Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)

Challenges of deflection wall design for the protection of existing bridge piers—a rail case study

Défis de la conception des murs de déflexion pour la protection des piliers de pont existants—une étude de cas ferroviaire

Manjesh Narayana & Robert Kingsland
Geotechnics and Tunnels, WSP, Australia, manjesh.narayana@wsp.com

Nirmal Shrestha
Bridge Engineering, WSP, Australia

ABSTRACT: A direct collision of a derailed train on a bridge pier may lead to total collapse of a bridge. Bridge failure as a result of derailment might be classified as a rare incident, though, there is no doubt that its impact on both train and bridge has catastrophic consequences. In order to prevent such a disastrous incident, deflection walls are designed to withstand potential collision load. This paper describes the challenges of design of deflection walls for existing bridges on the Parramatta Light Rail project in Sydney. The derailment protection for the bridges typically comprises deflection walls on the approach side of the bridge piers. Deflection wall design is undertaken with reference to AS5100 (2017). In this paper, an economical design methodology is detailed for the assessment and behaviour of deflection walls under ULS loadings. The main challenges in the deflection wall design result from recent code requirements to design these elements to ensure zero impact on the existing structure. The design method utilising routine finite element tools (Plaxis 3D) was used to deliver an optimised piled foundation solution that aimed to not only solve the issue but also avoid overly excessive conservative design. The paper also explores the design option to utilise passive bar anchors in moderate to high strength rocks on future projects. This could lead to considerable savings on the cost of these foundations compared to the use of bored piles which is the norm in Sydney.

RÉSUMÉ: Une collision directe d'un train déraillé sur un quai de pont peut entraîner l'effondrement total d'un pont. Toutefois, la défaillance de la passerelle à la suite d'un déraillement pourrait être considérée comme un incident rare, mais il ne fait aucun doute que son impact sur le train et le pont a des conséquences catastrophiques. Afin d'éviter un incident aussi désastreux, les murs de déflexion sont conçus pour résister à une charge de collision potentielle. Cet article décrit les défis de la conception de murs de déflexion pour les ponts existants sur le projet de train léger parramatta à Sydney. La protection contre le déraillement des ponts comprend généralement des murs de déflexion du côté d'approche des piliers du pont. La conception du mur de déflexion est entreprise en référence à l'AS5100 (2017). Dans cet article, une méthodologie de conception économique est détaillée pour l'évaluation et le comportement des murs de déflexion sous les chargements uls. Les principaux défis dans la conception du mur de déflexion résultent des exigences récentes du code pour concevoir ces éléments afin d'assurer un impact nul sur la structure existante. La méthode de conception utilisant des outils d'éléments finis de routine (Plaxis 3D) a été utilisée pour fournir une solution de fondation empilée optimisée qui visait non seulement à résoudre le problème, mais aussi à éviter un design conservateur trop excessif. Le document explore également l'option de conception pour utiliser des ancrages de barres passives dans des roches à résistance modérée à élevée sur de futurs projets. Cela pourrait conduire à des économies considérables sur le coût de ces fondations par rapport à l'utilisation de piles ennuyées qui est la norme à Sydney.

KEYWORDS: deflection walls, bridge collision, bridge protection, rail impact, pile foundations

1 INTRODUCTION

Parramatta Light Rail is announced by the NSW Government as a key component of an integrated transport network supporting Western Sydney growth. Parramatta Light Rail is a part of $2.4 Billion program and consists of two stages. Stage 1 of this network (PLR Stage 1) comprises of an approximate 12km two-way track alignment connecting Westmead to Carlingford via the Parramatta CBD and Camellia, see Figure 1.

Stage 2 will link Stage 1 to Sydney Metro West, existing heavy rail network in Parramatta and Sydney Olympic Park, and ferry services at Rydalmere and Sydney Olympic Park.

The PLR Stage 1 alignment will run through the existing T6 Carlingford Line rail (single lane) corridor. One of the key scope and performance requirements (SPR) of the PLR is to preserve and protect existing structures. This becomes potential derailment impact challenge where rail tracks are in the vicinity of existing bridge piers. In order to prevent the catastrophic consequence of derailment, deflection walls are designed to withstand potential collision load; this was considered for three PLR bridges: Victoria Road Overbridge, Adderton Road Overbridge and Pennant Hills Road Overbridge.

