Ground Improvement using Turbojet Deep Soil Mixing - Case Study

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ABSTRACT

This paper presents a case study on the inaugural use of Turbojet deep soil mixing (DSM) in New Zealand. DSM was selected to provide the necessary ground improvement required for the Hastings District Council (HDC) Waste Water Treatment Plant upgrade. Reduced settlement and mitigation against liquefaction were key design considerations for the construction of two new bio-filter trickling tanks.

1 INTRODUCTION

1.1 Background

In October 2001 Hastings District Council (HDC) was issued a coastal permit (resource consent) to discharge treated wastewater from a new Domestic Wastewater Treatment Plant (WWTP) to the coastal marine area through HDC's existing 2.7km ocean outfall at East Clive, some 10km north east of Hastings.

Hastings District Council engaged MWH to provide professional services in relation to the project management and design of the new WWTP, adjacent to the existing milliscreening facility which is to be retained as an industrial WWTP.

Separated industrial flows are to be treated through the existing facility (fine screening & grit removal prior to outfall discharge) and all domestic and non-separable industry flows and septic imports are to be treated through the new domestic WWTP plant.

The new domestic WWTP is based upon the concept of the biological filtration of finely screened wastewater.

1.2 Project Description

Key structures in this process are two 37m diameter Biological Trickling Filters (BTF's) 11m high. These structures are constructed from precast, prestressed and post-tensioned concrete, and are filled with plastic media to support the establishment of the biomass. The influent wastewater is pumped from a BTF feed pumping station to a rotating distributor in the BTF and the influent trickles down through the media. Influent passes over the biomass, which establishes on the plastic media. The biomass removes organics from the wastewater by adsorption and assimilation of the soluble and suspended constituents.

A layout of the proposed plant showing the location of the two BTF's is shown below in Figure 1.

