TRAPEZOIDAL REINFORCED SOIL WALLS – DESIGN DEVELOPMENT AND CHALLENGES

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ABSTRACT

The widening of the existing rail bridges and approach embankments for the Gosford Passing Loops Project necessitated the construction of retaining walls adjacent to existing embankment slopes. Trapezoidally-shaped reinforced soil walls (RSW) were proposed to cater for the various constraints and challenges faced, including allowance for the uninterrupted operation of the existing rail lines during construction. Due to the unconventional wall geometry and load transfer mechanisms, design of trapezoidal RSW is not covered by typical standards and codes, such as RMS R57. The assessment process necessitated consideration of wall design based on first principles, and variations on the conventional assessment of failure mechanisms to ensure the wall achieved the design intent. Numerical modelling was undertaken to verify achievement of wall stability and serviceability requirements. The successful implementation of these walls is demonstrated by the observed stability of the existing rail track and RSW during and after construction, which is further supported by conforming instrumentation records.

1 INTRODUCTION

The Gosford Passing Loops Project forms a part of the Northern Sydney Freight Corridor (NSFC) Program delivered by Transport for NSW (TfNSW), to improve the capacity of the rail freight network between Strathfield, NSW and Broadmeadow, Newcastle. It forms one of three other projects along the existing lines, including North Strathfield Rail Underpass, Epping to Thornleigh Third Track, and Hexham Passing Loop.

The project comprises the construction of two (2) new Passing Loops between Gosford and Narara stations. Each Loop extends approximately 2km in length, providing an alternative route for slower-running freight trains as they are overtaken by passenger services on the existing rail lines. Refer to Photo 1 for an aerial view of the Project site prior to construction.

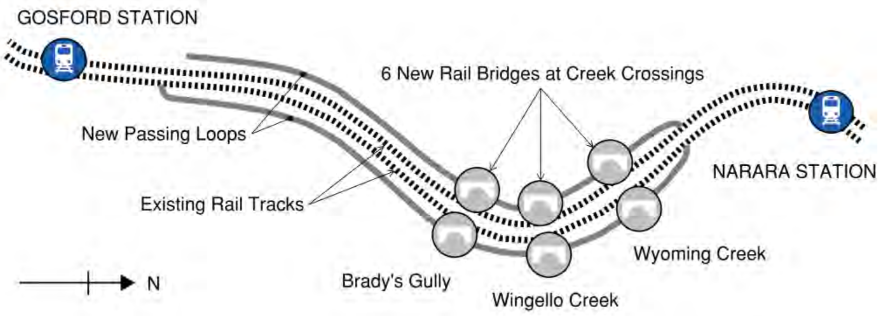

Figure 1: Plan of Gosford Passing Loops project (schematic, based on Transport for NSW, 2014).

The Passing Loops comprise extensions of the existing track footprint to the west and east, by incorporating the width of an additional rail track on the up and down main lines. Existing rail embankments had to be widened to accommodate construction of the Passing Loops to a similar elevation above natural ground. Refer to Figure 1 for a plan view of the Project and Figure 2 for a typical cross section through the proposed embankment widening. Photo 2 shows a typical site where embankment widening was proposed.

The majority of the larger embankment widening sections were located at bridge approaches where the Passing Loops crossed above one (1) of three (3) existing waterways, namely Wyoming Creek, Wingello Creek and Brady's Gully. A total of six (6) bridges were proposed for the Project, with three (3) on each of the up and down main lines.

This paper presents the challenges faced in the design of the proposed widening, the design development and methodologies, assessment outcomes, and the construction performance of the final embankment widening solution, which comprises trapezoidally-shaped reinforced soil walls (RSW).

2 RETAINING WALL – CHALLENGES AND CONSTRAINTS

2.1 REQUIREMENT FOR RETAINING WALLS

The embankment widening comprised fill heights up to 4.3m above natural ground level. Solutions for the widening proved to be a challenge for this project, as site boundary limitations prevented the widened sections from being supported by embankments with self-supporting batters. This limitation necessitated the embankment extensions to be supported semi-vertically with retaining walls, to minimise the footprint of the widened sections. Refer to Figure 2.

