Case History

Geotechnical Design of Transition Structures for the Port Botany Expansion

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Abstract:-

The Port Botany Expansion (PBE) project involves the construction of an extension to the existing port in Sydney, Australia. The transition between the new structures and the existing Brotherson Dock (EBD) structures is a critical aspect of the geotechnical design. The Client, Sydney Ports Corporation (SPC), specified tight differential movement and settlement limitations for the transition between the new and old structures, including a stringent 5mm differential movement limit (horizontal and vertical) up to 20 years after handover of the new terminal. The subsequent geotechnical and structural design of transition structures included measures to comply with these movement limits. The Main Contractor, Baulderstone Hornibrook – Jan de Nul (BHJDN) are carrying out construction trials, in-situ testing and movement monitoring to assess performance against Golder Associates' (Golder) design predictions. This paper describes the key design issues, design approach and verification processes established to confirm the predicted behaviour of the structures and surface infrastructure in order to satisfy criteria extending up to 50 years following handover.

Introduction

The PBE project comprises a new container terminal on the north-eastern shore of Botany Bay, about 12 kilometres south of the Sydney CBD. The new terminal lies between the existing port and the parallel runway at Sydney International Airport, extending approximately 550 metres west and 1,300 metres north of the northern quay of the EBD container terminal and covering an area of approximately 63 hectares. The project includes reclamation of the terminal area from Botany Bay and construction of 2 kilometres of berth structures, breakwaters, bridges, access corridors and revetments associated with the port facility.

In this paper the writer discusses the geotechnical design of the transition structures that connect the new and existing container terminals. Two anchored caisson structures weighing 2100t (Main Blockwork) and 684t (Infill Blockwork) form the transition with the EBD. Geotechnical analyses and design work included all aspects of geotechnical stability and serviceability design of retaining structures, including assessing the effect on the existing structures.