This paper details the design process adopted on the project for the analysis and design of deflection walls. Deflection walls from the outset seem a simple design element. However, recent code changes and requirements to design for 'collision loads applied to the deflection wall are not transferred to the primary structural element' make the problem an interesting engineering endeavour. This paper uses 'Pennant Hills Road Bridge' (see Figure 3) as a case study, detailing the analysis, assumptions and engineering judgement used to complete the delivery of protection works.

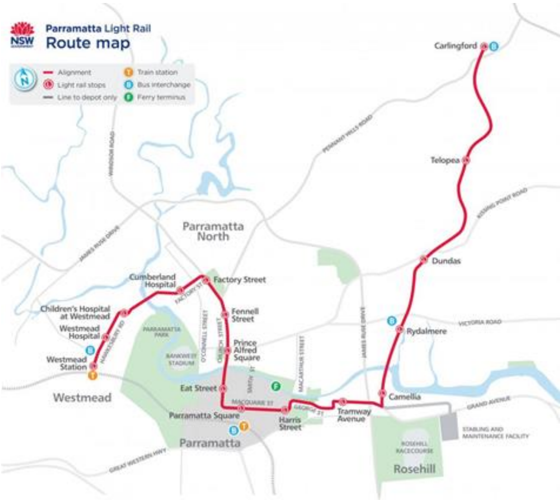

Figure 1. PLR route alignment.

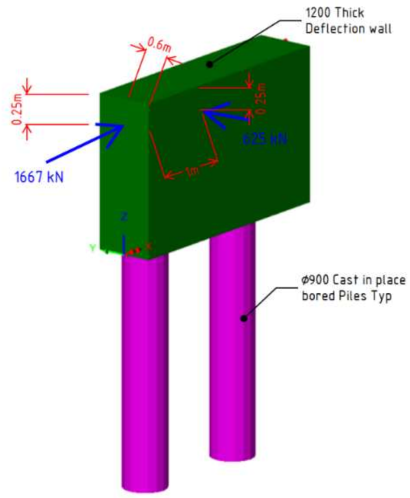

Figure 2. Typical PLR deflection wall geometry and loading for light rail

2 CHALLENGES IN DEFLECTION WALL DESIGN

The challenges identified in the deflection wall design are a result of new code provisions, i.e. to ensure collision loads applied to the deflection wall result in no transfer of load to the primary structural element.

Other than no load transfer on to the existing structure, several other design challenges were identified during design process, which included:

- The methodology to determine the length of the deflection wall is not explicitly defined in AS 5100.
- Confusion in regard to load cases. Given that deflection walls are designed for one ULS load case. Aiming to differentiate ULS and SLS load components in FEM models may lead to overdesign.
- As the standards provide limited guidance on level of impact (or transfer of load), an acceptable level of impact must be determined by the designer in cases where it is not possible to fully achieve “no impact”, particularly in the case of foundations.

Use of FEM analysis for pile analysis and design may result in overdesign if the impact load case is treated as a “SLS”. Thus, requiring the actions from the FEM model to be factored further for member design, which results in overdesign, as the loading provided in the code is already ULS. Therefore, to demonstrate compliance from a geotechnical strength reduction perspective and satisfy the requirements of AS2159; these factors must be introduced into the numerical modelling process.

3 AUSTRALIAN STANDARD REQUIREMENTS FOR DEFLECTION WALLS

The revised AS 5100-2017 Bridge Design code was published by Standards Australia on 31 March 2017. This revised standard contains new provisions for deflection walls to prevent collision with bridge supports. Furthermore, the design collision longitudinal load in AS 5100.2 has been increased from 3000 kN to 4000 kN.

The following are the new provisions in AS5100.1-2017. The new clause redefines the entire provision for deflection walls.

3.1 *Key code requirements (Clause 15.3.6)*

The purpose of a deflection wall is to prevent a head-on impact with a primary structural element including pier or abutment for structures above rail, or end of a through truss, arch or through girder for rail bridges.