2.2 LIMITED CONSTRUCTION SPACE

The geometric extent of the design solution in the direction of the existing embankment was also constrained, as the existing rail line had to remain in full operation during construction of the Project works. This imposed the greatest challenge on the design, as any encroachment into the existing embankment would impact on its stability, potentially introducing risks of deformation or failure, and ultimately endangering passenger and rail safety. Photo 3 illustrates the proximity of the existing rail line to a site where embankment widening was proposed. Accordingly, maintenance of the stability and serviceability of the existing embankment was of utmost importance. Any excavations and / or negative impacts had to be minimised, otherwise temporary stabilisation works would be required.

2.3 WEAK GROUND CONDITIONS

The highest retaining walls were located at bridge abutments where the Passing Loops were expected to cross existing waterways. Due to the proximity to natural watercourses, the subsurface geology was alluvial in origin and of poor strength, consisting of loose density clayey sands and sandy clays of firm consistency. High groundwater levels were observed at or above the existing ground level.

2.4 WALL ARRANGEMENT

A reinforced soil wall (RSW) solution was proposed in favour of other retention systems due to its flexibility to "absorb" movements and deformations expected from the weak ground conditions, as well as its suitability to meet the constrained site conditions.

RSW's comprise a system of mechanically stabilised fill (typically granular), reinforced with a series of tensile straps to effectively form a self-supporting, gravity "block". Concrete panels or blocks are often used to form the wall facia.

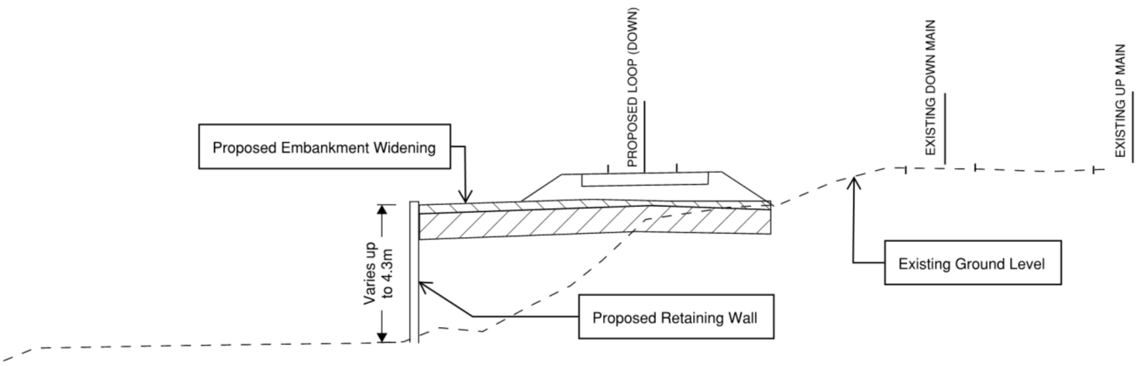

Figure 2: Typical cross section of proposed rail embankment widening.

3 DESIGN DEVELOPMENT

The RSW underwent three (3) stages of development, starting with a conventionally designed rectangular block, and concluding in a trapezoidally-shaped block sitting atop the existing embankment. Details of the design development are summarised below. Reference is made to an example design taken from RSW's designed at Wyoming Creek Underbridge, to facilitate in the reader's understanding of the design process and outcomes. The design stages are summarised below.

- **Stage 1: Initial Design** – The initial RSW design was undertaken using conventional design methods, following RMS QA Specification R57, Design of Reinforced Soil Walls (RMS, 2012), as stipulated in the Project Works Brief. Details of the design methodology are contained in Section 4.1. The resulting designs comprised rectangular RSW block widths which encroached a significant distance into the existing rail embankment. For example, the assessed block width at Wyoming Creek was 7m, refer Figure 3. Installation of the proposed RSW designs required significant excavation into the existing embankment, thereby necessitating the installation of temporary sheet piles to retain the existing rail tracks at the embankment crest. Due to large deformations predicted at the top of the sheet piles, anchorage mechanisms were proposed in the form of dead men or tie backs attached to top of the sheet piles.

