COLMIX - Deep Soil Mixing in New Zealand – An update

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ABSTRACT: This paper presents recent developments in the use of deep soil mixing technique in New Zealand road slip repair works. A brief overview of New Zealand road maintenance history is presented, and the current role that deep soil mixing is playing is described. Valuable experience has been gained through the design and construction of deep soil mixing road remedial works. Key issues include composite behaviour and group effects of deep soil mixing of columns, and identifying failure mechanisms. The benefits of deep soil mixing are illustrated through case studies.

1 INTRODUCTION

New Zealands' geology generally comprises a range of young and geotechnically challenging soils. As a result, New Zealand roads have long suffered from over and under slip settlements, many associated with increased porewater pressure buildup and/or weak soil properties. A photograph of a road underlip is shown in Figure 1.

Figure 1: A recent New Zealand road underslip

The engineering methods and available technologies in New Zealand for dealing with these soils have often been limited to certain traditional techniques, with sometimes inconsistent and often poor results. Figure 2 shows alternative remedial work options which would have been implemented if deep soil mixing was not used for the road slips repaired to date. A majority of the alternatives comprise H-pile and gabion wall and drainage based solutions.

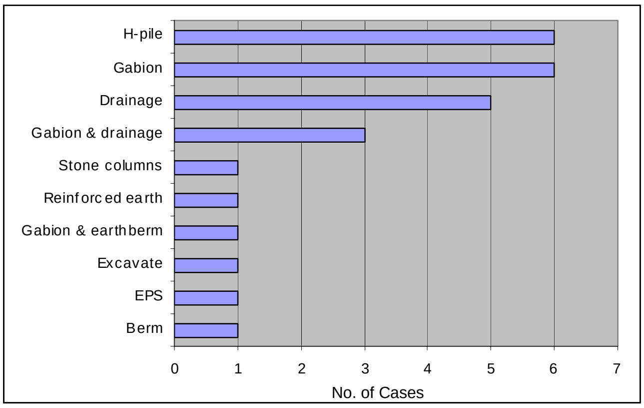

Figure 2: Alternative to Colmix solutions

In 2002, Hiway Stabilizers completed an evaluation of the various soil mixing technologies available worldwide which could be specifically applied to road maintenance works. It was concluded that insitu deep mixing using the "wet" process was the most suited to New Zealands' soft soil types. The Colmix soil mixing system was selected and imported to New Zealand in late 2002 under a technology transfer agreement. Colmix is now constructed in New Zealand by Encore – a joint venture between Hiway Stabilizers and Works Infrastructure.

Colmix is a proprietary method developed by Soletanche Bachy, utilising multiple augers to achieve highly efficient mixing and resultant soil mixed columns. A Colmix rig is shown in Figure 3. Binder slurry is mixed in a batching plant and pumped through the hollow stemmed augers where the grout is discharged at the drill head. The batching, pumping and drilling is a computer controlled and monitored process ensuring complete quality control throughout the mixing and drilling process. Binder mix designs are selected based on the soil characteristics and the results from laboratory reactivity testing of site samples.

The Colmix auger arrangement comprises twin overlapping discontinuous flight augers. Binder is injected during the insertion phase to achieve soil homogenisation and lubrication of the mixing tool. During the extraction phase, the augers are reversed and along with an applied downward thrust, compaction of the soil column is achieved. Typical dimensions of column sections range from 400 mm to 1000 mm.

This paper reports on progress achieved with Colmix over the last two years in New Zealand and specifically design and construction issues. Several case histories are presented to reach conclusions on the success of this process.

Figure 3: Colmix rig

2 ROLE OF COLMIX IN NEW ZEALAND

New Zealand has a low population, 4 million, spread across a land mass approx 10% larger than Great Britain.

The country's early reliance on primary produce export, coupled with the population characteristics, have influenced the development of the roading network. The necessity for transporting farm products in all weathers required roads to be constructed as quickly and cheaply as possible.

This has resulted in a staged development. As volumes and loads increased, roads were progressively upgraded from dirt tracks of the early 1900's to today's multi-lane facilities. The approach to road construction was developed in the 1920's and 1930's, an approach that still serves as the basis for current construction and maintenance technology.

