Soft ground instrumentation and data management for Woolgoolga to Ballina Pacific Highway upgrade

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ABSTRACT: One of the biggest challenges on the Woolgoolga to Ballina Pacific Highway upgrade involved constructing more than 26 kilometres of road infrastructure over soft ground within one to two years, as part of upgrading 155 kilometres of the Pacific Highway in NSW. This included one of Australia's largest soft ground instrumentation programs. The project is Australia's largest regional public infrastructure project.
The design required instrumentation of embankments on soft ground to meet pavement performance criteria, and address risks of instability of high fill embankments, and the potential impact of the new works on existing infrastructure. Data-management systems and automation maximized the value of site monitoring data collected using GIS and document management capabilities. The project adopted web based real-time reporting which provided high information availability, transparency, efficiency and reliability. This paper provides a frame-work of the system with its unique features and functionalities. It demonstrates the monitoring and feedback process at several sections of the project, looks at innovations introduced as part of the work, discusses how monitoring could be improved, and describes applications of smart digital technology and high-performance computing which were used to facilitate early decision making, and enhance project and client outcomes.

1 PROJECT BACKGROUND AND OVERVIEW

Woolgoolga to Ballina Pacific Highway upgrade (W2B) involved the duplication of 155 kilometres to a four-lane divided road on the Pacific Highway, NSW. The project starts from Woolgoolga, about six kilometres north of Coffs Harbour, and ends about six kilometres south of Ballina, NSW.

Roads and Maritime Services engaged Pacific Complete (PC), a joint venture between Laing O'Rourke and WSP (formerly Parsons Brinckerhoff), as its delivery partner to deliver the W2B.

Key elements of the project included:

- Over 90 cuttings with a maximum depth of up to 44 metres
- Over 143 embankments with a maximum fill height of 16 metres
- Nine grade-separated interchanges,
- More than 60 bridge sites involving mainline carriageway overpasses of waterways, floodplains and local roads, and over 31 overbridges to maintain access to local roads that cross the highway.
- 110 hectares of soft soil sites over 26 kilometre cumulative route length, with compressible ground up to 23 metres thick.

This paper provides an overview of how challenge and innovation was addressed and managed in relation to geotechnical aspects of monitoring data management, and soft ground design across the project and summarises the benefits observed to date. Figure 1 shows the entire route of the project.

2 VALUE ENGINEERING AND INNOVATION

From the earliest engagement of the delivery partner, significant effort was applied to value engineering of the existing owner-developed concept design. This value engineering effort was concentrated in key discipline areas and was proportionate to the cost and/or programme associated with that discipline.

