BALLISTIC SOIL NAILING

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Abstract
Ballistic soil nailing has been used successfully in Cairns, Australia on a number of road and construction projects. The ballistic nailing device (Shotrods®) is mounted on a tracked excavator enabling it to deliver soil nails to overhead embankments as well as over the side of embankments. The steel nails are fired into the soil at high velocity with lengths up to 6m. Where the soil conditions permit, ballistic nailing can offer cost and time advantages over traditional soil nailing techniques. It has been used in isolation to reinforce embankments and used in conjunction with Geosynthetically Confined Soil (GCS) walls.

Ballistic soil nailing has been successfully utilised throughout the USA, Canada and New Zealand as a soil reinforcement method. To date some 500 sites have been successfully completed.

Shotrods were first introduced to Australia in late 2009 and have since been implemented on five successful projects within the Cairns region.

History of soil nailing
The first use for soil nailing occurred in 1972 when the French railways undertook the stabilization of an 18m high battered face of cemented sand. The success of this project encouraged others and soil nailing was adapted for use in the Paris underground extensions. However, in the late seventies there were two notable failures in France which highlighted the need for a much more thorough examination of the design philosophy and the execution of soil nailing. These difficulties gave impetus to the Clouterre programme. At about the same time, a major research programme was being undertaken at the University of Karlsruhe in Germany which also involved extensive full-scale trials which were loaded to failure. Both government and private industry participated in these two large research projects.

The ballistic soil nailer is a declassified British military cannon developed for military applications by Ferranti to launch chemical weapons. Canisters weighing just over a kilogram were projected up to 10km in field demonstrations. Upon discontinuance of the chemical weapons program, the technology was declassified and modified by South African mining engineers to launch soil nails in order to prevent shallow landslides endemic to coal mine tailing stockpiles. In conjunction with the University of Wales and Bernard Myles of Soil Nailing Limited UK, the launcher was further refined (1).
The ballistic nailer is a compressed air cannon that can accelerate a 40mm diameter, 6m long steel tube (nail) to speeds up to 400 km/hr in a single shot. Compressed air up to a pressure of 330bar (4785 psi) is used to fire the soil nail.

The ballistic soil nailer was first used in the UK in 1989, and in the following years had undertaken repairs to road, railroad-related landslides and stabilisation works in the United Kingdom and Western Europe (2). Two launchers were built and used in the United Kingdom and Europe under a world wide licence from 1989. The majority of that work was on road and rail related landslides.

Discussions occurred in 1989 between employees of the US Forest Service and the co-inventor of the soil nailing technology, Bernard Myles of Soil Nailing Limited UK. In 1992, the US Forest Service and the Federal Highway Administration, in conjunction with four state highway departments brought a device to the United States and undertook successful repairs to eight demonstration sites (3,4). Complicated business developments resulted in the two launchers lying idle for a period of time before being purchased by Soil Nail Launcher Inc in 2002 and moved to the USA (5). There are currently four ballistic soil nailing machines in the world — two are the original cannon units owned by Soil Nail Launcher, Inc USA. Another unit is in Canada with Morsky Industrial Services and the fourth is currently being operated in Australia under a business arrangement between Probin Drilling and Construction Pty Ltd and Hiway Stabilizers from New Zealand. The ballistic nailer has a number of trade names; in Australia and New Zealand it is known as a Shotrods®. The Probin Drilling & Construction Shotrods® machine featured in this article was manufactured by Hiway Stabilizers, New Zealand.

Conventional soil nails
The technique of reinforcing existing ground without excavation involves some form of insertion of reinforcement. This method is generally applicable to walls and slopes. In some projects the reinforcement will be installed during a staged excavation whilst in other instances the reinforcement will be required to improve the stability of an existing slope or earthworks. A widely used technique for such reinforcement is ground anchors, however, this technique is regarded as an active reinforcement in which a stress is induced and transferred to the soil. Passive reinforcement is where soil movement is needed to activate forces in the reinforcement. The most common techniques of passive reinforcement are: soil nailing, reticulated root or micro-piles and soil dowels.