Deflection walls shall be designed for the collision loads specified in Clause 11.4.2.3 or Clause 11.4.3 of AS5100.2.

NOTE: This is in addition to the requirement for the pier or abutment to be designed for the same collision loads.

The design shall ensure that the collision loads applied to the deflection wall are not transferred to the primary structural element (Clause 15.3.6).

The deflection wall shall be designed as a continuous concrete wall.

The minimum height of the deflection wall shall be 2.0 m above rail, or not less than the top of the uppermost primary structural element, whichever is lower.

The deflection wall shall have a minimum thickness of 500 mm. The wall face shall be smooth with no snagging points, including at a transition from deflection wall to a primary structural element. The design of the transition shall allow for the lateral movement of the deflection wall due to the collision loads.

The approach end of the deflection wall shall be rounded.

Unless approved otherwise by the relevant authorities, deflection walls shall be provided in the following locations:

1. *On the approach to a retained abutment, through truss, through arch or through girder in order to protect a derailed train from head-on impact with the abutment and wing wall, truss, arch or through girder. The angle between an abutment wall or deflection wall and the rail tracks shall not exceed 20 degrees. The deflection wall may also be incorporated as the abutment wing wall.*
2. *On the approach to a pier other than a frangible pier. The deflection wall shall be aligned with the pier, extending the pier towards an approaching train.*

The length of the deflection wall shall be determined from a risk assessment or as specified by the relevant authorities.

The above new clauses for deflection walls represent a major change to enhance protection against head-on collisions by:

- Deflecting a train derailed on the approaches to the pier.
- Providing a point of impact away from the pier end.
- Providing some impact energy dissipation before impacting the pier wall.
  (Rapattoni et al., 2017)

The main geotechnical design challenge identified in the deflection wall design results from the new provision to ensure collision loads applied to the deflection wall have no load transfer on the (existing) support structure. Whilst this may be attainable for above ground structures, this cannot be attained absolutely for the foundations where some amount of stress and strain transfer from the impact will be transferred to the bridge foundation. Therefore, engineering judgement is required in evaluating this requirement.

As deflection walls are built in close proximity to the bridge, the passive pressure transfer through the ground cannot be restrained to zero. Typically, deflection walls are built with pile foundations, which require both lateral restraint and vertical restraint to perform. Very long and large deflection walls would be needed to make these systems work predominantly in push-pull. Designing the geometry of the wall to ensure majority of the load is resolved in push-pull becomes uneconomical as the size of the size of the wall becomes very large. On the PLR project numerical modelling was used as the primary tool to assess the deformations and load transfer characteristics of the deflection wall. A level of risk-based reasoning was used applied to justify an acceptable level of load transfer to the bridge foundations.

4 PENNANT HILLS ROAD OVERBRIDGE

4.1 *Existing structure*

The existing bridge (see, Figure 3) was built in 1940. The overlength of the bridge is 24.4m, consisting of a 7.61m (span 1), a 9.22m (span 2) and a 7.56m (span 3). The bridge has a carriageway width of 12.7m and carries four lanes of traffic. The bridge deck is skew at an angle of 40 degrees.

The bridge has twelve rolled steel joist (RSJ) girders, continuous over piers and reinforced with a concrete deck slab. The girders are supported by steel trestle piers and concrete sill beam abutments. The steel pier trestles are supported on concrete strip footing. The bridge pier footings are founded on weathered Shale (Class V/IV – Pells et al., 2019), with 0.5m (approx.) embedment.

Figure 3. Pennants Hills bridge

4.2 *Proposed bridge modifications*

The existing Pennant Hills Road Overbridge is to be retained and modified to suit the operation of PLR. The modifications to the existing bridge comprise retrofitting a shared cycleway and footpath known as an Active Transport Link (ATL) by excavating and supporting a cut into the eastern abutment and installation of deflection wall at the ends of the main support piers, see Figure 4.

