Slope Stabilisation-Site investigation, Design and Application of Deep Soil Mixing

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Abstract: State Highways in the Northland region of New Zealand are susceptible to instability due to slope failure. One of the main reasons is the unique properties of the Northland Allochthon that is underlying the area. Typical geomorphology within the Northland Allochthon is characterised by numerous shallow-seated failures due to low residual strengths. In some locations the problems have been compounded by inappropriate drainage measures or additional surcharging by placing fill on a subsiding road formation.

Deep soil mixing has been used as one of the remedial solutions to this problem. This paper presents a discussion and description of the regional geology and unique geotechnical characteristic properties of the materials. A case study is presented to demonstrate typical methods of investigation, interpretation and design of the adopted remedial works.

INTRODUCTION

Many slopes within the Northland Allochthon geology in the Northland region of New Zealand are known to be susceptible to instability and creep over time, partly due to the unique characteristic of the Northland Allochthon which has a low strength and a highly sheared fabric (Winkler [1]). Given the unique characteristics of this material, road instability due to slope failures are not uncommon. In some locations the slope problems have been compounded by inadequate drainage and inappropriate remedial work in the past such as placing additional fill on a subsiding road foundation.

Transit New Zealand embarked on Performance Specified Maintenance Contracts (PMSC) 002 which is the state highway maintenance contract that covers Northland. This contract places significant emphasis on maintenance/repair works innovation. SKM provides the professional services input to Encore who provides fixed price quote design repairs works to Works Infrastructure, who is the main contractor of PMSC 002. Encore is a joint venture of Work Infrastructure and Highway Stabiliser who brought the deep soil mixing technology to New Zealand.

This paper discusses developing deep soil mixing methods as a viable option to address the road slips. The regional geology and the unique geotechnical characteristic properties of the material are also discussed. A case study is presented to demonstrate the typical methods of investigation, interpretation and design of the adopted remedial work using deep soil mixing.

GEOLOGICAL SETTING AND GEOMORPHOLOGY

The distribution of the Northland Allochthon is shown on Figure 1. The Northland Allochthon stratigraphy is very distinctive due to the inversion of the normal stratigraphic sequence where older rocks (late cretaceous-90Ma) are found to lie on top of younger rocks (earliest miocene-25Ma) in many places. It is believed that large scale movement of the rock layer occurred with the layers sliding off from the top first followed by the second layer which came to rest on top of the first and so on. Consequently many shear planes have developed in the material producing the unstable formation (Isaac et all [2]).

Based on the age of original deposition (Winkler [1]), the Northland Allochthon is subdivided into three categories as follows:

i. Tangihua Complex -submarine basaltic volcanics, about 90Ma to 65Ma
ii. Mangakahia Complex – Variably calcareous and siliceous mudstones and sandstones that were initially deposited during Paleocene to Eocene times about 65Ma to 38Ma. It is also known as Onerahi Chaos.

iii. Motatau Complex – Predominantly calcareous limestones, mudstones and sandstones that were deposited later during the Oligocene period about 25Ma to 38Ma

The Mangakahia complex is the most problematic group of materials from a geotechnical perspective. The soil mantle over this lithology consists of light colour, stiff to very stiff consistency, plastic silty clay (upper zone) and silty clays/clayey silts with gravel sized fragments (lower zone). (Winkler [1])

The geomorphology of Northland Allochton is typically long, gentle to moderately grading broad hummocky slopes with hummocks generally extending all the way from the toe of the slope to the crest of the ridge, and side spurs. The hummocks are generally between 5m to 20m wide, tend to be oval and aligned parallel to the surface contours. Swamp reeds are found growing on the surface due to the very low permeability of the underlying soil (Figure 1). Another characteristic is the presence of numerous shallow-seated slope failures. Shallow failures have been observed on relatively gentle slopes of 5 ^{o} to 15 ^{o}, due to the low residual strength and ongoing creep movement of the in situ material (Winkler [1]).

