

DEVELOPMENT AND APPLICATION OF GEOTECHNICAL MONITORING AND DATA MANAGEMENT FOR WOOLGOOLGA TO BALLINA PACIFIC HIGHWAY UPGRADE

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ABSTRACT

One of the major challenges on the Woolgoolga to Ballina Pacific Highway upgrade involved constructing more than 26 kilometres of road infrastructure over soft ground within 1 to 2 years, as part of upgrading 155 kilometres of the Pacific Highway. This included one of Australia's largest soft ground instrumentation programs.

As with many other sections of the Pacific Highway, the design required 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 investigation 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 framework 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.

Keywords: instrumentation and monitoring, soft ground, dashboard, ground improvement, slope instability

1 PROJECT BACKGROUND AND OVERVIEW

Woolgoolga to Ballina Pacific Highway upgrade (W2B) involves the duplication of 155 kilometres to a four-lane divided road on the Pacific Highway. The project starts about six kilometres north of Woolgoolga (north of Coffs Harbour) and ends about six kilometres south of Ballina. W2B bypasses the towns of South Grafton, Ulmarra, Woodburn, Broadwater and Wardell.

On behalf of the Australian and NSW governments, Roads and Maritime Services is progressively upgrading the Pacific Highway to dual carriageway between the Hunter and NSW/Queensland border. Roads and Maritime Services engaged Pacific Complete (PC), a joint venture between Laing O'Rourke and WSP (formerly Parsons Brinckerhoff), to partner with its Pacific Highway Project Office to deliver the W2B. PC works closely with Roads and Maritime to manage multiple contracts in delivering the design and construction of the W2B project.

W2B includes upgrading the highway to motorway (Class M) or arterial (Class A) standard over its 155 kilometre length, nine grade-separated interchanges, 170 bridges, fauna crossings, three rest areas and a heavy vehicle checking station. Key elements of the project include the following:

- Over 90 cuttings with a maximum depth of up to 44 metres
- Over 143 embankments with a maximum fill height of 16 metres
- 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 were 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 this project.