The existing design procedures for passive reinforcement fall into two categories: those that take into account shear bending and tension and those that recognise only tension as a contributing restraint mechanism. As in all soil reinforced structures there is a requirement to analyse the reinforced mass for an external failure. The detailed design procedures for the installation of soil nails are well documented and follow standard accepted geotechnical practice hence will not be commented upon further. The internal stability mode of the soil nailed structure can be considered as having several mechanisms, however, in most procedures the failure surface is regarded as a log spiral or circular arc.

Figure 1 shows an embankment that has been stabilised with soil nails. Ideally the installation of the soil nails should occur progressively as the embankment is excavated. Figure 2 shows a road where a slip plane has developed, but is in the early stages prior to a landslide. Intervention at an early stage can act as a temporary holding measure or as a long term solution.
There are a number of techniques used to deploy conventional soil nails. One method is to auger or drill a hole substantially larger in diameter than the nail. A nail is inserted into the hole and the annular space filled with cementitious grout. For drilled and grouted nails, a vertical or steeply sloped face must be capable of standing unsupported for a period of one or two days. Another technique is to drive the soil nail from the surface with an air or hydraulic impact hammer. Using this technique, the small repetitive percussive impacts disturb the soil and reduce the available skin friction.

Even within soil nails there are different types, sometimes referred to as flexible nails and stiff nails. Flexible nails are generally nails with a diameter less than 25mm which are installed in a drilled and grouted hole and orientated to mobilise tension. Stiff nails are often directly inserted without the addition of grout and are orientated to generate both shear and bending in the nail as well as tension. The geometry of directly inserted nails may, in some cases, be considered as soil dowelling where the influence of tension can be disregarded. While it is common to ignore the effect of shear on flexible nails, it is always wise to ascertain the shear forces in all soil nails as these should be taken into account in assessing the permissible tensile load on the nail. A similar argument applies to the tensile force on nails that are primarily used in shear. Full-scale trials in Germany and France have shown that shear and bending do exist in the nails.

Steel nails should have ductile properties and should not be brittle. This is particularly relevant as at the ultimate condition the nail must retain its ability to carry tensile forces whilst deformed. The use of stainless steel is not generally recommended unless soil conditions are highly aggressive. The use of fibre composite or synthetic nails, as yet, are not widespread and their application is limited. Synthetic nails should be orientated into a tension mode and any bending and shear should be avoided.

**Ballistic nail details**

A ballistic nail is one which is fired into the ground at high speed in a fraction of a second. About any type of material can be utilised in the construction of a ballistic soil nail as long as it has the desired physical properties. The nails can be manufactured from solid bar, threaded bar or pipe. Steel bars can be left as a mill finish, galvanised, epoxy coated, plastic sheathing or a combination of finishes. While it is understood that fibre composite or synthetic nails may be used for ballistic nailing no experience currently exists in Australia with this material.

The majority of ballistic nails used to date in Australia have been manufactured from ERW 42.4mm diameter x 3.2mm wall Gr250 galvanised water pipe. The nails are supplied in 6m lengths and cut to length as required. These hollow nails are low cost and demonstrate good strength and ductility. If desired, grout can be pumped into the hollow perforated nails to stabilise embankments or other areas. The hollow nails can also be utilised as subsoil drains if holes are drilled along their length. Where an embankment is saturated or where there is a sub-surface water source feeding water into an embankment, hollow nails with drainage holes can stabilise these embankments and at the same time act as a dewatering system (Figure 3).

