Innovation in soil nail design and construction in New Zealand

Pathmanathan Brabhaharan
Opus International Consultants, Wellington, New Zealand

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ABSTRACT

Innovative design and construction methods have been developed to allow soil nails to be used as cost-effective solutions to retain or stabilise poor ground and steep slopes under high levels of earthquake shaking. Performance-based earthquake design approaches, allowing for limited displacement with adequate performance in large earthquake events, has allowed cost-effective soil nail design solutions to be developed for projects in high seismicity areas of New Zealand. The innovative designs have been supplemented by construction methods that were specifically developed for soil nails in difficult ground conditions, through trials involving different drilling and grouting techniques, and soil nail pull-out tests. Such innovative construction has included concentrix down-the-hole hammer or auger drilling as well as adoption of special grouts depending on ground conditions, double corrosion protection and post-installation grouting. Another case involved soil nail stabilisation of a cut slope with a vegetated face to preserve the landscape and environmental values. Case studies are presented to illustrate the innovative application of soil nailing in steep terrain and poor ground, in the high seismicity area of Wellington, New Zealand.

1 INTRODUCTION

Soil nailing involves the installation of reinforcement (nails) into the ground to stabilise existing slopes, or to retain excavations. Soil nailing reinforces the existing ground, and therefore does not require a high strength retaining wall face or active high capacity anchors used with more rigid wall systems. Although it similar to reinforced soil walls in that it reinforces the ground, it differs in that it involves reinforcing existing ground rather than newly placed controlled fill. Because soil nailing reinforces existing ground, it has the advantage that it does not require excavations outside the wall or slope face to be retained or stabilised, and allows top-down construction, eliminating the need for temporary support and minimising the risk of failure of unsupported slopes.

The benefits of top-down construction, and the associated cost-effectiveness has led to soil nailing being increasingly used in New Zealand over the past 10 years, since the first use of soil nailing for the State Highway 2 Silverstream to Manor Park widening project in the Hutt Valley (Saul & Chisnall 1998). A key conseqeunce of top-down construction of soil nails installed into existing ground, rather than in fill, is that the existing ground and groundwater conditions have a significant influence on the feasibility, design and construction of soil nailing. For this reason, soil nailing tended to be used only where the ground conditions were relatively favourable.

This paper presents innovative design using soil nailing solutions for high earthquake loads, and construction methods to facilitate cost-effective construction in less favourable poorer ground.

2 SEISMIC DESIGN : CASE STUDY – NGAIO GORGE ROAD STRENGTHENING

2.1 Seismicity and Performance Expectations

High seismicity areas, such as the Wellington Region in New Zealand, require structures to be designed for large earthquake loads. In particular, lifeline facilities, such as arterial roads, provide an important function to the community, and are expected to remain functional, or be able to quickly be restored to function after major earthquakes. These facilities are therefore designed for larger, longer return period earthquake events.

Typical earthquake loads that have been used for design or strengthening of key arterial roads in Wellington are summarised in Table 1.

Table 1: Seismic Design Parameters

Importance	Return period of design earthquake	Peak ground acceleration	
		Rock	Shallow soil
Arterial road	670 years	0.35g	0.6g
Wall also supporting structures	1,000 years	-	0.7g

Important roads and walls are typically designed for a design event and checked for a larger event such as the Maximum Credible Earthquake (MCE) event for performance. In Wellington, the MCE event is usually an event involving characteristic rupture of the Wellington Fault, with a peak ground acceleration of about 0.75g.

The recent amendment of the Bridge Manual (Transit New Zealand, 2006) requires an even higher level of earthquake design.

2.2 Seismic Design Philosophy

Retaining structures are currently designed to resist earthquake design loads. However, a majority of the retaining walls supporting Wellington's arterial road network have been designed and constructed in an era where seismic design wasn't adopted or the design was to a much lower level of ground shaking. Many of these walls are of crib or concrete breastwork construction, and are also underlain by loose side cast fill and colluvium on steep slopes, making them highly vulnerable to failure in moderate to large earthquakes.

Soil nailing represents a useful technique to strengthen these slopes, because:

- It can be used to retain and strengthen the existing facing systems
- Soil nails can be installed without closure of the existing roads
- It can also reinforce the slope below in addition to the retained fill
- The system is *ductile* and can de designed for displacement.

Soil nailed walls would be less economical if they had to be designed using a conventional approach to achieve a predetermined factor of safety under the large earthquake design loads associated with the high seismicity of the area. A performance based design approach has therefore been developed and applied to achieve a practical and economical design (Brabhaharan & Saul 2005). This is based on allowing limited displacement of the soil nailed block during large earthquakes. Soil nailed walls are suited to be designed as *"ductile"* systems which are able to displace under larger events such as the MCE event, rather than more *"brittle"* systems, where damage or even failure could occur, such as a rock anchored wall.

