

PIPE JACKING THROUGH A RAIL EMBANKMENT

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ABSTRACT

Pipe jacking through rail embankments inevitably causes ground movements during excavation and construction. Excessive ground movements can lead to embankment instability and rail track distortions which could result in train derailment. Therefore, ground and track movements must be closely monitored during construction in accordance with the respective rail authority standards and geotechnical assessment. This paper presents the project overview, construction method, prediction of ground movements associated with pipe jacking, track deformation design criteria and construction performance for the Gerringong Bypass Belinda Street Culvert where seven 1500mm diameter reinforced concrete pipes needed to be constructed beneath the existing South Coast Line railway embankment. Extensive instrumentation and real time monitoring were undertaken during construction to ensure safety of the rail operation. The measured ground movements were back analysed and the assumptions were calibrated for the prediction of future movements due to subsequent pipe jacking. A contingency plan was implemented to ensure that the settlement criteria and operational safety were met.

1 INTRODUCTION

The Gerringong Upgrade Project is part of the Princes Highway upgrade program which comprises 7.5km of four lane divided highway with a design speed of 100km/h. The project was awarded by the Roads and Maritime Services (RMS) to Fulton Hogan to design and construct the project with SMEC Australia as the Principal Consultant. As part of the upgrade, Fulton Hogan constructed a culvert located under the proposed highway alignment, running from a diversion channel on the west of the Princes Highway, crossing under the South Coast Railway Line and discharging into the south east.

The Gerringong Bypass Belinda Street Culvert (Culvert C4480) is the crossing under the South Coast Railway Line and consists of seven 1500mm diameter (1800mm external diameter) reinforced concrete pipes constructed beneath the existing railway embankment in order to provide additional flood immunity in the area. The pipes were spaced at a nominal separation distance of 2604mm centre to centre with a nominal horizontal clearance of approximately 800mm between adjacent pipes. The distance from the top of the embankment to pipe axis level was approximately 6.4m. The pipes were excavated through Fill and Alluvium consisting of sandy and silty clay. Figures 1 and 2 show various cross sections of the works.

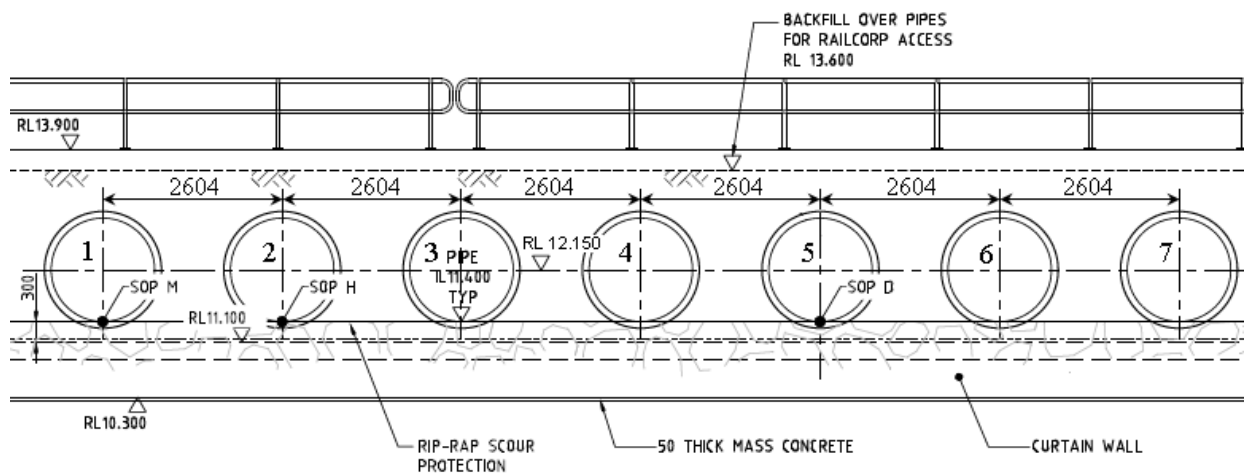


Figure 1: Gerringong Bypass Belinda Street Culvert C4480 finished cross section at embankment toe.

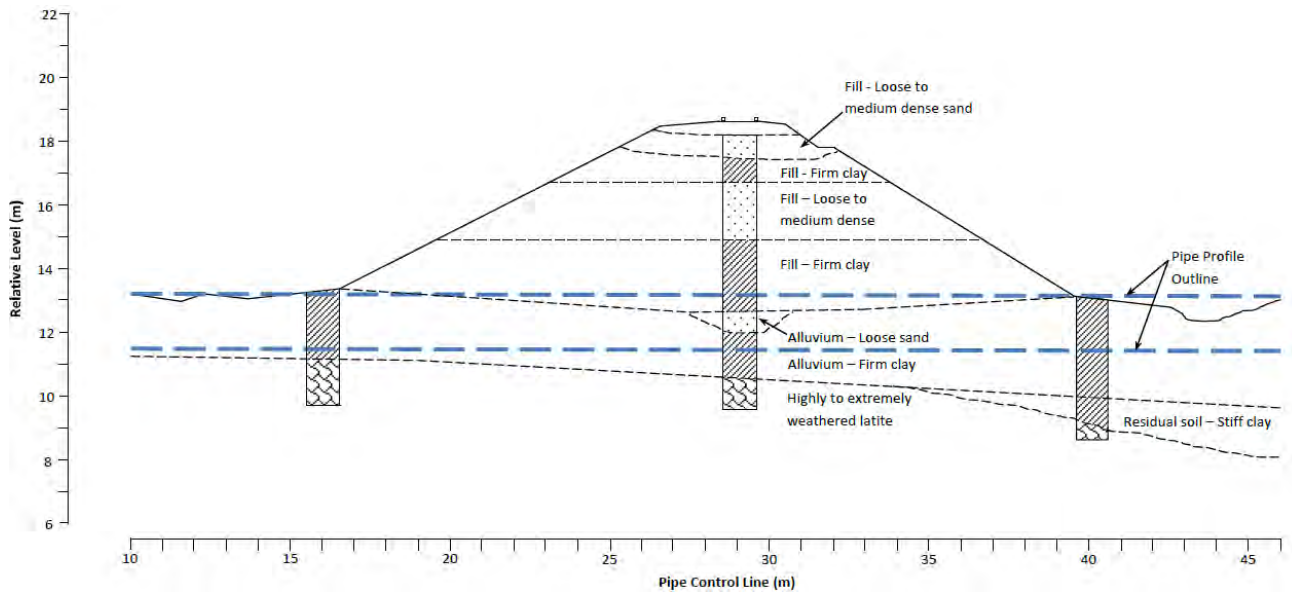


Figure 2: Gerringong Bypass Belinda Street Culvert C4480 embankment cross section.