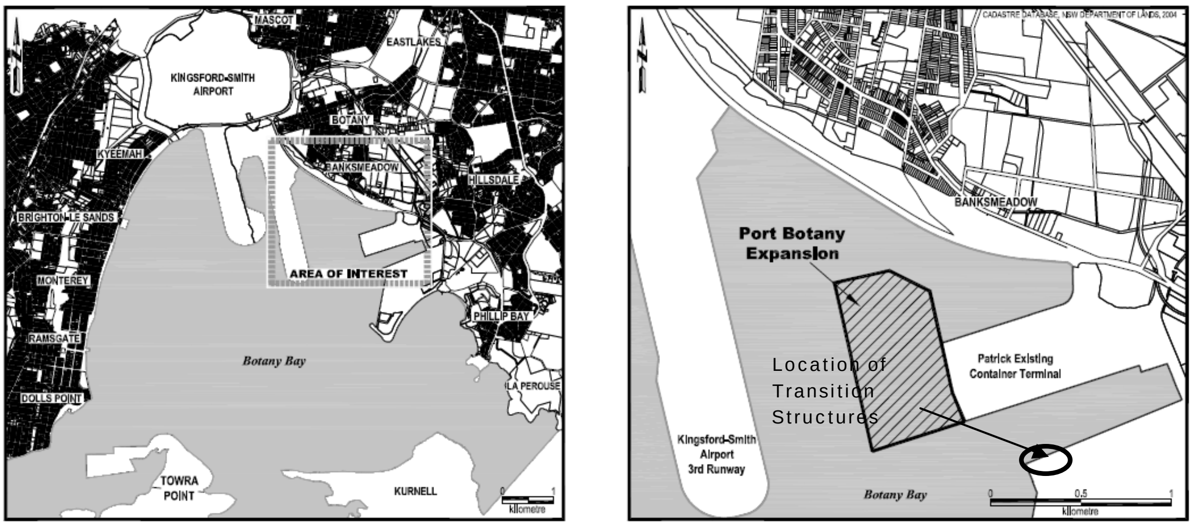

Figure 1: Plan View of Port Botany Expansion Project

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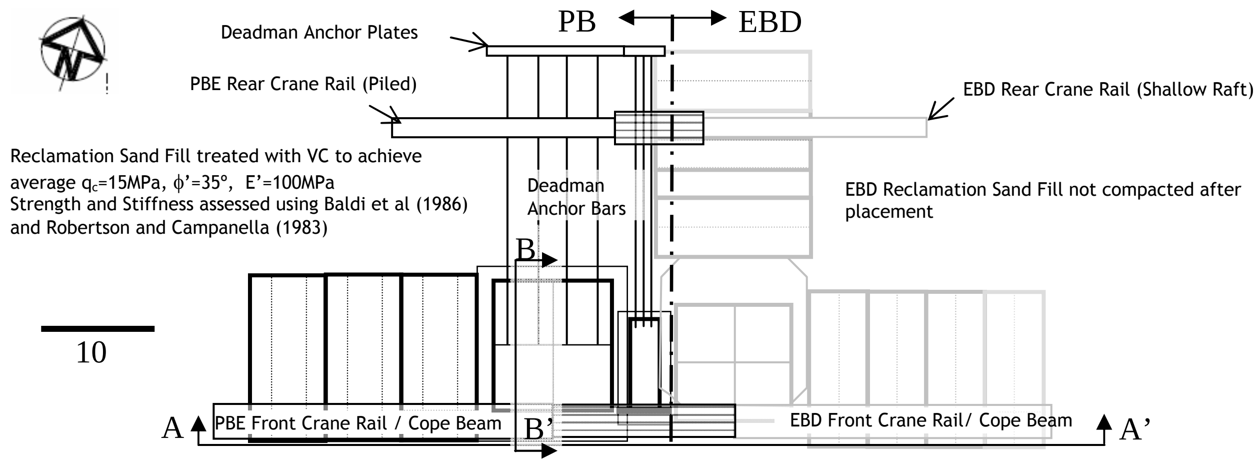

Figure 2: Plan View of Transition Structures

The Golder design team used a wide range of geotechnical software packages, including PLAXIS, Slope/W and Settle 3D. Other issues considered during the design included the effect of vibrocompaction close to the structures and assessment of bearing capacity under seismic loading. An important aspect of the design involved modelling the performance of the existing berth structure; designed to different design standards than the new structure as reported by Moss-Morris (1981). There was uncertainty regarding the historic loading regime applied to the existing structure. This lead to discussion on how the previous loading of the structure could affect ongoing movements once the new port terminal is in operation.

Geological model

The design team reviewed the geology of Botany Bay as part of the overall design, the geology of the locality is well summarised by Thorne (1985). As part of the design, a geotechnical model for the transition structures was developed as shown in section A-A' below:

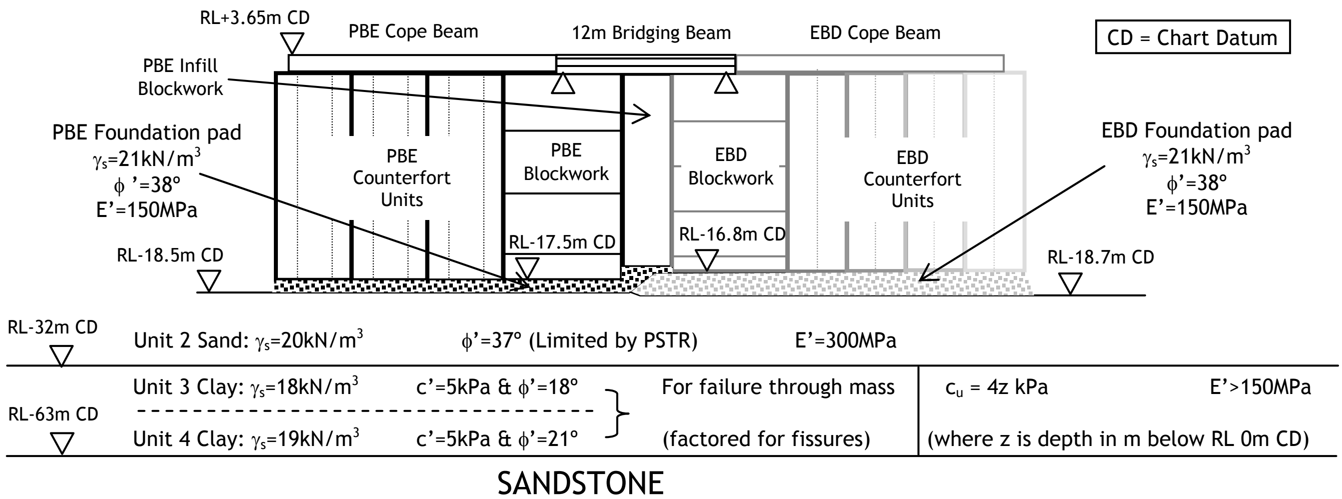

Figure 3: Section A-A': Geotechnical Model and Geotechnical Design Parameters for Transition Structures