The deflection walls are located at the ends of the piers, are 1200mm thick and extend 2.0 m above rail level and have a length of 5.0m. The length of the deflection wall was agreed with the client based on similar size walls used on other projects. A 50mm gap filled with compressible fibre board is provided between the existing structure and the new deflection wall. This gap allows the deflection wall to undergo movement towards the existing structure due to collision load with negligible load transfer.

The cast-in place concrete deflection walls are supported directly on top of two 900mm diameter piles without pile caps.

The existing pier trestle on either side of the railway track are infilled with a reinforced concrete wall to provide a continuous smooth face designed for collision loads meeting the requirements of AS 5100.1 Section 15.3.4 and AS 5100.2 Section 11.4.3. These concrete encasements extend to a height of 3.6m above the rail level and thickness of 900mm similar to the pier masonry footings. The top of existing pier footings is approximately 1.6m above top of rail level.

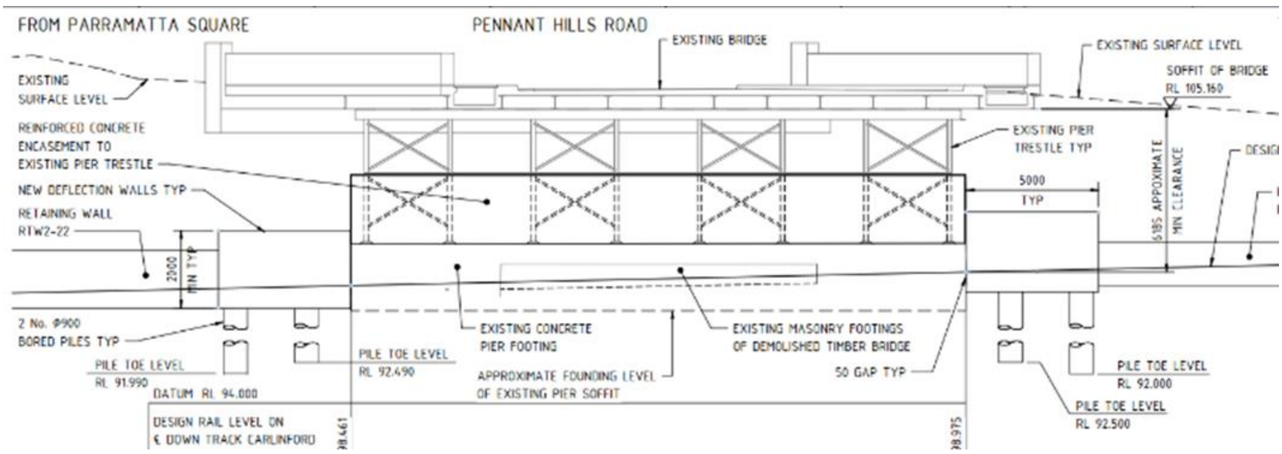

Figure 4. Elevation of proposed protective works

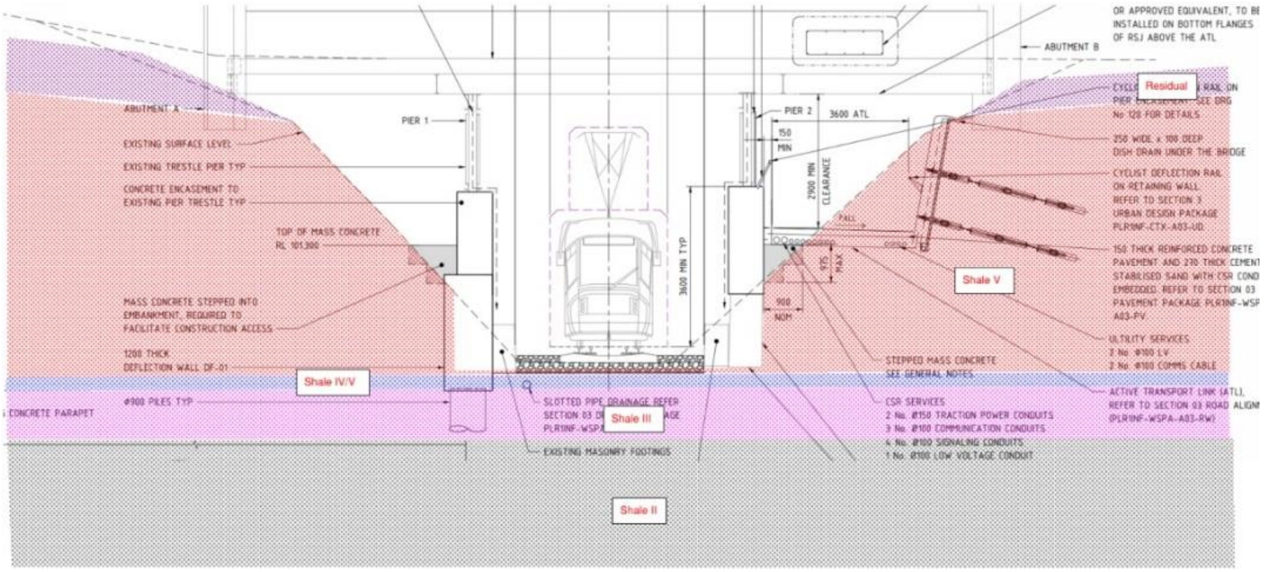

Figure 5. Ground model

4.3 *Geological conditions and geometry*

The geological formations encountered along the project comprise of; fill layers of variable thickness and nature overlying a thin layer of residual formation, followed by bedrock. The ground profile at Pennant Hills Road Bridge consists of residual soils of 0.5m overlaying weathered rock. The existing cutting has been excavated in primarily low to very low strength, extr -emely weathered shale (Class V). The base of the cutting is in slightly weathered to fresh shale, of medium to high strength. The bridge pier footings are founded on the boun -dary of Class V/IV.

5 GEOTECHNICAL DESIGN OF DEFLECTION WALLS

On finalising the wall geometry and pile locations of the deflection walls, the foundation and structural designs were jointly undertaken to analyse the performance and ability of the system to meet code requirements. Plaxis3D was used as the primary tool of design analysis and validation on the project. Plaxis was selected based on the design teams experience with the code, however, this paper provides a general framework which can be adopted in other similar packages.