The installation of the new set of pipes was undertaken by jacking pipes through the embankment so as to minimise disruption to the operation of the railway line. Bothar Boring & Tunnelling carried out the excavation and installation of the pipe underbores as the subcontractor for Fulton Hogan. The pipe jacking operation commenced in May 2013 and was completed in September 2013. Figure 3 shows the culvert alignment plan.

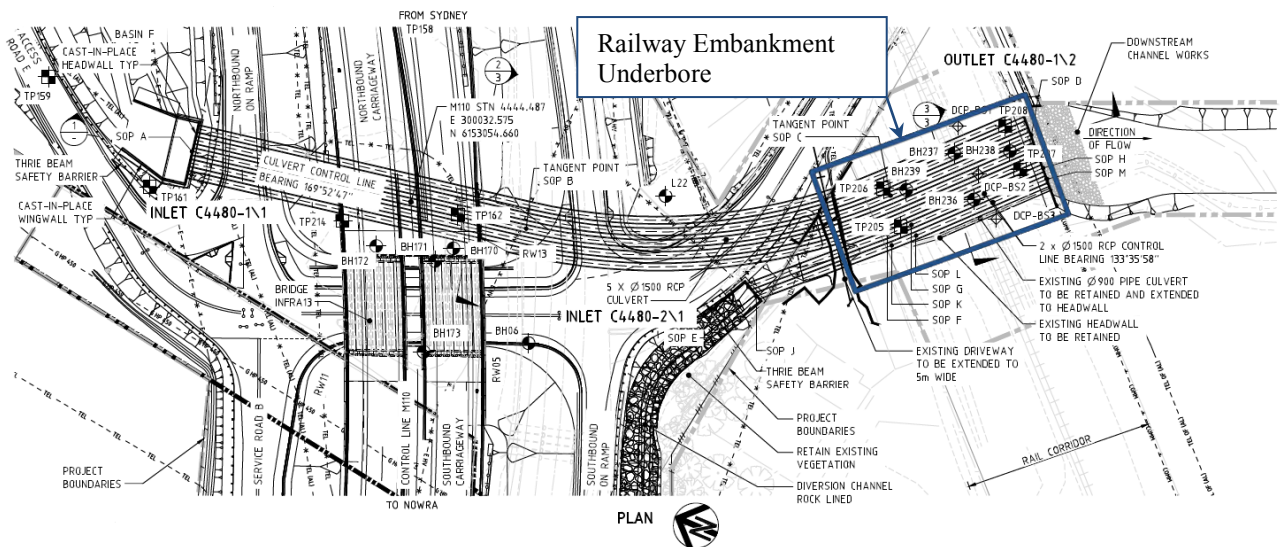


Figure 3: Gerringong Bypass Belinda Street Culvert C4480 alignment plan.

Construction of pipes through live railway embankments using trenchless construction methods such as pipe jacking is common. Tunnelling through rail embankments inevitably causes ground movements. This can lead to embankment instability and rail track deformations which could impair track performance. Therefore, embankment ground movements must be strictly monitored and suitable mitigation measures set in place in accordance with the respective rail authority standards and geotechnical assessment.

This paper presents the project overview, construction method, prediction of ground movements associated with pipe jacking, track deformation design criteria and construction performance for the Gerringong Bypass Belinda Street Culvert. Extensive instrumentation and real time monitoring of the track and embankment were undertaken by Lynton Surveys during construction to ensure safety of the rail operation in accordance with RailCorp Standards. The measured ground movements were back analysed and parameters were calibrated for the prediction of future movements due to subsequent pipe jacking. A contingency plan was implemented to ensure that the settlement criteria and operational safety were met.

2 TUNNELLING METHODOLOGY AND CONSIDERATIONS

2.1 TUNNELLING METHOD

The embankment was excavated using a Hydraulic Arm Tunnelling Machine (HATM) rig. Exit pits and jacking pits with thrust blocks and launch frames were constructed and located at a minimum distance of 2.5m from the toe of the embankment to prevent destabilisation. The HATM rig consists of a Hydraulic Telescopic Excavator (HTE) with a cutting head mounted on a slew ring and fixed in the crown of the shield (Figures 4 and 5). The digging action was obtained by a bucket cylinder mounted within the boom. Excavated material was removed by a hydraulic driven conveyor belt into an electrically driven skip which ran along a set of rails from the HATM back to the jacking pit where it was removed and tipped by an excavator.



Figure 4: Face of HATM rig.