The rolling hilly topography meant that the first single lane dirt tracks were constructed by hand, usually by excavating into the slope and casting the cut material over the side. The load bearing carriageway was on the cut portion of the construction. Today's engineers would cringe at the lack of proper treatment of gulley crossings, soft materials, etc. Fill materials were often spread directly onto the soft materials. These roads were fit for the loads that used them at the time of construction. As loads increased, the pavements built over the soft gulley fills settled. The deformed pavements were topped up to restore shape. As volumes increased, the side cast cut material started to get traffic as vehicles pulled over to pass. The continual volume increase finally resulted in two lane roads, with the outer wheel tracks of the outer lane founded on the uncompacted sidecast material. Again, the treatment was often to keep filling the resulting depressions with more material.

The vast majority of the countries roads are built using unbound crushed rock granular materials surfaced with sprayed bituminous chipsealing. This relatively cheap technology, by international standards, results in maintenance costs that can be relatively high.

The 1980's saw the introduction of economic guidelines, which take into account road user costs, to establish priorities for maintenance and construction works. Amongst other things, this resulted in road managers paying particular attention to road user costs attributable to road roughness, and on sudden changes in road shape that can influence user safety.

This focus leads to a significant part of the maintenance funds being spent on smoothing roads. The smoothing is often required because of

- the settlement and consolidation of deep down layers of soft material – material that would have been removed if the road was being built today
- or the rotational or translational movement of oversteep or uncompacted weak materials

The best solution that the geotechnical engineer can produce is one that will permanently restore a smooth road. Solutions that arrest lateral movement, without addressing settlement or consolidation, must be regarded as less than ideal. Wherever there are soft materials being compressed by the overlying pavement and traffic loadings, traditional drainage and/or wall type solutions may only be addressing half of the problem.

3 GEOLOGY

3.1 Northland geology

To date, a vast majority of the slips that have been repaired are in Northland, New Zealand. Much of the Northland geology comprises the problematic Northland Allochthon soils, which are prone to slope instability and creep movements. This, in combination with a high rainfall (over 1200mm), results in the numerous road slips observed in this region.

Many of the properties of this material originate from the significant presence of sheared crush zones and sheared fabric in combination with a distinct highly weathered zone. The residual friction angle of this type of material is generally very low, and could be as low as 8°, though the softened friction angle is often around 20° to 26°. The intact unweathered material is strictly an extremely weak to weak rock. This provides for large contrasts in strength, permeability and stiffness.

3.2 Implications on failure mechanisms

The typical geomorphology is characterised by numerous shallow-seated failures within the slope. Such shallow failures have been observed on gentle slopes of 5° to 15° because of the low residual strength and creep movement. Much of the Northland Allochthon soil is highly plastic and has a high shrinkage swell potential, which exacerbates the soil's susceptibility to creep.

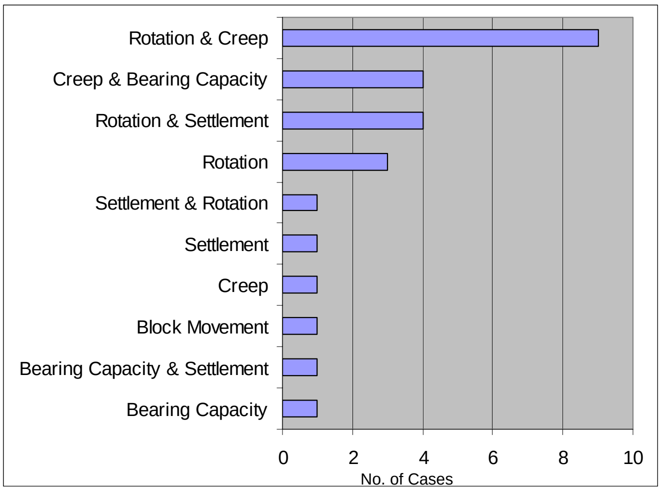

Figure 4: Types of failure mechanisms repaired to date

Topographically the area, even though of limited height, is quite rugged. As a result of this, in combination with the high rainfalls, there are many gullies present with recent soft deposits. The road is particularly prone to slip movement where it is built on such soft deposits without proper cleanout of the gully floor first.

Because of the above characteristics of the Northland Allochthon, several slip mechanisms are observed in Northland, including rotational and translational slips, settlement, bearing capacity failure and creep. Slips often result from a combination of multiple mechanisms. Therefore sound assessment of the slip mechanisms is important as appropriate remedial measures cannot be implemented without identifying all of the mechanisms taking place. Figure 4 summarises the primary and secondary mechanisms of the road slips that have been repaired using Colmix remedial solutions. Primary mechanisms are mentioned first, followed by secondary mechanisms.