- **Stage 2: Intermediate Design** – Due to the uncertainties and risks posed by the temporary works on the existing embankment in the Initial Design, consideration was made to exploit the stability of the existing rail embankment. Development of the trapezoidally-shaped RSW was born on the theory of "attaching" the RSW onto the embankment – thereby removing the need to excavate into the existing embankment and consequent elimination of the temporary sheet piles. As this wall geometry and design approach is not covered in conventional design codes, assessment of its feasibility was based on first principles, as detailed in Section 4.2. The resulting solution comprised a narrow 1.5m wide "base" at the toe of the embankment formed with cement stabilised sand, upon which the RSW would be constructed. The rear of the RSW comprised a stepped interface following the existing gradient of the underlying embankment. An illustration of the proposed solution at Wyoming Creek is shown in Figure 3 below.
- **Stage 3: Final Design** – In the absence of design standards specifically targeted for the proposed trapezoidal-RSW solution, the Federal Highways Administration (FHWA, 2006) document on "Shored Mechanically Stabilised Earth (SMSE) Wall Systems Design Guidelines" was used as a guiding document. Design refinements were made based on FHWA's (2006) recommendations, eventuating into the Final Design solution, whereby the "base" of the RSW was increased up to 3.5m. The design necessitated a 1H:1V temporary excavation into the existing embankment to accommodate the widened base. Reference can be made to Figure 3 for an illustrative sketch summarising the relative dimensions and design features proposed at the Final Design phase at Wyoming Creek.

4 DESIGN METHODOLOGY

RSW design is typically delineated into two parts, Internal Design, and External Design. In general terms, Internal Design addresses the requirements of the RSW to form a self-supporting, coherent, gravity block; and External Design assessments review the interaction of the RSW with the surrounding ground.

For this Project, SMEC was responsible for the External Design, and a specialist RSW supplier was responsible for carrying out the Internal Design. Accordingly, the design developments and stages mentioned in Section 3 above pertain to developments made in addressing the satisfaction of External Design. The sections below describe the methodologies and theories behind the solutions formulated at each stage of External Design development contained in Section 3. It was assumed that the Internal Design would be adequately addressed by others.

4.1 CONVENTIONAL RSW

Design Specification R57 (2012) was followed for the design of the rectangular RSW block formulated in Stage 1 of the design (Initial Design). R57 (2012) follows conventional RSW design theories, whereby the RSW block provides a means of retention to the adjacent soil mass, resulting in the imposition of destabilising lateral earth pressures on the back of the RSW.

External Design assessments following conventional design theories review the interaction of the RSW and the surrounding ground, with the overarching assumption that the wall acts as a rigid body, against which the soil mass is retained and lateral earth pressures are applied. Typically, External Design assessments comprise:

- Ultimate Limit State: bearing capacity, forward sliding, overturning (tilt), and slip failures
- Serviceability Limit State: settlement, tilting, eccentricity, rotational and lateral movement, and deformation associated with slip failures.

In addition to R57 (2012), there are a number of standards commonly used in Australia and in the international arena which provide guidelines for RSW design which adopt conventional design theories as outlined above. Examples of such standards include, British Standard, BS8006 (2010), "Code of Practice for Strengthened/Reinforced Soils and other Fills", and Australian Standard, AS4678 (2002), "Earth-retaining Structures".

