

Localised Failure of Cliff Top Waitemata Group Residual Soils, an Approach to Remediation

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ABSTRACT

Cliff top soil failures are a common occurrence along the coastal margin of the Auckland Urban Area. With the continued development of this space for residential infill housing the impact of localised slope failures have increased. As the majority of development along the coastal margins are privately owned, any remediation measures proposed must be cost effective for individual landowners, constructible and provide a robust engineering solution to meet local authority requirements. WSP Opus and Earth Stability Limited have remediated numerous localised shallow slope failures along Auckland's coastal margin through the use of soil-nailing and the installation of drainage within the overlying residual soil mantle.

Due to access, budgetary and health and safety constraints, geotechnical investigations undertaken for cliff top properties are typically limited to the areas adjacent to the failure and terrain evaluations. The prominence of terrain evaluations in the development of geotechnical models has facilitated the use of WSP Opus's UAV capability to determine any underlying factors driving slope failure. Shallow slope failures are often the initial driver for the landowner to engage geotechnical specialists, however as geotechnical practitioners and stability contractors, the underlying cause of slope stability issues along the cliff line cannot be ignored.

The use of soil-nails to enhance the stability of a slope has long been established, but is typically constrained by site geometry to primarily provide support perpendicular to the slope. Therefore, it must be communicated to the client that soil nailed remediation of slope failures are not intended to prevent global cliff failure or lateral regression adjacent to the soil nailed section.

1. INTRODUCTION

Auckland's coastal cliffs have become highly desirable with dwellings constructed to exploit the expansive, unobstructed ocean views. In order to minimise the visual impacts from neighbouring structures, houses are often built as close to the top of the cliff as allowed by the regulatory authority, with ancillary structures such as decks and pools often constructed beyond this.

The Auckland urban area is concentrated on the Eastern Coastline and surrounds the Waitemata Harbour and extends from Beachlands in the south to Orewa in the North. The urban area generally overlaps with the spatial extent of the East Coast Bays Formation of the Waitemata Group (figure 1).

As the coastal margin continues to be developed, the impact of naturally occurring localised slope failures which occur within the over-steepened soils overlying the cliff have increased. The majority of development along the coastal margin in Auckland is privately owned, and as such any remediation measures developed must be cost effective for landowners and unobtrusive, while still providing a robust solution that meets the regulatory requirements.

Although many options are available for the remediation of cliff top soil failures paper focuses on soil nailing, a low-cost remediation technique, especially useful where material and plant access is limited. Soil nailing of numerous localised shallow slope failures across the Auckland Region has been undertaken by WSP Opus and Earth Stability Limited.

2. GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The majority of the Auckland Urban Area is underlain by Miocene-aged East Coast Bays Formation of the Waitemata Group. The formation comprises marine deposited fine-grained sandstones and mudstones. The overlying soil mantle is typically 3 -7m in thickness, derived from residually weathered Waitemata Group and can be overlain by younger sediments of the Tauranga Group (Edbrooke, 2001).

The Waitemata Group typically sub-horizontally bedded and largely undeformed, with localised bedding contortion and highly faulted. The contorted bedded is inferred to be the result of soft sediment deformation post deposition. The spatial variability of bedding and faulting is significant, due to its effect on the types of mass movement and associated cliff line retreat. Three main mechanisms for cliff failures are commonly encountered in the east coast bays formation, gravitational collapse of sandstone blocks following the frittering of the interbedded mudstones, planar failure along steeply dipping faults, orientated normal and parallel to the cliff line and planar failures along gently dipping bedding plans (Moon and Healy, 1994) (Figure 2).

Regression of coastal cliffs is observed along much of Auckland's coast line. Although not the focus of this paper, the process of retreat is important to recognise, as any global cliff retreat will be reflected in the subsequent failure of the overlying soil mantle to regain an equilibrium. To propose a robust solution for slope stability issues in the soils at the top of the cliff, one must first identify the root cause of the failure. The root cause of failure can include both natural

processes and manmade effects features, including over steepened soil mantle resulting from cliff line regression, high pore water pressures within the soil mantle, stormwater and overland flow discharge over the cliff that contribute to the slope failure need to be considered in order to develop robust remediation measures.



Figure 1: Simplified geological map of the Auckland Region, showing the approximate extent of the East Coast Bays Formation outcrops. The formation underlies the majority of the Auckland urban area.