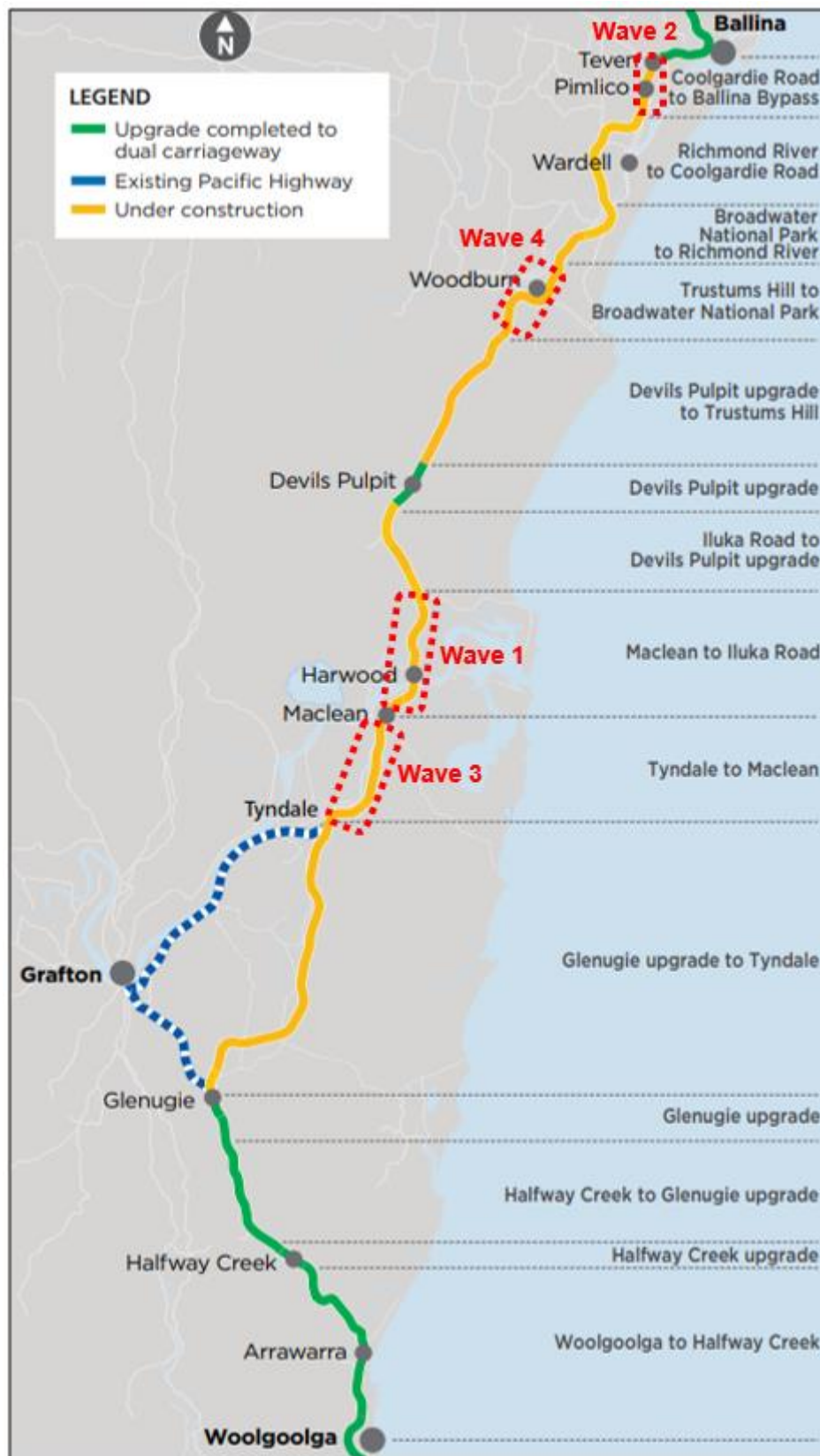


Figure 1: Woolgoolga to Ballina project map and early works “wave” package locations shown in red

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. Review of value engineering and innovation around geotechnical aspects was completed by the project's Geotechnical Review Group (GRG), which comprised 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 geotechnical issues is presented in Table 1.

Table 1: Value engineering achievements by Pacific Complete

Item	Benefit
Instrumentation and monitoring “dashboard”	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 \$2.5 million in manual information handling costs alone.
Earthworks Volume Reductions	From award, reduced total cut volume by over 900,000m ³ and total fill volume by 1,500,000m ³
Rationalised Foundation Treatments	Set minimum embankment heights to minimise shallow embankments wherever possible. Raising embankments allowed cheaper foundation treatment options compared to tender stage design/cost with VE benefits of est \$25m
Maximisation of Plain Concrete Pavement extents	Developed ground treatment solutions to maximise the area where the post construction settlement is anticipated to be less than 100mm in 40 years so rigid pavement can be constructed. Approx. 23% increase in Pacific Complete area from owner-developed concept design; 170km SPIR design v 210km final design.
Pavement re-use	Maximised re-use of existing concrete pavement where possible
Soft Soil Treatment	Design optimisation of soft soil treatment and surcharge designs including programme implications. Addressed as design development with emphasis on construction staging to significantly reduce hard treatment. Approximately \$60m of hard treatment removed from initial concept design costing including: <ul style="list-style-type: none"> • Optimisation of stabilising berm requirements • Removal of high strength geotextile requirements • Rationalisation of high strength geotextile requirements in Maclean Interchange in Wave 3 (Figure 1) • Reduction of waiting periods for early works surcharged embankments
Instrumentation and monitoring	Optimisation of instrumentation and monitoring with: <ul style="list-style-type: none"> • reduced frequency of HPG, extensometers, settlement markers • reduced total number of HPG, extensometer and VW piezometer in general fills over relatively shallow soft ground with maintaining one settlement monitoring point at every 50m interval • grouping instruments into “banks” of instruments for better protection and access • Use of telemetry technique at critical structures that is expected to be affected by ground treatment
Replacing Culverts with Bridges	Replacing 24 No and 14 No. culvert banks with single 120m long plank bridge for improved ride quality and flooding outcomes at reduced cost. Use of bridges

	instead of large banks of box culverts on soft soil floodplains saved time in program / cost by removing pre-loading / ground treatment requirements.
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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. Key features of soft soils include high water content, low capacity for allowing water to pass through and low strength. Without soft soil treatment, there is the potential for highway foundations and main alignment to sink and crack because the bearing capacity of the soil is not strong enough to support the highway.