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At the location of the transition structures approximately 15m of dense Unit 2 sands exist over the Unit 3 fissured clays. This profile meant that fissured clays had less impact on the design of the transition structures than some counterfort walls on the site. The design of the counterfort structures incorporates a sand foundation trench, compacted using vibrocompaction. Discussion of the influence of fissured clays on the design of structures has been discussed extensively by Thorne (1984). Further discussion of the fissured clays in relation to the recent PBE design work would be valuable to add to the existing knowledge of these materials.

Design Requirements

The design of the transition structures needed to satisfy stability, settlement and movement criteria, which SPC specified in the Project Scope and Technical Requirements (PSTR). This document also specified the surface, crane and mooring loads that the new berth structures need to carry, including point loads to be applied to the EBD blockwork structure. Discussions were held between Golder, the structural designers Hyder Consulting and Scott Wilson and SPC to develop appropriate load cases for geotechnical analysis of the EBD blockwork structure, taking into account structural redistribution of loads.

2D PLAXIS modelling included different loads before and after construction of the PBE transition blockwork structures, taking into account structural re-distribution effects. The design assumed that the use of the western end of the EBD will not change significantly after construction of the new terminal. Additional live loading of the existing blockwork will be primarily due to crane rail load transferred across the bridging beam between new and old terminals. Operational loads used for the initial design development are shown in Table 1:

Table 1: Loads for PBE Transition Blockwork Structures and EBD Blockwork Structures

Proposed PBE Transition Blockwork Structures	Sustained Loads		Transient Loads	
Surface Loading between the front and rear crane rails	40kPa		40kPa	
Surface Loading landward of the rear crane rail	60kPa		60kPa	
Vertical Crane Load on the front crane rail	350kN/m		970kN/m	
Horizontal Crane Load on the front crane rail	N/A		97kN/m	
Vertical Crane Load on the rear crane rail	460kN/m		Up to 1000kN/m	
Horizontal Crane Load on the rear crane rail	N/A		Up to 100kN/m	
Horizontal Mooring Load on the cope beam	N/A		91kN/m	
Existing EBD Blockwork Structure	**Sustained Loads**		**Transient Loads**	
Surface Loading landward of the front crane rail	40kPa		40kPa	
Vertical Crane Load on the front crane rail	290kN/m [1]	385kN/m [2]	N/A	507kN/m [2]
Horizontal Crane Load on the front crane rail	29kN/m [1]	39kN/m [2]	N/A	51kN/m [2]
Vertical Crane Load on the rear crane rail	125kN/m [1]	250kN/m [2]	N/A	250kN/m [2]
Horizontal Crane Load on the rear crane rail	N/A	N/A	N/A	26.5kN/m [2]
Horizontal Mooring Load on the cope beam	25kN/m [1]	25kN/m [2]	25kN/m [1]	25kN/m [2]

1. ‘Historical Loads’ used to assess performance of EBD Blockwork prior to the construction of PBE.
2. ‘Future Loads’ used to assess performance of EBD Blockwork after handover of PBE (operational use of the new port).

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The sustained loads shown above are for "normal" crane operations. The transient loads assume that a 1 in 500 year storm causes higher loads as it pushes cranes and moored vessels away from the wharf structures. The most onerous load case used for the design of the transition blockworks included both transient crane loads and transient mooring loads.

The PSTR set the following movement limits for the PBE blockwork structure:

- Total vertical settlement of PBE blockwork to be less than 40mm after 20 years.
- Total horizontal movement of PBE blockwork to be less than 40mm after 20 years.
- Vertical differential settlement between EBD and PBE blockworks to be less than 5mm over 5m after 20 years.
- Horizontal differential settlement between EBD and PBE blockworks to be less than 5mm over 5m after 20 years.

