the model shown in Figure 12. The model covers 600 metres in the X (east-west) direction, 130 metres in the Y (vertical) direction, and 250 metres in the Z (north-south) direction. The material properties used in the 3D analysis were the average of the upper and lower bound values used in the original analysis.

As for the 2D analysis, a staged analysis was carried out, with the first stage allowing the foundation layers to consolidate under their own weight, and subsequent stages modelling construction of the successive stages of the embankment. The analysis was carried out using Strand7, with an Excel spreadsheet controlling the stages of loading, through the Strand7 API. The model was extended to 50 metres past the centre line of conveyors 110 and 410 in the Z direction, and fixed in the Z direction along these planes; that is the embankment was treated as symmetrical about these planes.

Settlement Results

The final settlements predicted from the 3D analysis are compared with the measured settlements in Figures 13 to 16. It can be seen that the 3D analysis has predicted the reduction in settlement from south to north much better than the 2D analyses. Predictions for conveyors 410 and 310 were in reasonably good agreement with the measured values over the full length of the tunnel, and conveyor 210 was in good agreement at the east end. The measured settlements for conveyors 310 to 110 were increasingly asymmetrical, with significantly larger settlements at the west end. There is no obvious reason for this behaviour related to the construction method or sequence, and it is probably due to an area of poorly compacted fill in the existing ground. The assumed soil properties were the same for each layer in the analysis, so this feature has not been captured. Predicted settlements for conveyor 110 were significantly greater at the east end than those measured, and to a lesser extent predictions for conveyer 410 were too small. These errors can probably be attributed to boundary effects, since the extent of the model past the zone of interest in the Z direction (50 metres) was quite small compared with the overall width of the embankment (up to 400 metres).

