Innovation in Slip and Settlement Remedials: the Soil Mixing Option

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Summary: New Zealand roads have long suffered from over- under-slips and settlement, many associated with increased porewater pressure build up and/or weak soils.

Traditionally such slips have been remediated through measures including bored horizontal drains, gabion or other mass gravity walls, embedded walls (pole/panel, H-piles and bored concrete piles) and excavation/replacement/shear key earthworks.

Soil mixing is a new technique to New Zealand originating in Europe. To date the process has been used to remediate slips within the Northland region, which effectively improves soil shear strength through mixing of the in-situ soils with lime and/or cement.

This paper examines the soil mixing technique, its applicability to slope instability remedial works and outlines the design and construction process including a number of case studies.

INTRODUCTION

MWH (NZ) Ltd provide the professional services inputs into the Performance Specified Maintenance Contract (PSMC) 002, which covers Northland in the North Island of New Zealand. The soils of Northland pose interesting geotechnical challenges in respect of maintaining linear structures, such as road and rail, in place on a highly mobile landscape.

Intense and or prolonged rainfall within the Northland region generally results in landslip, often impacting upon the State Highways. Traditionally such slips have been remediated by drainage (deep counterfort drains, sub-soil drains or horizontally bored drains) or retention (mass gravity or embedded retaining structures), or earthworks (shear keys and berms). As part of the PSMC002s continual drive to identify and adopt innovative techniques, where they can be applied within Northland, new and/or improved methods of undertaking remedial repairs to slips are continually being assessed. One such method, soil mixing, has been adopted and trialed within the Northland region.

SOIL MIXING

Soil mixing was first used some 50 years ago in the United States (US) with a mixed-in-place technique developed by Intrusion Prepakt in 1954. This was followed by developments in Japan and Sweden in the late 1960s using dry lime to treat soft clays which lead to the first commercial applications in the late 1970s.

Methods developed rapidly in Scandinavia, with the technique being used in foundation, embankment stabilisation, excavation support, barrier walls and for vibration reduction. Similar development followed in Japan, the US, and mainland Europe, with soil mixing being used in a variety of soil conditions and resulting in soil mixing becoming a recognised and widely used ground improvement technique.

The concept of soil mixing is fundamentally different to that of conventional slip remediation processes, such as retaining structures and excavation and replacement, where either a structure is constructed founded within stable ground at depth or the weak materials are excavated and replaced. With soil mixing the unique properties of each site are modified in-situ to meet the required performance criteria (settlement, bearing capacity, or stability).

Soil Mixing in New Zealand

Soil mixing can be undertaken by an array of differing methods; from simple hoeing at near surface through to the development of soil mixed piles.

Soil mixing in New Zealand adopts a process of in-situ mixing of the original soil with a binder resulting in an increase in the soils shear strength. The principle of the process relies on three distinct phenomenon (destructuration, incorporation and recompaction) occurring either simultaneously or separately.

The process is performed by using twin counter rotating augers with opposite pitches. The twin augers are located at the end of drill rods and each features a disaggregating drill head with grout outlet port. The result of the twin auger mixing is interlocked helixes over the full length of soil mixing.

During the first phase of drilling the destructuration and incorporation of the binder occurs during either one or several drives as the result of injection of grout (mixture of binder and water). The second phase is recompaction, which results in the mixtures being forced down and compacted as the double augers are unscrewed under a constant thrust.

The binder used for the stabilisation of soil is either lime, cement or a combination of the two depending on the soil and the characteristics of the column required. The use of lime as a binder results in the strength of the clay soils being increased by ion exchange during the first phase of the process and over the long-term by a pouzzolanic type reaction occurring. The use of cement strengthens the soils by its hydraulic binding characteristics. The selection of the binder and the quantity used is based on the mineral characteristics of the soil, its water content and the expected results.

A high level of quality control is obtained during the process through an on board computer within the auger rig. The computer system controls the accurate delivery of grout to the augers and monitors the drilling parameters. This permits the modification of column constituents should ground conditions differ from those anticipated.