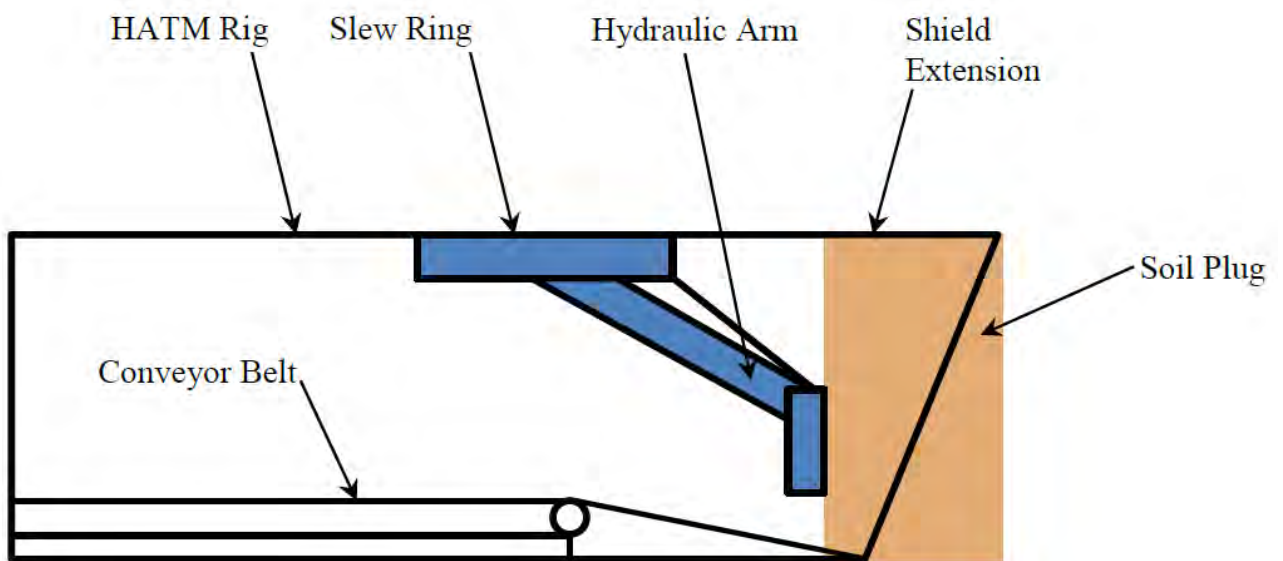


Figure 5: HATM rig schematic.

The cutting head was advanced by means of hydraulic rams exerting pressure off the thrust block. The cutting head produced a 1820mm diameter hole through the existing earth to allow the pipes to be jacked through. After the cutting head was advanced to the full stroke of the hydraulic rams and the rams retracted, the pipe was inserted into the jacking frame to make a continuous line with the cutting head.

The bore was to be cased at all times (steel HATM shield and pipe string). Excavations were to take place in supported ground at all times, i.e. no excavation to take place ahead of the steel shield. The HATM rig selected was configured so that the hydraulic arm could not extend past the face of the shield. The initial underbore design required a sufficient length of soil plug to be maintained ahead of the bore to maintain face stability. Therefore, the hydraulic arm was not to be extended into the soil plug. This was to be monitored by the Designer's Site Geotechnical Representative (DSGR) to ensure that the soil plug was not compromised. This assessment was based on conservative assumptions and was to be recalibrated after the installation of the first pipe.

To prevent local instability due to the HATM rig pushing the soil plug out of the embankment, the advancement rate was to be slowed to a level considered appropriate by the operator. If this did not have the desired effect, there was provision for temporary support around the bore exit. Upon reaching the required location, the ground above the shield was to be supported as the shield is jacked into the exit pit. The shield and equipment were to be split and prepared so that they could be lifted out. This process was then to be repeated for the remaining six pipes.

Each pipe joint was made using a 16mm thick medium density fibre board fixed to the pipe collar before delivery. A water stop and rubber joint sealant was installed under a 6mm thick pre-fabricated steel collar which was cast onto an external rebate in the pipes. The band was to be pulled tight providing a strong and durable water proof connection between adjoining pipe elements.

2.2 TRACK MONITORING AND REMEDIAL ACTIONS

A track monitoring regime was undertaken by Lynton Surveys and a Track Certifier prior to, during and after the boring works was completed. The intention of track monitoring is to notify the construction team of any performance issues during the operation to allow a staged decision making process.

A geotechnical engineer was available to review track monitoring records. A Track Monitoring Plan was produced in accordance with RailCorp Engineering Specification SPC 207 which specifies intervention levels and actions, including track monitoring records distribution. The Fulton Hogan supervisor, Track Certifier and Protection Officer were responsible for implementing the relevant Track Monitoring Plan incident response procedure where out of tolerance ground movement had occurred.

The first pipes were to be installed into the embankment using the HATM without injecting bentonite into the grout ports. The embankment was to be monitored closely at this stage of the operation. If the settlement was less than the alarm levels specified in the Track Monitoring Plan and lateral resistance was low, pipe jacking was to be continued using the same methodology.

If Alarm Level 1 was raised (specified in the Track Monitoring Plan) or significant lateral resistance was encountered, then the following remedial actions were to be implemented:

- Inject bentonite into injection ports near the leading edge of the pipe string to reduce the annulus gap and closure onto the pipe.
- Mixtures of bentonite and/or other materials shall be developed and applied as required to control convergence around the pipe.
- After completion of installation, the annulus shall be fully filled with cement grout.

2.3 INSTALLATION SEQUENCE

The pipes were not installed in sequence and each alternate pipe was installed followed by the intermediate pipes in between. This construction approach was identified as a key factor to limit cumulative settlement due to volume loss of the embankment. The culvert installation sequence consists of:

- Excavation of launch and retrieval pits either side of the railway embankment.
- Construction of launch frame and thrust block within the launch pit and installation of the HATM jacking shield ready for the first pipe jack.
- Advancing the string of jacking pipes beneath the rail embankment at embankment toe level.
- Bentonite injection through injection ports in each pipe if required to limit jacking load and/or control settlement during jacking.
- Grouting of annulus around each pipe if required to limit settlement prior to the installation of the adjacent pipe culvert.

- The above process was repeated for each of the seven pipe culverts to be installed.
- The pipes were installed in the following order (refer to Figure 1): (1) Pipe 3, (2) Pipe 1, (3) Pipe 2, (4) Pipe 5, (5) Pipe 7, (6) Pipe 4 and (7) Pipe 6.
- Permanent works were completed which included a head wall and outlet on the eastern side of the embankment and connection to the upstream culverts and backfilling on the western side of the railway embankment.