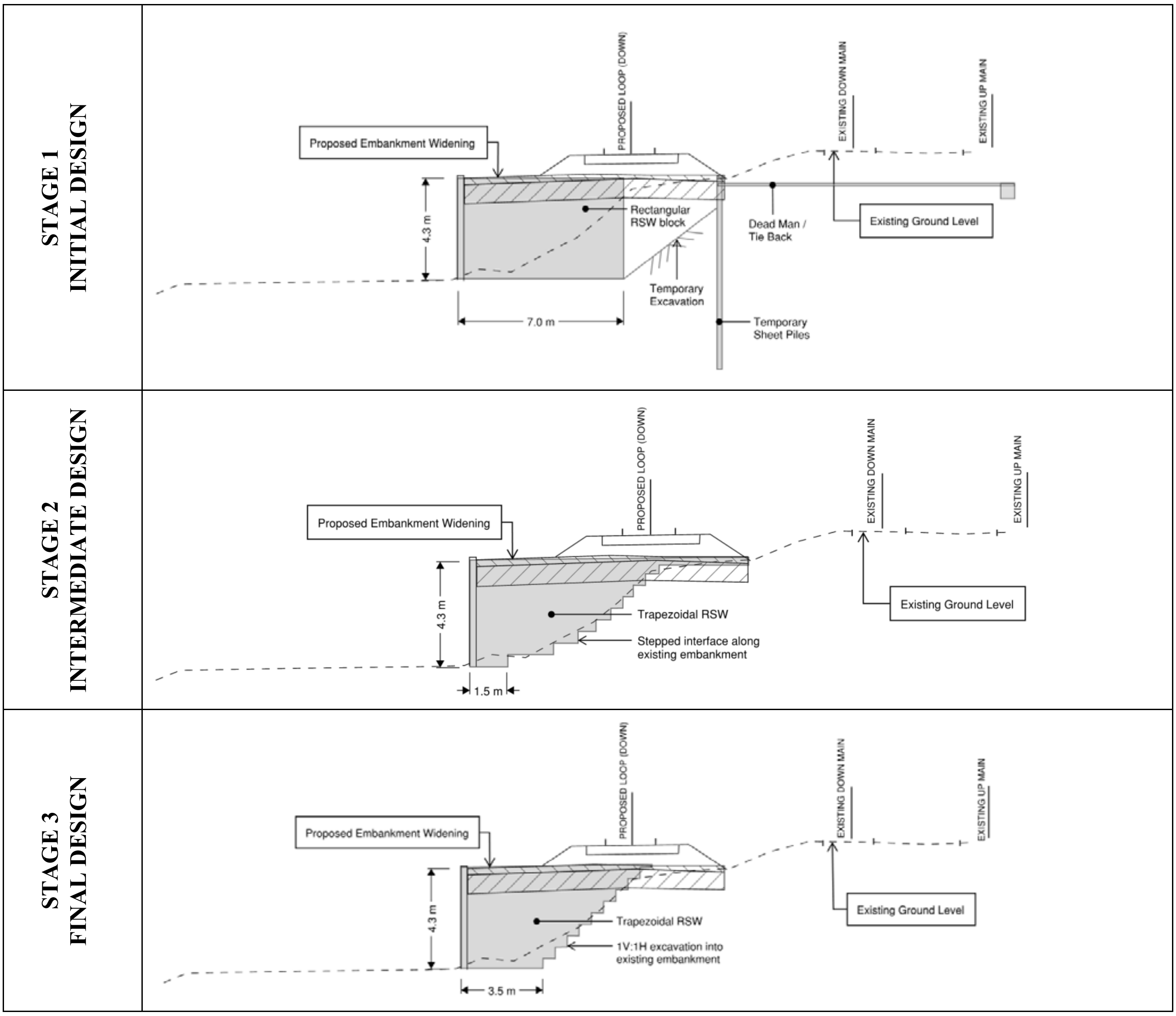

Figure 3: Sketches showing RSW design development solutions at Wyoming Creek.

4.2 TRAPEZOIDAL RSW

As mentioned in Section 3, the concept of trapezoidally-shaped RSW's originated from the theory of "attaching" the RSW block onto the embankment, while exploiting the evident stability of the existing rail embankment. Adherence to conventional RSW External Design theories and standards was no longer applicable, as the RSW block was no longer assumed to retain the adjacent earth fill, and consequently, was not subjected to lateral earth pressures. Accordingly, assessment of External Design failure mechanisms for compliance with R57 (2012) such as bearing capacity, sliding and overturning were no longer considered relevant. Alternative methodologies / design criteria were sought to assess the stability and serviceability of this unique retention system, as presented in the following sections.