Treating soft soil before building the main alignment takes time but saves money. The aim was to consolidate the soil so it can be built on. Consolidation involves squeezing the water from the soil to make it stiffer. It will take about two and a half years for the soil to consolidate once the water is removed.



Figure 2: Early work construction on W2B (a) bogged excavator (b) wick drains installed

Prediction of the time dependent deformations of embankments constructed on soft and compressible ground is required when preload or surcharge design solutions are adopted, with or without the use of wick drains. Accurate predictions are essential to achieve cost-effective outcomes. If the settlements are underpredicted then the embankments will end up below design levels, leading to additional earthworks during construction or post construction performance not meeting the project criteria. If settlements are overpredicted, too much fill will be placed initially and more fill will need to be stripped and spoiled than expected after settlement has been completed. Either of these issues will result in additional construction time and unnecessary costs. Both underprediction and overprediction of embankment settlement has occurred on sections of the Pacific Highway upgrade between Sydney and the Queensland border. Underestimates or overestimates of the time-rate of settlement can also lead to opportunities for early completion of construction being missed; create a risk of excessive construction time, and in some cases cause stability problems.

On W2B, construction of embankments over these soils would cause significant settlement issues during construction and in the long term if the foundation is not treated prior to pavement. 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 PSC provided detailed design after the tender was awarded. Soft ground treatment methods adopted on W2B were as follows.

1. Preload only (filling at pavement level at the end of preloading with no surcharge, no wick drains).
2. Surcharging (filling above pavement level at the end of preloading, no wick drains).
3. Surcharging with wick drains.
4. Concrete injection column (CIC) at critical bridge approaches and box culverts where the above solution was not viable

Figures 3 and 4 (Zhang et al, 2016) show the interpreted geotechnical long section and design parameters at Yamba, south of Harwood bridge, corresponding to one of the most challenging soft ground areas on this project.

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: for pipe culvert 150mm in 100 years and for box culvert 110 mm in 100 years as a guidance. At culvert locations, pavement complies with the performance criteria in items 1 & 2 above. The culverts were also designed according to the supplier's recommendations.

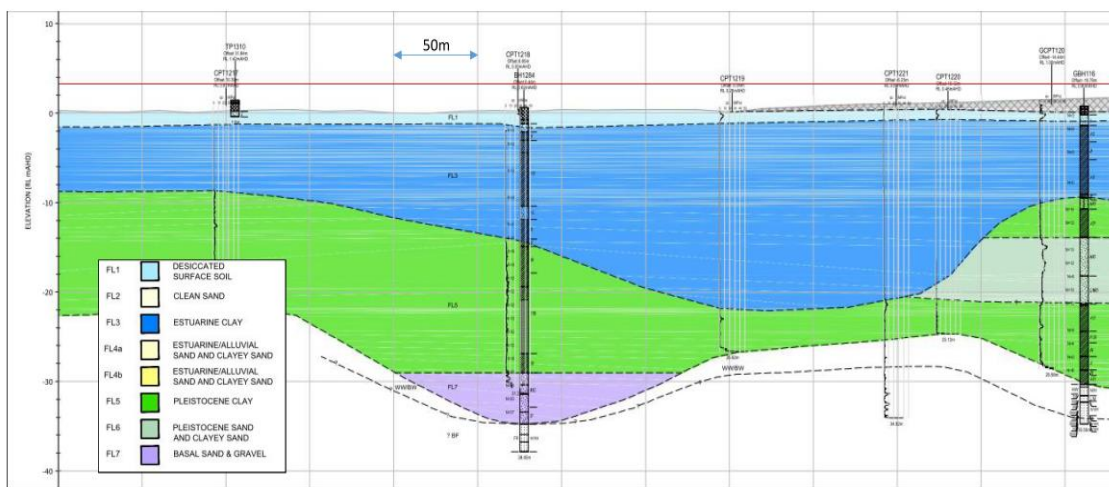


Figure 3: Geotechnical long section at south of Harwood bridge (FL3: very soft to firm clay)