2.4 POTENTIAL IMPACTS

The impacts on the railway due to pipe jacking are highly dependent upon the construction methodology and the control measures used to minimise convergence of the ground around the concrete pipe (i.e. closure of the annulus gap). Potential impacts on the railway due to the pipe jacking operation are:

- Vertical settlement at rail track level due to closure (volume loss) of material around the jacking pipe.
- Horizontal movement of the embankment due to jacking loads and disturbance around the jacked pipe strings.
- Potential local instability due to push-out of soil plug ahead of and friction on the shield of the advancing HATM.
- Collapse of the excavated face at the front of the HATM or in case of over-excavation ahead of the HATM shield by the hydraulic arm.
- Instability of the rail embankment due to excavation of jacking and receiving pits.

3 PREDICTION OF GROUND MOVEMENTS

3.1 METHOD OF SETTLEMENT PREDICTION

A method proposed by Peck (1969) and more recently developed by O'Reilly and New (1982), Mair, Taylor and Burland (1996) and Burland (2001) is a commonly adopted approach used for the empirical prediction of ground movements. The method assumes that the transverse ground settlement profile above a tunnel is of a Gaussian form and that ground deformation takes place at a constant volume, so its overall magnitude can be specified as a 'volume/face loss'. The volume loss (VL) is defined as the total magnitude of displacement (i.e. area above the Gaussian profile) expressed as a percentage fraction of the excavated area for the pipe (Figures 6 and 7).

The shape of a settlement trough above a pipe excavation can be represented by a function curve of the form:

$$S = S_{\max} \times \exp(-y^2 / 2i^2)$$

Where:

- S is the surface settlement at a transverse distance from the pipe axis.
- S_{\max} is the maximum settlement which occurs directly above the pipe axis.
- y is the offset from the pipe axis.
- i is the horizontal distance to the point of inflexion on the settlement trough.

It is assumed that the magnitude of ground movements varies linearly with depth below the surface, which leads to the following expression:

$$i = K \times Z_o$$

Where:

- K is the trough width parameter
- Z_o is the depth to tunnel axis level from ground surface level

The value of K is dependent upon the soil type and according to O'Reilly & New (1982) it varies from 0.4 for stiff clays to 0.7 for soft silty clays and 0.2 to 0.3 for granular materials. The methodology is commonly used in assessing surface movements due to underboring and the results have shown good correlation with actual in-situ measurements.

The maximum settlement, S_{\max} , is given by the following equation:

$$S_{\max} = VL / [(2\pi)^{1/2}i]$$

According to published data from field measurements, values of VL < 1% can be consistently achieved with modern tunnelling techniques if appropriate control measures are implemented. Results of experimental research specific for pipe jacking (Borghi, 2006) have concluded that volume loss values could be conservatively used for settlement

prediction assuming that full closure of the annulus gap (overcut) around the pipe takes place. Other published data from pipe jacking for sewer installation in Hong Kong (Mok et al, 2007), indicates maximum measured values around $VL = 4.0\%$.

