# Soft ground improvement – construction challenges and practical experiences from the field

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## ABSTRACT

The construction of highway infrastructure on soft ground presents unique geotechnical challenges that require solutions which fulfil the design objectives, account for site constraints, meet long-term maintenance requirements and provide a comfortable road user experience for motorists. This paper presents a case study of the construction challenges encountered during delivery of a recent NSW highway upgrade project and evaluates the implications of several construction issues on embankment performance throughout the entire project lifecycle. The project involved two major creek crossings with 5 m high bridge approach embankments overlying compressible ground between 10 m to 25 m thick. Ground improvement methods comprised of concrete injected columns (CIC) and driven concrete columns (DCC) in combination with wick drains and surcharge. Numerous technical and constructability challenges were met, including strict settlement and deflection tolerances; a narrow construction footprint near live traffic; adjacent existing bridge structures; and variable soft ground conditions. The practical application of soft soil engineering principles in solving these challenges is discussed, including mitigating the impact of CIC installation on existing structures by selection of an appropriate construction sequence to limit soil lateral displacement and ground heave; interpretation of wick drain installation records to assist planning and verification of DCC and CIC treatment extents; and the assessment of alternative construction methods to avoid CIC and bridge abutment interface clashes. Monitoring data from geotechnical instrumentation used to manage ground treatment performance is also presented.

*Keywords:* Ground improvement, soft soil, construction, concrete injected columns, installation effects

## 1 INTRODUCTION

The delivery of a recent highway upgrade project on the east coast of Australia involved the duplication of 1.5 km of the existing NSW highway network to dual carriageway. The works included the construction of two major creek crossings with associated bridge approach treatment works for embankments up to 5 m in height overlying soft compressible ground. The new bridges replaced existing bridges that were demolished, after being originally built in the 1960s, to form the southbound carriageway. Figure 1 shows the new southbound bridge and embankment under construction, adjacent to the recently constructed northbound carriageway at the second creek crossing.

The objectives of the ground improvement works were to control settlement at the bridge approaches to protect the new and existing bridge piles from excessive ground movements, meet pavement performance criteria that would require limited maintenance over 40 years and provide a smooth transition zone from the bridge to the embankments.

The author provided geotechnical advice to the project construction delivery team, acting as the Principal on behalf of the client, to oversee implementation of the geotechnical design in the field. Construction risks included the potential impact of the new works on the existing bridge abutment piles, which had strict tolerances for the allowable lateral movement imposed by the new works, cracking of the existing embankment pavement, working within a narrow construction footprint and a tight construction program.

## 2 SITE GEOLOGY

The highway alignment is underlain by highly compressible, Holocene-age soft to firm estuarine clay deposits over Pleistocene-age stiff clay, residual soils and weathered argillite. The Holocene clay thickness ranged from approximately 10 m to 20 m thick at the bridge abutments, extending up to 25 m thick where a paleochannel exists to the east of the second creek crossing. The underlying Pleistocene clay continued to approximately 40 m depth below ground level.

*Figure 1: Southbound carriageway embankment and bridge construction at the second creek crossing*

## 3 GROUND IMPROVEMENT DESIGN

The ground improvement design was completed by a third party geotechnical consultant engaged by the client under a design only contract. Interactions between the newly constructed embankments and existing highway were to be limited to mitigate the risk of significant settlement causing damage to adjacent bridge structures. Ground treatment methods using rigid ground inclusions were employed to support the embankments via load transfer to stiffer underlying materials, including concrete injected columns and driven reinforced concrete columns, in combination with wick drains and surcharge.

Concrete injected columns (CICs) with diameter of 450 mm at 1.8 m and 2.25 m spacing were to be installed by displacement auger techniques within the abutment zone adjacent to the bridge structures. The CICs were embedded 4 m into the stiff Pleistocene clays below the soft clay layer at the location of abutments, with gradually reducing embedment depth to 1 m away from the abutment in order to maintain a smooth transition gradient. Five rows of sacrificial 400 mm square driven concrete columns (DCCs) at 2.25 m spacing were installed immediately adjacent to the surcharge and wick drain area to protect the CICs from excessive lateral movement during fill placement.

## 4 CONSTRUCTION CHALLENGES

The following section presents a case study of the construction challenges encountered during delivery of the ground improvement works and evaluates the implications of these issues on embankment performance throughout the entire project lifecycle. The practical application of soft soil engineering principles in solving these challenges is discussed, which aimed to fulfil the design objectives, account for site constraints, meet long-term maintenance requirements and provide a comfortable road user experience for motorists.