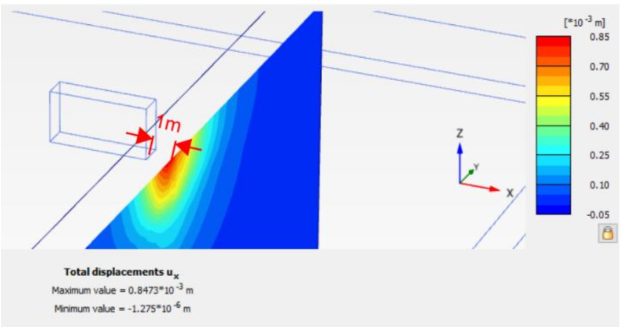

Figure 6. Assessing lateral deformation impacting the bridge foundation

5.1 *Design assumptions, loading and limitations*

The applied deflection wall loadings (or design action effects) comprise two concurrently acting ULS lateral impact loads (see Figure 2) applied to the top of the leading face and top corner of the trackside face of the deflection wall. These loads were provided by the Structural Engineer and were in accordance with ASA Standard T LR CI 12500 ST. These forces are resisted by the axial (push-pull of piles), and passive restraint from the rock, resulting in bending, and shear forces generated in the piles.

5.2 *Design workflow*

The design and modelling workflow comprised of the following steps:

A) Develop subsurface profile in accordance with available information.
B) Assign geotechnical parameters for foundation design for each soil and rock class.
C) Define pile capacities (end bearing and friction).
D) Define embedded pile row properties for initial pile length assumption.
E) Develop geometry for piles and deflection wall.
F) Run ULS load case for design impact load (PLAXIS 3D)
G) Assess deformation and pile forces. Revise pile length & pile spacing if required (PLAXIS 3D).
H) Assess deformations, pile loads, and stress transfer (PLAXIS 3D).
I) Finally, run a Safety Analysis to assess the robustness of the design. For example, a typical strength reduction factor of 0.56, equates to target SumMsf of 1.76 within Plaxis. Revise pile length & pile spacing as required.
J) Define the maximum axial, shear, and moment in the piles from the dominating cases (ULS or Safety analysis) (PLAXIS 3D). Revise pile length & pile spacing if required
K) Assess the lateral loads applied to the bridge foundation. If excessive load transfer occurs, revise pile spacing or deflection wall size to increase load transfer via push pull. The designer should use engineering judgement to assess and justify what is a reasonable amount of load transfer to the existing footing structure or foundation stratum. As AS5100 requires the collision loads applied to the deflection wall are not transferred to the primary structural element; whilst this may be attainable for above ground structures, zero load