4 DESIGN ISSUES

4.1 Mechanism

Understanding the movement mechanism prior to carrying out the design is crucial to the success of the final design. This simple step is often not carried out, and leads to many unsuccessful designs. It is often more complicated as many sites have multiple mechanisms operative, making traditional design approaches difficult.

4.2 Composite behaviour

In order to perform the desired design, one needs to understand how the columns work and interact with the surrounding soil. Initial approaches to the problem utilized a composite approach, using a weighted average of soil and column strength and stiffness. This weighted average approach takes account of the theoretical column section area and column spacings. Whilst this is an intuitive approach, and demonstrated to work well in some areas, it is clearly not sufficient for inclusions in soils.

The reason for this is not hard to determine. Soils have both a frictional and cohesion component to their strength. As result, the comparative behaviour of the soil fraction and the column fraction is strongly influenced by the amount of load that the column attracts. Whilst this is in part determined by the relative stiffness of the two fractions, it is also strongly influenced by the amount of arching that may occur.

The net effect is that provided the columns are sufficiently close to interact, it is more appropriate to consider a block of treated soil rather than individual columns. The issues on surrounding this are discussed in the next sections. However, suggestions for design rules are still in development.

4.3 Group effects

Field observations imply that the spacings and layout of Colmix columns strongly affect the post construction performance of the remedial work. Colmix columns appear to behave like individual piles when they are installed at spacings that are larger than a threshold value. When the column spacings are smaller than the threshold value, they behave more like a pile group. Consideration of pile group loadings such as those suggested by Poulos and Davis (1980) indicate that the group behaviour at 2.5 m by 2.5 m spacing will be 10% higher than the individual components will indicate.

The Colmix remedial work, if spaced together closely, creates a block of improved soil, which mitigates the vertical and circular horizontal slip movement. The remedial work performs much better on a long term when group behaviour develops. The Colmix columns remain stable even if the surrounding soil creeps, and therefore keeps the road pavement structure intact.

Minor post construction pavement deformation has been observed at a road slip site where the slip has been treated with Colmix columns with large spacings. Field observations to date suggest that the column spacings should be limited to a maximum of 2.5 m for standard Colmix columns (290 mm diameter twin augers), which is consistent with the analytic observations above.

4.4 2D and 3D issues

Design of deep soil mixing remedial work has mostly been carried out using a 2D finite element analyses to date. Whilst the remedial works designed with 2D analyses have generally performed satisfactorily to date, there are behavioural issues that need to be addressed on a theoretical basis. For example, the design at Portland (Case history described further below) has clearly performed and appear to have resolved long standing issues, yet the conventional theory would raise many question marks due to the level of lateral loads and settlement. Many of these issues are adequately addressed by considerations of pile group theory, yet this has yet to be applied in a systematic way to deep soil mixing.

3D analyses have been carried out in a few cases as a supplement to 2D analyses. Both 2D and 3D analyses predicted the overall behaviour of Colmix remedial works in a consistent manner. 3D analyses however have a definite advantage in that they simulate the pile stresses and lateral loads in a more realistic manner. Whilst 2D analyses may be adequate for simple slip mechanisms, 3D analyses are desirable for more complex slips where lateral loads and pile group interaction play a major role in the slip mechanism.

4.5 Groundwater flow

The detailed analyses of the case histories indicated that groundwater flow has significant impact on the stability of the slip. This means that the conventional slope stability analysis with phreatic groundwater pressure tends to overestimate the factor of safety. In the case of Portland, the calculated factors were 1.5 using phreatic pressure analysis and 1.2 in analyses coupled with groundwater flow calculations.

4.6 Remedial work design

In recognition of the issues discussed above, a methodology for design has been developed.

The design approach developed usually comprises two stages. Firstly, a preliminary design is carried out using a composite soil strength approach. This approach assumes that the shear strength of the Colmix column is averaged over the whole reinforced soil block. Relative cross sectional areas of columns and soil are used to calculate the averaged composite strength. The composite strength block is analysed using the conventional slope stability and settlement analysis. The preliminary design is used for the purposes of cost estimation and feasibility study.

Most road slips are driven by complex and often multiple mechanisms beyond the ability of conventional slope stability programs to analyse. For the Portland and Mountain Road slips, it was found necessary to use a more sophisticated approach for the final design. Detailed design was carried out via finite element analyses to model failure mechanisms, and design layout for remedial measures.