The performance criteria adopted for design of strengthening for sections of the Ngaio Gorge Road is given in Table 2.

Table 2: Earthquake performance criteria

Earthquake Level	Performance
Design Level (Bridge Manual)	No more than minor damage and cracking of road with deformation not exceeding 150 mm.
Contingency Level (Wellington Fault Rupture Event)	Some damage to structure requiring repairs and extensive deformation of road is acceptable, but road should be able to remain open for traffic.

The displacement of the soil nailed slope during earthquakes were assessed based on assessment of the critical acceleration (acceleration at which the factor of safety of the relevant failure surface in the slope is one) from the slope stability analysis, and the empirical method presented by Ambraseys and Srbulov (1995). The innovative performance based earthquake design approach of allowing limited displacements enabled the cost-effective design of strengthening of vulnerable sections of Ngaio Gorge Road, and this work is ongoing for further sections of the road.

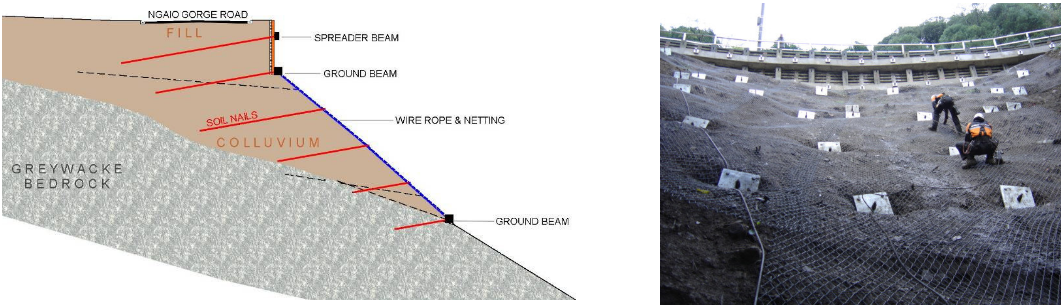

Figure 1: Soil nailing for strengthening Ngaio Gorge Road

The existing 3.5 m to 5 m high breastwork walls supporting Ngaio Gorge Road have concrete pillars with dead man anchors and infill walers between the pillars.

Soil nails were installed through the wall as well as the slope below to strengthen the road. Two rows of 25 mm to 32 mm diameter 500 MPa deformed Reid bar soil nails at 1.8 m horizontal spacing was used with spreader and ground beams in the wall. The soil nails were up to 15 m long. Sub-horizontal drainage holes were installed to control groundwater in storm events. The slope below was stabilised with similar soil nails at 2.5 m to 3.5 m vertical and horizontal spacing, with wire rope and netting to stabilise the slope against shallow or progressive failures.

3 SOIL NAILING IN POOR GROUND

3.1 Open Ground : Case Study - Ngaio Gorge Road Strengthening

One of the key features of the Ngaio Gorge Road strengthening works is the poor ground with loose highly permeable gravels, cobble with silt and sand (colluvium and quarry fill) which extend up to 9 m below some walls (Stewart & Brabhaharan 2006). Soil nails comprise reinforcement bars placed and grouted into pre-drilled holes. The permeable ground led to difficulties in drilling and grouting the soil nails using neat cement grout, as the initial grout-take at one of the sites was large, and the soil nail holes still were not fully grouted. Pre-grouting and redrilling was unsuccessful as the redrilled hole deviated from the original hole, with further grout loss during subsequent grouting.

A concentrix system of drilling, where the hole is cased as the drilling proceeds with a down-the-hole (DTH) hammer was used to ensure that the hole remains open during drilling. Grouting trials were carried out, using a variety of grouts including:

- Neat cement grout of varying consistencies.
- Foamed grout
- Cement-aggregate grout (block mix)

The neat cement grout and foamed grout were unsuccessful in achieving a fully grouted hole. The use of cement – aggregate grout (block mix) was successful for the worst ground conditions with open ground. However, this required a larger hole size (minimum 150 mm diameter) than originally envisaged with larger grout tubes, a ready mixed supply of cement-aggregate grout and a concrete pump to place the grout for the soil nails. The trials included soil nail pull-out tests to determine the ground-grout bond capacity. A ground-grout bond capacity of 100 kPa was adopted for design based on the trials.