### 4.1 Variable soft ground conditions

Geotechnical investigations completed for the project, including numerous boreholes, test pits and cone penetration tests (CPTs), revealed a highly variable ground profile with soft clay depths extending up to 25 m below ground level at discrete locations. The development of a ‘live’ geotechnical model during the construction phase, using additional information gathered from wick drain and geotechnical instrument installation records, provided an improved understanding of the ground conditions.

Wick drains, or prefabricated vertical drains, were installed to provide shorter drainage paths which enable faster pore water dissipation and accelerate the consolidation process. The drains were driven through the soft Holocene sediments using a vibrating mandrel mounted onto an excavator and anchored into the underlying stiffer Pleistocene deposits. A review of the penetration resistance over the depth of installation for 8,000 wick drains showed a distinct inflection point which indicated the inferred depths to the base of the soft soils. These depths were compared with information from CPTs adjacent to specific wicks. The interpreted depths were plotted spatially to map the varying soft soil thicknesses. This information assisted construction planning and verification of DCC and CIC lengths, which rely on site-specific termination criteria based on the depth to the Pleistocene clays. The data was also compared to the interpreted profiles used in the design and, where necessary, the ground treatment was refined to suit the actual ground conditions.

An example of the output from this exercise is presented in Figure 2. The data indicated that the depth to the base of soft clay underlying the embankment footprint increased towards the east to approximate RL -23 m AHD, associated with a deep paleochannel. In comparison, the original design profile assumed that the base of soft clay was at approximate RL -14 m AHD. Consequently, the surcharge height at this location was increased to reflect the deeper soft soil profile and maintain a smooth transition gradient between the bridge treatments and adjacent low embankment zone.

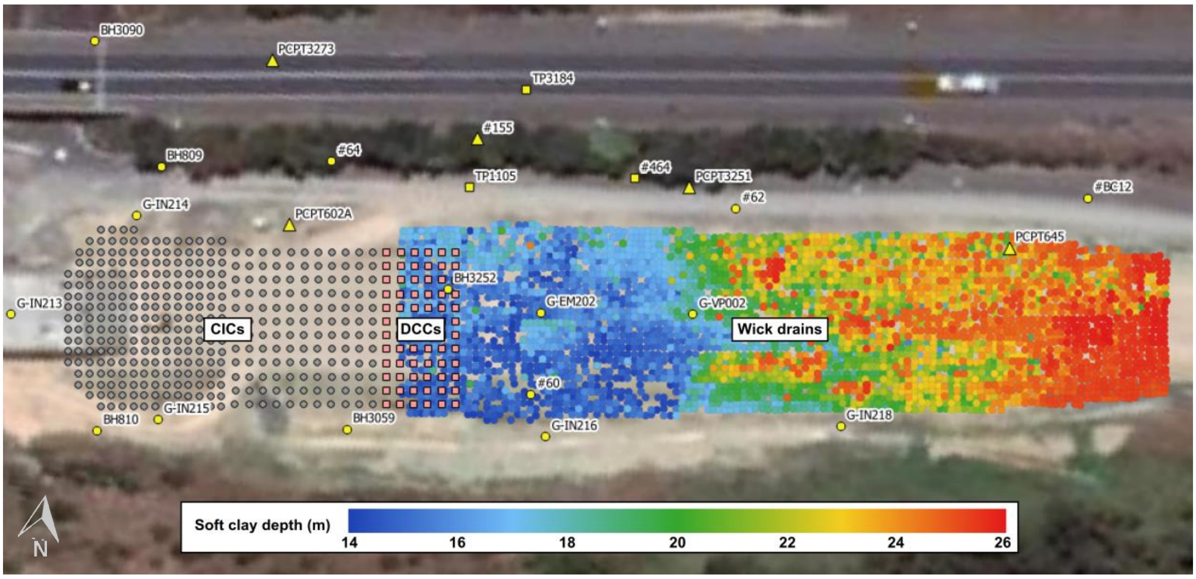

Figure 2: Estimated soft clay depths based on wick drain installation records (plotted using QGIS)

## 4.2 CIC installation effects

The presence of existing bridge structures directly adjacent to the ground improvement works imposed construction challenges on the concrete injected column (CIC) installation process. CICs, also known as drilled displacement columns, are rigid inclusions that are installed using piling rigs attached with displacement auger heads. The auger is rotated and pushed though the soil formation to the design depth, which displaces the soil laterally rather than excavating soil to the ground surface, followed by grout injection through the hollow stem while the auger is extracted to form the column in-situ. Vertical (heave) and horizontal soil movements occur as the volume of the installed element exceeds the volume of soil extracted and compressed, with the most significant effects observed in soft clays with low permeability which generate high excess pore water pressures (Zhang and Choi 2015).