transfer is not possible for foundation-footing elements. As the two elements (bridge foundation & deflection wall) share the same ground, on PLR in order to demonstrate compliance the lateral deformation was to limited to <1mm which was judged to demonstrate negligible level of impact via deflection and stress change within the bearing stratum (See Figure 6).

Design geometry may need to be modified within steps F to K on a trial and error basis to satisfy either strength, deflection, and or load transfer requirements.

5.3 *Plaxis 3D modelling characteristics*

The ground conditions at Pennant Hills Road overbridge consisted primarily of weathered shale. The rock structure and defect spacings were considered to be large in relation to the problem geometry and loading. Therefore, the use of continuum properties for the rock was justified in this case.

The shale was modelled using linear elastic- perfectly plastic (LEPP) stress-strain relationship, with Mohr-Coulomb yielding criteria. The rock mass characteristics were based on Hoek-Brown analysis using site specific UCS data to derive characteristic properties.

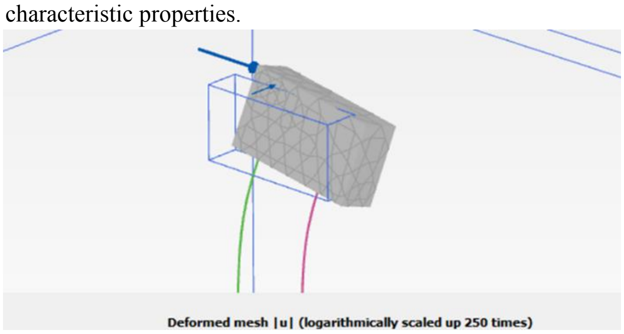

Figure 7. Overall deflection wall response

The pile behaviour was modelled using embedded pile elements with shaft adhesion and bearing capacity predefined. The capacity of the piles within the model satisfied the requirements of AS5100.3.

Figure 7. Overall deflection wall response

5.4 PLAXIS *modelling steps*

Three stages of analysis were performed:

Stage 1: Generate initial conditions (Ko – procedure)

Stage 1 of the model generates the in-situ stress state in the rock. For this stage Ko (earth pressure coefficient at rest) is calculated using the Jaky (1944) equation for normally consolidated soils where

$$Ko = 1 - \sin(\emptyset')$$

This was an acceptable approach, as the lateral pressures have been cautiously taken into consideration. Higher than Ko pressures are routine for excavations and tunnelling problems as the anisotropic stress state is critical to member design. For shallow piling problems it is conservative to ignore any benefit of higher in-situ locked-in lateral stresses in the analysis and design of laterally loaded piles.

Stage 2: SLS analysis

Stage 2 of the model assessed the forces and deflections (Figure 8) of the piles with characteristic rock strength parameters as per routine SLS analysis. This stage is also used to assess the deformations and stresses at the bridge pier position.

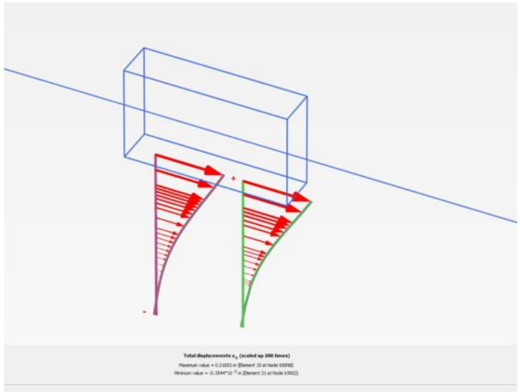

Figure 8. Assessing pile response

Stage 3: ULS: Safety analysis with reduced shear strength parameters

Stage 3 of the model represents a ULS case which is undertaken to check the forces in the piles with reduced rock strength parameters to define an ultimate condition for the rock strength (see Figure 9).