Some of the key benefits of the soil mixing approach within the PSMC context are:-

- the ability to adjust the soil treatment (mix) as the work proceeds to provide a ground stiffness commensurate with the end-use requirements;
- the ability to adjust the soil mix column length to cater for changes in ground conditions within the treatment area as work proceeds;
- the ability to work around and within existing services without the need to remove/relocate services (and therefore the associated costs therewith);
- the ability to undertake the treatment through the existing pavement thereby limiting temporary works, land entry requirements and associated regional/local authority consents;
- avoids inherent risks associated with boring/excavations immediately adjacent to the highway and the resulting health and safety implications.

ADOPTED DESIGN APPROACH

Conventionally, the remediation design is based on a composite soils strength approach. It is possible to start with a back analysis of the existing slope, work out what increment of strength is required to achieve the desired factor of safety, and then work out the required soil replacement or column spacing on that basis. These calculations can be done on a slope stability software package or using simple slope stability charts.

This approach assumes that the shear strength of the column is averaged by area with the unit area of soil around each column. This is usually done on the basis that the column has a shear strength of 0.5 times the unconfined compressive strength. The treated block is analysed in an undrained, or total stress, limit equilibrium stability analysis to confirm the final factor of safety. A similar analysis can be performed using effective stress parameters.

A similar simplified approach can be used for settlement problems where the compressibility of the treated ground can be considered to be proportional to an aerial average of the combined stiffness moduli.

Such an approach works fine when the failure mechanism is simple and the resulting spacing leads to group action of the soil mixing columns. However, many of the failures are more complex and more sophisticated analysis is required.

In many of the slips remediated to date, there have been competing mechanisms and it is difficult to identify what is genuinely responsible for on-going movement. Many of these slips have been situated in environments where there are possibly deep seated slip planes, as well as shallow soft clay zones, underlying poor road construction (by modern day standards). These conditions are often exacerbated by poor surface water drainage.

Finite Element Analyses have been performed to model competing failure mechanisms and identify the dominant features at work. With FEA it is possible to optimise the position of the columns and demonstrate the effectiveness of the proposed repair. These analyses have demonstrated the compound nature of the failures incorporating elements of bearing capacity, creep (both on slope and secondary compression), fluctuating groundwater and simple slope instability.

To illustrate the process two sites have been selected as case histories. Edwards 1 is an example of a simple slip and Rawene is an example of a complex slip.

Site investigations at Edwards 1 indicated that the ground conditions comprised a fill layer overlying a soft to firm clay layer situated on top of stiff to hard mudstone. The soft clay layer may have been softened by surface water infiltration through from the up-slope drainage channel.

Analysis using Hoek and Bray charts with a water table consistent with observations on the site was sufficient to explain the failure. Adopting the simplified solution described above meant that the required increase of strength was satisfied by the introduction of three rows of 1.5MPa columns at 2.5m centres. The simplified design approach located the first row of columns on the down-slope edge of the road and worked down hill from there. Subsoil drainage and re-grading the up-slope drainage channel was also recommended.

In contrast, Rawene illustrated more complex failure mechanisms. Site investigation suggested two to three metres of fill on top of a soft to firm clay layer of variable thickness. Site topography suggested that the road was part cut and part fill along the edge of the adjacent tidal river, with the soft clay layer being part estuarine mud, and part alluvial mud from a tributary stream which passed underneath the road at the failure location.

The site history was clearly complex with multiple pavement top-ups forming over one metre of pavement layering over the original fill. This is in addition to fill being placed along the side of the road to mitigate "slumping" along the edge. However, none of the site works had ever been clearly documented.

Preliminary analysis indicated that a minimum of four rows of columns at 1.5m centres would be required to stabilise the failure. However, the mechanism of failure was not clear, so additional analysis was performed using the finite element program 'PLAXIS'.

This analysis illustrated the complexity of the site and the mechanisms at work. The existing bank was clearly shown to be unstable, but failure of the bank would not (at least initially) affect the road. The analysis also showed that the road fill was undergoing a bearing capacity failure and that some form of secondary compression or creep within the soft clay layers was also occurring. As a result of this analysis, a partial fifth row of columns was introduced to mitigate these effects. Figure 4 illustrates a typical analysis output.

CONSTRUCTION: CASE HISTORIES

Edwards #1 and #2

Location
State Highway 12, just west of Maungaturoto Township, Northland.