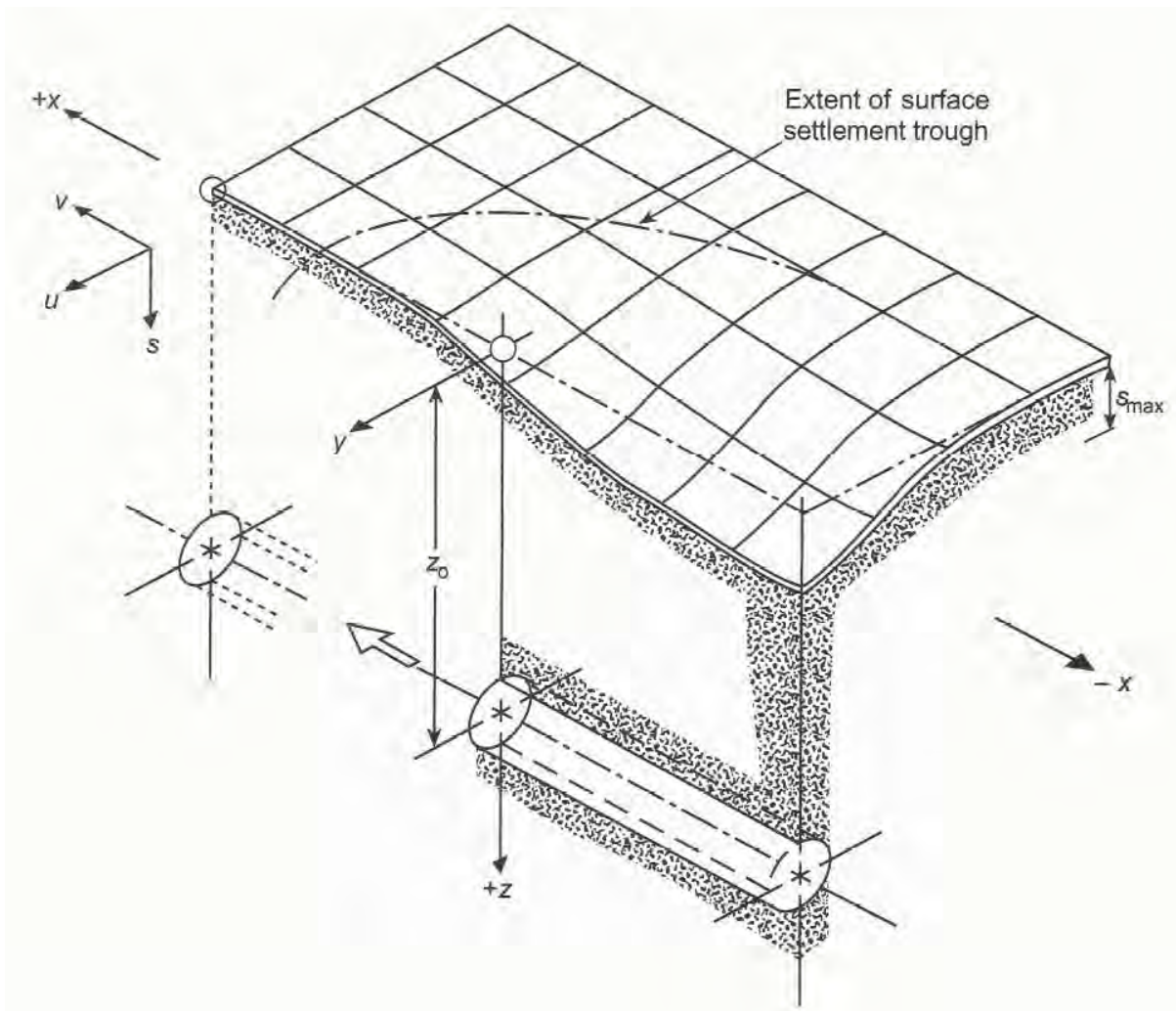


Figure 6: Settlement above an advancing tunnel (Burland 2001).

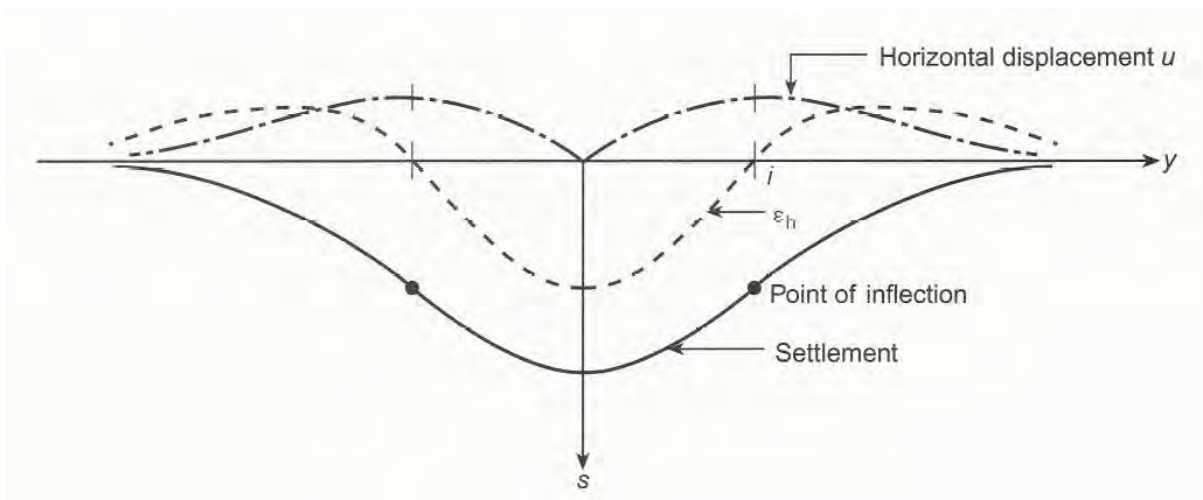


Figure 7: Transverse settlement trough (Burland 2001).

3.2 ASSUMPTIONS OF PREDICTION

The following inputs were assumed in the settlement prediction calculations:

- Ground conditions: The pipes were located along the fill/alluvium transition, embedded approximately 1.2m into alluvium consisting of soft to firm clays. Overlying the alluvium, fill materials were variable and consisted of sandy clays and clayey sands of soft to firm consistency and loose density (see Figure 2).
- Ground and pipe levels: The obvert of the proposed drainage pipes were approximately level with the toe on both sides of the embankment. Ground levels across the rail embankment had been taken from the available survey information. The maximum embankment height from the top of pipe to the rail level was approximately 5.5m, and the batter slopes of the embankment on either side of the rail was approximately 2H:1V.
- The trough width parameter (K) was calibrated to fit the measured settlement profile shape and the volume loss was adjusted to match the maximum measured settlement.
- Predicted settlement troughs for each pipe were superimposed in the back analysis to estimate the combined ground movements.

4 DESIGN CRITERIA OF TRACK DEFORMATION

Excavation of the culvert pipes under the railway line could result in ground movements which would be evident as settlement at the top of the rail embankment. RailCorp Engineering Specification SPC 207 – Track Monitoring Requirements for Undertrack Excavation provides deformation limits and associated rail monitoring intervention levels for changes in track geometry as a result of under track excavation. For a normal track speed of 100km/hr, the limits which apply are summarised in the following table.

Table 1 – Rail monitoring intervention levels for a normal track speed of 100km/hr.

| Monitoring Parameters (Note 1) | Normal Limits 100% | Gradual movement up to: Alarm Level 1 (Note 2) Normal Limits 25% - 50% | Gradual movement up to: Alarm Level 2 (Note 2) Normal Limits 50% - 75% | Sudden movement > 50% of Normal: Alarm Level 3 (Note 2) Normal Limits 75% - 100% |
|-----------------------------------|-----------------------|---|---|---|
| Track Top (4m) | 14 mm | 7 mm | 9 mm | 12 mm |
| Track Line (8m) | 11 mm | 6 mm | 7 mm | 10 mm |
| Short Twist (2m) | 11 mm | 6 mm | 7 mm | 10 mm |
| Long Twist (14m) | 30 mm | 15 mm | 18 mm | 26 mm |

Notes:

1. The monitoring parameters relate to changes to track geometry and are as defined in RailCorp Engineering Manual TMC 202 – Track Fundamentals.
2. The definition of “Alarm levels”, measurements and notification required and continuation of works following exceedance of the limits are outlined in Section 6.1 of RailCorp Engineering Specification SPC 207.

The parameter which relates to vertical settlement above the culvert installation is track top, which is the longitudinal level of the track with a chord of specified length (4m chord length). Figure 8 illustrates the definition of the track top measurement. It was assumed that all vertical settlement along the top of the embankment as a result of pipe excavation directly below the rail level would be reflected in the track top measurements.

The track line is the horizontal smoothness of the track without reference to permanent survey marks. This is measured using string lining methods with an 8m long string line. Figure 9 illustrates the definition of the track line measurement.