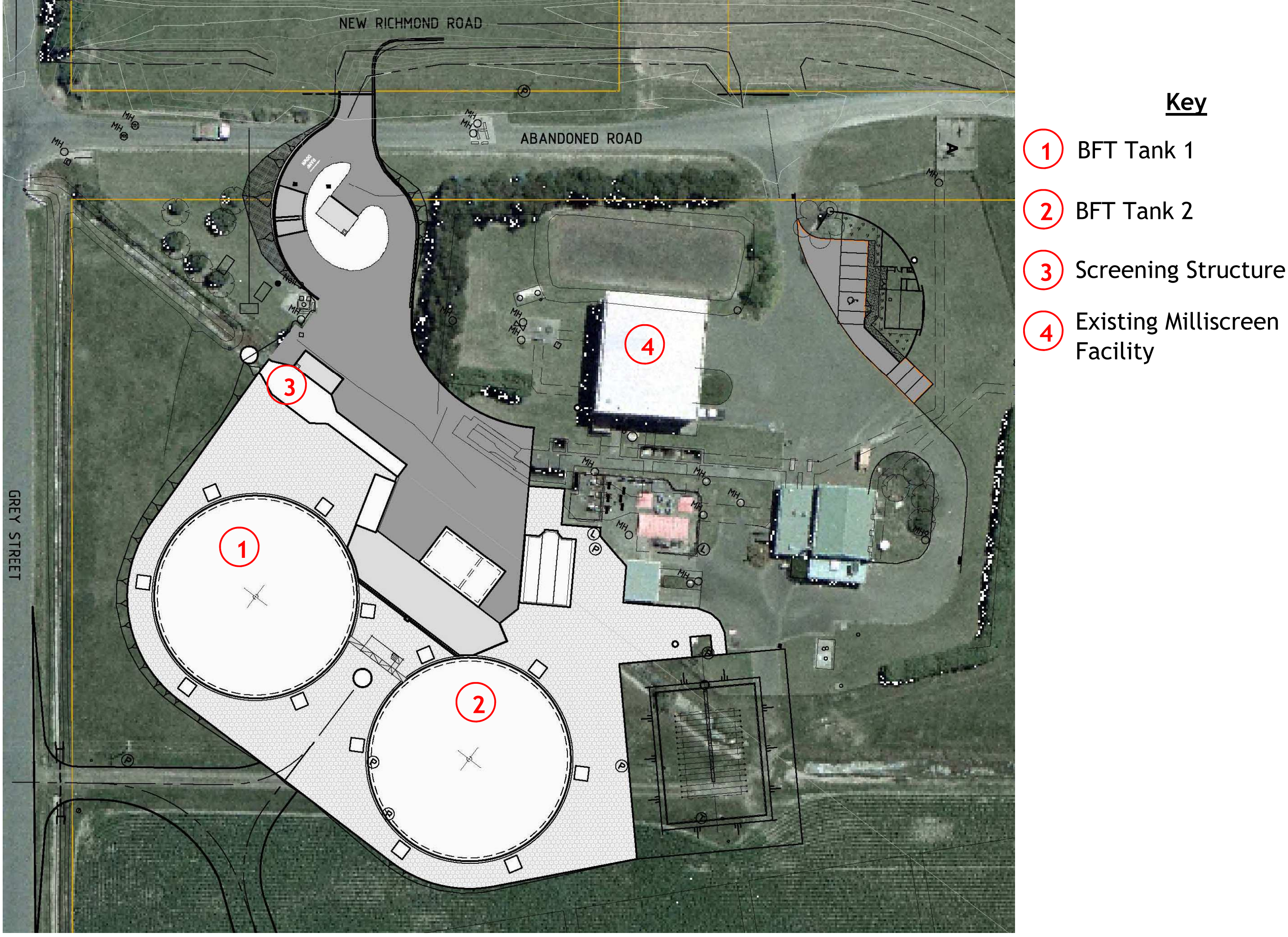

Figure 1 Site layout

1.3 Geotechnical Investigation, evaluation, and contract award

Geotechnical investigations were undertaken in June-August 2006 and further testing in 2007. Tests identified ground conditions considerably different to that experienced on the existing milliscreen/outfall pump station site. Laboratory testing was commissioned to determine consolidation parameters, liquefaction potential, strength characteristics, etc. . . .

Options for foundations for the BTF were investigated and reported on along with their inherent risks.

A number of design options were considered, including:

- Stiff concrete raft founded at approx. 2m below ground level
- Wick drains and preloading
- Stone columns
- Soil Mixing
- Piled solution – steel H piles
- Lightweight fill replacement
- Move the tanks to where gravel strata is more persistent (eastwards on existing site or a new site altogether)

After consideration and discussion the options were narrowed to either a pre-load and wick drain option, or stone columns. At that time it was believed that no NZ company had the ability to undertake the required depth of deep soil mixing (DSM).
The stone column option was favoured over the pre-load option Hiway Stabilizers advised that they intended to import plant suitable for DSM to the depths required at the site. Thus the request for tender documents permitted flexibility in the improvement technique to ensure that the best value solution could be obtained for the client, in the event a DSM option was tendered along with the stone column option.
The tenders were evaluated and the tender awarded to Hiway Stabilizers Environmental (HSE) using DSM columns as it was considered to be the best value solution based on the design, technical submission, price, plus the assurance afforded by the high degree of quality assurance provided.
Compliance testing is an important aspect of DSM works, and is a major advantage of the DSM ground improvement option. A proposed series of trial mixes, test columns, and production column tests provided high levels of quality assurance.
There is a shallow confined aquifer at the site and the nature of the DSM columns provided assurance to the Hawke's Bay Regional Council during the resource consenting of this work that the penetration of the aquifer by the DSM columns would preclude contamination and saline intrusion via the DSM columns.

The contract was awarded to HSE in 2007. The site was mobilised in early January 2008 and by late February the ground improvement was complete with 496 DSM columns being installed up to 14.5 metres depth.

2 GROUND CONDITIONS

2.1 Geotechnical Investigations

The geotechnical investigation carried out by MWH comprised 25 cone penetration tests, 6 machine boreholes and 5 test pits. Boreholes were drilled to a maximum depth of 25.5. The CPTs were investigated to a maximum depth of 25 metres. Two additional boreholes were drilled by SKM, HSE's designer, in 2007. A series of laboratory testing was carried out.

2.2 Geological Model

The site is underlain by Holocene alluvium of the Heretaunga series which comprises fossiliferous marine sands intercalated in fluviatile sands and silts.

Available investigation data reveal that the upper 3 to 5 metres of the alluvial deposit consists predominantly of very soft to soft clayey silt with undrained shear strength ranges from 6 to 45 kPa. It is subsequently underlain by a layer of granular deposits comprising very loose to loose silty sand/ sand and sandy gravel. The gravel layer is thickest on the eastern side of the site and gradually thins out toward the west. The granular layer is then underlain by soft to stiff clayey silt and medium dense sand.

The inferred subsurface profile and testing results are summarised in Table 1.