In addition, the PSTR specified the stringent differential movement and settlement criteria to provide crane beam continuity between the new and old docks. If future movement exceeds these limits then the crane rails would need to be reset, resulting in potential disruption to the new and old terminal operators and potential commercial ramifications.

The PSTR required that the design had to achieve the following minimum Factors of Safety (FOS):

- Bearing capacity: 3.00
- Sliding and Overturning: 2.00
- Global Stability: 1.50 Circular / 1.40 Non-circular / 1.10 Design Earthquake Event (1 in 1,000AEP Earthquake)

Design Solution

PLAXIS software was used to model the movement of the structure and earth pressures acting on the structure at different times during construction and the operational life of the structure. Global stability of the structures was assessed using SLOPE/W software and spreadsheets were used to check the stability of the structure using limit equilibrium analyses for sliding, overturning and bearing capacity.

Deformation Analyses

The design team used PLAXIS software to assess the total and differential deformation behaviour of the EBD and PBE blockwork structures and to estimate the earth pressures acting behind the structures; both during construction and in operation. At an early stage of the design development the design team identified that meeting the differential movement limits between the existing and new structures would be the critical aspect of the design of the transition blockwork. In the 2-D plane-strain analysis a strain hardening model was used for granular materials to limit heave and soft soil creep models for Unit 3 and 4 clays.

The design team back analysed the performance of the EBD counterfort structures using PLAXIS and Settle3D to select the most suitable deformation parameters for the design of the PBE structures. The effect of different deformation parameters for the soil units was modelled, based on laboratory testing results, the design of the EBD as discussed in technical papers historic design reports and statistical assessment. The design deformation parameters were then calibrated to match the measured movement of the EBD counterforts at four locations along the existing dock using the original design loading.

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The movement response of the EBD blockwork due to the new load regime was assessed, based on the design deformation parameters and the design loadings. With the predicted movement of the EBD blockwork available the deformation behaviour of a free-standing PBE blockwork structure was modelled and it was found that horizontal movements of the new blockwork would not comply with the horizontal differential requirements. To reduce movement of the PBE blockwork lightly pre-stressed deadman anchors were added to the proposed structure, in a movement reducing role. The stiffness of these anchors had to be carefully assessed. If their response was too rigid, it could lead to unacceptable differential movements and high structural forces in the PBE blockwork unit and front cope beam. The design has since been completed using four 50mm diameter Maccolloy post-tensioning bars. As the design proceeded the geotechnical team worked collaboratively with the structural designers to ensure compatibility between the movement response and load inputs to the structural and geotechnical models, including the anchorage system.

Even with the deadman anchors, the structures were close to the PSTR compliance limits for differential movement. The geotechnical and structural design team resolved this by reviewing two aspects of the design:

1. Review of the input load cases and the input load distribution assumptions.
2. Extending the length of bridging beam between the new and old structures from 8.6m to 12m.

The load case review found that the transient loadcase used for the PLAXIS modelling included a hypothetical combination of loads; a transient load caused by a crane operating in high winds could not occur at the same time as the transient mooring load under normal port operating procedures. This resulted in a reduction of the maximum horizontal transient loading (Horizontal Crane Load + Horizontal Mooring Load) from 191kN/m to 128kN/m, which caused a similar proportional reduction in predicted horizontal movement of the new blockworks. Extension of the bridging beam helped to improve the differential performance, to achieve the PSTR differential limit criteria.

Assessment of conventional limit equilibrium seismic bearing capacity was supplemented by a displacement based seismic analysis. Seismic displacement criteria were subsequently adopted as the main performance criteria. The dynamic displacement of the PBE blockwork structure was assessed under the design earthquake event (PGA=0.14g) using a 2D dynamic seismic PLAXIS analysis. Interestingly, this analysis showed a similar movement mechanism to recorded movements of port caisson units after the approximately 0.51g Kobe Earthquake (Soga, 1998). The PLAXIS model predicted minimal settlement and a seaward translation of the structure of approximately 30mm. The analysis also showed a reduction of earth pressures towards K_a, during the earthquake which supported the use of a modified Mononobe-Okabe incremental seismic force for sliding and overturning checks (Value used = 130%ΔP_{ae}).