Figure 1. Location of Northland Allochthon (Winkler [1]) and typical geomorphlogy of the Northland Allochthon

GEOTECHNICAL CHARACTERISTIC PROPERTIES

The Northland Allochthon soils typically comprise high plasticity, light coloured, clayey silts and silty clays with some gravel. These soils, in their undrained condition are usually stiff. However the residual friction angle is significantly affected by the presence of shear zones and sheared fabrics and is typically in the range of 10^0 to 15^0. Winkler [1] has reported residual friction angles as low as 8^0 in this material. It is noted that the friction angle within the sheared zones for the calcareous and siliceous rocks are likely to be higher and typically in the order of 20^0.

Northland Allochthon soils are highly plastic with a high shrink-swell potential. Liquid limit is highly variable and typically in excess of 80% and shrinkage limit less than 15%, indicating that the soil is highly reactive and is susceptible to creep. (Winkler [1])

A CASE STUDY: GALLIES SLIPS

The Gallies Slips are located on State Highway 12, approximately 90 km south east of Whangarei as shown on Figure 2. The slips have occurred in an existing road embankment. This stretch of the highway has previously been subjected to slope failures and unsuccessful slip repair work. The selected case study includes three slips with a total length of 50m over 190m of highway. The site is bounded on the north by water logged hummocky farmland and on the south by a farmhouse and some sheds (Figure 2). Figure 3 illustrates the extent and shape of each slip.

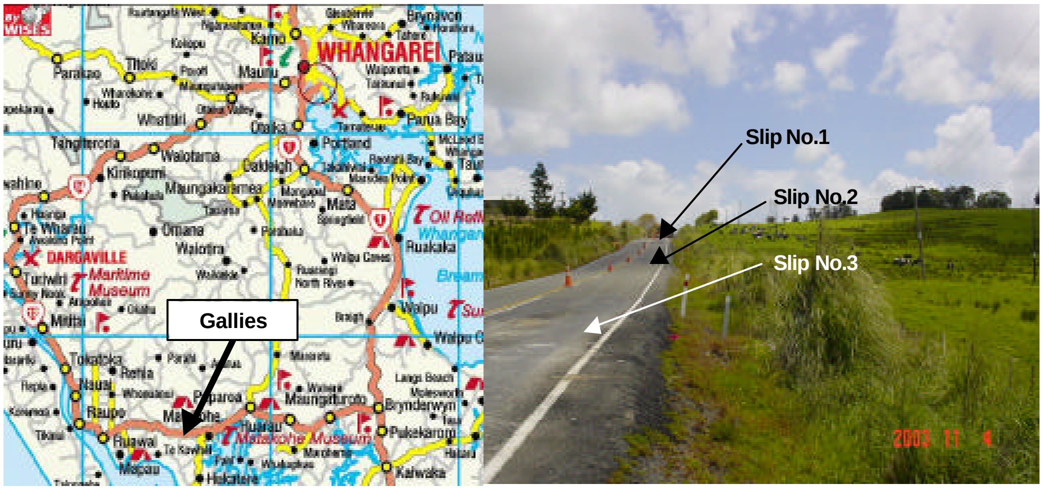

Figure 2. Location of Gallies Slip.

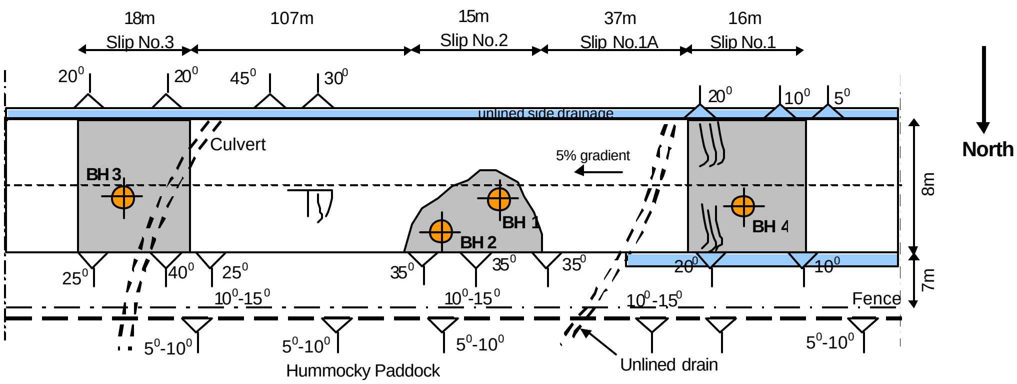

Figure 3. The geomorphology sketch of the site including borehole locations.