It is noted that trapezoidally-shaped walls are covered in R57 (2012), BS8006 (2010) and AS4678 (2002). However, these codes stipulate that such geometries are only applicable for walls founded into sound rock and concrete. Such wall geometries are designed in accordance with conventional design theory, as they are considered to retain adjacent ground materials and consequently are subjected to lateral earth pressures. R57 (2012) provides guidelines to modify the trapezoidal block geometry into an equivalent rectangular shape for the purposes of design calculation and assessment.

4.2.1 First Principles

Design of the trapezoidal RSW-embankment composite system formulated in Stage 2 of the design (Intermediate Design) was undertaken based on first principles. Assuming the RSW block was adequately designed to act as a self-supporting, coherent unit (i.e. satisfaction of Internal Design requirements), and in the absence of lateral earth pressures on the back of the RSW, consideration of first principles suggests that the feasibility of the system need only be addressed for potential slip failures.

Adopting a minimum base width of 1.5m at the toe of the RSW, trapezoidal RSW blocks were formulated in the Intermediate Design based on the achievement of industry-adopted Factors of Safety (FOS) against slip failure. Limit equilibrium software, SLOPE/W was utilised for this assessment.

Guidance was sought from RSW Internal Designers and suppliers to advise on the shortest practicable wall base width – as minimisation of this dimension would reduce the potential excavation into the existing embankment. A base width of 1.5m to 2m was suggested based on literature reviews and recommendations based on the practical benefit of creating a workable construction platform. It was also suggested that the base could be formed using concrete or cement stabilised sand up to a height where a 1.5m wide base could be created – in the event space limitations necessitated such a "pointed" base.

4.2.2 Reference Design Standards

A literature review indicated that no design standards were available for the proposed trapezoidal RSW-embankment composite solution. However, similarities could be drawn with the "SMSE Wall Systems Design Guidelines" documented by the FHWA (2006). FHWA (2006) provides guidelines for the design of RSW located in front of excavations reinforced with soil nails. This document recognises the stabilising effect of the shoring wall and suggests the consequent elimination of lateral earth pressure loads being imposed on the RSW. For the purposes of External Design, FHWA (2006) suggests that failure mechanisms associated with sliding and overturning need not be considered.

For the RSW formulated in Stage 3 of the design (Final Design), the guidelines presented in FHWA (2006) were used as a basis for the adopted External Design methodology, as summarised below. Load factors and strength reduction factors from R57 (2012) were adopted to address the various load combinations expected during the RSW's lifetime.

- Bearing capacity – Applicable for RSW portion supported on natural ground, as suggested by FHWA (2006). Refer to Figure 4.
- Sliding and overturning – Although earth pressure loads were not considered to exist, destabilising lateral loads from other sources such as earthquake loading and hydrostatic pressure were assessed against the available resistance at the base of the trapezoid.
- Slip failure – Assessment of global slip failures through the existing embankment and supporting ground, due to application of the trapezoidal wall. Modelling of the composite system was undertaken using limit equilibrium software, SLOPE/W.

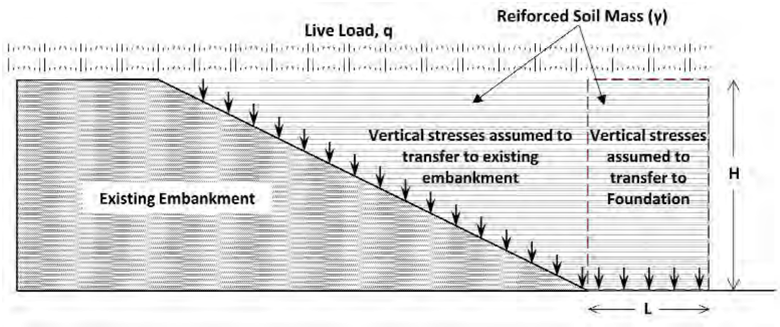

Figure 4: Sketch showing RSW External Design Bearing Capacity Assessment, based on FHWA (2006).

5 NUMERICAL MODELLING

The composite system was modelled using finite element software, PLAXIS 2D, which facilitated in detailed stability assessments and deformation predictions.

5.1 DESIGN INPUTS

The composite system was modelled in stages, simulating the proposed construction sequence, starting with the excavation of the existing embankment, construction of the RSW in 1m to 2m lift increments, up to final completion of the wall. The software facilitated in the assessment of interim stability and expected deformation magnitudes throughout the modelled construction stages.

