

Use of Deep Soil Mixing for Excavation Retention and Groundwater Control

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ABSTRACT

Several buildings at St George's Hospital were damaged as a result of the 2010/2011 Canterbury earthquake sequence. Four new buildings are being constructed, which when completed, must remain operational following a similar seismic event.

Arup provided design services to Hiway Geotechnical, for the use of Deep Soil Mix (DSM) columns below the buildings to mitigate the effects of liquefaction and provide support and groundwater cutoff for a 4m deep basement excavation. With a groundwater table within 1.0m of the ground surface and a ground profile consisting of loose sands which were susceptible to instability and piping, the DSM columns provide an alternative to typical sheet pile solutions.

Based on previous research by Arup, the design also made use of ground improvement effects in the soils between the DSM columns. On-site trials and testing verified the ground improvement, enabling cost savings compared with traditional DSM column layouts and other ground improvement solutions. DSM columns also provided advantages over sheet pile which have installation issues and don't provide the same level of versatility.

The adoption of DSM enabled several design issues to be addressed with one construction technique, providing construction cost and programme time savings.

This paper presents the main geotechnical challenges for the site, describes how various elements of the DSM columns were designed to address these issues and summarises site observations and performance during construction including observations of wall movement.

1. PROJECT SETTING

The 2010/2011 Canterbury Earthquake sequence caused widespread damage through the city of Christchurch, New Zealand, through a combination of high ground accelerations and liquefaction of loose alluvial deposits. In particular the 22 February Mw 6.2 event caused large scale liquefaction and lateral spreading, affecting commercial structures in the Central Business District and was estimated to have severely compromised 15,000 residential structures (GEER 2011).

Peak ground accelerations in excess of 0.6g were recorded in the CBD (GEER 2011). Liquefaction occurred over approximately 50% of the city centre, through a combination of loose near surface alluvial sand and silts, and a high groundwater table which is typically within 1-2m of the ground surface.

At St Georges Hospital in Papanui, several buildings were either destroyed during the earthquakes, or damaged to an extent that they required subsequent demolition.

2. PROJECT OBJECTIVES

The \$120m (NZD) redevelopment works at St George's hospital include the construction of 4 new buildings up to five stories (including one basement level) with additional basement space to accommodate base isolation. As the hospital forms a key piece of the city's emergency response infrastructure, the new buildings will be classified as Importance Level 4 and 6, requiring robust and reliable foundation design solutions.

Geotechnical solutions at the site needed to address three key design issues:

- Retain 4m deep excavations in poor ground conditions;
- Control groundwater inflow during construction;
- Provide a robust foundation solution to address site seismic risks including liquefaction, settlement and reduced bearing capacity.

The preferred option at St George's hospital was the use of deep soil mixed columns as a cost effective method to provide a combined solution for the support of basement excavations, dewatering and ground improvements.

3. GROUND CONDITIONS

The geology of Christchurch is built up of a sequence of alluvial deposits, ranging from loose silts and sands to dense gravels, with occasional organic peat lenses. Brown and Weeber (1992) describe the original site conditions and development of Christchurch as follows: *“Originally the site of Christchurch was mainly swamp lying behind beach dune sand; estuaries and lagoons, and gravel, sand and silt of river channel and flood deposits of the coastal Waimakariri River flood plain. The Waimakariri River regularly flooded Christchurch prior to stopbank construction and river realignment. Since European settlement in the 1850s, extensive drainage and infilling of swamps has been undertaken.”*

Ground conditions at the site consisted of an upper layer of loose silt and sand to a depth of approximately 10m depth, overlying a medium dense to dense sandy gravel layer approximately 6m thick. This was underlain by a lower sequence of loose/medium dense silt/sand to a depth of approximately 22m where the dense Riccarton Gravels were encountered.

Over part the eastern portion of the site, an intermediate medium dense gravel layer up to 4m thick was encountered through the middle of the upper silt/sand layer (ie 4 to 8m below ground level), which tapered out along the middle of the site, complicating the ground conditions and providing a variable strength profile.