The detailed design stage usually starts with replicating the observed mode of failure in the pre-remedial condition to back analyse and verify the soil properties and ground conditions used in the model. This is followed by modelling the behaviour of the Colmix columns, and optimising the quantity and positions of the columns. 2D modelling has been used in most cases.

5 CONSTRUCTION ISSUES

5.1 Traffic

All work has been on two lane, undivided roads. Traffic management plans require keeping at least one lane open to reduced speed traffic during the day, and both lanes opened to reduced speed traffic during non-working hours. Where designs position columns in traffic wheel paths, these columns have to be drilled early enough during the day to allow the binder to gain sufficient strength to allow them to be trafficked at the end of the day.

5.2 Types of soil

All types of soils have been encountered during the course of remedial works except for boulders and gravels. The typical profile consists of the pavement layers (of variable thickness and quality depending on history), a fill layer of usually dubious quality and a completely weathered layer, followed by intact rock.

5.3 Binder mixes

All sites have used cement as the binder. The cement has been introduced in slurry form. Average cement usage has been 30 % by dry weight of original material. This “standard recipe” has been used in all of the slips repaired to date.

5.4 Pavement layers

Existing pavement layers are slow to drill through and are hard wearing on equipment. This is particularly the case in situations where some of these layers may be bound with cement or lime. It has been found to be more economic to pre-drill these highly cemented layers and/or very thick bituminous layers (created by ‘topping’ up the slip zone).

5.5 Working platform

Slips that are close to factor of safety of 1 at time of construction need to be approached in a manner that will minimise the risk of construction loading causing further failure during construction. This usually requires consideration of the column placement sequence with regard to traffic management issues.

5.6 Seismic testing for QA/QC

Post construction seismic testing was recently carried out on two Colmix columns. About 50% of the test records show stress wave patterns that can be replicated using a simple finite element model. The material properties of the Colmix column can be back analysed by adjusting the model properties to match the finite element model output with the seismic wave records. The remainder of the test records, however, show unexpected and irregular wave pattern. This could be attributed to the presence of a grout cap at the top of the column. In other words, there is a zone where the column is solely made up of grout and the soil has been displaced. Such zones reflect stress waves much more readily than the soil-cement mixture, and result in irregular wave pattern.

At this stage, it is concluded that further research is required to investigate the irregular test results and validate the use of finite element analysis for comparison with seismic testing records. It is hoped that seismic testing will someday become a quick and useful QA/QC testing method for checking the characteristics of Colmix columns and detecting any defects.

5.7 Applicability of Colmix

Colmix has proven particularly effective and applicable to New Zealand road maintenance applications in the following conditions:

1. The failure zone is at a depth greater than 4 m. Some of the conventional remedial measures can only address shallower seated failures. The current Colmix rig is capable to installing columns up to 8.5 m depth.
2. The road slip has occurred in soils. Colmix cannot be installed in hard rocks as the drill are unable to penetrate such material.
3. The primary slip mechanism is due to either settlement, sliding, rotation or bearing capacity. Colmix is not used where the failed area has dropped out, or physically detached from the original pavement structure.
4. Colmix has been successfully installed in clays, silts and sands. Drills have been damaged in some cases where gravel and boulders have been placed as a fill material under the failed road section.
5. As a general rule of thumb, the length of the road to be repaired needs to be at least 25 m for Colmix to be economically viable.

5.8 Performance to date

1230 linear metres of road spread over some 26 slips has been repaired in 18 months. The average job is approximately 50m long and typically takes 10 days to construct the Colmix columns. Additional time is required to then re-construct the road, which is performed by a different company.

The slip repairs have been performed all year round providing major advantages over other systems.

6 CASE STUDIES

6.1 Edwards

6.1.1 *Failure Mechanism*

The Edwards slips comprise two road underslips affecting 30 m and 35 m lengths of the road. The primary mechanism for these slips is rotational slip movement, with settlement contributing as a secondary mechanism.

6.1.2 *Subsurface Conditions*

The subsurface conditions comprise 1.5 m thick embankment fill overlying 3.5 m of soft to firm clay and 1-1.5 m of stiff to very stiff clay. The stiff clay is probably weathered material derived from the underlying mudstone. The ground conditions and Colmix column layout adopted for the Edwards slips are shown in Figure 5.