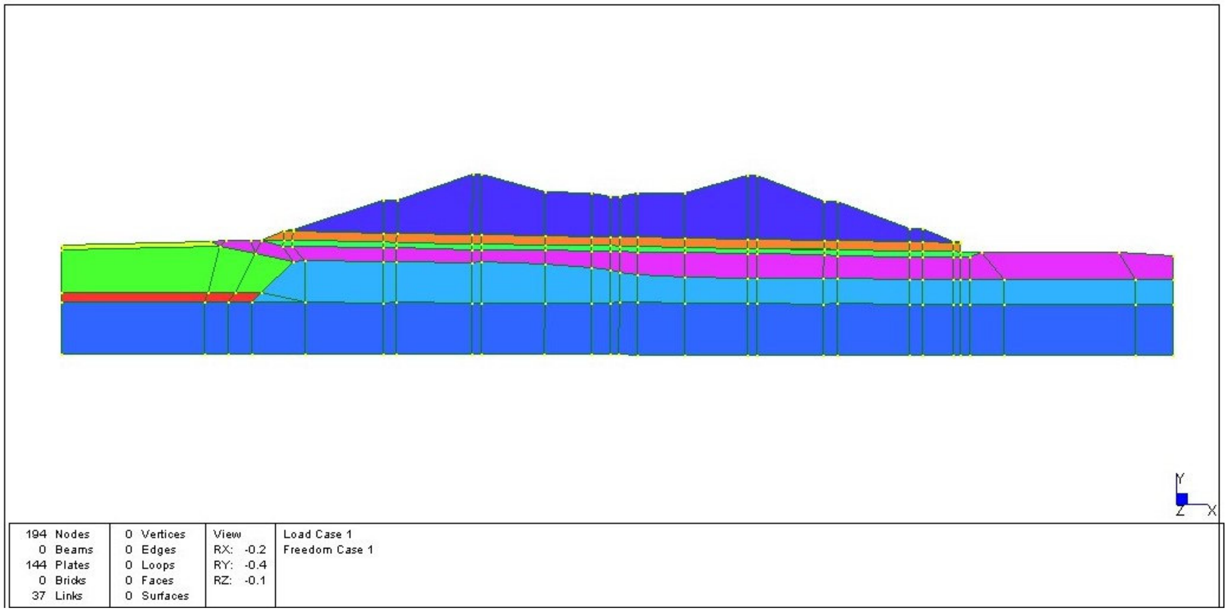

Figure 9: Simplified 2D Mesh for Conveyor 410

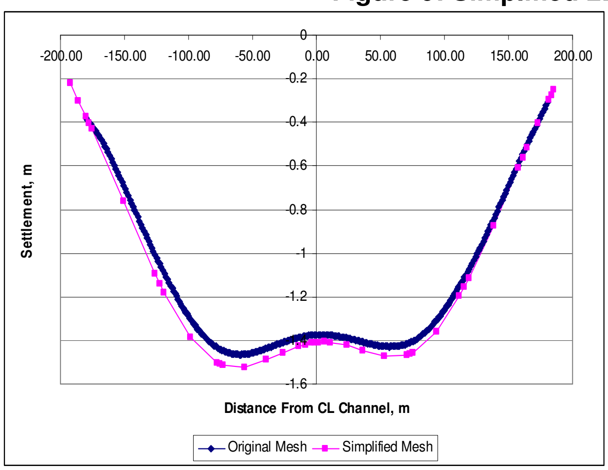

Figure 10: Settlement predictions for original and simplified mesh

Figure 11: Construction of Conveyors 210 (foreground), 310 and 410

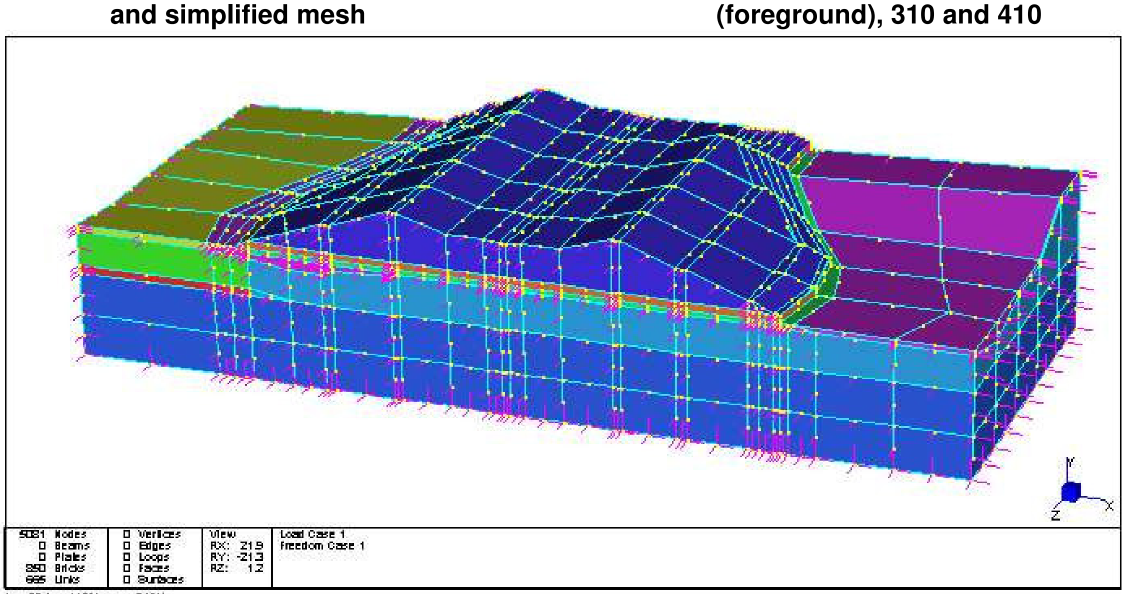

Figure 12: 3D Model

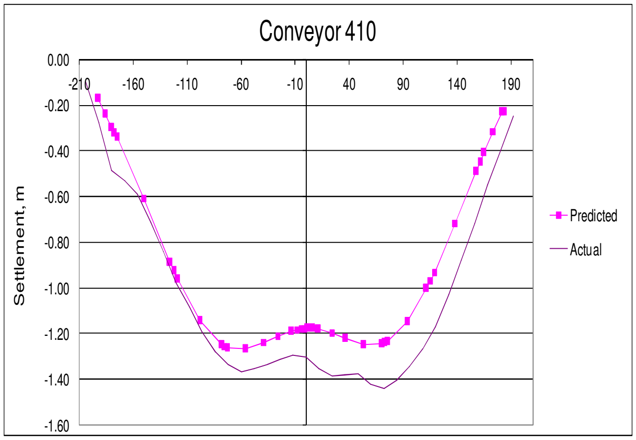

Figure 13. Conveyor 410

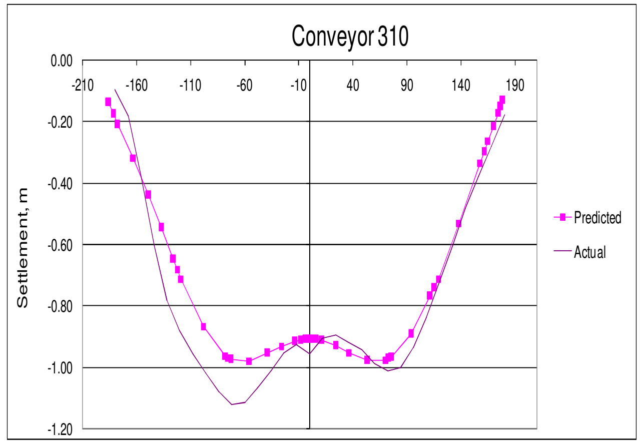

Figure 14. Conveyor 310

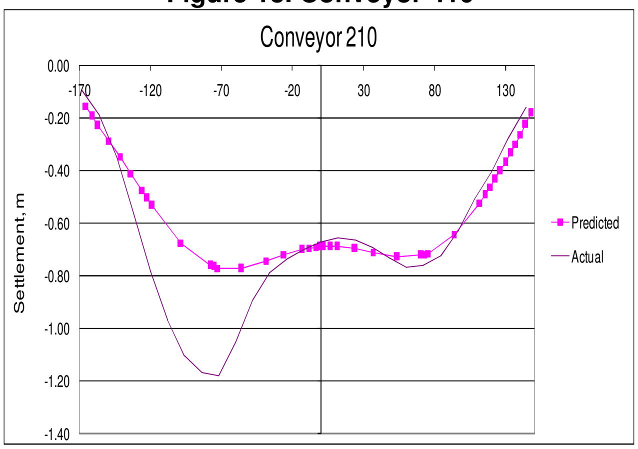

Figure 15. Conveyor 210

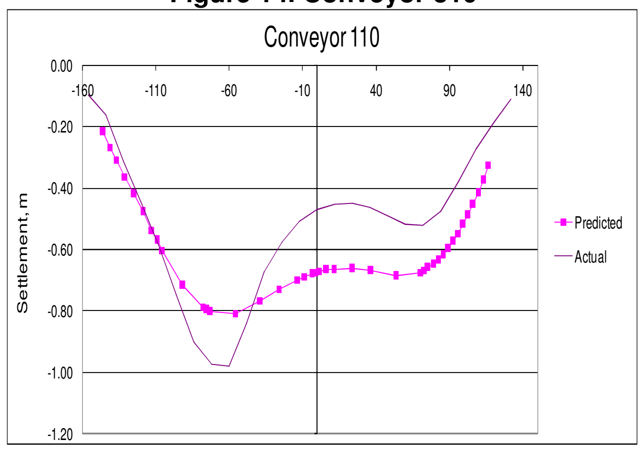

Figure 16. Conveyor 110

Improvements in the quality of the predictions could be achieved by further refining the 3D analysis:

- More detailed geotechnical data, particularly in areas of uncontrolled fill.
- Extending the model in the Z direction to reduce boundary effects.
- More detailed modelling of the construction sequence. In the analysis the fill to each conveyor was applied in one stage. Modelling the fill operations in layers, replicating the actual sequence, would result in a significantly better model of the stress history in the underlying soils.

Longitudinal Strain Results

Significant longitudinal strains occur in long buried structures due to a combination of longitudinal spreading of the material under the embankment with rotation due to differential settlement. Longitudinal strains were a particular concern on this project because of the high embankment, and the uncompacted fill at the west end, and for this reason the structure was provided with frequent movement joints with wide gaps. Figure 17 shows typical predicted horizontal deflections for Conveyor 410 at the level of the base of the tunnel from the original 2D analysis and from the 3D analysis. It can be seen that the predicted deflections are in good agreement, with the differences between the two analyses being similar to those for vertical settlement.