This method reduces the c' and ϕ' values incrementally to a predefined target value. The predefined value is set based on the site geotechnical strength reduction factor (AS2159-2009).

During this stage additional yielding occurs due to the reduced strength in the rock mass, thus increasing the bending, shear, and axial forces in the piles. The deformations of course also increase. However, the two-pile system, which is predominantly working in push-pull generally is able to accommodate the applied strength reduction. This step is primarily for checking the robustness of the lateral capacity. In cases where the axial capacity is large and can be confidently gauged; there is only marginal increase in bending during this stage. If non-convergence does occur; a first step fix would be to increase pile spacing.

The advantage of adopting a target MSf (phi/c reduction) method to demonstrate code compliance was found to be more economical, than traditional methods. In routine practice the modelling is undertaken using characteristic strength and stiffness properties (Stage 2). The structural actions from this analysis are factored by 1.5 (typically) to derive ultimate design actions for design of members. Adopting such a method for deflection wall design results in excessively high pile forces. This is because the applied load is already an ultimate limit state load provided to the geotechnical engineer. Therefore, by introducing strength reduction into the soil-structure modelling process results in a justifiable economical design. Through the design and review processes of the project, the acceptance from TfNSW and Certifiers was obtained for the design to be certified for construction.

The use of workflow detailed here and adopting the safety analysis approach provides a tool to satisfy factor of safety requirements, whilst still ensuring the design process assesses robustness; which is the fundamental aim of the new code.

If a designer is undertaking the design of a one-off deflection wall, extensive overdesign using routine simplified lateral pile design methods such as Broms (1964) may not warrant a concern for the client or contractor. However, if the same approach is undertaken on a new rail line or new road project with extensive number of bridge structures requiring collision protection, the design of these protection measures would likely become uneconomical. Undertaking simplified bespoke FEM analysis of foundation systems can lead to efficient and cost savings, without requiring extensive modelling effort by the designer. The model also becomes a one stop tool to understand and demonstrate impacts on adjacent elements.

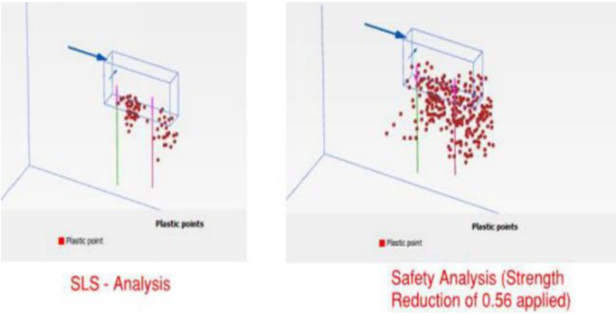

Figure 9. Yielding behaviour (characteristic- SLS and ULS -strength reduction)

6 ALTERNATIVE DESIGN CONCEPT

The PLR project design and construction team early in the design process aimed to provide a novel design of a deflection wall using passive anchors (rock bolts) as the primary elements to transfer the impact load into the ground. An example of an early working model of an 'anchored down – un-zipping' deflection wall is shown in Figure 10. The aim of this deflection wall was to provide a 'so called' unzipping response under impact. Given that an impact load is dynamic problem of energy dissipation; the safety implications of considering such an approach were considered to be advantageous. On the PLR project this idea was curtailed due to construction constraints and buildability of installing inclined passive anchors close to the existing structure and potential review and approval delays in proving the new concept, the concept was not pursued past early level modelling. The use of 'un-zipping passive anchors/rock bolts could provide cost saving in terms of the systems efficiency, load-deformation behaviour, and overall ease of construction and ability to test and confirm the capacity. It is also beneficial as the system allows the transfer of lateral loads away from the superstructure foundation, thus, being closer to a solution which achieves limited foundation load transfer.