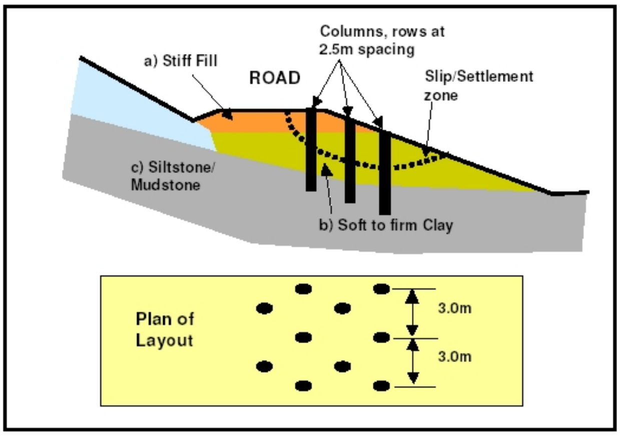

Figure 5: Ground conditions and colmix layout at Edwards (Finlan et al., 2004)

6.1.3 *Remedial Works*

The remedial works installed comprised 3 rows of columns over a 50 m road length. The columns were spaced at 3 m in the longitudinal direction, and the rows were spaced at 2.5 m centres. The columns were generally installed to a maximum of 6 m depth although early refusal was encountered in some places. The remedial works was designed assuming 1.5 MPa unconfined compressive strength (UCS) for the Colmix columns. The design factors of safety adopted were 1.5 for normal groundwater conditions, and 1.1 for the extreme groundwater conditions. The construction of the Colmix remedial works took 9 working days.

6.1.4 *Economics*

The Colmix solution provided 12% saving on the cost of traditional gabion wall solution, which was the cheapest alternative. It should be noted that the gabion wall is a higher risk solution that would not have dealt with the settlement issues.

6.1.5 *QC Testing*

Core samples were taken from 2 columns after the columns had been cured 80 days. UCS testing was carried out on the core samples. The measured UCS typically ranged from 3 to 9 MPa, which is well above the design strength of 1.5 MPa.

6.1.6 *Post Construction Monitoring*

Road deformation has been monitored at the Edwards slips on a regular basis. The ongoing monitoring has shown some presence of pavement deformation that looks like a "telegraph wire", that is, the deformation is characterised with small continuous undulation with localised depressions at several places. The maximum vertical displacement of 40-50 mm has been observed as shown in Figure 6. The relatively large displacements coincide with areas where columns were terminated short of the bedrock. Back analysis by finite element has indicated that the 3m spacing is too great. Subsequent designs have limited column and row spacings to no greater than 2.5m.

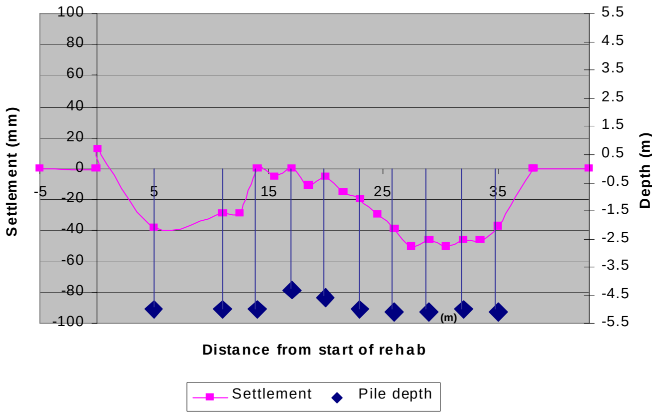

Figure 6: Post construction road deformation at Edwards

6.2 Portland

6.2.1 *Failure Mechanism*

The site has at least a 50 year history of settlement. Previous remedial attempts, which include filling and deep well drainage, did not effectively address the slip mechanism. While these solutions have slowed the slip movement, they have never completely stopped the settlement. The primary mechanism for the observed settlement is likely to be bearing capacity failure of the soft clay layer underlying the road embankment. As the embankment is subjected to cyclic traffic loading, the soft layer fails instantaneously, resulting in very small incremental displacement. The observed slip movement is a result of the cumulative bearing failure induced displacement.

6.2.2 *Subsurface Conditions*

The slip site comprises a 1.5m deep embankment fill over 4.5m of soft to very soft clay layers. High groundwater levels occur at the Portland site as the site is in close proximity to a river subject to tidal actions. The ground conditions at Portland are shown in Figure 7.