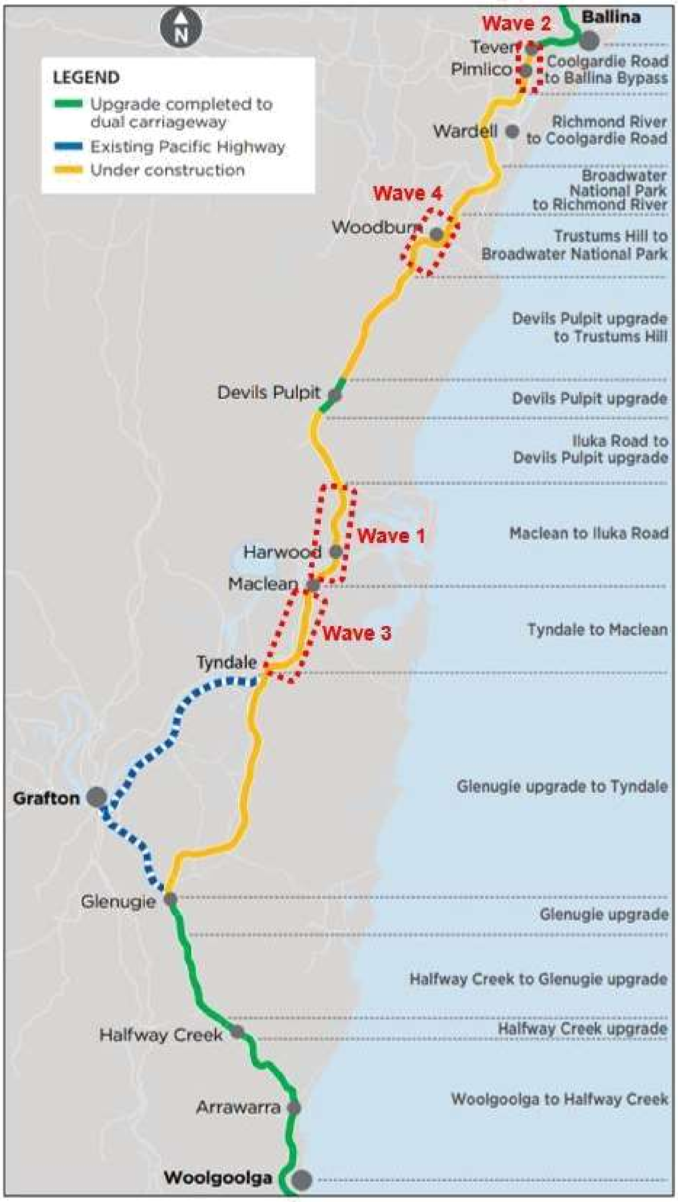

Figure 1. Woolgoolga to Ballina project map and "early works" wave package locations shown in red

Review of value engineering and innovation around geotechnical aspects was completed by the project's Geotechnical Review Group (GRG) which included the writers, who were selected as technical experts representing senior leadership.

"Value engineering" was defined as those changes that yield quantity and/or programme reductions to provide some improved project outcome but did not require any change in Roads and Maritime standards or specifications. They may however have involved some change to the works brief. "Innovation" items are those that required some change to existing Roads and Maritime standards or specifications to yield some improved "public value" outcome. Both value engineering and innovation initiatives served to mitigate cost plan and programme challenges and better align cost plan with project budget.

A subset of value engineering achievements related to instrumentation issues included:

- Instrumentation and monitoring "dashboard" - First online monitoring system implemented with full success on a Roads and Maritime project. Adopted web based real-time reporting which provided high information availability, transparency, efficiency and reliability. PC system automatically warehouses project data and presents real-time dashboard using GIS. Expected savings of \$2.5M in manual information handling costs.
- Soft soil treatment - Design optimisation of soft soil treatment and surcharge designs addressing programme implications. Addressed during design development with emphasis on construction staging to significantly reduce hard treatment. About \$60M of hard treatment removed from initial concept design including:
  - Optimisation of stabilising berms
  - Removal of high strength geotextile
  - Rationalisation of high strength geotextile in Maclean Interchange in Wave 3
  - Reduction of waiting periods for early works surcharged embankments.

3 GROUND CONDITIONS AND SOFT GROUND TREATMENT DESIGN

One of the key challenges on this project was the construction of embankments over deep soft and compressible soils that required ground treatment to address the long-term settlement problems. Soft soils are an important design consideration for the project as there are deep soft soils in floodplain areas along the upgrade. Without soft soil treatment, there is the potential for highway foundations and the alignment to sink and crack because the bearing capacity of the soil is not strong enough to support the highway.

On W2B, site investigation data identified that construction of embankments over these soils would cause significant settlement issues during construction and in the long term if the foundation is not treated well in advance of pavement construction. For this reason, soft soil treatments were started early using an early work contract. There were 11 soft soil sites with the majority covered in an early work "wave" package (Figure 1).

For the soft ground outside the early work, PC provided preliminary design for tender and subsequently Professional Services Contractors (PSC) provided detailed design after the tender was awarded.

Soft ground treatment methods adopted on W2B were as follows:

- Preload only (no surcharge, no wick drains)
- Surcharging (no wick drains)
- Surcharging with wick drains
- Concrete injection columns at critical bridge approaches and box culverts where the above solutions were not viable.

Figure 2 shows a view of Yamba interchange, south of Harwood bridge, at one of the more challenging soft ground areas where some of the above treatment methods were adopted.