A summary of the static movement predictions from PLAXIS for the PBE blockwork structure is shown in Figures 4 and 5:

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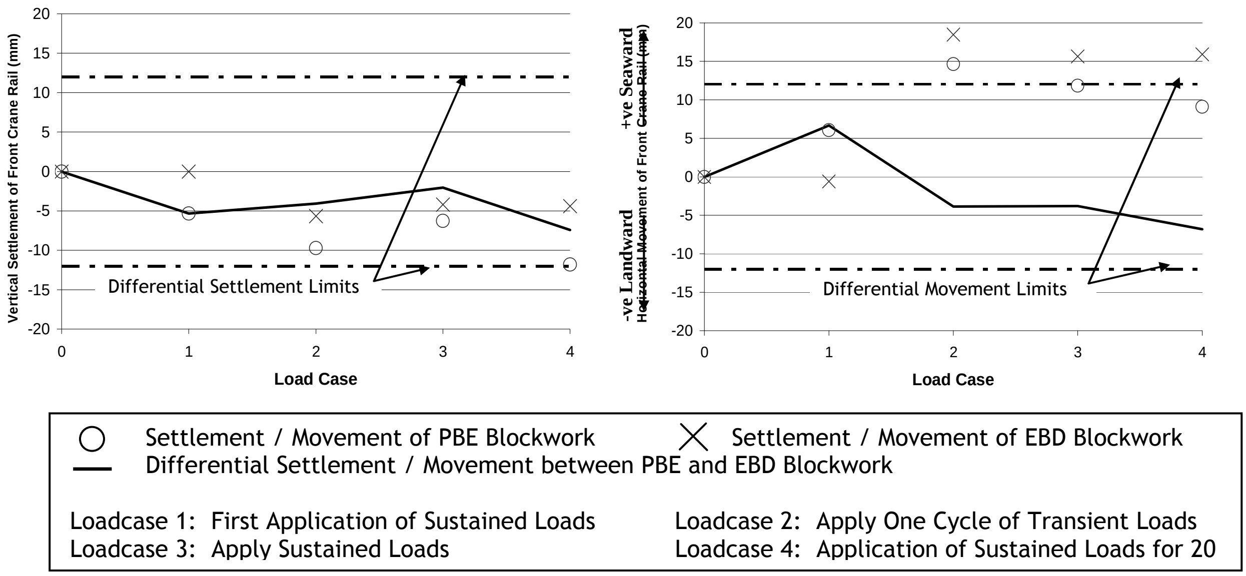

Figure 4: Predicted Movement of New and Existing Structures AT Section B-B' (Figure 3)

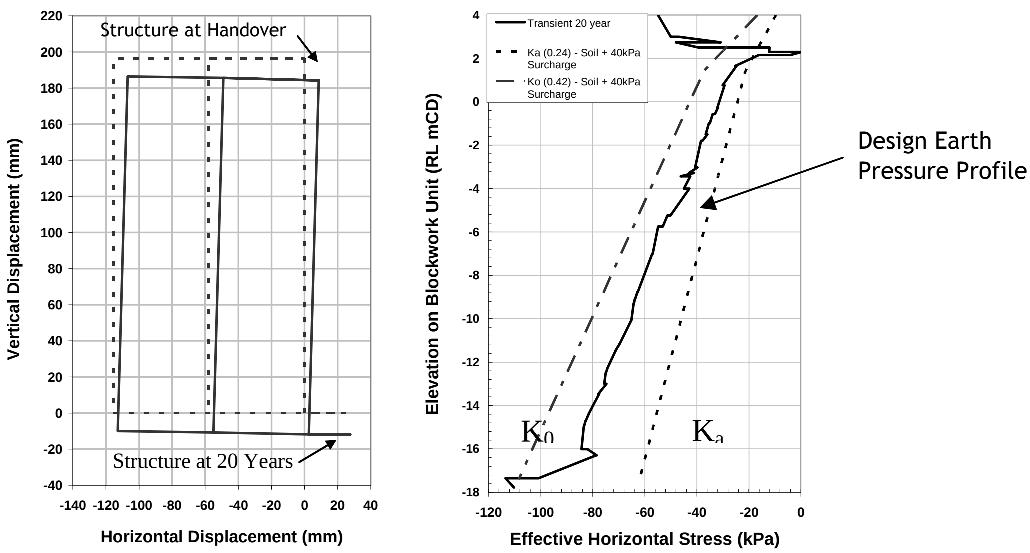

Figure 5: Earth Pressures and Block Deformation: 20 Year Consolidation after Application of Transient Loads