The track twist is the variation in cross level when measured at different points along the track (every 2m for short twist and every 14m for long twist). The cross level is defined as the level of one rail in comparison to the other when measured along the track (Figure 10).

An assessment of the measured monitoring parameters was required if movements exceeded Alarm Levels 1 and 2 for approval for continuation of works, while all works must cease immediately if Alarm Level 3 was reached.

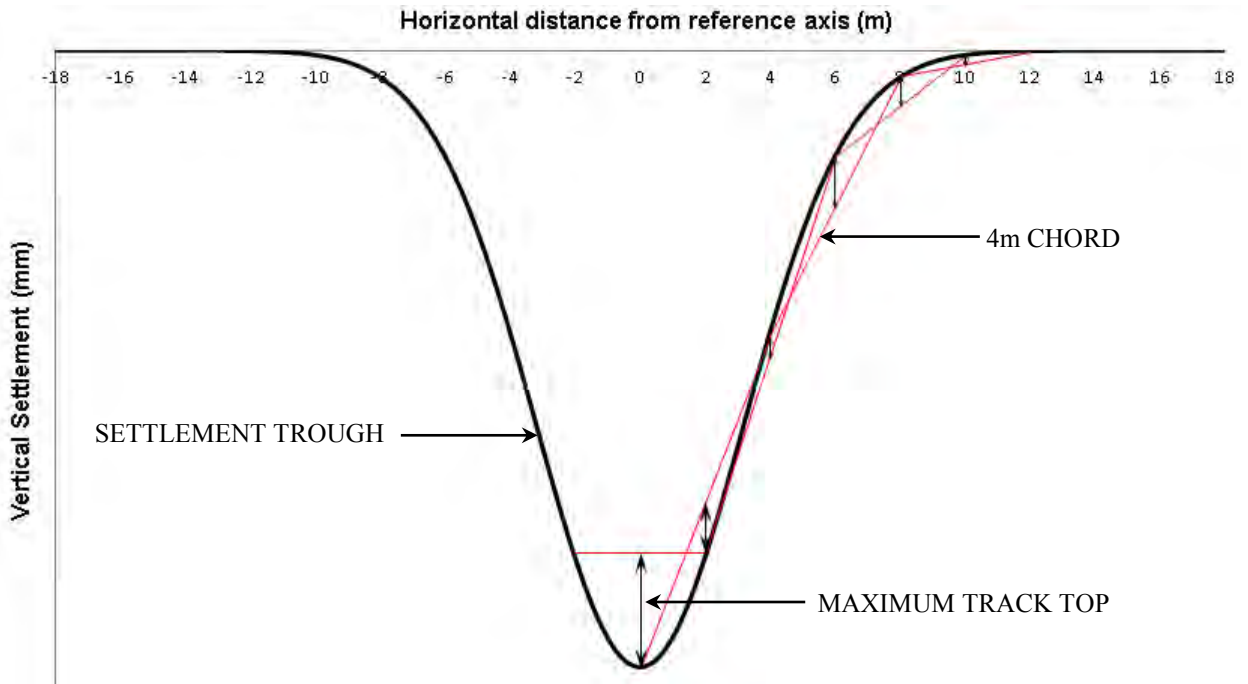


Figure 8: Example of track settlement trough showing track top measurements.

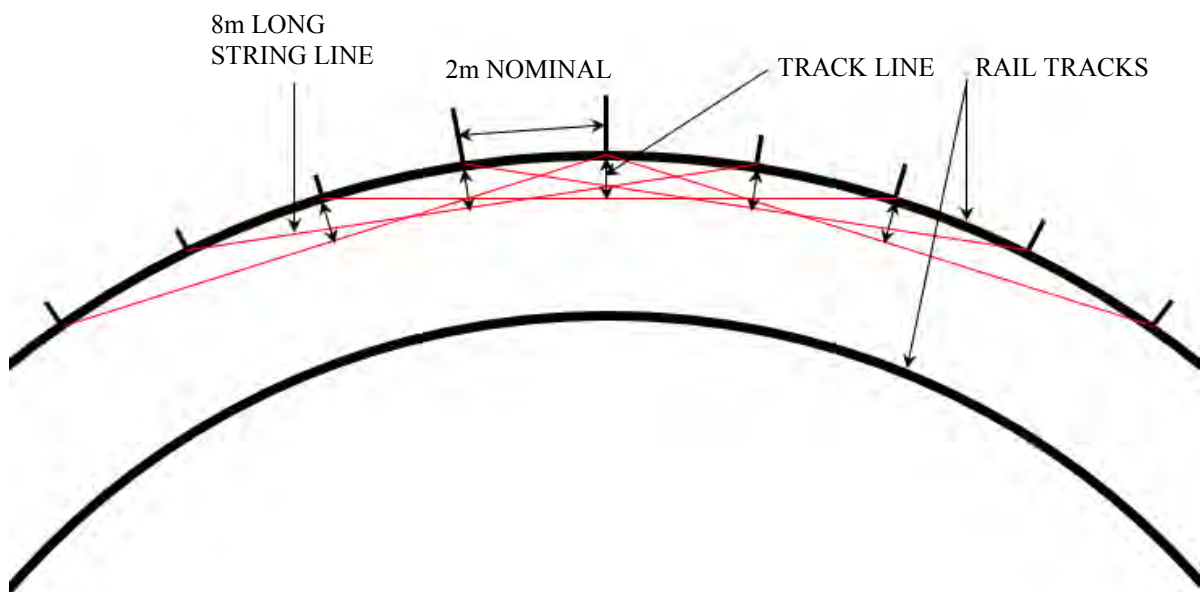


Figure 9: Example of track plan showing track line measurements.