Figure 2. Early works construction at Yamba interchange (2017)

3.1 *Design criteria*

Geotechnical design was developed to meet the requirements of the Pacific Highway Design Guidelines, RMS Standards and Technical Guidelines, and relevant Australian Standards. The following criteria were adopted in the design:

1. Total residual settlement (pavement settlement in 40 years): within 100mm and 200mm for rigid and flexible pavement respectively for general embankment; within 50mm in the 20m structural zone from a bridge abutment.
2. Differential settlement: 0.3% and 0.5% in both directions for rigid and flexible pavement respectively.
3. Slope stability: Factor of Safety (FOS) of any batters not less than 1.2 for short term end of construction, flooding and earthquake cases; not less than 1.5 in the long term drained case.
4. Culvert settlement (100 years): within 150mm and 110mm for pipe and box culverts respectively. Pavement settlement to comply with the performance criteria in items 1 & 2 above. The culverts were also designed according to the supplier's recommendations, with differential settlement limited to the design structural or hydraulic tolerances, whichever is more stringent.

3.2 *Short term slope stability assessment*

Accurate prediction of embankment behaviour on soft soil required a systematic process that ideally includes high quality sampling techniques in combination with high quality laboratory and in situ testing data, the adoption of an appropriate constitutive model, and calibration of the constitutive model. Short term slope stability design requires analyses of settlement, lateral deformation and rate of pore water pressure dissipation. On W2B, short term slope stability was monitored and delivered adopting different trigger levels which addressed the rate of lateral displacement as shown in Table 1. Parameters are de-fined in Figure 3.

PC assessed that the trigger levels achieved a minimum calculated FOS of 1.2 to meet design requirements. In addition to the trigger levels in Table 1, the trend of maximum lateral displacement versus fill height was monitored for a decision to slow down or stop filling.

Table 1. Trigger levels for embankments with and without wick drain

Parameter	Wick drains		No wick drains	
	AL	WSL	AL	WSL
hm/S (=DRc)	0.25	0.35	0.5	0.7
hm/ S (=DRi)	0.5	0.7	N.A.	N.A.
hm/ t (mm/day)	10	15	10	15
Action	Increase measurement frequency	Stop filling	Increase measurement frequency	Stop filling

Notes:

h_m = max cumulative horizontal displacement from an inclinometer; S = cumulative settlement from adjacent settlement plate; = incremental; t = time in days; hm/ t = daily lateral displacement; AL = Alert Level; WSL = Work Suspension Level; DRi only applies for high risk areas (Yamba and Maclean Interchanges)

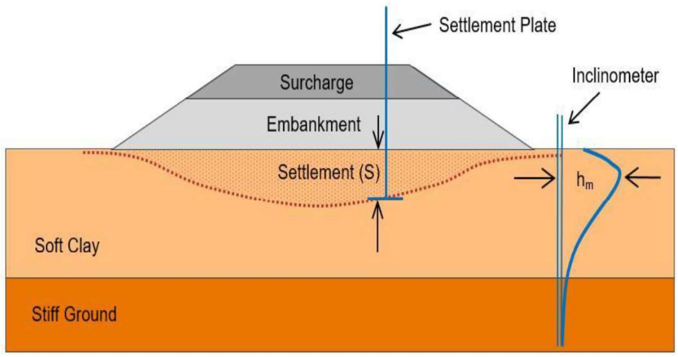

Figure 3. Definition of embankment deformation ratio

Analytical measures adopted by PC to address settlement and slope instability during design and construction included:

- "Field Deformation Analysis (FDA)," based on a simple concept dealing with lateral and vertical de-formation characteristics of soft foundations under embankment stage loading. This method was used to delineate and quantify different settlement components, namely, immediate settlement, consolidation settlement, and creep settlement, from the total settlement measured during field observations, for the loading and consolidation stages (Loga-nathan, 1993).

- Changing the groundwater table with time to match measurements.
- Correcting pore pressure measurements for settlement and changes in the water table.
- Systematically modifying key parameters:
  - Recompression ratio and permeability / coefficient of consolidation prior to the yield pressure being exceeded
  - Yield stress ratio
  - Compression ratio over the stress range of interest
  - Permeability variation with stress level and permeability reduction in wick drain smear zone
  - Creep parameters.

Measuring the progress of consolidation during construction played a critical role in the long-term success of embankments founded on soft soil. Records of its actual performance allowed PC engineers to verify design assumptions and recommend early interventions if its as-built behaviour deviated from predictions. One of the most critical predictive decisions involved assessment of when residual settlements are sufficiently small to allow the construction of settlement-sensitive structures above the embankment, such as the overlying pavement. Accurately recorded consolidation measurements were used to predict embankment behaviour, and provide meaningful estimates of residual settlement.