Previous slope failures have been re-surfaced at Slip No.1. Cracks that are perpendicular to the road are visible. The slip follows the slope of the road (approximately 5% gradient) for a distance of about 16m. The measured slope angle of the southern embankment batter ranges between 5^o to 20^o and the northern slopes are typically 10^0 to 20^0.

Slip No.2 is about 37m downhill of the first slip. It is located on the eastbound carriageway and slightly encroaches into the westbound carriageway. An open crack is observed on the eastbound carriageway that starts at the edge of the road and extends to the centre line. This slip is approximately 15m long, and the embankment on the north is battered at approximately 35^o. The measured slope angle below the embankment ranges between 10^o and 15^o.

Slip No.3 is approximately 107m downhill from Slip No.2. It straddles the eastbound and westbound carriageways. An open crack and minor settlement is visible within the westbound carriageway. The length of the slip is approximately 18m with embankment slope angles ranging between 20^o and 40^o. The measured slope angle below the embankment ranges between 10^o and 15^o.

This paper presents the remedial design for Slip No.3 in some depth. A similar remedial methodology was also successfully applied to slip No.1 and Slip No.2, but is not presented in this paper.

Site Investigation Performed and Results

Four boreholes were drilled in October 2003 to investigate the subsurface conditions. The locations of the borehole are shown on Figure 3. Undrained shear strengths were measured at approximately 1.5m depth intervals within the softer materials encountered. Push tube samples were taken from the soft sediments below the road fill. The recovered soil/rock cores were photographed. A selection of soil samples was subjected to geotechnical laboratory testing. A piezometer was installed in BH 2. The groundwater level in BH2 was recorded at 1.9m BGL 6 days after drilling.

The subsurface geology consists of road embankment fill ranging in thickness from 1.5m (BH1 and BH2) to 2.7m (BH3). The road embankment fill overlies soft to firm grey silty clays and light grey sandy silts. Bluish grey to grey mudstone of the Tangowahine Formation was generally encountered at depths ranging from 2.4m (BH4) to 7.35m (BH2) beneath the present ground level. The corrected undrained shear strength of the Tangowahine Formation clay/silt ranged from 50 to 150 kPa.

Slip Mechanism (Slip No. 3)

The geomorphology at Gallies comprises typical undulating Northland Allochthon landforms, which are suggestive of creep movement occurring on a global scale. It is likely that a majority of the existing hills are gradually creeping towards gullies and valleys.

Slip No.3 has occurred in a road embankment that has been constructed in a cut and fill slope. The rotational movement is unlikely to be the primary slip mechanism as no evidence of toe heave was observed. The depth of the fill material found indicates that settlement and slippage have been occurring for some time, and the road fill was probably re-graded and re-surfaced on more than one occasion in the past. These previous repair works has probably resulted in increasing the weight of embankment which causes further slippage. The on going creep movement reduces the strength of the soils and impacts on the bearing capacity of the subgrade.

High groundwater during wet periods and a lack of adequate drainage are likely to have contributed to the slip occurrence. Further, any leakage from the culvert crossing to the north of the carriageway would have contributed to de-stabilising the slope.

The pavement crack profile and geomorphology suggest that there is significant lateral creep movement towards the farmland, while some longitudinal movement is likely to be occurring as well. The slope angle to the north of the embankment ranges between 10^{o} and 15^{o}, which is sufficiently large to induce creep movement in the Northland Allochthon materials.

Deep Soil Mixing Column Design

It is judged that, Slip No.3 is likely to be developing multiple failure mechanisms. The conventional remedial measures such as gabion wall, soldier pile wall, stabilising berm and counterfort drains do not address all of the failure mechanisms.