Nguyen et al. (2016) note that when construction sites involving CICs are located in close proximity of existing sensitive structures such as an existing bridge foundation, the risk of damaging adjacent structures due to lateral soil movement can be high if a proper installation sequence is not considered, as demonstrated by several studies (Brown 2005, Hewitt et al. 2009 and Larisch et al. 2014).

Furthermore, Zhang and Choi (2015) report that the resulting soil displacement has the potential to adversely affect previously installed adjacent columns, with several recent projects in Australia recording damage to CICs during construction as well as ground deformations and soil heave. Larisch et al. (2014) conclude that this damage creates potential conflicts between contractors and clients during construction, and recommends that all stakeholders involved understand the consequences of soil deformations, which can be effectively managed provided the process of installation is well understood and the contractors are knowledgeable and experienced in the design and construction of CICs.

The risk of significant ground movements and damage to adjacent bridge structures caused by CIC installation effects was addressed by selection of a construction sequence that aimed to limit lateral soil displacement and ground heave. Interactions between the newly constructed embankments and existing highway were to be limited to an acceptable level, with lateral soil displacement due to CIC installation on the bridge piles estimated during the design phase to be up to 10 mm.

*Figure 3: Concrete injected column (CIC) installation at the first creek crossing*

The columns were proposed to be installed in a sequence which achieved a balance between preventing damage to columns already installed and the adjacent existing bridge structures. To limit installation effects, the preferred construction sequence was to start installing columns close to the existing bridge structures and then work away from the existing embankments, as described by Hewitt et al. (2009) and Nguyen et al. (2017). However, the installation process was constrained by site geometry, with the narrow construction footprint surrounded by the creek, existing highway and project boundary, as illustrated in Figure 3 at the first creek crossing.

An alternative sequence was proposed by the contractor to work outwards from the centre of the new embankment to protect the integrity of the columns and provide an exit point for the piling rig. Concerns were raised over the impact of this approach on the existing bridge piles, so a compromise was reached to install every second column in a ‘hit and miss’ sequence, similar to the staggered approach adopted by Zhang and Choi (2015). The presence of existing embankments that settled several metres also provided construction challenges and required pre-drilling to limit surface ground heave.

The CICs were installed using a Casagrande B250 piling rig with 250 kNm rotational torque capacity and an average concrete overconsumption of approximately 12%. Over 1,800 columns were installed with typical column lengths between 15 m to 25 m and a total combined length of 35,000 m. Monitoring data from geotechnical instrumentation was used to manage the ground treatment performance, with inclinometers installed within the soft soil formation to measure lateral soil deformations and displacement markers in the form of survey prisms placed on the adjacent bridge abutments to record lateral movement caused by CIC installation.

During the installation process, lateral soil movement of 60 mm (at a depth of 7 m) was identified in one inclinometer adjacent to an existing bridge abutment, with corresponding survey marker readings indicating that the structure had moved laterally by approximately 30 mm. This was caused by rapid installation of a small portion of CICs in a continual ‘wet-on-wet’ fashion due to miscommunication between the lead contractor and piling sub-contractor. The bridge was assessed for structural integrity and was found to be in an acceptable condition.

Following this event, all remaining columns adjacent to bridge structures were mandated to be installed working outward from the bridge abutments using the 'hit and miss' sequence. With this adopted construction sequence and regular monitoring, the maximum lateral movement was limited to less than 10 mm during subsequent column installation. Monitoring indicated the existing bridges were not affected by ground movements during CIC installation.

Research work by Larisch (2014) and Larisch et al (2015) suggest that inadequate penetration rates may also be potential causes for excessive ground movements, with test results indicating that the depth of the heave cone and the diameter of the heave radius around the column depend on the penetration rate of the displacement drill tool. Inadequate penetration rates were found to cause disturbance of the clay to greater depth, leading to greater heave volumes of up to 60%. The study results highlight the importance of utilising adequately powerful piling rigs to provide sufficient installation energy to maintain the required penetration rates during installation.

The quality of each individual column and performance of the construction sequence was also controlled by continual review of installation records (including torque, auger penetration rate and down-thrust applied during advancement) to assess that the design objectives were met and limit the risk of longer than required socket lengths into stiff material. In one instance, close monitoring of these records, in combination with the development of the 'live' construction phase geotechnical model described earlier, assisted in identifying a dense sand deposit which was interbedded between the soft soil and stiff clay founding layer. This discovery, which was later confirmed during bridge pile excavation, allowed the column socket lengths to be terminated within the sand layer and avoided the need to penetrate the deeper stiff clay layer, limiting associated ground heave and lateral movement.