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**Figure 2. Stabilised road embankment with slip**

**Figure 3. Ballistic soil nails dewatering an embankment**
At the high speed that these nails/projectiles enter the earth (up to 400km/h), a shock wave is generated in front of the nail tip that causes the soil particles to “jump away” from the main shaft of the nail. The nail subsequently enters the earth without significant abrasion or coating damage. The soil particles then collapse onto the nail providing a high pullout resistance which is much greater than a surface driven nail. Ballistic nails increase the soil density in the nailed area. In contrast, conventional open-hole drilling techniques allow the soil to relax prior to installation, which can adversely affect bond capacity.

The ballistic nailer is typically mounted on a tracked excavator with a hydraulic swivel to facilitate easy alignment. It can be mounted on a range of vehicles or slung from a crane. The ballistic nailer weighs 2t, making it portable and able to reach remote locations. Hence it is capable of reaching over an embankment or up a slope face.

Ballistic soil nailing is not suitable for all situations. Prior to its use, an embankment will require exploratory drilling. Occasional large stones will not restrict the installation of ballistic nails, however, any abundance of boulders or zones of cobbles, will make ballistic nails impractical. Under these rocky conditions, holes can be bored with a rock drill and nails grouted in position.

Ballistic penetration of the soil nail overcomes the buckling problems and the swift single impulse inserts the nail in less than one fifth of a second resulting in a uniform annulus of displaced soil whilst minimising the disturbance of the soil structure. Ballistically installed nails are propelled by high pressure compressed air from its tip to which the force of the air pressure is transferred via a frangible plastic piston/collet. In this way the nail is placed in tension in flight. The tension, induced by the tip firing ensures that the nail does not buckle on impact. Once the nail enters the ground it is restrained against buckling by the soil and its straightness maintained.

The launching sequence is controlled by a microprocessor ensuring correct and safe operation. In the following photographs the ballistic nail launcher is attached to a 19 tonne Caterpillar 318CL hydraulic excavator. A specially constructed extension at the rear of the excavator houses two separate high pressure compressors driven by Lombardini 25kW diesel engines.

The launcher makes a sharp loud ‘boom’ on firing. The noise is reduced by a baffled louvred shroud which also captures the shattered disposable piston/collet. The standard shroud has been wrapped with conveyor belt material in a further attempt to contain any flying debris and help reduce the noise.

The Shotrods® and supporting equipment are very portable, transportable on standard industry trailers to enable mobilisation at short notice. The ballistic nails can be installed at a rate of approximately 15 nails per hour which averages to around 80-100 nails per day. A day’s production is equivalent to over 100m² of stabilised slope.

**Operational details**

**Loading** — For safety reasons, during the loading cycle there is no high pressure air in the onboard reservoir on the Shotrods® machine. The nail with attached piston is loaded into a guide tube and then slid into the open breach (Figures 4 & 10). The breach is then closed. In the intervening time between firings, the high pressure compressors are charging four high pressure cylinders on board the excavator.

**Charging** — After the soil nail’s piston is engaged with the cylinder and the breech is closed, the on-board accumulator is charged to the desired air pressure (Figure 5). The maximum design air pressure is 330bar (4785psi). However the firing pressure can be varied depending on soil types, nail penetration and design requirements.

**Setup** — The Shotrods® is lifted into position and aligned in the desired direction. To prevent the accidental free-flying of nails, the machine has three spring loaded feet located under the main body (Figure 13). Two of these three feet must be simultaneously depressed against the work face before a nail can be fired. (This is similar in principle to the safety mechanism on a hand held nail gun). The safety systems and firing sequence are electronically controlled. Personnel must be clear of the firing zone and ear plugs must be worn. Following a sequence of auditory warning sirens, the nail is fired. Figure 6 shows the high velocity nail just before the piston leaves the barrel. The nail is now travelling near maximum speed (Figures 6).
Penetration — After the nail emerges from the barrel, the compressed air expands through slots in the machine base-plate. The exit hole through the base-plate is smaller than the piston diameter resulting in the plastic piston assembly shattering upon impact. The nail then penetrates to the required depth leaving a short length of nail protruding from the reinforced soil.