Table 1: Interpreted subsurface profile

Subsurface Material		Maximum Thickness (m)	SPT Values	Qc (MPa)
1	Clayey silt (very soft – soft)	5.0	0 – 3	<0.5MPa
2	Silty sand (very loose – loose)	4.0	0 – 20	>5MPa
3	Sandy gravel (very loose – medium dense)	2.5	24 – 27	>20MPa

4	Clayey silt (soft – firm)	5.5	2 – 7	<1MPa
5	Clayey silt (firm - stiff)	7.0	7 – 10	1 – 2MPa
6	Silty sand/ sand (medium dense)	NA	13 – 32	>10MPa

Groundwater seepage was recorded at 2 to 2.5 metres below existing ground level. For design purpose, a groundwater depth of 2 metres has been adopted.

3 DESIGN

3.1 Design Concept

DSM is a ground improvement technique that improves the foundation characteristics by mixing insitu soil with cementitious binders to form stabilised soil-cement columns.

To minimise consolidation settlement and reduce the likelihood of soil liquefaction, an array of DSM columns were installed over the tank footprint. The DSM columns were founded at the non-liquefiable stratum. This arrangement mitigates liquefaction by restraining the shear deformation of the soil during an earthquake. Both the dynamic earth pressure and inertia force of the surrounded soil mass will be carried by the soil-cement columns. The DSM columns were design to support the BTF tank structures during an earthquake.

3.2 Design Approach

The performance of ground treatment design in terms of settlement reduction and liquefaction mitigation was evaluated using a finite element programme, Plaxis version 8.6.

The effectiveness of the ground treatment design in terms of mitigation of the effect of liquefaction has been measured by comparing the liquefaction potential of the liquefiable deposit prior to and after the ground treatment. The liquefaction potential of the site has been evaluated using the modified Robertson method. This method calculates an equivalent safety factor against liquefaction by comparing the cyclic resistance ratio (CRR) with the cyclic stress ratio (CSR) induced in the soil during a seismic event.

The cyclic resistance ratio (CRR) refers to the shear capacity of the soil. It is determined using the available CPT data and can be calculated for the loose sand deposit at various depths.

The cyclic stress ratio (CSR) is the normalised shear stress induced during an earthquake. The CSR can be determined by simulating a design seismic event using the dynamic module in Plaxis to estimate the amount of shear stress being induced in the soil during an earthquake.

3.3 Performance Criteria

The ground improvement was designed to achieve the following criteria:

- Maximum post-construction settlement under static conditions - 50mm.
- Differential settlement 5 mm.
- The columns designed to carry all applied load under dynamic conditions.
- Factor of safety against liquefaction of 1.1 or above.

3.4 DSM Properties

The design was based on column strength achievable in the lower bound strength material being the silty clay layers. The design column stiffness was assumed to be 360MPa and corresponding UCS strength of 2 MPa. Column diameter is 600 mm.

55 unconfined compression strength (UCS) tests were carried out to determine the strength of stabilised soil using various cement mix designs. These results are consistent with the previous laboratory test results from similar soil-cement column samples completed to date.

3.5 Design Seismic Acceleration

The design peak ground acceleration is taken as 0.56g.

Seismic action is simulated in Plaxis using the actual accelerogram recorded in March 1987 at Matahina Dam recording station during the Edgecumbe earthquake. The input motion has been scaled to generate a maximum ground acceleration of 0.56g.

3.6 Results

The recommended DSM design is summarised in Table 2.

Table 2: Turbojet design

DSM Configuration						
Treatment Area (m2)	Spacing		Depth (m)	Equivalent Replacement Ratio (%)	Total No. of Columns	Total Linear Length (m)
	Radial (m)	Circumferential (m)				
2175	1.2 to 2.0	1.6 to 3.0	12.5 to 14.5	6.6%	496	6576

Results summarised in Table 3 indicate that the DSM design can significantly reduce the induced shear stress in the soil mass. This demonstrates the proposed ground treatment arrangement will confine and restrict deformation of the liquefiable sand deposit.

Table 3: Summary of liquefaction potential

Depth below EGL (m)	Baseline Conditions – No Ground Treatment		With Ground Treatment	
	Max Shear Stress (kPa)	FOS against Liquefaction	Max Shear Stress (kPa)	FOS against Liquefaction
4	16	0.5	12	1.1
6	24	0.6	15.2	1.4

The shear stresses within DSM columns were checked using finite element analysis. It is noted that the maximum deviatoric stress within the column will be less than the design UCS value, indicating the columns are unlikely to be failed by shear.