Measured longitudinal movements were not available, so in order to assess the likely magnitude of these movements, consistent with the actual vertical settlements, a 2D plane strain analysis was carried out, with back-analysed soil stiffness properties to replicate the actual vertical settlements as closely as possible. Conveyor 210 was used for this analysis, since this had the greatest curvature in the longitudinal profile due to vertical settlements.

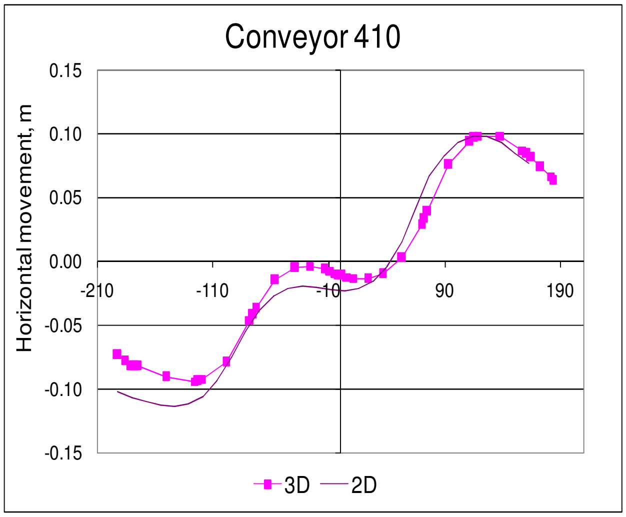

Figure 17 Conveyor 410 Horizontal movements from 2D and 3D analyses

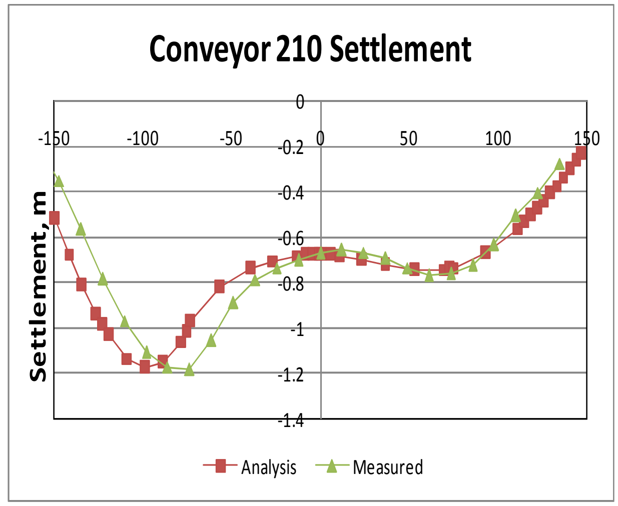

Figure 18 Conveyor 210 Settlement with adjusted stiffness parameters

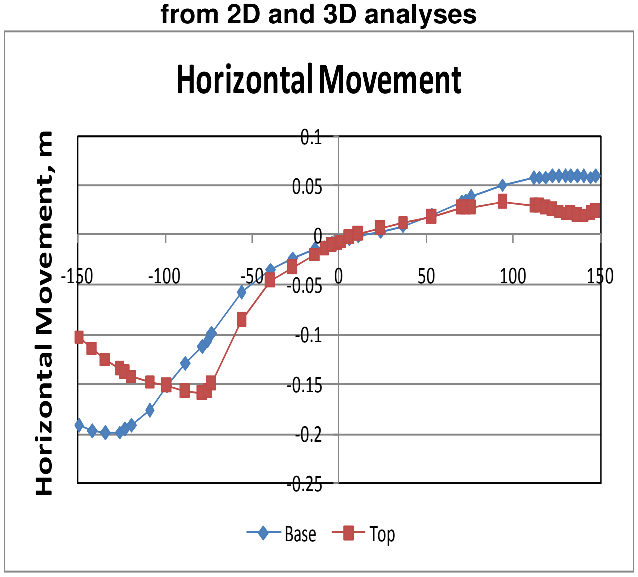

Figure 19 Conveyor 210 Horizontal movement

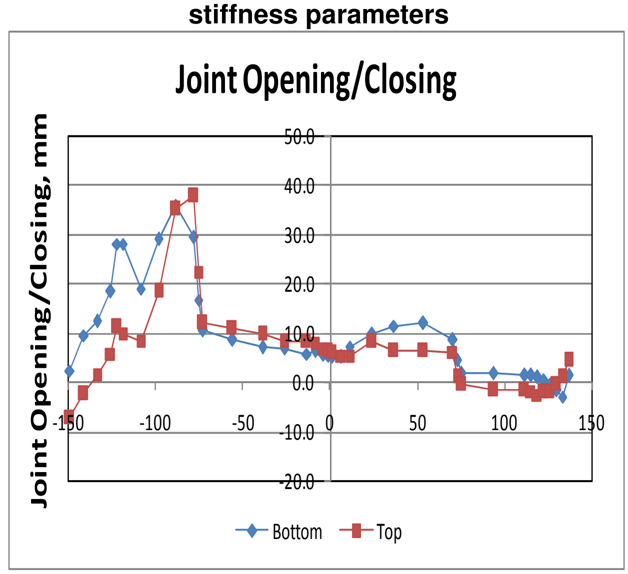

Figure 20 Conveyor 210 Joint Opening/Closing

The results of this analysis are shown in Figures 18 to 20. Figure 18 shows that the vertical settlements found in the revised analysis were in reasonable agreement with those measured in the actual structure. Horizontal movements from the analysis were up to 200 mm at the west end and 60 mm at the east end. Assuming that all the soil strain was concentrated at the movement joints the predicted joint movements ranged from 40 mm opening to 10 mm closing. This is consistent with the values found in the original analysis, and the joints provided allow for approximately double the predicted movement. Measured joint movements were not available at the time of writing the paper, but the predicted values are expected to be conservative because in the actual structure a significant proportion of the soil strain will be taken up by strain in the concrete between the joints, and the arch structure will provide significant stiffening to the embankment, which was not considered in the analysis.

In the original design analysis of the tunnels the maximum longitudinal strains determined from the plane strain analyses were applied to a 3D structural model of the arch and base slab, Jenkins(1), and the resulting stresses were found to be well within the design requirements. This analysis was not repeated, since the maximum longitudinal strains found in the new analyses were similar to those used in the original design.

Conclusions

Measured settlements of four conveyor tunnels under high embankments were found to be progressively different from the predictions of plane strain finite element analyses carried out for each conveyor.