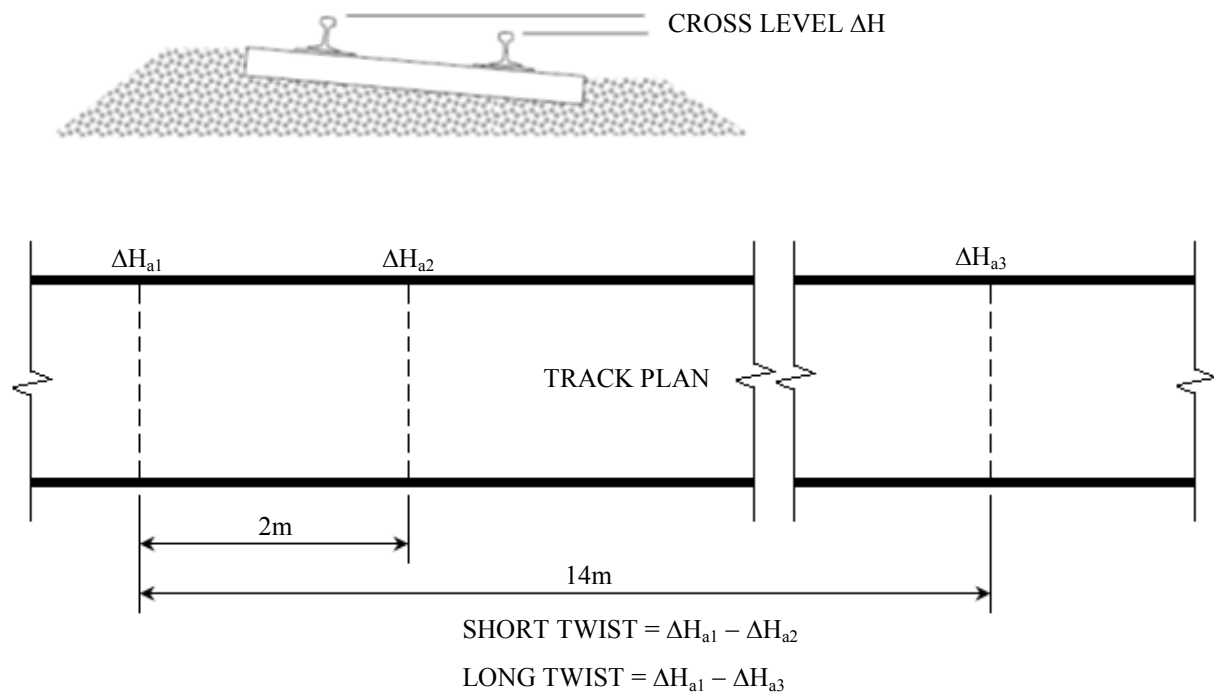


Figure 10: Example of track twist.

5 CONSTRUCTION PERFORMANCE AND BACK ANALYSIS

An initial settlement prediction was carried out using a volume loss of 2.2% and a K value of 0.25. A maximum vertical settlement of 22mm was estimated after construction of all 7 pipes. A maximum vertical settlement of approximately 24mm was recorded along the tracks following excavation and construction of the first two pipes (Pipe 3 and Pipe 1). Although SPC 207 track monitoring parameters for track top, line and twist were below Alarm Level 1, the following tasks were performed:

- Back analyse the measured settlements, recalibrate design parameters to match measured values and predict future ground movements due to subsequent pipe jacking.
- Review/comment on the existing embankment monitoring data and their effects on track performance.

During the back analysis, the settlement trough parameters for each pipe were adjusted to match the measured track vertical settlement profiles from Lynton Survey’s real time monitoring data (Figure 11). The calibrated parameters were used to predict future track top and total settlement values during the construction of the 7 culverts. A K value of 0.4 and maximum volume loss of 5.3% were estimated. Table 2 summarises the settlement trough parameters estimated in the back analysis.

Table 2 – Summary of track settlement trough parameters estimated in the back analysis.

| Sequence | Pipe 1 | | Pipe 3 | |
|--------------------|-----------------|-----------------------------|-----------------|-----------------------------|
| | Volume Loss (%) | Trough Width Coefficient, K | Volume Loss (%) | Trough Width Coefficient, K |
| 1 (Pipe 3 only) | - | - | 2.7 | 0.48 |
| 2 (Pipes 3 & 1) | 5.3 | 0.4 | 4.1 | 0.4 |

Possible sources of the high volume loss, greater than the initial assumption, included:

- Unstable excavation face due to the soil plug not being maintained.
- Ground convergence into the annulus.
- Friction at the embankment exit toe during pipe exit causing lateral ground movement which spreads and drags the top of the embankment down.