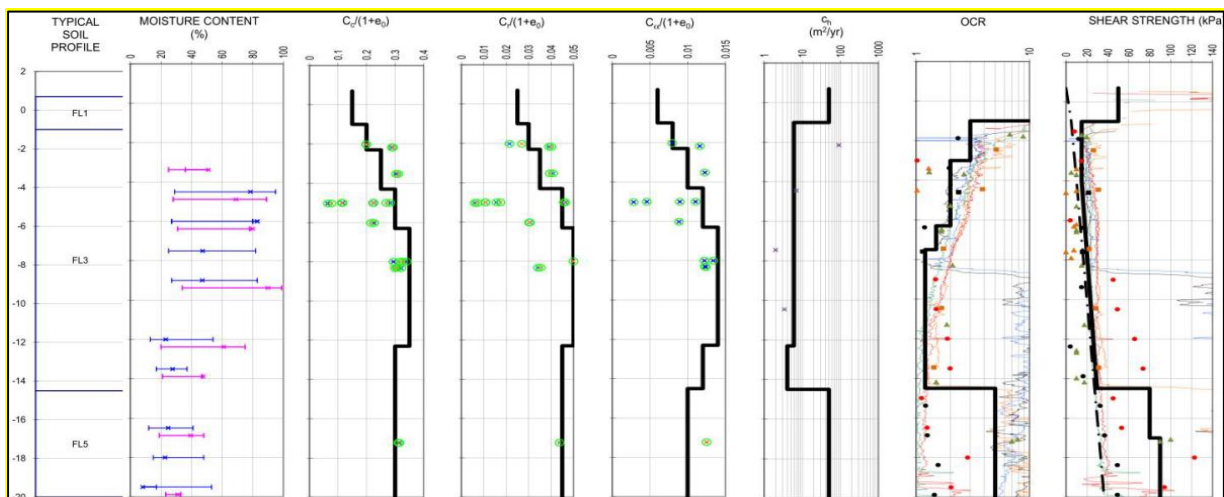


Figure 4: Profiles of material parameters with depth

3.2 SHORT TERM SLOPE STABILITY ASSESSMENT

Accurate prediction of embankment behaviour on soft soil requires 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 2. Parameters are defined in Figure 5. Two deformation ratios were assessed: total deformation ratio ($= h_m/S$) and incremental ratio ($= \delta_{hm}/\delta S$).

We 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 2 (Zhang et al., 2016), the trend of maximum lateral displacement versus fill height was monitored for a decision to slow down or stop filling. Three criteria (DRc, DRi and Di) were adopted for high risk areas (Yamba and Maclean Interchanges); while only two criteria (DRc and Di) were adopted for the remaining areas.

Table 2: Trigger levels for embankments with and without wick drains (Zhang et al., 2016)

Parameter	Wick drains		No wick drains	
	AL	WSL	AL	WSL
h_m/S (=DRc)	0.25	0.35	0.5	0.7
$\delta h_m/\delta S$ (=DRi)	0.5	0.7	N.A.	N.A.
δ_{hm}/δ_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; δ = incremental; t = time in days; δ_{hm}/δ_t = daily lateral displacement; AL = Alert Level; WSL = Work Suspension Level; DRi only applies for high risk areas (Yamba and Maclean Interchanges)

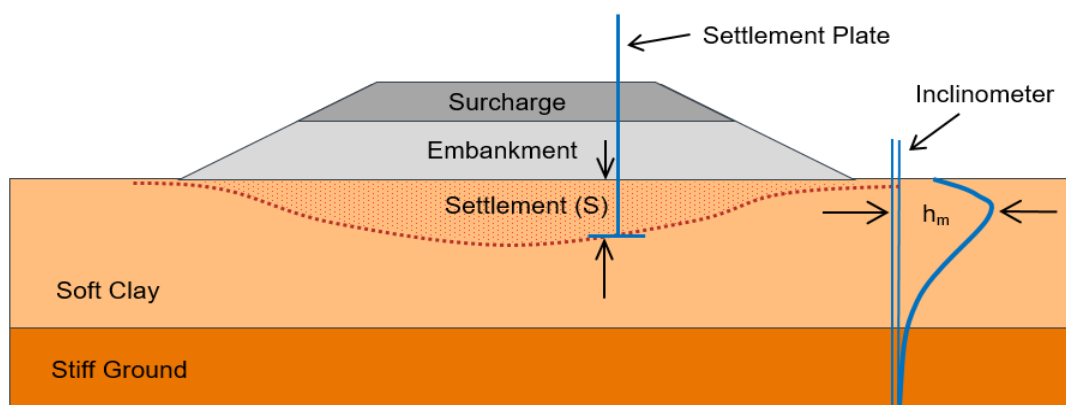


Figure 5: Definition of embankment deformation ratio

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 deformation 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 (Loganathan, 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: a. Recompression ratio prior to the yield pressure being exceeded. b. Permeability / coefficient of consolidation prior to the yield pressure being exceeded. c. Yield stress ratio. d. Compression ratio over the stress range of interest. e. Permeability variation with stress level and permeability reduction in wick drain smear zone. f. Creep parameters.