Groundwater was located within 1 to 1.5m of the ground surface and the upper soil layers were anticipated to have a high permeability based on previous experience in Christchurch.

3.1 Site Seismic Performance

Medium to severe liquefaction was observed on parts of the site and in surrounding areas during the Canterbury Earthquake sequence, including foundation settlement, damage to ground surfaces and utilities, and surface expressions including sand boils. Several of the older structures onsite experienced significant cracking and damage and required demolition.

Liquefaction assessments indicated that under design accelerations, liquefaction was very likely in the upper silts/sands to 10m depth, and unlikely in the denser gravel layers encountered. Liquefaction analysis indicated the potential for liquefaction to occur in the lower silt/sand layer, however the overlying thick dense gravel layer was considered to confine and bridge over this layer and mitigate any surface effects of liquefaction. On this basis foundation improvements were designed to found in the top of the medium dense gravels at approximately 11m depth.

4. DEEP SOIL MIXING (DSM)

Deep soil mixing is an insitu ground improvement technique that enhances the characteristics of weak soils by mechanically mixing them with a cementitious binder. The binder can be added through either the wet or dry process as either a wet slurry or dry powder. DSM columns are constructed by using an auger mixing tool as shown in Figures 1 and 2, to improve the ground to depths of 25m and form columns typically 300 to 1200mm in diameter. Through the use of different binders, DSM can be effective in a wide range of soils. Soil mixing can be used in a variety of applications including slope stabilisation, liquefaction mitigation, improved bearing capacity, excavation retention and settlement control.



Figure 1. The DSM cutting and mixing tool

The original concepts for deep soil mixing were developed in the 1960's, with the developments in contemporary techniques mainly reflecting developments in Japan and Scandinavia (FHWA, 2000), and more recently China and the United States. This project was the first use of deep soil mixing in Christchurch.

5. BASEMENT RETENTION AND FOUNDATION SOLUTION OPTIONS

The original buildings construction in the 1920's adopted a shallow foundation solution, nominally within 1m of the ground surface to avoid excavation below the ground water table.

Subsequent developments onsite had adopted open cut excavations with dewatering systems or sheet pile walls to facilitate construction below the water table.

The conventional option to retain the excavation and control groundwater would be through the use of a sheet pile wall with local dewatering within the excavation. DSM columns were preferable to sheet piles as they could be installed with significantly reduced noise and vibration which was a key consideration for the ongoing operation of the hospital.

Methods for ground improvement include stone columns, vibro-compaction or piling, all of which could provide a suitable foundation option for the proposed development. Advantages of DSM over these options include reduced vibration, minimal excess spoil, lower embodied energy, durability, ground improvements which can improve liquefaction resistance and cost effectiveness.

Of the above advantages the three key factors for this project were the ability to address both foundation improvements and excavation retention, cost effectiveness and reduced vibrations effecting hospital operation.

5.1 Design of DSM for Basement Retention

Soil mixing techniques have been used for the retention of deep excavations in various forms over the last 40 years and have been designed as mass gravity, reinforced or cofferdam arrangements. Early uses in Shanghai in 1987 adopted rows of DSM columns to effectively form a mass gravity wall of improved ground around the basement excavation (FHWA, 2000). In the 1990's reinforcing elements were introduced to strengthen the columns to act as retention for deeper basements and reduce the extent of the works. The use of rings of DSM columns to construct shafts (Elliot, 1989) is particularly effective the columns can be maintained in a compressive state.

DSM columns are effectively a weakly cemented concrete with a low unconfined compressive strength (UCS), and as such for design purposes cannot be relied upon to have any tensile strength for design. Subsequently retention designs typically need to either be designed with some form of tensile inclusions or overlapping columns which create an improved soil mass which can act as a gravity structure.