Stability assessment

Spreadsheet calculations were developed to assess the stability of the structures for sliding, overturning and bearing capacity mechanisms at the base of the structure and at the base of the gravel pad. The earth pressures used in the spreadsheets were matched with the earth pressure envelope predicted by the PLAXIS model. The best match occurred using a K_0 earth pressure coefficient in combination with a wall interface friction coefficient of 0.5.

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Base roughening of the blockwork units was also analysed to assess FOS against sliding failure of the blocks. A system of shear teeth on the underside of the base slab was developed to enable a base interface friction coefficient of 1.0 to be used. The design achieved PSTR compliant FOS values and meets the requirements of AS 4678 (2002). Although this Standard adopts a limit state methodology, it supports alternative design approaches including use of global "lumped" geotechnical resistance factors.

Temporary works

Temporary support was required for the EBD counterfort structures to the north of the EBD Blockwork as these were founded at approximately RL-13.5mCD, compared to the required excavation for the PBE blockwork of RL-18.5mCD, a retained height of up to 5m. PLAXIS and hand calculations were used to assess the deformation and shear and moment capacity of a cantilever soldier pile wall, using 10No 840mm diameter, 20mm thick tubular steel piles at 1.5m centres. Movement trigger levels were developed to monitor the performance of the wall as described in Section 4.5.

Effect of Vibrocompaction on Earth Pressures

The potential impact of vibrocompaction (VC) adjacent to retaining structures was reviewed as part of the overall PBE design. It was recognised that the earth pressures acting on structures change with time and are affected by the method of placement of reclamation fill, compaction type and energy and structural movements. A review of published literature found no published method of assessing the impact of VC on retaining structures. The geotechnical team produced a design assessment of the impact of VC, based on previous work by Greenwood et al (1984) and Massarsch and Fellenius (2002). This design assessment indicated that structures are unlikely to experience stressing beyond operational earth-pressures due to VC improvement from q_c 5MPa to 15MPa when carried out beyond a distance of approximately 4 to 5m from the back of the structure.

During the design process the importance of site trials was recognised to assess suitable compaction methods immediately behind the wall. In addition, the potential for use of reduced compaction criteria immediately behind the wall was explored. The objective of this was to balance the risk of creating unacceptably high earth pressures against achieving the required backfill strength and stiffness and thereby acceptable movement performance of the structure.

The risk of locking in higher than designed for stresses was mitigated by the following strategy:

- Consideration of alternative types/sizes of compaction equipment;
- Assessment of an amended compaction procedure, including changing offset distance or lift rate;
- Investigating the possibility of revised compaction criteria immediately behind structures;
- Verification of assumptions at early stage of production works, including CPTs, Pressure Cell monitoring and introduction of Hold Point before commencing production compaction; and
- Pressure cell locations were moved to the eastern end of the East-West berth to allow the effect of production compaction to be verified at an early stage of the construction.

Site trials subsequently proved that reduced energy VC compaction produced earth pressures and vibrations that were acceptable for VC probes located to within 2.5 m of moveable structures. The author plans to document the effects of VC and extensive trial data from the Port Botany site as part of a separate, more detailed technical paper.

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Verification Testing

To provide confidence that the performance of the as-constructed structures is similar to the design predictions, monitoring of the structures is being carried out as an integral part of the construction process. This monitoring considers both the movement of the structure (using tiltmeters, inclinometers and surface monitoring points) and the earth pressures acting behind the structure (using five earth pressure cells down the rear face of the structure). For different construction stages the movement of the structure and the earth pressures acting on the structure were assessed, as shown in Figure 5. Trigger levels were developed for movement and earth pressures using a “traffic light system” to help communicate the action required during construction if movements and/or earth pressures approach or become higher than the design values. This is especially important as there are over 1,000 monitoring points on the PBE site and without an effective action plan to respond to the data collected, critical information could get missed. Currently movements are in accordance with the design predictions. It is anticipated that more information will be provided in a separate paper at a later date.

Acknowledgments

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