4 CONSTRUCTION

4.1 Turbojet Description

Turbojet is a recently developed "wet" method of DSM. The method was developed as a hybrid system incorporating the benefits of both high pressure "jet" cutting and mechanical mixing to provide a highly efficient method of soil mixing.

Grout is injected at high pressure through a series of outlet nozzles on the mixing tool cutting soils as the mixing tool advances. Soil cutting (pre disgregation) is thereby achieved in most soil types including conventionally more problematic cohesive plastic clays.

The mechanical mixing of grout and soil (disgregation) is achieved using a mixing tool featuring cutting teeth and inclined blades and mixing head. The mixing tool for this project was modified and configured to allow for cutting and mixing of both silty clay soils and the sand and gravel layers.

Figure 2: Turbojet rig, batching plant and pump

4.2 Implementation

The type of binder and application rate was selected based on the existing knowledge of soil types and the results of the laboratory mixing and testing of recovered soils. Following initial laboratory testing, a series of 7 trial columns were initially constructed immediately beyond the periphery of tank 1 to a depth of 14.5 metres. The trial columns comprised three different mix designs representing 300 to 400 kg cement per m^3 plus the addition of lime to one trial mix design. Various water cement ratios were also selected along with differing nozzle sizes, outlet positions and varying delivery pressures. The primary purpose of the trial columns was to determine the effectiveness of achieving mixing and homogeneity plus confirmation that the design column strength and stiffness could be achieved.

The trial incorporated both single phase (grout injection during drilling and withdrawal) and double phase (water injection during drilling and grout injection during jetting). Based on the field trial results, the higher cement and lime mix was selected with the addition of lime notably achieving effective breakdown and homogenising of the silty clays. As a result of the trial, the single phase method was selected.

Grout was batched on site using an automated GM14 grout batching plant featuring automated electronic weighing of binders, accurately controlled water injection and a series of high sheer mixer and agitator tanks. Grout was continuously tested to ensure correct density.

Grout is delivered to the mixing tool using a high pressure triplex piston pump capable of delivery pressure up to 500 bars. Grout pressure can be varied and is selected depending on the soil types and the column mix design. 200 Bar grout pressure was selected for this project.

During production up to 8 underground obstructions were met, preventing column installation to full design depth. These logs and wood obstructions were found predominately at the top of the

gravel layer at approximately 6 metres depth, representing the geological riverbed deposition. The possibility of obstructions was foreseen based on site investigations and was addressed at tender time. The client and contractor took a risk share approach towards dealing with obstructions with new replacement columns required due to the obstructions, were installed within 1.5 metres of the design position.

4.3 Quality Assurance

Turbojet features a high degree of quality control throughout the installation process. A Jean Lutz Taralog computer within the cabin of the drill rig provides continuous monitoring and real time data capture of both drilling and grout parameters. This provides continuous and accurate recording of drilling depth, drilling rate, rotation speed, rotary torque and thrust, plus grout flow, volumes and pressures.

Individual columns are continually recorded in both the Drilling (insertion) and Jetting (withdrawal) phase. The Taralog features preset automated drilling functions plus a manual control function. Data download and processing enables analysis of individual columns to ensure that design parameters are achieved.

A comprehensive sampling, testing and post construction testing programme is implemented to validate design strengths and ensure that the design criteria are met.

4.4 Results

The QA plan required recording of grout batch data. The computer Memory block was downloaded daily to check drill and grout parameters. Column samples were extracted daily using a push tube sampler. Soil cement cylinders were then tested at 7, 14 and 28 days.

Additionally, two production columns were cored using PQ drill tool to full 12.5 metre depth. A series of recovered cores at 2 metre incremental depths were strength tested. These cores provided verification that both strength and stiffness were achieved. UCS results revealed that an average strength of 3.5 MPa and an average Youngs modulus of 520 MPa was achieved. In the silty clays and almost double that strength and stiffness was achieved in the in the sands and gravel layers.

Figure 3: Excavated Turbojet column

5 CONCLUSIONS

Assessments indicate that the DSM ground improvement successfully improved the soil characteristics such that the liquefaction potential and post-construction settlement comply with the clients needs. DSM proved to be a cost effective and rapid ground improvement solution which met with the clients requirements on this project.

REFERENCES

Youd, T.L. et al. (2001) Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/ NSF workshops on evaluation of liquefaction resistance of soils. *J Geotech. and Geoenvironemental Engrg., Vol. 127(10), ASCE, 817 - 833.*

Youd, T.L., Idriss, I.M. (1997) *Proceedings of the NCEER workshop on evaluation of liquefaction resistance of soils.* NCEER.