Further trials were carried out for another section of Ngaio Gorge Road, where cement-sand mix was found to be appropriate. The cement-sand mix was easier to mix on site and place using a grout pump. Post-grouting was also added to ensure a fully-grouted hole and improve bond capacity. Post-grouting comprised incorporating an additional grout tube (with valves at a spacing of 1.5 m) within the soil nail hole during primary grouting of the hole as the casing was withdrawn. After about 12 hours when the grout was not fully hardened, high water pressure was applied to the tube, and the primary grout was cracked at the valve (node) locations. Later, grout under pressure was applied to the tube to force the grout out through the cracks to grout any voids in the primary grout surrounding the soil nail, and also grout the primary grout – ground interface. Based on these trials, a higher ground-grout bond capacity of 160 kPa was adopted for design, on the basis of using cement-sand grout and post-grouting. The higher bond capacity enabled reduction of the number of soil nails required to strengthen the section of road, and is likely to reduce the deformation necessary to mobilise the bond capacity of the soil nails during earthquakes.

3.2 Weak Ground : Case Study - Wellington Inner City Bypass

Wellington Inner City Bypass is located in the Te Aro area of the city, and included the construction of a 450 m long trench up to 8 m deep for the northbound carriageway immediately south of the Terrace Tunnel portal. A 200 m long section of the west side of the trench, which is up to 8 m high, was supported by soil nail walls (Brabhaharan 2007). The walls were generally designed for an earthquake peak ground acceleration of 0.6g, with a section of wall below the existing Ghuznee Street bridge designed to a high 0.7g.

The alignment is located at the foot of Wellington's western hills, where the colluvium / fan deposits meet the alluvium, swamp and marine deposits on the Te Aro flats. The soils are highly variable, and comprise a mixture of gravelly sandy silts and sandy silty clay with variable clay and silt contents, and with thin (up to 1.5 m thick) layers of clayey silt and clay. The medium dense to dense cohesionless soils are inter-layered with soft to stiff clay / silt layers.

Soil nail pull-out tests during design using conventional installation and neat cement grouting gave ground-grout bond capacities varying between 65 kPa and 390 kPa. The results also indicated that the deformation required to mobilise the bond capacities was large, typically 40 mm to 100 mm, particularly in the weaker fine grained materials with lower bond strengths, see Figure 2. Therefore the ultimate bond capacities chosen for design were limited to the capacities that can be achieved with a maximum deformation of 40 mm.

In the weaker area with silty clay / clayey silt and sandy silt materials the ultimate bond capacities chosen for design were between 45 kPa and 125 kPa. The use of down-the-hole hammer with compressed air without a casing was also considered to have affected the results.

The experience from the design stage trials enabled the construction of the soil nails to be specified better. Drilling with a casing system was specified to ensure hole stability, and post-grouting was suggested to ensure that the hole is fully grouted instead of the more traditional water testing that is used for rock anchors. Additional post-grouting was specified in the weaker soil areas, to increase bond capacity and reduce the deformation required to achieve the soil nail capacities.

Soil nail trials and pull-out tests were carried out during the early stages of construction. Drilling trials comprised using a concentrix drilling system with casing and down-the-hole hammer, as well as a variety of augers. The concentrix system was effective in more granular soil and fill, but was less effective in silt and clay materials. Various methods to groove the soil nail hole were tried to increase bond capacity. The two-stage grouting included an initial stage of grouting with neat cement, followed by post-grouting through nodes (valves). The node spacing along the post-grout tubes installed with the nail was 1.5 m, with a closer spacing in areas with weaker soils.

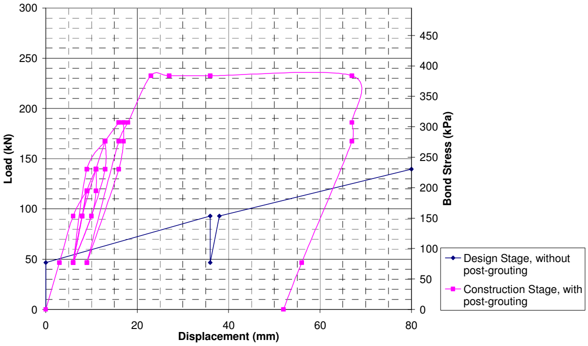

Figure 2: Deformation to mobilise ground-grout bond capacity with and without post-grouting

Figure 3: (a) Exhumed trial soil nail showing post-grout (pink), and (b) construction of soil nail wall

The pull-out tests with post-grouting gave higher bond capacities (limited to 40 mm displacement), typically 100 kPa to 180 kPa in the weaker soil area. More importantly the displacements to mobilise the soil nail ground-grout bond capacities were generally lower, see Figure 2. This gave a much higher level of confidence that with post-grouting, a lower deformation of the wall will be required to mobilise the soil nail capacities both during construction (static conditions), and also during earthquakes where the soil nails will be loaded to a higher level. A sample of nails was exhumed to check grout surface roughness, and post-grout spread along the interface, see Figure 3.