The Problem

The road is constructed on a part cut/fill embankment over sloping ground. There were two 25m long slips in the downslope batter that encroached into the edge of the outer lane and affect the pavement.

Investigation

The geotechnical investigation undertaken by MWH included boreholes, trial pit's and CPT's. These revealed that the road had been constructed on soft to firm clay over stiff clay grading to mudstone. Groundwater from the upslope drain was also inferred to be seeping under/through the embankment.

Design Analysis

The analysis, undertaken by SKM using parameters derived from the ground investigation, indicated the slip failure mechanism was shallow (less than 3 to 4m) and coincided with the soft/firm zone above the mudstone. Some settlement was also occurring within the road mainly due to additional loading from previous repairs on the soft soils.

Back analysis of the slope failures indicated for each slip the Factor of Safety could be increased from 1 to 1.5 by introducing 3 x 30m long rows of columns at 3m centres and 5m depth, as indicated in Figure 1.

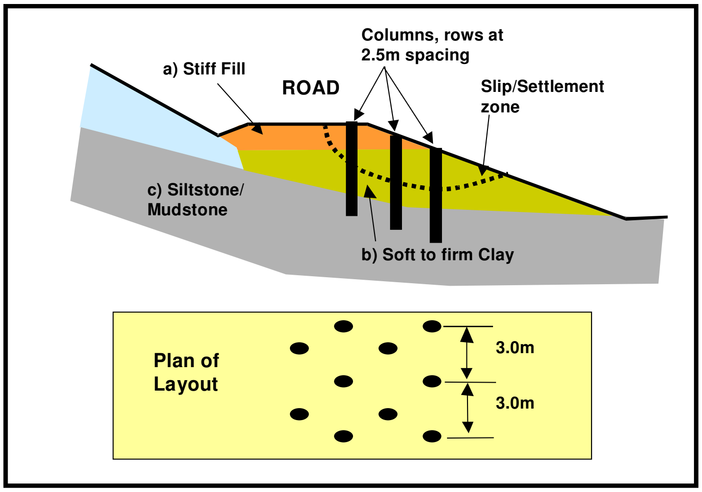

Figure 1. Column Layout at Edwards #1 and #2

Construction

Construction begun in March 2003 and 60 columns were installed in 10 working days using the twin counter-rotating auger as shown in Figure 2.

Figure 2. Close-up of the counter-rotating auger head assembly

Quality Control

Complete construction records for each pile, including depth, rate of penetration and material quantities are maintained, together with a layout plan of the columns. To monitor construction quality, selected columns were cored after 80 days to provide samples for UCS testing.

The resulting unconfined compression strengths of the tested core samples are shown in Figure 3 below. The test results are compared to the design values to ensure design requirements have been met.

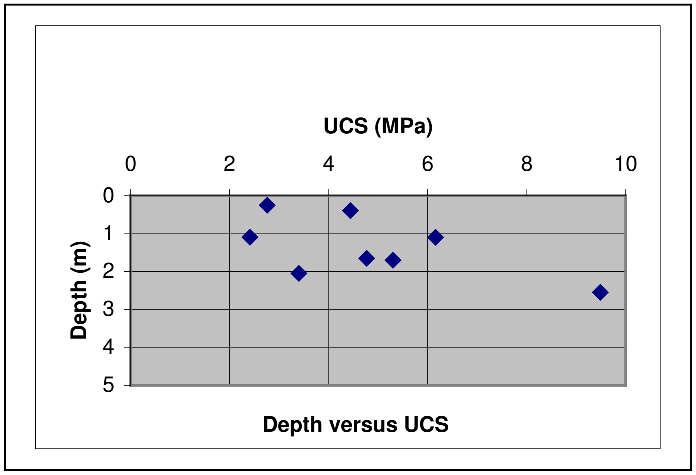

Figure 3. Unconfined Compressive Strength Test Results

Following completion of the column installation, sampling and testing, the pavement was reconstructed by Works Infrastructure Limited, the PSMC contractor.

Costs

Costs (excluding pavement reconstruction) were around $78,000 compared with $100,000 for the conventional lowest cost option of gabion walls.

Rawene Bluff

Location

State Highway 12,adjacent to the Omania River, near Rawene on the Hokianga Harbour.