4 PROGRAM DEVELOPMENT

4.1 *System development*

Online monitoring systems were tried previously on other Roads and Maritime projects but were only partially successful. For W2B an in-house, online monitoring system was developed because of the scale of this project with extensive soft ground treatment.

The system was developed collaboratively by PC who set up the format and calculation process for each instrument type and the link between different instrument types, e.g. inclinometer and settlement plate, piezometer and settlement plate. Review levels were set up to control short term slope instability and hold-point release.

The system was then developed using a data application for data uploading/editing/downloading, a Microsoft SQL Server database for all calculations and the Qlik Sense dashboard with the QlikMap GIS ex-tension for visualisation. A screenshot of the dash-board is shown in Figure 4.

The tables, charts, graphs and maps used are interactively linked to the underlying data, so that selecting a project area, period, instrument type or instrument, will automatically filter the data being displayed on every control. The same session being open on multiple pages, screens or even computers and mobile devices will maintain a link to this dynamic filtering.

The data management process was structured to address the following:

- Alert system – allows anomalies to be reviewed to judge where settlement behaviour was of concern, and where unusual behaviour was caused by errors in the monitoring data. Information about the construction process was integrated with monitoring data to aid interpretation of movement ‘signatures’ in the data.
- Observational approach – to allow flexibility during construction to address unexpected behaviour and implementation of mitigation measures to rectify the as-built condition, and improve long-term project performance.
- Monitoring optimisation – based on historical monitoring data and on engineering judgment, it was possible to identify where there was redundancy in the monitoring system and reduce the amount of monitoring being carried out to reduce costs.
- Forecasting – it was possible to predict when settlement might exceed an acceptable level, thus allowing engineers to introduce contingencies in advance, such as reducing fill placement rate or adding an earthworks berm, and release of hold-points to release fills for pavement construction.

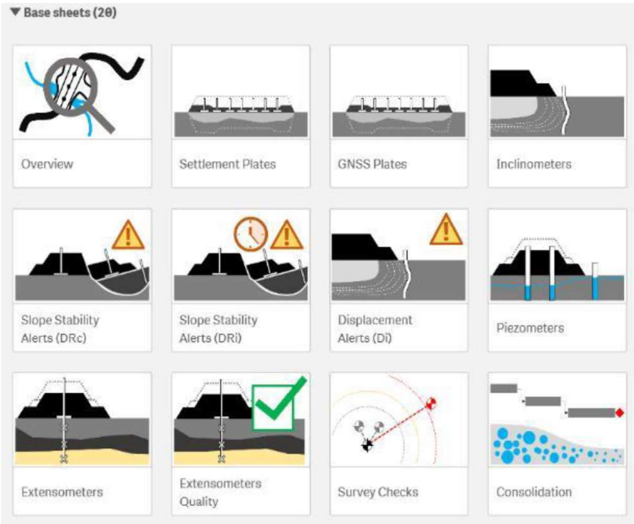

Figure 4. Geotechnical dashboard screenshot

4.2 *Features*

Features of this online monitoring system included:

- Automatic uploading using standard format for all instruments, either via email or a third-party website (e.g. piezometers owned by the suppliers)
- Automatic alert system: an email was automatically sent to all relevant parties once the predetermined trigger/ review levels were reached

- A quick comprehensive review of all relevant instruments linked with a GIS Map to enable a quick decision making, which is critical for short term slope stability
- Open/flexible for further improvement
- Automatic email reminders of late reading of any instruments.

Further information on the system is given in Zhang et al (2018).

5 INSTRUMENTATION AND MONITORING

5.1 *Objectives*

An objective of the project team was to streamline data collection to maximise system and project integration and shorten the review and decision-making process to improve construction safety.

As a general trend, advances in construction monitoring are moving away from physical measurements at a limited number of points, to widely distributed, wirelessly connected sensor networks, and to aerial scanning techniques. This data allows contractors to optimise construction processes and increase project safety performance. Integrating data from multiple sites can facilitate a quick overview of the whole project to pinpoint the sites with higher risk, improve performance prediction and understanding of zonation and ground properties. Monitoring for enhanced safety was also critical due to the project scale and proximity to existing infrastructure (e.g., bridges).