The details of the soil nail wall are described by Brabhaharan (2007). The soil nail holes were drilled using a combination of concentrix drilling and augering depending on the soils (with no grooving adopted), and double corrosion protected 25 mm and 32 mm diameter 500 MPa deformed Reid bar soil nails installed with primary grouting and secondary post-grouting through nodes at 0.5 m to 1.5 m spacing. The facing comprised a 150 mm to 200 mm thick 30 MPa shotcrete with mesh reinforcement and additional bars around the soil nail heads, and a pre-cast panel facing for aesthetic appearance, see Figure 3. Drainage included cellular geo-composite drains behind the shotcrete facing, 1.5 m long weep holes, up to 15 m long sub-horizontal drainage holes and sub-soil drains at the toe to ensure that the soil nail wall is fully drained.

Four inclinometers were installed in the ground behind the soil nail wall facing over the length of the soil nail walls, and monitoring of the inclinometers indicated generally very low displacements of the wall (less than 10 mm) during construction of the soil nailed wall and associated staged excavation. At one location, larger deformation of 15 mm was recorded. This was the location with the weakest ground conditions. The deformation was very low at the critical section of soil nailed wall that supports the existing Ghuznee Street bridge west abutment.

4 DOUBLE CORROSION PROTECTION FOR SOIL NAILING

Soil nails are sometimes installed without adequate corrosion protection on the basis that they are similar to the galvanised strips used in *Reinforced Earth* walls, where a sacrificial thickness is allowed for corrosion. *Reinforced Earth* walls are installed with quality controlled uniform fill containing little fines and with consistent resistivity levels that minimise corrosion.

However, soil nails are installed in natural ground which is typically variable, and sometimes highly variable (Wellington Inner City Bypass). Therefore a higher level of protection is warranted to ensure a long life (100 years required by Transit New Zealand for highway structures), and when the facility is of high importance. The Bridge Manual (Transit New Zealand 2006) was amended recently to require corrosion protection based on the aggressivity of the soils, importance of the facility, consequences of failure and the additional cost of protection (Brabhaharan 2006).

On this basis, double corrosion protection of the soil nail bars was adopted for the arterials roads discussed, the Ngaio Gorge Road and the Wellington Inner City Bypass. Double corrosion protection was achieved by grouting the bar into a corrugated plastic tube under factory conditions, and installing and grouting the pre-grouted tube into the soil nail hole drilled into the ground.

5 SOIL NAILS IN SENSITIVE AREAS : CASE STUDY – SILVERSTREAM TO MANOR PARK WIDENING

A section of State highway 2 between Silverstream and Manor Park is between a steep hillside regional park and the Wellington to Masterton railway line. Widening the highway required cutting into the hillside and forming a wall between the highway and railway. The cutting into the hillside was unacceptable in the regional park as it would have compromised the landscape values.

An innovative soil nailed wall concept was developed and implemented to provide an environmentally acceptable solution (Saul & Chisnall 1998). This comprised cutting a steep 50° slope into the hillside with soil nailing to ensure stability of the colluvium slope. The soil nailed cut slope was partially shotcreted, with mesh supported gaps, to allow water and nutrients from the hillside to reach the front facing, which comprised ponga logs tied to the soil nail face. There is now full natural revegetation, facilitated by the ponga logs, and the cut face cannot now be seen.

6 CONCLUSIONS

Soil nailing is a useful method to stabilise steep slopes and to retain ground as excavation proceeds using the top-down construction approach or in areas requiring environmental protection.

A performance based earthquake design approach enables soil nail stabilisation to be designed cost-effectively to provide the expected level of performance by allowing limited displacements. This approach makes soil nailing ideally suited for earthquake strengthening of slopes.

Soil nails are often constructed with little regard to the drilling and grouting methods. The case studies illustrate that improvements in construction techniques can help significantly improve the performance and cost-effectiveness of soil nails by enhancing the bond capacities and reducing deformations. Although some trials involving drilling methods are discussed in this paper, there is scope for further development and refinement of drilling methods to enhance soil nail performance. Adequate corrosion protection is important to ensure long term durability of the soil nails.

The innovations discussed in this paper on the design and construction of soil nails has helped in improving the cost-effectiveness and usefulness of soil nailing techniques.

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