An understanding of groundwater is a key component of any slope stability investigation. Due to the complexity of the formation, groundwater is often found to be present in the form of locally perched aquifers confined by siltstone beds, and can be highly controlled by discontinuities. Following heavy or prolonged rainfall events, perched ground water is often encountered within the upper 1m of the soil mantle immediately following large or prolonged rainfall events, with saturated zones typically encountered along the soil-rock interface. Correlation between saturated zones and seepage provides a good indicator of the location of the soil-rock interface.

The interaction between groundwater and stormwater are a common contributor to slope instability, and as such, is particularly important to investigate areas of cliff line seepage and identify the correlation between seepage and saturated soils. Following heavy or prolonged rainfall, ground water is often encountered within the upper 1m of the soil mantle. The ingress of water into the saturated soil mantle from damaged or overwhelmed stormwater systems and concentrated overland flows above the cliff face can contribute to further destabilising the slope.

3. INVESTIGATIONS

3.1. GEOTECHNICAL INVESTIGATIONS

Site investigations of cliff top slope failures are typically limited in extent; and usually only comprise hand augers with shear vane tests and accompanying Scala penetrometer tests. Investigations are typically focused on the area directly adjacent to the slope failure.

Some of the limiting factors include:

- Health and safety: Cliffs in the Auckland area can exceed 45 m in elevation, and can be overhanging. Due to the safety risks of manually handling equipment on often uneven ground at heights WSP Opus conservatively setback the closest investigation test localities a distance exceeding twice the thickness of the residual soil, or closest safe location behind the head scarp. Soil profile thicknesses are conservatively estimated during a site walkover and/or during the Unmanned Aerial Vehicle (UAV) surveys.
- Budget: The extent of investigations undertaken on small cliff top slope failures are typically limited by the owner's funds available, an expected constraint when operating within the residential environment, due to the lack of private funding or insurance to cover these types of works. Investigations budgets for projects are typically 5-10% of the total remediation costs. As such, WSP Opus employs a small field team consisting of two experienced geotechnical professionals to undertake geotechnical investigations and UAV surveys.
- Access constraints: Access to coastal properties within Auckland is very often limited by lack of public spaces along most of the cliff tops in the Auckland area. In addition to with public reserves where they exist often lack vehicle access.

3.2. UNMANNED AERIAL VEHICLE (UAV) UTILISATION

To overcome the constraints of the physical geotechnical investigation, detailed mapping and terrain evaluations become increasingly important. The use of 3D-models developed from UAV photogrammetry surveys combined with on the ground mapping methods have become extremely useful in the identification of the geotechnical issues driving cliff top failures (Figure 2). Traditional terrain evaluations of cliff top properties that are typically limited to visual observations from the top or bottom of the cliff and any rock exposures and blocks located at the base of the cliff and on shore platform.

3-D terrain models can be used to produce geological profiles and create accurate slope stability models to evaluate the stability of the slope (Figure 3). Survey control can be used, however even sites with not survey control can produce models with a spatial accuracy of 0.5m, which is an improvement over visual inspection methods.

4. DESIGN PHILOSOPHY

Due to the risk of soil failure to properties and the at times limited investigation data available, a conservative approach to design is typically adopted.

The design of any remediation works is often constrained by a number of factors, including:

- The wishes of the landowner, if their budget allows, they may seek to reinstate a portion of the lost material in order to maintain the extent of useable land use area, or also to stabilise the soil mantle in front of a wall, or may just wish to stabilise the head scarp of the failure, while provide an aesthetically pleasing solution (Figure 3).
- Coastal environments are highly dynamic and the probability of similar failures occurring within the neighbouring properties is high. It can be enticing for neighbouring landowners to enquire about the continuation of the remediation scheme across property boundaries. A comprehensive review of adjacent sites should be undertaken prior to extending remediation works, to ensure site conditions remain consistent and any design assumptions remain appropriate. Soil-nailed remediation measures are limited to providing support to the residual soil and are constrained by geometry to provide support perpendicular to the cliff, therefore the designer and contractor must be explicit with the design limitations, as these measures are not intended to prevent global cliff failure or prevent lateral regression from adjacent failures.

Groundwater concentrates along the soil-rock interface along the majority of East Coast Bays Formation cliff lines, therefore horizontal drains should be targeted along the soil rock interface and inclined 3-5° above the horizontal. To limit the requirement for maintenance, drains should be of adequate size and covered with a fine filter sock to limit sediment ingress. Over the design life it should be expected that blockages from sediment and microbial growth will occur Drains are typically installed at 3 m centres, with the intention to reduce the maximum groundwater levels immediately following heavy prolonged rainfall events if high discharge volumes are encountered, spacing should be reduced.