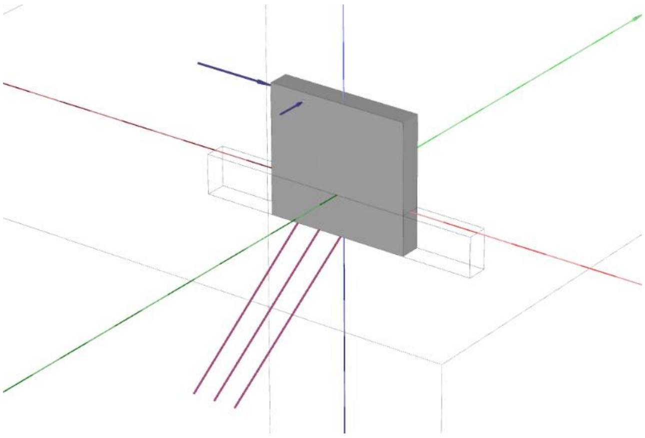

Figure 10. Deflection wall restrained with inclined rock bolts

7 CONCLUSIONS

The design of deflection walls presented in this paper is aimed to provide an overview of the approach to deflection wall design adopted on the PLR project. The method could be used in similar ground conditions and design constraints. The paper has highlighted the issues of interaction, load transfer, and design economy.

There will be cases where the ground conditions are not so straightforward; leading to further challenges. In such scenarios the designer will need to have an appreciation for the critical failure modes and modify the design methodology and modelling to provide robustness for the additional uncertainties. Nevertheless, the overall aim of this paper is to demonstrate numerical tools such as Plaxis3D are now fast and efficient and can be used with focus on simplified purpose-built models for efficient design solutions.

8 ACKNOWLEDGEMENTS

The authors acknowledge the support of WSP Aurecon Design Joint Venture in the preparation of this paper and the Parramatta Connect CPB-Downer Construction Joint Venture for the approval to publish this paper.

The authors gratefully acknowledge the contribution of fellow colleagues for their ongoing support and guidance in the review and overall development of this paper.

9 REFERENCES

AS 5100 – 2017 Bridge Design Standard, Standards Australia

Broms, B. 1964a. The Lateral Resistance of piles in cohesionless soils. Journal of the Soil Mechanics & Foundation Divisions. ASCE, Vol. 90, Issue 3, pp. 123-156.

Broms, B. 1964a. The Lateral Resistance of piles in cohesive soils. Journal of the Soil Mechanics & Foundation Divisions. ASCE, Vol. 90, Issue 2, pp. 27-63.

Hossein, J. 2006. "A New approach in determining the load transfer mechanisms in Fully grouted bolts. University of Wollongong Thesis.

Pells, P.J.N., Mostyn, G., Bertuzzi, R. and Wong, P.K. 2019. Classification of Sandstones and Shales in the Sydney

Potts, D. M. and Zdravkovic´, L. 1999. Finite Element Analysis in Geotechnical Engineering: Theory. London: Thomas Telford.

Rapattoni, F and Grzebieta, R, H 2011. "Railway Bridges – Safety in design for train derailments" Proceedings of AUSTROADS Seventh Conference, Sydney, September 2011.

Rapattoni, F and Muscat, J, H 2014. "Safety in Design for Railway Bridges – New Provisions in AS5100-2015" Proceedings of AUSTROADS Ninth Conference, Sydney, September 2014.

Rapattoni, F, 2004. "Safety first for Bridges – by design", Proceedings of AUSTROADS Fifth Conference, Hobart, 2004.

Rapattoni, F, 2009. "AS 5100 Bridge Design Standard – Focus on Safety for Railway Bridges" Proceedings of AUSTROADS Sixth Conference, Auckland, May 2009

Rapattoni, F, Dauth, J, Muscat J and Prasad P. "Derailed Train Collisions – Leading Safety Provisions in Bridge Design to Prevent Disasters" Proceedings of AUSTROADS Tenth Conference, Melbourne, April 2017.

Reese, L. C., Cox, W. R. and Koop, F. D. 1974. Analysis of laterally loaded piles in sand. In Proceedings of the 6th Offshore Technical Conference, Houston, Texas, Paper 2080, pp. 473–483

Region: a Forty Year Review. Australian Geomechanics, Vol. 54, No.2, June 2019