Gabion wall and soldier pile wall do not address settlement and bearing capacity issues. A stabilising berm, although it is low cost could exacerbate settlement. Counterfort drains control groundwater and soft weak material is removed. However, it can cause disruption to traffic, unacceptable road roughness and presents a risk of clogging during operation. Counterfort drains was commonly used in the past because there were no other viable solutions at that time. In addition, formal consents are required for all of the aforementioned methods which would incur additional delay.

Deep soil mixing, not only addresses all the failure mechanism, but the speed of repair, minimal earthwork and minimum traffic disruption make it a cost effective alternative to other conventional methods. The fact that minimal sludge is generated during installation makes it an environmentally attractive alternative. Moreover, in almost all cases no consents are required.

Deep soil mixing columns are designed using numerical modelling with PLAXIS finite element software. Geotechnical parameters used in the design are derived from laboratory test results of the selected core samples collected during the site investigation. In some cases, geotechnical parameters are assessed from other site information based on the geology. An initial analysis is carried out to verify the geotechnical parameters used by simulating the actual slip failure in the model. Figure 4 shows a cross section of the slip and the geotechnical parameters used for the analysis.

Once the actual slope failure is successfully simulated, deep soil mixing columns are introduced into the model. The columns are modelled as soil using volume elements. Properties of the composite material (cement/lime soil mixture) are derived from column strength test results combined with the geotechnical properties of the on-site material. Typically the unconfined compressive strength of a deep soil mixing column is about 1.5 MPa.

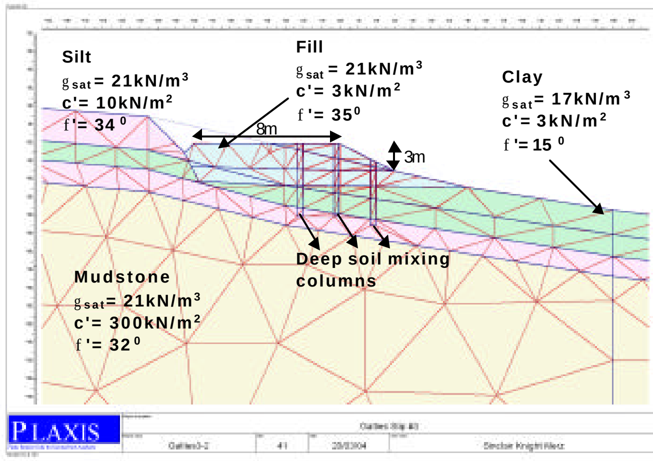

Figure 4. The cross section of slip (PLAXIS analysis model) and geotechnical parameters used on the analysis

The columns are positioned in such a way that a block of improved soil is created in the pavement and the slope below the road. This area is expected to remain stable even if further slip movement occurs below this area, so that the road structure will remain intact. The analyses are performed for normal groundwater conditions (expected groundwater during the winter months) and extreme events (full saturation of the slope and recharge-rapid drawdown analysis). The design factor of safety of 1.3 is required under the normal groundwater condition and 1.1 under the extreme events.

In this case, the analyses indicated that three rows of columns spaced at 2.5m were required to achieve satisfactory factors of safety under both groundwater conditions. The column length varies from 3.5m to 4.5m to maximise the columns' resistance to slope failure. The actual length of the columns are verified during construction. Figure 5 illustrates the simulated slip mechanism before and after the remediation under the extreme events. The calculated factors of safety are shown in Table 1.