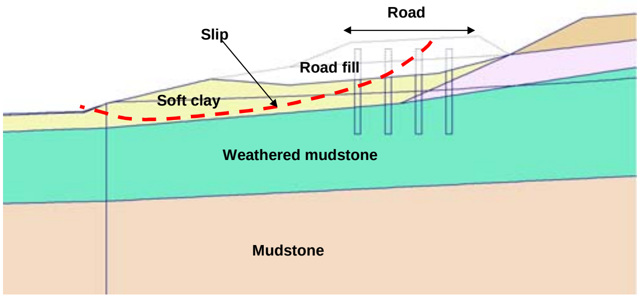

Figure 7: Ground conditions at Portland

6.2.3 *Remedial Works*

The Portland slip was repaired with 4 rows of Colmix columns over a 45 m road length. The columns were spaced at 2.5 m intervals, and staggered between adjacent rows. The four rows of columns were constructed at 2.5 m spacings. The Colmix columns were designed to be installed to a maximum depth of 7 m below ground level. The Portland remedial works was designed assuming 0.8 MPa UCS design strength. The design factors of safety adopted were 1.5 and 1.1 for the normal and extreme groundwater conditions, respectively. The remedial works were completed in 18 working days. It proved difficult to drill through the highly plastic clays, and predrilling was therefore required in some places.

6.2.4 *Economics*

The Colmix remedial option provided 39% savings over a traditional 15m high, H-Pile wall with tie backs and 4m deep counterfort drains. These options are higher risk solution and do not address settlement issues.

6.2.5 *Post Construction Monitoring*

Nails were installed on the pavement following the completion of the Colmix columns. The movement of the nails was monitored in three surveys over eight months. Insignificant vertical and lateral movements were observed in the post construction surveys, as shown in Figure 8. Small settlement was observed immediately adjacent to the main slip area where the slip movement is visible.

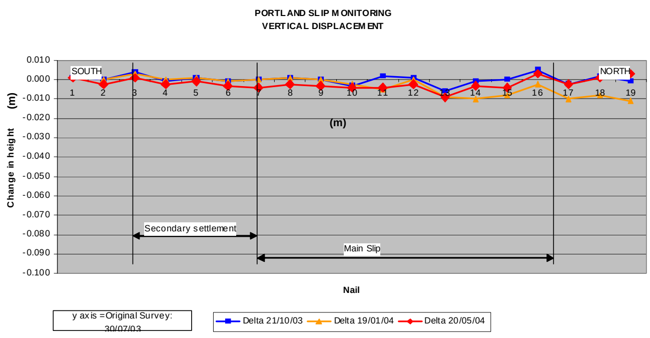

Figure 8: Post construction road deformation at Portland

6.3 Mountain Road Crawler Lane

6.3.1 *Failure Mechanism*

The Mountain Road Crawler Lane slip is a translational slip that has affected a 30 m road length. The slip is located on a very long slope, and creep movement of the residual material on which the road was built is probably contributing to the slip.

6.3.2 *Subsurface Conditions*

The ground conditions of the Mountain Road Crawler Lane slip comprise 2.5m embankment fill, 1.5m stiff to very stiff clayey silt, 2m very soft to soft silty clay, 1.5m stiff silty clay, overlying mudstone, see Figure 9.

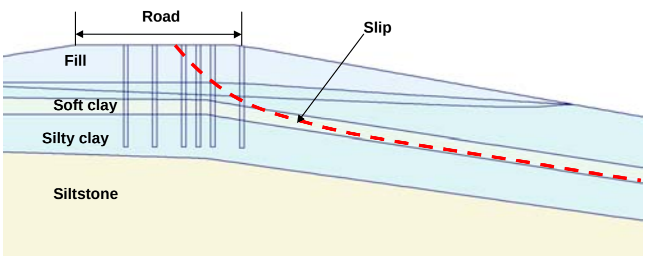

Figure 9: Ground conditions at Mountain Road Crawler Lane slip

6.3.3 *Remedial Works*

4 rows of Colmix columns were constructed at 2.0 m intervals over a 50 m road length. The row spacing was also 2.0 m. The columns were constructed to a depth of 7 m except where bedrock was shallower than expected. The Colmix columns were constructed in 7 working days.

6.3.4 *Economics*

The Colmix option cost was 2% higher than a traditional H-pile wall. The Colmix option, however, was the preferred option as the H-pile wall option was a higher risk option and does not address settlement.