The design life has long been an important consideration for any structure, safety in design and the whole life cost have been increasingly important in the New Zealand engineering sector in recent years. Three of the most important safety in design aspects that must be accounted for over the course of the typical 50-year design life of the remediation measures are the constructability of a design, maintenance requirements of a design and decommissioning. Decisions made in the early design phases can greatly influence these aspects.

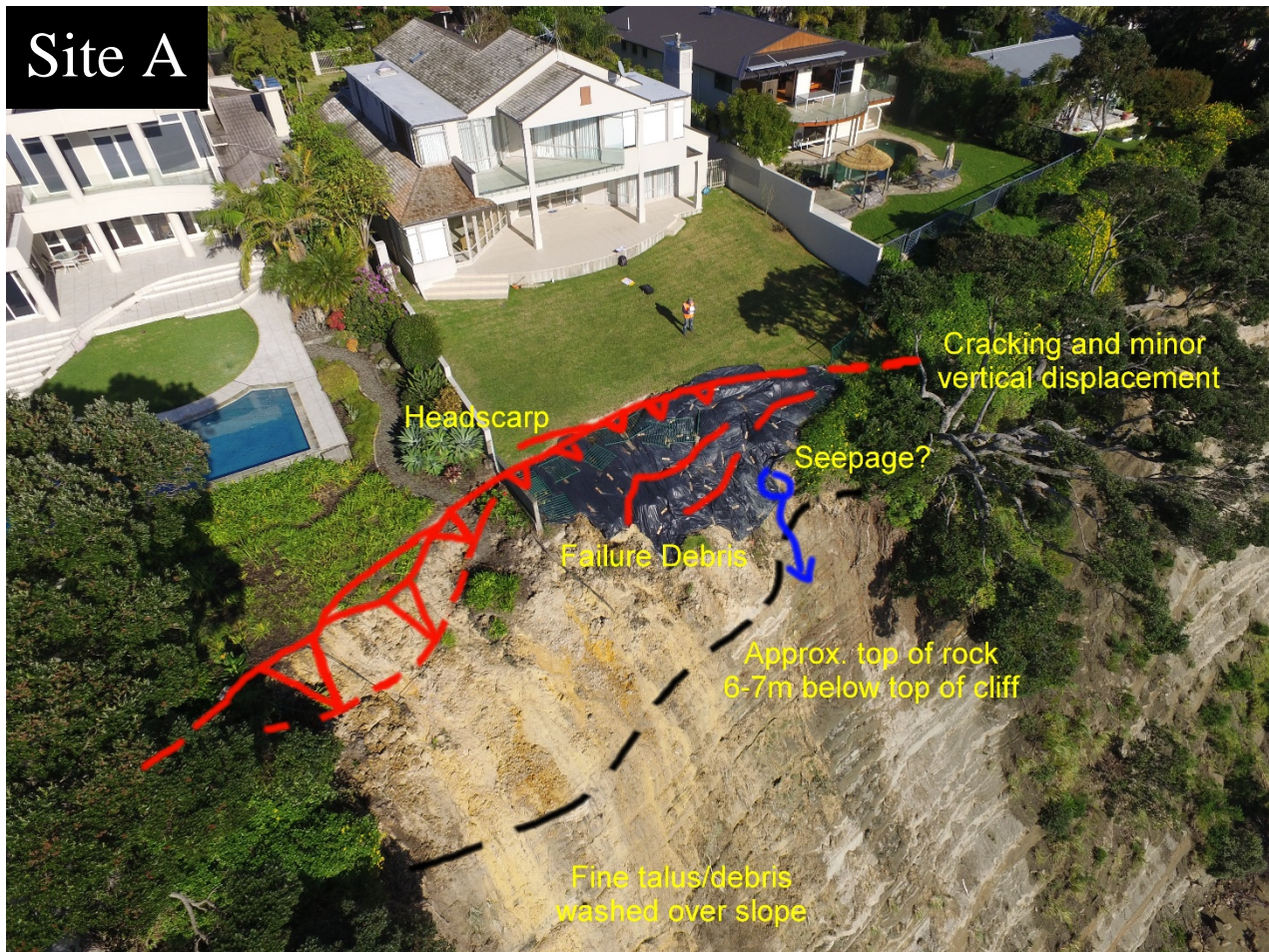


Figure 2: Examples of terrain evaluations produced from UAV photography. Site A) Typical soil failure observed along cliff tops in the Auckland Area. Site B) The variability of the East Coast Bays Formation geologic structure, the influence of the underlying geological structure of soil failures is important (Moon and Healy, 1994).