Freight trains were simulated as pressure loads of 76kPa across a track width of 2500mm. Two train loads were modelled on the existing embankment to simulate the passage of trains on the up and down main lines. One (1) additional train load was modelled on the widened section to simulate train services on the Passing Loop.

5.2 ASSESSED STABILITY

Wall stability at Wyoming Creek was verified through the achievement of FOS against slip failure of 1.35 and 1.6 in the short term and long term design cases respectively, in accordance with standard industry practice. The assessed factors of safety based on the Phi/C reduction method, and potential slip failure plane are shown in Figure 5 and Figure 6 respectively.

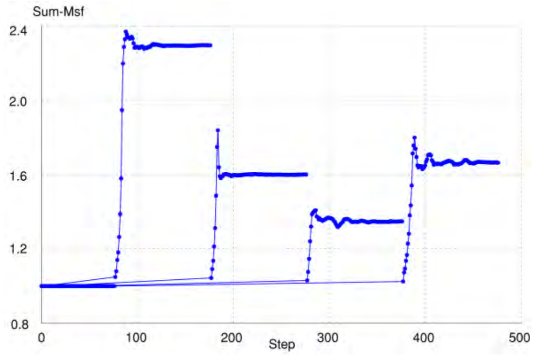

Figure 5: Output of Phi/C reduction (Factor of Safety) for various construction stages at Wyoming Creek (PLAXIS 2D).

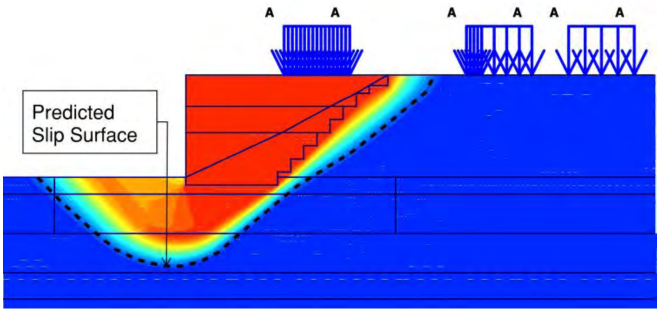

Figure 6: Output of Phi/C reduction (Factor of Safety) of potential slip failure plane at Wyoming Creek (PLAXIS 2D).

5.3 ASSESSED DEFORMATION

Figure 7 presents the deformations predicted within the composite system at Wyoming Creek. The predicted deformations were within the allowable tolerances for the affected structures.

Maximum assessed deformation	Settlement (mm)	Lateral deformation (mm)
Existing embankment	40	35
Existing rail tracks	14	11
Trapezoidal RSW	110	60

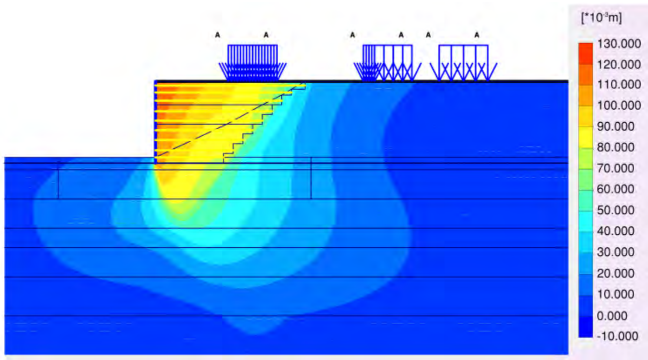

Figure 7: Predicted total deformation at Wyoming Creek.

6 CONSTRUCTION PERFORMANCE

6.1 INSTRUMENTATION

Instrumentation and monitoring were implemented during construction to confirm the performance of the trapezoidal RSW as per the design predictions. A plan showing the proposed instrument locations is provided in Figure 8.