Measuring the progress of consolidation during construction plays a critical role in the long-term success of embankments founded on soft soil. Records of its actual performance allow engineers to verify design assumptions and recommend early interventions if its as-built behaviour deviate from predictions. One of the most critical predictive decisions involves 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 FEATURES

Online monitoring systems were tried before 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 work. The system development was funded by Roads and Maritime, and retained by Pacific Complete.

This system was developed by the 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.

We then developed the system 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 extension for visualisation. A screenshot of the Geotech Dashboard is shown in Figure 7.

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.

We structured the data management process 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.

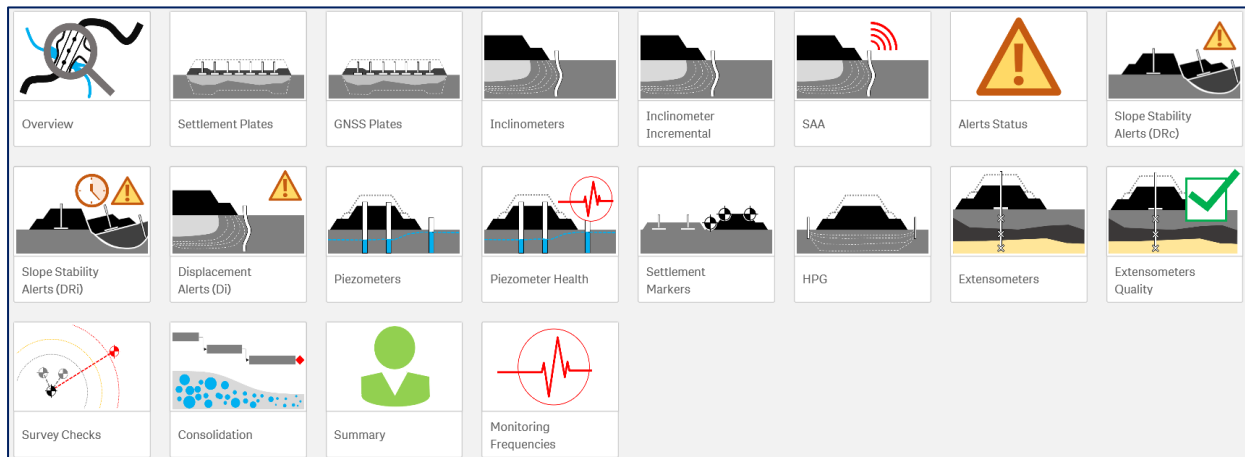


Figure 6: Geotechnical dashboards

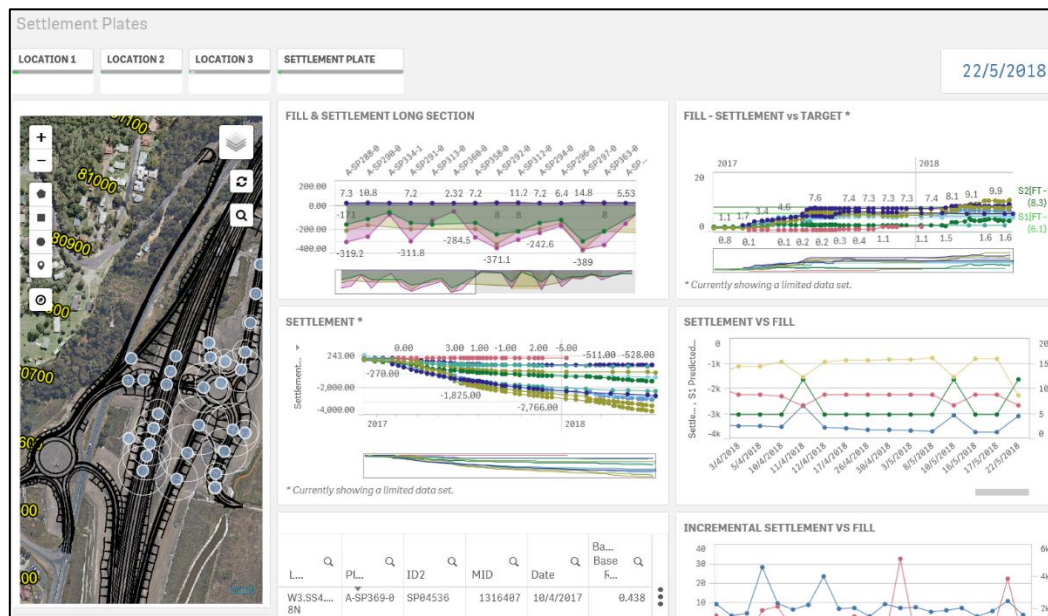


Figure 7: Example design vs measured fill height, settlement, settlement rate time plots

Features of this online monitoring system included:

- Automatic uploading using standard format for all instruments, via either an email or a third-party website (e.g. VW piezometers owned by the suppliers).
- Automatic Alert System: an email was automatically sent to all relevant parties once the predetermined Review Levels were exceeded.
- 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.

4.2 APPLICATION

Part of the success of the geotechnical “dashboard” lay in effective visualisation of the data in a dashboard, allowing project managers to interpret and act quickly on settlement and groundwater data. The program took the data from each site and, with some complex statistical analysis, produced visualisations of the information to try to understand spatial and time-dependent correlation between monitoring points, and alert engineers to issues of

concern. A method of quality assurance was introduced: for each issue that was flagged up, engineers could enter in a box that they had reviewed the issue and dealt with it appropriately.

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, the design team, with support from the construction team, has managed to build all the embankments safely without slip failure and 75% of all the preloading fills has been released for pavement construction.

5 INSTRUMENTATION AND MONITORING

5.1 OBJECTIVES

An objective of the project team was to streamline data collection to maximise the system and the project integration, and shorten the review and the 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. The process and associated responsibilities for collection, distribution and review/analysis of the monitoring data is outlined below:

- Instrumentation reader collects data in the field (the main contractor in the case of settlement plates, settlement markers and survey targets), review data for quality, consistency and reliability.
- Instrumentation reader compiles the measured data (the main contractor in the case of settlement plates, settlement markers and survey targets) using the template provided by Pacific Complete.
- Instrumentation reader to email the template with data, as soon as it is collected, to PC for automatic upload of data to the Data Warehouse.
- PC Geotechnical Team and or the Project / Site Engineers review data to check if actual movements being experienced by the embankment or structure is as expected and within the agreed trigger levels.
- During the settlement period, regular reviews occur to ensure that the performance of the embankment is occurring in accordance with the predicted design. This review addressed opportunities to reduce settlement period, increase the settlement period or increase the surcharge to maintain time.
- Where the performance trend lines up with design prediction indicating preload can be removed or the next lift can be placed, PC to liaise and share outcomes with the detailed designer and organise a hold point sign off from the designer.
- Where the actual performance does not follow design expectations, PC to consult with GRG and, if required, with the detailed designers, to develop a course of corrective actions/ intervention measures and submit action plan to GRG for approval. Once approved, PC will provide the plan to the contractor for implementation.

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 mid July 2018. Based on the average manual processing time, automating the processing of the data would generate savings in the order of \$A2.5M (Zhang, 2016). Instrument types and purpose are given in Table 3.

Table 3: Instrumentation schedule

Instrument Type	Monitoring Purpose	Number
Settlement plate	Settlement at ground surface	957
Multi-depth magnetic extensometers	Settlement at depth	94
Hydrostatic profile gauge (HPG)	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 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 installation practice is inadequate which needs to change because it leads to uncertain decision making.
- Underestimation of field settlement led to separation of extensometer tubing making it unable to function (for extensometers).
- Project-wide issues with HPGs with the vast majority 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 summarises 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 155-km 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, the team has avoided slope instability of all fills on soft ground and released 75% of the fills for pavement construction with both cost and timesavings.

This system was the 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, real-time VW piezometers.
- Automatic uploading using standardised format.
- Automatic alarming 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.

7 ACKNOWLEDGEMENTS

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