### 4.3 Bridge abutment interface clashes

Successful delivery of the ground improvement works required tailored construction solutions to avoid CIC and bridge abutment interface clashes, whilst satisfying long-term pavement performance criteria and providing a smooth transition zone to each bridge from the approach embankments.

The CIC foundation concept often requires the presence of a load transfer platform (LTP), comprising a geosynthetic reinforced gravel mattress beneath the supported embankment, to enhance load transfer to the columns through arching effects in the granular material (Filz and Smith 2006). The need for the LTP and reinforcement should be based on assessment of the differential settlement at road level, particularly for low embankments which do not have the ability to span between columns and require a minimum height of fill over the column heads (Zhang and Choi 2015) to prevent adverse localised deformations that present as dimpling of the pavement surface.

The original design assumed that the existing highway embankment would be stripped to natural ground level, or a level which provided sufficient clearance between the pavement and top of CICs (defined as a minimum height of 1.5 times the clear spacing between each column) to spread the load over a wide area, therefore avoiding the need for a geosynthetic reinforced LTP. However, during construction a decision had been made to retain the existing fill material to act as a working platform. A consequence of this change was that the minimum design requirement for adequate load transfer was not met. After review with the designer and client, a LTP with structural geofabric was placed on top of the CICs as a contingency measure to mitigate adverse localised differential settlement of the pavement, meet long-term maintenance requirements and provide a comfortable road user experience for motorists.

Further implications of this construction approach were that the CICs were constructed at a level higher than the base of the abutment headstock, and the piling platform would need to be lowered to allow construction of the bridge piles and superstructure. Several construction methods were considered to lower the column heads without causing damage. Direct use of an excavator bucket or saw cutting individual columns after localised excavation around the CICs were precluded due to the risk of uncontrolled cracking and time constraints. The adopted method was to 'post-bore' the CICs to the desired level by mixing the pre-injected concrete and platform material which typically resulted in a lower strength material similar to stabilised sand. After preloading, this material was removed by bulk excavation allowing rapid construction of the abutment piles and greatly benefitting the construction program. Figure 4 illustrates the constructed 'stepped' CIC transition profile following preload removal.

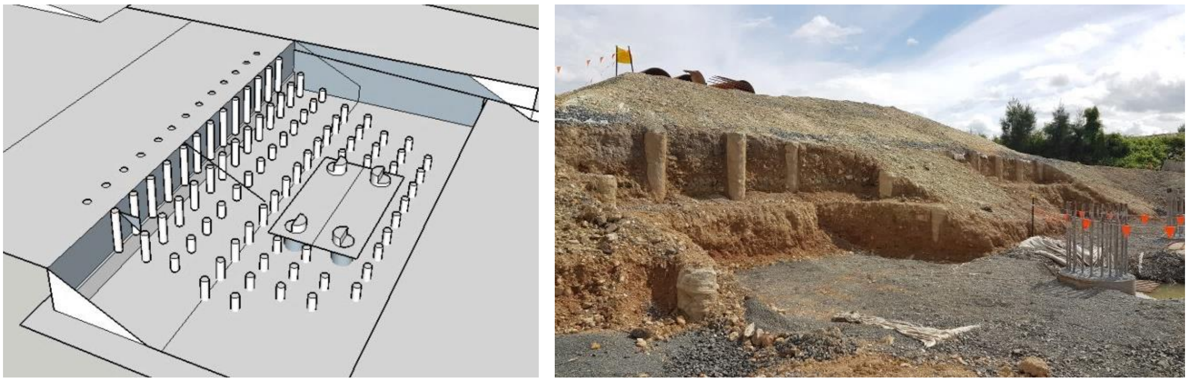

*Figure 4: Proposed 'stepped' CIC transition (left) and constructed CICs following preload removal (right)*

## 5 CONCLUSION

This paper presents a case study of the challenges encountered during construction of a recent highway upgrade project overlying soft ground and describes the geotechnical solutions which met numerous technical and constructability constraints. The key issues were associated with construction time limitations, strict settlement and deflection tolerances, a narrow construction footprint near live traffic, adjacent existing bridge structures and variable soft ground conditions.

The value of the practical application of geotechnical engineering principles in solving construction challenges is described, including the benefits of providing on-site technical support to manage the implementation of the geotechnical design. The highway upgrade is open to traffic and has displayed good operational performance, demonstrating the successful delivery of the ground improvement works.

Experienced geotechnical practitioners with expertise in the design and construction of highway infrastructure on soft ground should be consulted by all parties involved, including clients, contractors and sub-contractors so that that the finished product achieves the design objectives, accounts for site constraints, meets long-term maintenance requirements and provides a comfortable road user experience for motorists.

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