Proposed instrumentation and corresponding trigger levels (in brackets) for RSW at Wyoming Creek comprised the following:

- Settlement plates – located beneath the constructed RSW to capture total ground settlement (90mm)
- Settlement pins – located on the existing embankment, to monitor embankment deformation during and after construction (12mm)
- Survey targets – located at the RSW face to measure wall deformation (90mm vertical, 30mm lateral)

- Track monitoring – surveying of the existing main lines (trigger levels in accordance with track monitoring requirements specified in RailCorp Engineering Specification SPC 207, 2013)

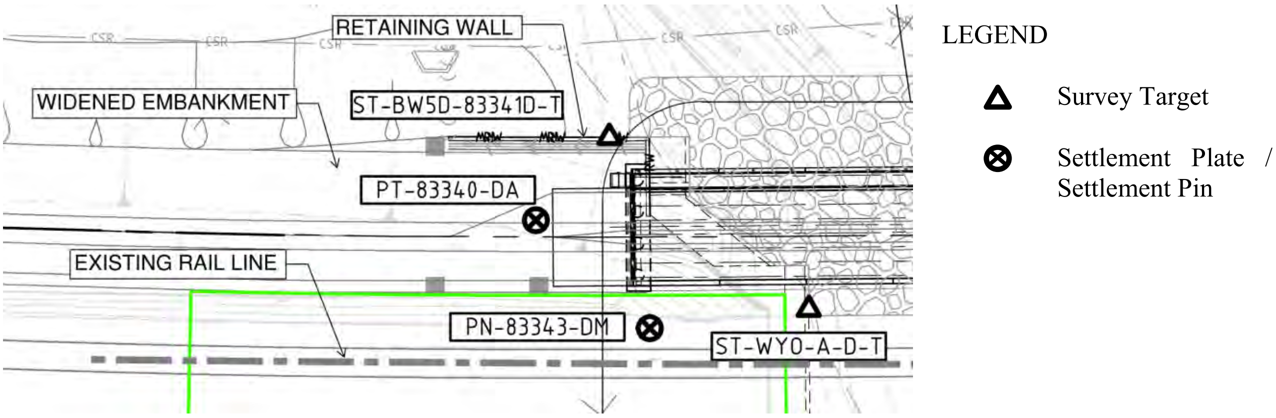

Figure 8: Plan view of proposed instrumentation at Wyoming Creek.

6.2 MEASUREMENTS

At the time of writing, construction of trapezoidal walls on the Project had just commenced, starting with walls at Wyoming Creek Bridge. Settlement plate data registered movements within the predicted values. Although construction works took place in close proximity to the existing rail line, monitoring of the tracks had not registered any excessive movement during excavation of the existing embankment and / or construction of the retaining wall. Photo 4 illustrates the proximity of the works to the existing rail line. The observed stability of the composite system to-date and adherence to the predicted behaviour as demonstrated through the monitoring records, suggests that the wall is performing as expected. Photo 5 provides a picture of a completed trapezoidal RSW at Wyoming Creek. Further monitoring data will be collected to verify the behaviour and performance of this wall and the other trapezoidal RSW.

6.3 CONSTRUCTION

Photos 6 and 7 illustrate typical rail track construction processes and machinery utilised upon completion of the supporting foundation for the new Passing Loops. Similar construction methods are expected to be adopted above the completed trapezoidal RSW.

7 CONCLUSIONS

A trapezoidal RSW-embankment system was adopted to support the embankment widening for the Gosford Passing Loops Project. The concept behind this system exploits the self-supporting characteristics of the existing embankment, and consequent elimination of lateral earth pressures imposed on the overlying RSW. The mechanics behind this system deviates from conventional RSW design theory, such as those followed by typical design standards, R57 (2012). In the absence of specific design guidelines, the External Design feasibility of the composite system was based on first principles, whereby assessment against slip failures was undertaken. Adoption of design guidelines provided in FHWA (2006) "SMSE Wall Systems Design Guidelines" was utilised in the development of the Final Design, which rendered a trapezoidal-RSW with narrow 3.5m base width and a stepped 1H:1V interface with the underlying embankment. Finite element analyses were undertaken to assess stability and formulate deformation predictions. Instrumentation points on the existing track and RSW registered deformations within the expected magnitudes at the time of writing, thereby confirming the observed stability and successful performance both during and post construction.