5.2 St George Hospital DSM Design

The DSM's at St Georges Hospital was modelled using the 2D finite element modelling programme PLAXIS with checks adopting simple hand calculations. The modelling of the upper alluvial layers was completed using the Hardening soil model with small strain stiffness (HS Small) with parameters developed from borehole, CPT and DMT testing. The DMT and some CPT testing was completed by Highways Ltd post contract award to enable more advanced analysis to be completed and verify ground improvement effects.

The preferred retaining wall design approach was to adopt a single row of secant pile DSM columns with steel I-beams as internal reinforcing. Additional DSM's were installed on a grid pattern behind the wall as part of the liquefaction mitigation works, which also assisted in reducing active loading on the DSM wall. DSM columns were 1.0m in diameter and spaced at 0.85m crs in the secant wall and on a 3.2m grid below the building footprint and around the building perimeter as shown in Figure 2.

DSM's were modelled as soil elements using the HS Small model with a target UCS of 2MPa and column stiffness and behaviour developed from the results of UCS tests completed as part of the QA from previous projects. Where DSM's were modelled on a grid pattern the properties were 'smeared' into the page. On the basis that DSM could not be relied upon to provide tensile resistance, a tension cut off was modelled which when exceeded, resulted in the redistribution of forces elsewhere in the model. The adoption of a tension cut off resulted in some modelling instability in the open face of the basement excavation wall and a series of sensitivities were completed adopting different soil models and values of tension cut off over part/all of the DSM wall. The modelling indicated the some form of reinforcing was required in the DSM basement wall.

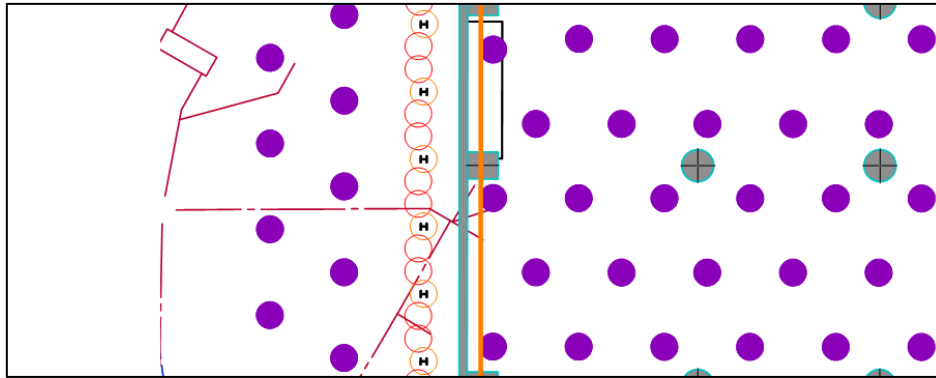


Figure 2. DSM columns layout showing the secant DSM wall with vertically reinforced piles slightly offset and the grid pattern inside the basement and around the perimeter to provide ground improvement and liquefaction mitigation.

5.2.1 DSM Basement Retention Design

The modelling of I-beams in DSM columns is complicated by the ability of the weakly cemented DSM columns to act with the smooth steel sections to behave as a composite member. Conventional design is to consider use only the reinforcing members to resist bending moments and shear forces, as the tensile strength of the columns is low. The improved ground between the reinforcing members is effectively considered as lagging and is designed to resist and redistribute the horizontal stresses to the adjacent reinforcement (Rutherford et al, 2007), (Taki and Yang, 1991).

For this project, various sensitivities were completed modelling the reinforcing members inside a wall of improved ground with an interface element between the reinforcing members and improved ground to assess the effects of the DSM and reinforcing acting in unison. Broadly the models considered three case:

- 1) Ignoring the DSM wall and modelling a 'plate' element based on the properties of the steel reinforcing only;
- 2) Modelling the reinforcing plate with the half of the DSM improvements on the inside of the basement excavation, on the basis that this portion of the column would be in compression; and
- 3) Modelling the reinforcing plate with DSM improvement on both sides.

The adoption of the strength of DSM columns under compressive or tensile loading in stability modelling is discussed further in EN 14679 (2005).