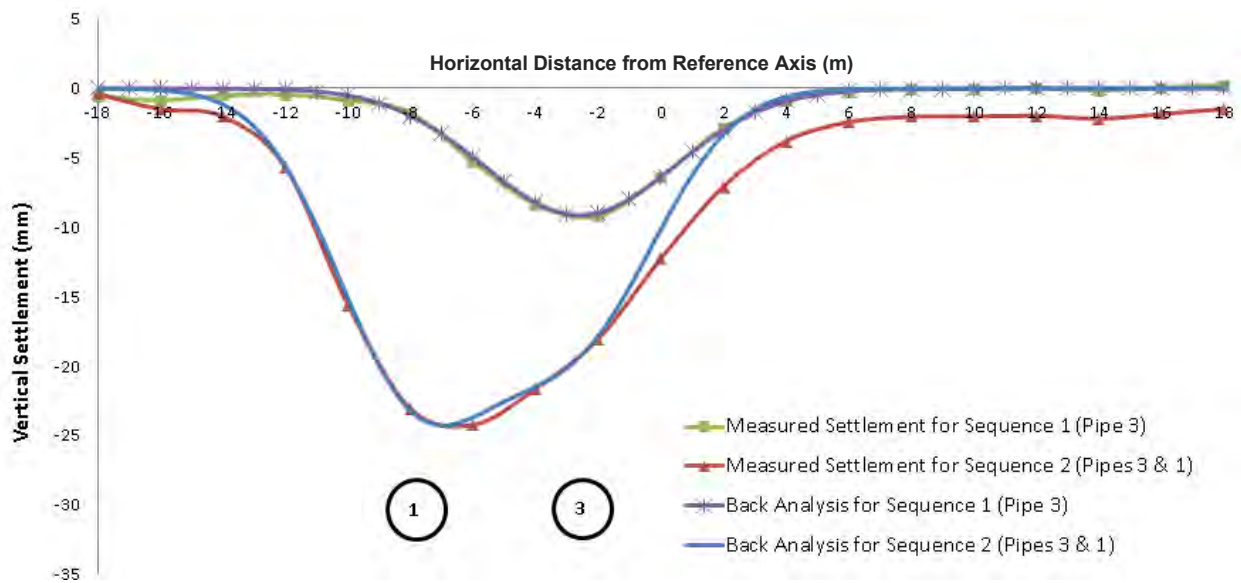


Figure 11: Back analysis of track vertical settlement measurements.

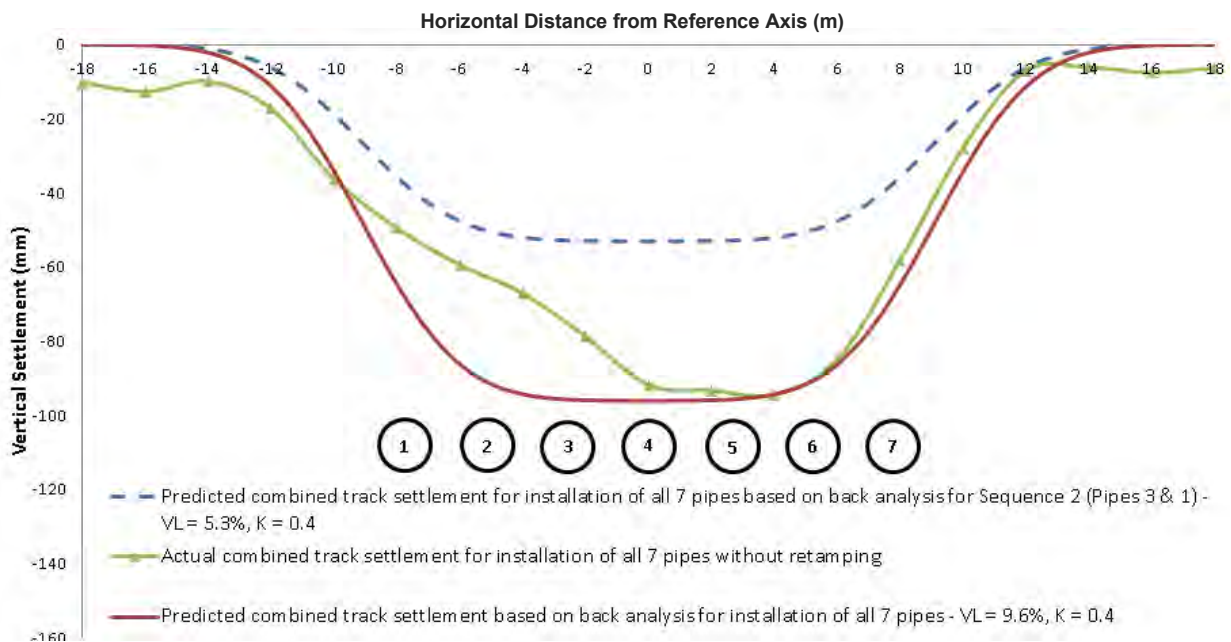


Figure 12: Predicted and actual vertical settlements following construction of all seven pipes.

The revised settlement trough parameters were used to predict future track top and total settlement values during the construction of the seven culverts. The maximum vertical settlement along the track and embankment was estimated to be approximately 53mm after installation of seven pipes (see Figure 12). This magnitude of total embankment settlement is not expected to affect the stability of the rail embankment. The maximum estimated track top value of 6mm was predicted during installation of 7 pipes which is under the Rail Monitoring Alarm Level 1 of 7mm.

Based on the calculated embankment settlements and track top values, the following were recommended:

- The underbore works continue under the current monitoring regime.
- Back analysis and prediction of further settlements to be carried out immediately after the installation of every pipe, if required.
- The embankment total settlement limit to be adjusted to 60mm and this criterion is to be confirmed via further back analysis after the installation of each pipe.
- Construction of rock toe berms at tunnel exits to maintain embankment stability due to lateral thrust load from pipe jacking.

The tracks were retamped twice during construction to ensure track stability of the live railway (see Figures 13 and 14). A maximum settlement of 27mm was recorded following the second retamping and construction completion.

The total combined settlement profile of the track following installation of all seven pipes without retamping was estimated by combining the actual track settlement measurements before and after retamping. A maximum track settlement of 95mm was estimated without retamping. This is higher than the 53mm predicted based on the back analysis of the measured data for the first and second pipes, i.e. Pipe 3 and Pipe 1 respectively. The retamping operations provided a precautionary remedial measure to ensure rail safety. A back analysis was carried out for the installation of all seven pipes based on the estimated combined track settlement without retamping. A final maximum volume loss of 9.6% and a K value of 0.4 were predicted from the back analysis. The combined settlement profiles are summarised in Figure 12. The greater predicted settlements above Pipes 1, 2 and 3 indicate smaller volume loss values, i.e. $\leq 9.6\%$, for earlier installed pipes.



Figure 13: Track profile before retamping.



Figure 14: Track profile after retamping.

6 CONCLUSIONS

Considerable ground movements will not always be detrimental to track performance as long as they do not cause embankment instability and excessive track top, twist and line deformations. Settlement limits may not always be specified by the respective rail authority. Hence, it is imperative that the track monitoring parameters are fully understood before settlement alarm levels are assigned for monitoring during excavation and construction of underbores. Setting an appropriate vertical settlement limit for embankment stability requires detailed engineering assessment and judgement. However, close monitoring of real time data is critical combined with appropriate back analyses and contingency measures to ensure safe construction and operation.

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