8 ACKNOWLEDGEMENTS

Acknowledgement is made here to Transport for NSW, Downer Engineering Australia and Robson Civil Projects for their approval to publish this paper.

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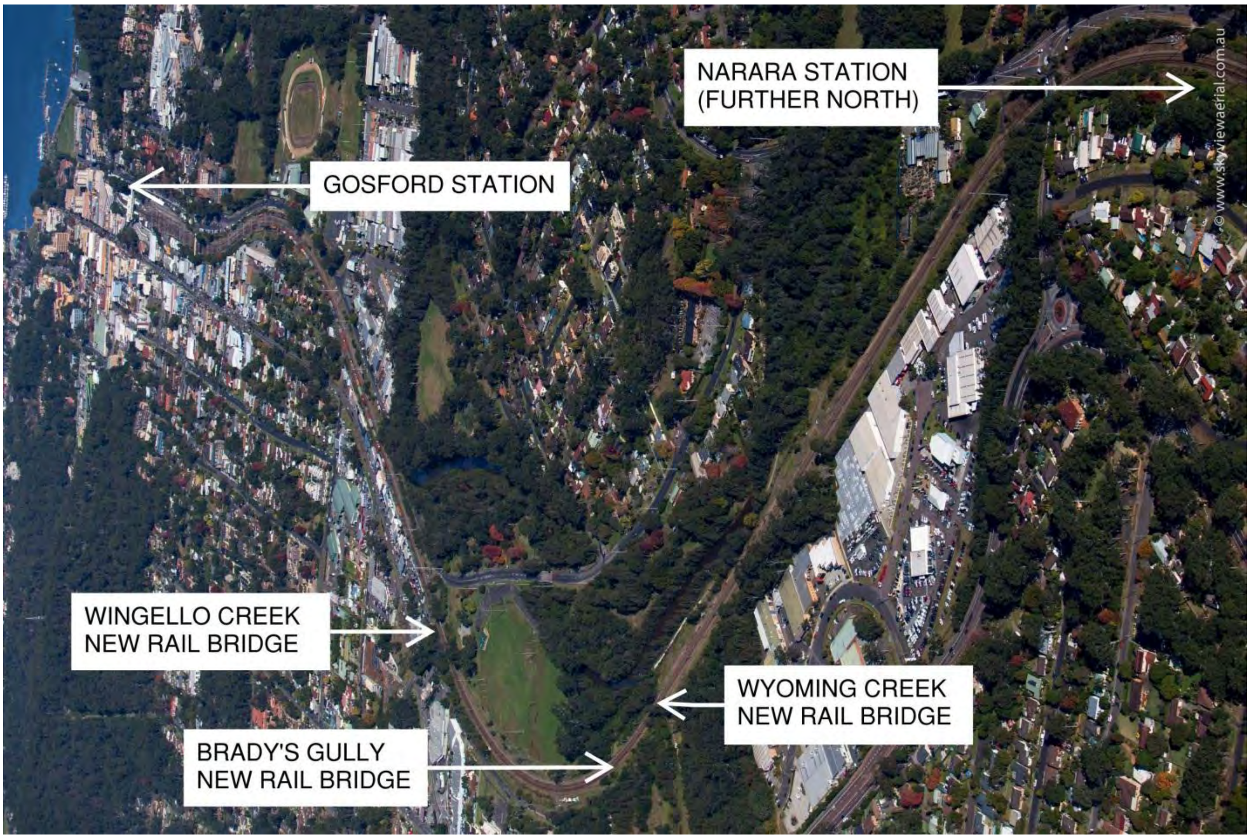

Photo 1: Aerial view Gosford Passing Loops (pre-construction)

Photo 2: Pre-construction – Site of proposed rail embankment widening

Photo 3: Pre-construction – Proximity of proposed embankment widening relative to existing train line.

Photo 4: During construction – Proximity of construction works to existing rail line

Photo 5: Completed Trapezoidal-RSW at Wyoming Creek

Photo 6: Construction of new rail track for Passing Loops

Photo 7: Construction of new rail track for Passing Loops