The ballistic nails in the following figures are comprised of a 170mm long solid steel tip welded into a 6m length of 42.4mm galvanised pipe. The tips are machined to form barbs which engage with a two-piece piston/collet. The piston acts as a seal in the barrel against the high pressure air and also acts as a collet with uni-directional engagement with the barbs. The piston assembly is held together by two circular plastic retainers. Figure 8 shows one half of the black plastic piston engaging with the barbs on the nail. Figure 9 shows both piston halves in place prior to fitting the two white plastic retainer rings.

Figure 8. Barbed end with half assembled piston/collet

Figure 9. Other half of piston/collet

The following figures are of a slip on Harvey Creek embankment, Bruce Highway just south of Cairns. The slip material has been removed and the embankment is being stabilised with 4.5m ballistic soil nails. After stabilisation, the slip area is reinstated with a geosynthetically confined soil (GCS) wall.

Figure 10 shows a nail being loaded into the Shotrods® machine. The breech is in the open position to allow the piston to enter. Figure 11 shows the Shotrods® machine a fraction of a second after firing a nail. What appears to be white smoke is condensed water vapour created from the expanding high pressure air.

Figure 10. Loading nail into Shotrods®

Figure 11. Immediately after firing
Figure 12. Partially stabilised wall

Figure 13. Base-plate safety contact feet and nail exit hole
Case study
A slip occurred on the Kuranda Range, Kennedy Highway during the wet season of 2008/09 that posed a significant risk to motorists. This busy two lane tourist route carries in excess of 8000 vehicles per day between Cairns and the Tablelands. Using conventional repair techniques, the project was estimated to take eight weeks. The repairs were undertaken using the Shotrods® machine in conjunction with a GCS wall technique (Figure 14).

Using these techniques, the project time was considerably compressed to eighteen days. A major advantage of this process was that traffic disruption was minimised and full traffic closure was only required intermittently as each nail was fired.

Ballistic nailing techniques are typically cheaper than conventional soil nails as evidenced in a 27% saving for this project. A contributing economic factor is the shorter job duration with subsequent lower traffic control costs. A further benefit was reduced delay and disruption to the travelling public.

Figure 14. Typical cross section showing soil nails and GCS wall.
The slip area was reinstated with Type 2.3 gravel in 200mm layers and reinforced with Miragrid GX40/40 geogrid. In this tropical environment, extremely high rainfall intensities combined with a steep embankment meant that traditional bank revegetation techniques were not suitable. A living-wall, made from “onion” bag material, was manufactured by a local nursery. The bags contained select compost material and revegetation seeds. The geogrid material was laid under the living-wall bags and then lapped back over so that the bags were fully encapsulated by the geogrid. The living-wall bags are therefore not subject to displacement or washout. Figure 16 shows a layer of living-wall bags being laid prior to the next 200mm layer of fill. Note the flat subsoil drains against the nail stabilised face. Figure 17 shows the living-wall after a short germination period.

The slip material was excavated in stages with each stage progressively stabilised with nails. This staged approach reduced the risk for a localised collapse under the weight of the Shotrod® excavator. As work progressed the full height of nail-stabilised embankment was exposed.
Conclusion
Ballistic nailing is an exciting innovation new to Australia and on the world scene is twenty-one years old. Ballistically fired soil nails have cost and time advantages over alternate soil nailing techniques. It is a technique which works exceptionally well with GCS walls. The use of the living-walls has proved to be a success especially where there is high intensity rainfall.

Ballistic nailing is not presented as a panacea for all slope stability problems but has a place in the engineering toolkit along with the many other remedial techniques.

The Shotrods® machine is easily transported to site with conventional transport vehicles hence it can respond very quickly to emergency work. Areas which will undoubted see increased interest in the future are preventative maintenance works. When roads show the early tell-tail signs of an impending slip, the associated embankment can be stabilised to either provide a short or long term solution.

References


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