Site A



Site B



Figure 3: 3D models produced from the UAV aerial photography, from these models it is possible to gain a new perspective of the site and the underlying geological issues, in addition to allowing the creation of accurate cross-sections for stability analysis.

| Site ID | Failure mechanism | Preferred remedial option | Other options considered | Approximate Investigation and design cost | Approximate Construction cost | Whole of life cost |
|---------|------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------|-------------------------------|--------------------|
| A | Residual soil circular failure across 2 properties, driven by high pore-water pressures during wet weather | 146 soil nails in six rows, from 2 to 9m long. Ten 9m long bored drains. | Do nothing. Extend existing in ground palisade wall across the property boundary. | \$20,000 | \$100,000 | \$150,000 |
| B | Failure of the soil mantle above a steeply dipping bedding present on the cliff face. | 54 composite rock bolts and soil nails in six rows, from 4.5 to 12.5 m long. Five 10 m long bored drains. | Do nothing: Due to severe access constraints, limited area was available behind the house and all materials and plant had to be bought through the existing house or craned in additional cost. | \$10,000 | \$50,000 | \$80,000 |

Safety in design promotes collaboration between the designers and contractors, in order to identify and eliminate as many hazards as possible. Collaboration during the design phase can greatly reduce the risk to those onsite. As construction often requires the use of rope access material weights and dimensions are limited, as materials must be moved and installed with minimal access to plant. Remediation measures must therefore be designed with the goal of utilising the limited material size and quantise available effectively, while providing a robust solution.

Over the 50-year design life of the system, specified maintenance may not be undertaken due to changes in landownership or budgetary constraints. Therefore, it should be assumed that no maintenance will occur during the design life. If maintenance of the soil-nails and bored horizontal drains is required, the only safe methodology likely requires the use of rope access professionals, at a significant cost. If maintenance is required over the course of the design life of the remediation measures it must be clearly communicated with those parties responsible and who is responsible to inform future land owners and users of any ongoing maintenance requirements. It must be stated that if the specified maintenance is not undertaken as specified, the design cannot be guaranteed to provide resistance to failure.

To overcome maintenance concerns, any steel soil-nail components specified require adequate corrosion protection. In the past, a minimum corrosion protection consisting of hot dipped galvanizing in accordance with ASTM A-153 and epoxy coated in accordance with ASTM A-934 and ASTM A-775 has been used, to provide resistance to the coastal atmosphere and some resistance to the typically corrosively non-aggressive East Coast Bays Formation residual soils. Due to the conservative nature of the design philosophy employed, it is considered good practice to also increase the diameter of soil-nails specified to allow for limited corrosion of the steel.

Following the 50-year design life, remediation measures should be reevaluated to account for any changes in the development of the site, changes in the geometry resulting from the failure of the soil mantle of neighbouring sections of the cliff top as well as an assessment of degradation of the soil nails. As required, the slope may have to be reinforced with additional soil nails and horizontal drains or other measures where appropriate.



Figure 4: Pre-and post-construction photos of the Site A. Remediation was undertaken in two stages across the property boundary a few months apart, notice the rapid revegetation of the distal slope

CONCLUSIONS

A significant proportion of the Auckland urban area is founded upon East Coast Bays Formation residual soils overlying sandstones and siltstones. Stability issues within the coastal setting are variable, the most common failure types observed are rotational failures along the interface between soil and rock, the underlying cause of instability is highly variable and typically relates on the geological structure and depth of weathering. Therefore, a consistent and rigorous engineering geological assessment of each site should be undertaken to address any site specific potential causes of instability. Although addressing the symptoms of failure is often the driver for engagement, as geotechnical practitioners and stability contractors the underlying cause of slope stability issues along the cliff line cannot be ignored, without a sufficient understanding of any underlying issues, stabilisation of the soil mantle cannot be achieved.

As coastal environments are highly dynamic and the probability of similar failures occurring within the neighbouring properties is high. Soil-nailed remediation measures are limited to providing support to the residual soil and are constrained by geometry to provide support perpendicular to the cliff, therefore the designer and contractor must be explicit with the design limitations, as these measures are not intended to prevent global cliff failure or lateral regression behind the soil nails from adjacent failures.

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