Examination of the data suggested that the differences between the analyses and the site measurements might be partially due to three dimensional effects associated with the construction sequence of the embankment. A three dimensional finite element analysis was therefore carried out to model the construction sequence. The conclusions from this analysis were:

- Preliminary 2D plane strain analyses with a greatly simplified mesh gave good agreement with the original 2D analyses.
- The settlement results from the 3D analysis replicated the main features of the measured settlements at the eastern end of the tunnels, indicating that three dimensional effects did have a significant influence on the settlements.
- Higher settlements found at the western end of the tunnels were not replicated in the analysis. It was therefore concluded that this additional settlement was probably due to the zone of poorly compacted in-situ fill extending further under the embankment than had been assumed in the original analyses.
- Some discrepancies between the analysis results and the actual settlement were found for the southern and northern tunnels (410 and 110), and these are believed to be due to the effect of boundary conditions, since the limits of the model in the Z direction were comparatively close to these two tunnels.

In order to assess the effect on the tunnel structures of the actual soil movements in the longitudinal direction a plane strain analysis of Conveyor 210 was carried out with soil stiffness parameters back-adjusted to replicate the settlements actually measured on site. Maximum soil movements of up to 200 mm were found at the level of the tunnel, with up to 340 mm in the soil at lower levels.

The longitudinal soil strains from this analysis were assumed to be concentrated at the tunnel movement joints, and the resulting joint opening and closing was calculated. The maximum joint opening and closing values were found to be close to those found in the original analysis, and less than half of the provision for movement provided at the movement joints.

The large horizontal movement found at the western end of the tunnels illustrate the need to consider longitudinal effects in long buried structures, particularly those under high fills with soft foundations.

Acknowledgements

The authors wish to thank the joint venture partners for the project, Roche, Thiess and Linfox, and the project design engineers, SMEC Australia, for their permission to use the project related information in this paper, and their assistance with providing the conveyor settlement data.

References

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