6.3.5 *Post construction monitoring*

Figure 10 shows the post construction road deformation measured at Mountain Road Crawler Lane. The observed deformation is generally within 10 mm, and could be partly attributable to survey accuracy.

The uniform nature of the observed deformation pattern is suggestive of shrink swell movement of the soil. This type of materials are likely to have undergone significant strain, and residual shear strength parameters may be more appropriate for design purposes. The design should also allow for shrink swell movement.

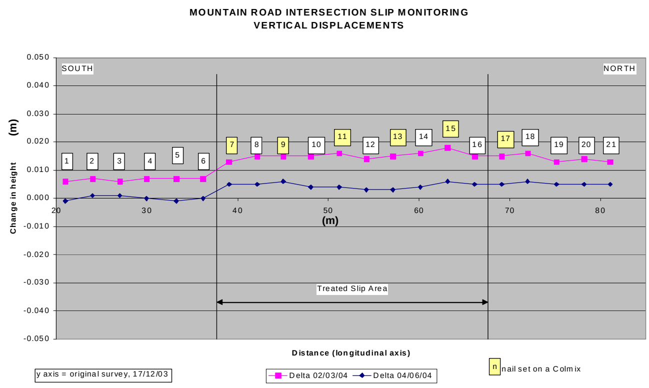

Figure 10: Post construction road deformation at Mountain Road Crawler Lane slip

7 Conclusions

7.1 Benefits of Colmix

Using the Colmix solution provides a fast and economical solution with enhanced road safety during all phases of repair. In addition, it fixes multiple mechanisms, and as a consequence of the methodology, ongoing maintenance is not required. It is a relatively aesthetic solution in that the more natural landforms are kept, and the slip scars are able to be rehabilitated.

The economics of the method average 20% cost savings on comparable solutions across all 26 slips performed at time of writing, see Figure 11. Even in the cases where there were no direct cost benefits, the intangible benefits in terms of construction time and road safety were considered to be sufficiently advantageous.

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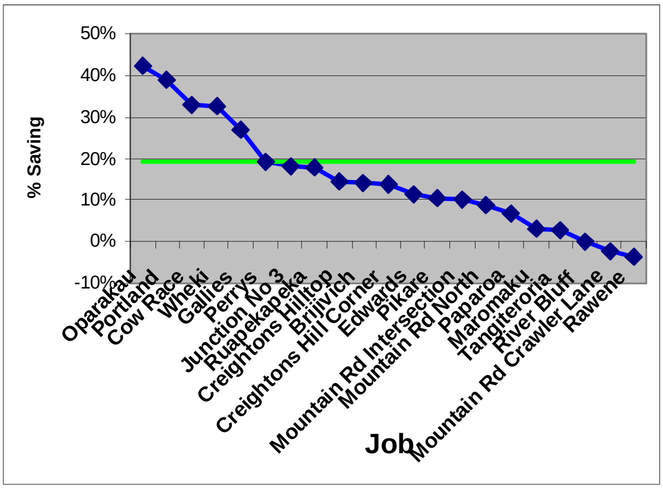

Figure 11: Cost savings of Colmix over comparable alternative options

7.2 Limitations of Colmix

The Colmix option involves a relatively high mobilisation cost, and therefore is often not economically feasible for small size projects.

The current Colmix rig is only capable of drilling down to 8.5 m below ground level. It is unable to effectively repair deeper seated slips.

7.3 Design of Colmix

Perhaps one of the most critical design issues is the group behaviour of Colmix columns. Remedial works should be designed so that the treated ground behaves likes a block and columns do not fail as individual piles. From this perspective, it is recommended that columns spacings of greater than 2.5 m be avoided as a general rule of thumb.

Analyses to date demonstrate the importance of allowing for groundwater flow. Phreatic line approach may overestimate the factor of safety in some cases.

Remedial works designed via 2D analysis have generally performed satisfactorily to date. However, 3D analysis is desirable particularly where column stresses and 3D deformation govern the design.

Whilst the current design approach uses a state-of-the-art finite element analysis, further work is required to establish a more sound theoretical design basis.

7.4 Construction of Colmix

Insitu wet process deep mixing has proven to be successful im most New Zealand soil types, which are predominantly of soft, clayey nature. Some drill damage has occurred in gravels and boulders.

A ‘standard recipe’ binder mix has been used in all slips repaired to date. Observations indicate that this binder mix is applicable to New Zealand conditions.

8 ACKNOWLEDGEMENTS

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