There was a significant difference in the displacements and moments induced in the reinforcing members between the models. Model 2 was considered to provide the most realistic behaviour for the wall behaviour based on observations of DSM's in excavation on previous project, the temporary nature of the works and land use behind the walls. For a permanent and or deeper basement excavation a more robust, conventional design approach may be considered suitable.

5.2.2 DSM Intermediate Support Design

DSM columns were designed to span between reinforcing members using conventional design approaches as shown in Figure 3, where I-beams are typically installed in every second column. The earth pressure behind the wall is transferred through the improved ground in simple shear and via a compressive arch. I-beams were installed in every third DSM column as opposed to every second column in the design, enabling the use of a more efficient steel section, less manual handling onsite and a reduced number of columns that would require removal if excavation was required for subsequent site development. However, the use of I-beams every third column resulted in a wider span between the reinforcing members where the load simple transfer mechanisms in the DSM could not be relied upon. Subsequently the design adopted required reinforced piles to be offset into the basement as shown in Figure 2, allowing arching mechanism to be adequately developed.

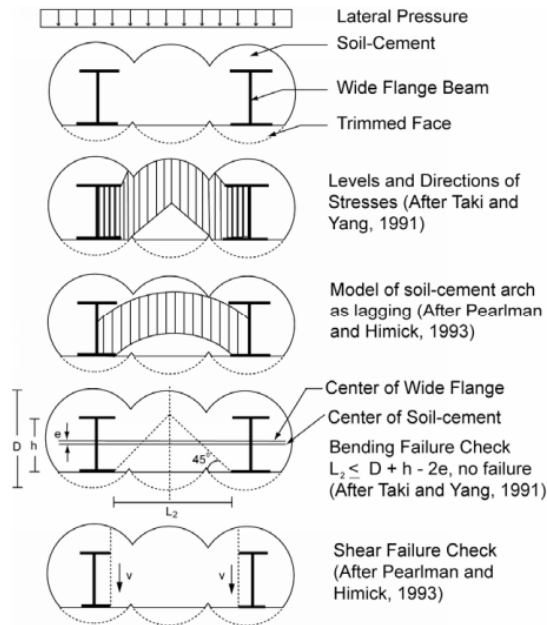


Figure 3. Summary of the design of improved ground as a lagging between reinforcing members (Rutherford, 2007)

6. DSM CONSTRUCTION

The construction of DSM columns was completed with a high level of quality control including preliminary trial columns, review of installation records and coring and testing of completed columns.



Figure 4. DSM installation in close proximity to an existing building with reduced vibration and noise compared with driven sheet pile or bored soldier pile options.

DSM trails consisted of a grid of 9 trial piles with an accompanying wall of secant DSM piles. CPT and DTM investigations were complete pre and post the DSM installation to investigate ground improvement effects due to the pressured installation and associated liquefaction mitigation effects. Trial columns were excavated and cored to confirm the strength and consistency of the DSM columns. An example of a core taken during construction is shown in Figure 5.



Figure 5. Quality control coring of DSM columns showing varying gravel sizes from different layers mixed through the column profile.

A data log was produced for every DSM column, recording drilling torque, rate of penetration and quantity of binder introduced with depth. Logs were reviewed to confirm construction quality including checking for increased torque to confirm penetration into the underlying dense gravels and potential issues with column construction and identify columns for proof coring and UCS testing. While isolated columns refused at depth on inferred buried wood in alluvial deposits, these did not compromise the overall design and no significant quality issues were identified

7. DSM PERFORMANCE

The DSM walls have performed admirably for retaining the groundwater control and basement retention for the construction of the first three buildings onsite.

An additional benefit of the use of DSM columns as part of the temporary works as they can be easily excavated and trimmed with conventional earthmoving equipment, allowing simple trimming of the excavated surfaces to accommodate any out tolerance construction and localised excavation of the top of DSM columns for lift pits or services/vehicle access routes in and out of the basement.