5.2 *Monitoring data collection, distribution and action*

The team carried out regular reviews of the collected data from instrumentation to check the actual ground movement performance against the design prediction.

Extensive real-time data monitoring and centralized data management were critical parts of risk control and the processes to monitor construction progress and control of ground movement and surface settlement. For example, the geotechnical "Dashboard" brings together all data from geotechnical and construction instrumentation and monitoring into a centralised resource. This significantly shortens the geotechnical team's decision-making process on filling rate to control short term slope stability, compared to conventional spreadsheet.

Over 3000 instruments were installed on W2B and nearly 3 million measurements made up to September 2018. Based on the average manual processing time, automating the processing of the data generated savings in the order of $A2.5M (Zhang, 2018). Instrument types and purpose are given in Table 2.

Table 2. Instrumentation schedule

Instrument type	Monitoring process	Number
Settlement plate	Settlement at ground surface	957
Multi-depth magnetic extensometers	Settlement at depth	94
Hydrostatic profile gauge	Settlement profile across the embankment	107
Standpipe piezometer	Baseline ground water table	72
Vibrating wire piezometer	Pore pressure change due to embankment loading	362
Inclinometer	Horizontal ground displacement	468
Settlement marker	Settlement/lateral displacement at embankment top, existing structures and pavement	797

5.3 *Application*

Part of the success of the geotechnical "dashboard" lay in effective visualisation of the data allowing project managers and engineers to interpret and act quickly on settlement and groundwater data (Figure 5). The program took the data from each site and, with some complex statistical analysis, produced visualisations of the information used to understand spatial and time-dependent correlation between monitoring points, and alert engineers to issues of concern. As part of quality assurance for each issue that was flagged, engineers could document that they had reviewed and dealt with the issue appropriately.

Figure 5. Example fill height, settlement time plot

A higher-level view was also generated, allowing project managers to assess progress without needing to look at the detailed data. The application helped field engineers interpret and act on data, and in turn helped improve the risk management of field engineers' work.

With this system, PC built all the embankments safely without instability, and at time of writing, 75% of all the preloading fills have been released for pave-ment construction.

5.4 *Performance*

The performance of various instruments on W2B is summarised below:

- Settlement plates and inclinometers generally gave accurate and reliable data for settlement and lateral displacement monitoring
- Monitoring demonstrated that data from piezometers and extensometers is variable, with some giving accurate and reliable results while others giving unreliable results; the issues demonstrate that quality control of installation practice is inadequate which needs improvement because it leads to uncertain decision making
- Underestimation of field settlement led to separation of extensometer tubing making extensometers unable to function
- Project-wide issues with HPGs with many giving unrealistic or unreliable results; the root cause may be associated with poor installation practice and/or the quality of the readout unit.

6 CONCLUSIONS AND RECOMMENDATIONS

This paper provides some examples of the use and value of data visualisation and geotechnical instrumentation for managing construction slope stability and embankment settlement performance for soft ground treatment on the Woolgoolga to Ballina Pacific Highway upgrade.

This system is the first online monitoring system that has been implemented with full success on a Roads and Maritime project, and provided an excellent platform to identify the key elements required to successfully manage and help optimise the overall design process.

At the time of writing, PC has avoided slope instability of all fills on soft ground and released 75% of the fills for pavement construction with both cost and time savings, which is testament to the well-structured and methodical process of risk identification, investigation and mitigation through design and data management.

This system was key to the successful delivery of the soft ground treatment on time and on budget. Key features of this system are as follows:

- Shortened turnaround time from reading to uploading to the dashboard system for early decision making
- Online, user friendly, flexible dashboard to the whole team
- Real time monitoring on critical structures and piezometers
- Automatic uploading using standardised format
- Automatic alarm system for early intervention on site to avoid slip failure
- Comprehensive visualisation of various instruments on GIS Map and grouping of relevant instruments to facilitate early decision-making
- Fast processing of large data, downloading and screenshot of monitoring results for quick internal monitoring reporting and external party data distributing
- System reliability, availability and data quality
- Flexible platform to new instrument types and graphs
- Additional functions e.g. curve fitting for predicting future settlement based on monitored data.

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