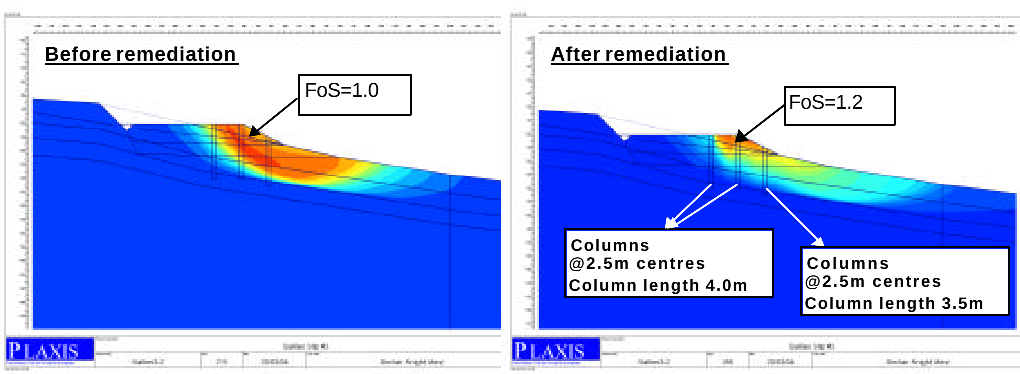

Figure 5. Slip mechanism and factor of safety before and after remediation – extreme groundwater conditions.

Table 1. The Factor of Safety of the Remedial Slope

Slope Structure	**Normal Groundwater**		**Extreme Events**	
Existing Slope	1.15		1.0	
	Achieved	Required	Achieved	Required
With Deep Soil Mixing columns @ 2.5 m	>1.5 , (1.3) (1)	1.3	1.2	1.1

Note: (1) FOS for slips down slope of the deep soil mixing columns, not involving the pavement. The FOS against the pavement failure exceeds 1.5.

The recommended column layout is shown on Figure 5 and Figure 6. The analysis also indicates that the columns are unlikely to fail by bending and shear under normal and extreme conditions.

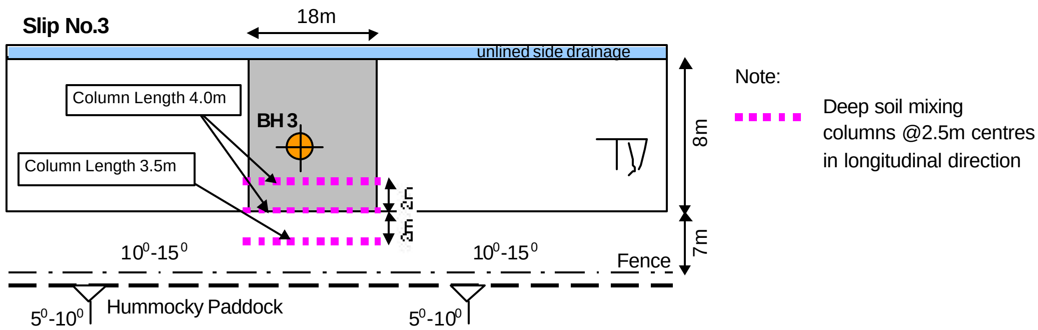

Figure 6. The Deep Soil Mixing column lay out

The factor of safety achieved is higher than requirement as shown on Table 1. The performance of deep soil mixing columns are regularly monitored on previously remedied sites. To date, no significant movement or instability has been reported.

Conclusion

Many roads in the Northland region have suffered from slope failure partly due to the Northland Allochthon that underlies this area. This material has unique characteristics due to the presence of many shear zones and sheared fabric. Numerous shallow seated failures within slopes of the Northland Allochthon have been observed on relative gentle slopes of 5^o to 15^o, which are attributed to the low residual strength and ongoing creep movement. The residual friction angle as low as 8^0 has been reported by Winkler [1].

Deep soil mixing technique has been successfully employed to address this problem. The factor of safety against slope failure has been increased significantly. However, it is noted that the effectiveness of this method is a function of column spacing and the type of material encountered on site.

Deep soil mixing has been opted due to its capability to address multiple slip mechanisms. The speed of repairs and minimal requirement for earthwork make it cost effective alternative. It is also environmentally friendly because minimal sludge is generated during construction and in almost all cases no consents are required.

The deep soil mixing remedial work is not expected to totally eliminate the ongoing creep movement up slope and down slope of the slip. However, the deep soil mixing remedial work, coupled with an effective drainage system, should mitigate the up slope and down slope creep movement to some degree.

Acknowledgment

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