7.1 Groundwater Control

The DSM column wall provided an effective barrier against groundwater infiltration and inspections of the columns showed a dry face with only isolated areas of dampness as shown in Figure 6. As part of the basement excavation a series of shallow spears with a drainage blanket were installed in the base of the excavation to provide dry base for excavation and construction. Groundwater observations did not indicate any significant changes in the groundwater level outside of the basement.



Figure 6. 4m deep basement excavation with typically dry walls with localised areas of dampness and no groundwater infiltration through the wall.

7.2 Wall Deflection

During the excavation of the Stage 2 basement, a single, continuous crack up to 10mm wide was observed running directly behind the DSM wall as shown in Figure 7. Continued monitoring of this crack did not show any significant change in the crack width and no additional cracking was observed.

Key observations were:

- The cracking magnitude (7-10mm) was similar to the displacements assessed from the PLAXIS modelling (11mm);
- No cracking or deformation was observed in the DSM column or the interface between columns;
- The cracking and associated wall movement supports the provision of I-beams as tensile reinforcement;
- Due to access restrictions, the additional grid of DSM columns behind this wall to provide liquefaction mitigation could not be provided. Subsequently this wall would have experienced larger soil pressure compared with most areas of the site, which is consistent with cracking only being observed along this one wall.

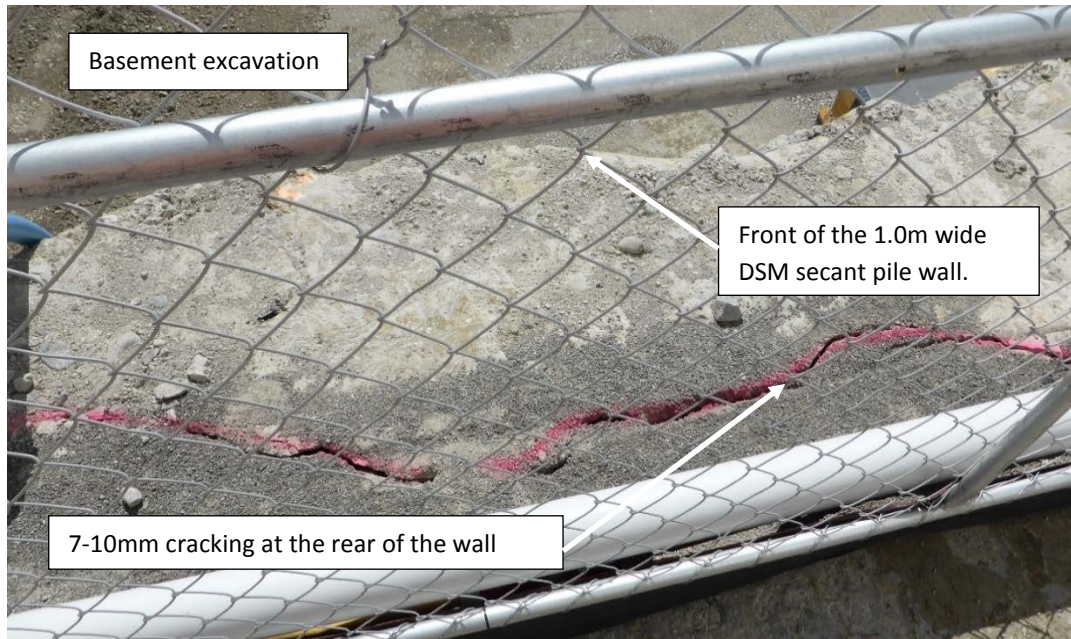


Figure 7. Looking down on cracking behind the front row of DSM columns

8. CONCLUSIONS

The adoption of DSM columns as a means of basement retention, groundwater control and ground improvement has brought cost and construction efficiencies to the construction of four new buildings at St George's Hospital. Additionally the low noise and vibration technique brought construction stage advantages over other systems, resulting in minimal impact on hospital operations.

The design of DSM columns for basement retention has been presented, along with a discussion on modelling approaches which brought efficiencies to the design, which have in part been validate by observed performance of the DSM column walls onsite.

9. REFERENCES

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