The Problem

The road is constructed on a fill embankment adjacent to a river. There is a history of ongoing road settlement/instability causing deformation along a 60m length of pavement resulting in poor road surface, repeated temporary repairs and continuing maintenance.

Investigation

The geotechnical investigation undertaken by MWH revealed the road embankment had been constructed over soft saturated alluvial soils associated with river deposits. Beneath the alluvium is a very stiff sandy clay (residual soil).

Soil samples were taken and mixed with a variety of cement grout quantities to determine the design grout percentage to provide design Unconfined Compressive Strengths (UCS) of > 1.5Mpa.

Design Analysis

The analysis was completed using Plaxis, a finite element design program. The analysis used parameters derived from the ground investigation, modelled the existing conditions, construction of the road embankment and subsequent long-term behaviour. The results indicated the failure mechanism of the road and embankment was due to instability (lateral movement) and deformation (settlement) from the soft underlying soils.

The analysis was re-run introducing 5 staggered rows of columns at 3m centres and to 7m maximum depth. The columns were designed to penetrate through the soft/weak zones and found on the stiff layer. The results showed a Factor of Safety (FOS) for stability of > 1.5 and settlements reduced to acceptable standards.

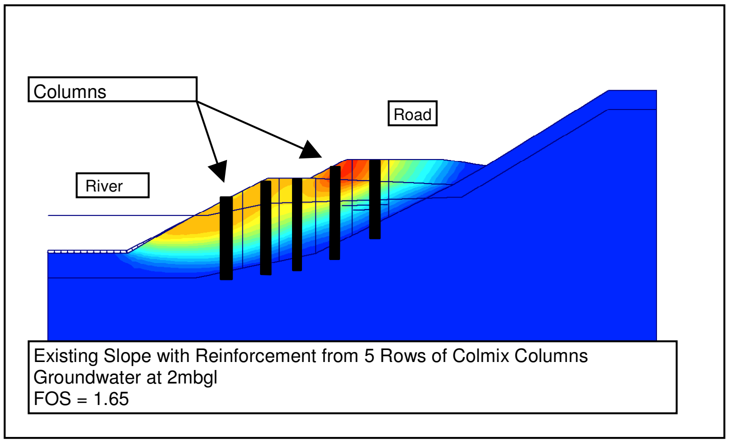

Figure 4. Typical Plaxis Output

Construction

Construction begun in December 2002 and 82 columns were installed in 12 working days. Since installation there has been no signs of instability and/or settlement after 7 months (to July 2003).

Figure 5. Installation of columns

Figure 6. Grout Mixing Plant

Quality Control
The onboard data recorder enables individual pile installation records of time, depth, torque and grout quantities and also identifies soft/stiff zones to confirm design assumptions. As built layout plans are also provided. Insitu samples of selected columns are taken for post site UCS testing to confirm design parameters.

Costs
Costs (excluding pavement rehabilitation) were $130k and were lower than the lowest cost conventional option.

CONCLUSIONS

Based upon the designs undertaken by SKM, the obtained FOS for the soil mixing option is comparable, for suitable sites, with that obtained by conventional methods of remediation and hence are comparable in terms of stability. The method does offer, however, some significant benefits over conventionally adopted methods in terms of reduced (if not eliminated) risks in the areas of temporary works, evacuation adjacent to a live highway and the accompanying health and safety aspects.

Soil mixing appears to be suitable for many of the Northland soils with the main criteria for suitability revolving around the mode of failure, adjacent topography and cost. The key benefits of the system within the PSMC context are:-

- limited, if any, consenting requirements;
- disruption to traffic of lessor duration that other conventional methods of repair;
- no spoil removal (and therefore limited regional and local authority consenting requirements);
- is adaptable to changes in ground conditions and can be modified during the works to cater for such changes;
- the ability to undertake the treatment through the existing pavement thereby limiting temporary works, land entry requirements and associated regional/local authority consents
- avoids inherent risks associated with boring/excavations immediately adjacent to the highway and the resulting health and safety implications
- avoids many temporary works risks.

Soil mixing has now made a step into the New Zealand market place and will be judged by its performance over the next few years. However its well proven overseas track record in terms of earthworks remodels, foundation construction and general stabilisation works should ensure a growing acceptance of this versatile method.

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