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Forensic Examination of Critical Special Geotechnical Measures: Soil Nails Information Note

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Executive Summary

The effective design, specification and construction of Special Geotechnical Measures (SGMs) is critical to the efficient operation of the National Highways' Strategic Road Network (SRN). Given the required performance of the SRN in terms of resilience, reliability, redundancy and recovery it is essential that SGMs are themselves reliable in terms of performance and life; resilient to external conditions such as earthworks deterioration and extraordinary conditions (e.g. climate change). Around 100 different types of SGMs are used on the SRN and the early installations of some SGMs are approaching the end of their design life and the design, specification and application of many of these techniques is based on limited studies.

This Information Note is part of a series that reports on investigations of specific SGMs, in this case Soil Nails, and makes recommendations on their future use. A detailed account of issues identified on the Strategic Road Network (SRN) and other infrastructure is given drawing from relevant research and applied studies and inspection of soil nails in various settings.

Advice is given on the design, construction, inspection, maintenance and decommissioning of such strengthened earthworks and a series of recommendations is made.

There is no compelling evidence that when properly designed, specified, constructed and maintained, including an appropriate inspection regime, Soil Nail SGMs cannot meet the required design life for either slopes (60 years) or for structures (120 years) of such SGMs. However, there is substantial evidence that in the UK, soil nail design, specification and construction is frequently not at a level that would promote longevity of this nature.

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1 Introduction

1.1 General

This Information Note on Soil Nails is part of a wider study of the performance of critical Special Geotechnical Measures (SGMs) (Duffy-Turner et al., 2022) and is one of a series that reports on investigations of specific SGMs, in this case Soil Nails, and makes recommendations on their future use.

Soil Nails (SNAL) are defined as *slopes of any angle reinforced using soil nails, except where any facing mesh actively contributes to stability* (Atkins/Jacobs, 2020). The first uses of soil nails were claimed to be in Brazil in 1970 (Ortigao et al., 1995) to stabilise a tunnel portal in São Paulo, and in France in 1972 to increase the slope of a 965m long railway cutting at Versilles-Chantier (Rabejac & Toudic, 1974).

Over the last few decades there has been a significant rise in the number of projects that have used soil nails, and this is especially the case where the work involves modifying the existing network, such as the Smart Motorway Programme (Arup/Aecom, 2020).

This Information Note provides advice for the design and construction of soil nail slopes and highlights known issues and pitfalls associated with these. During the original review of SGMs (Duffy-Turner et al., 2022), discussions were held with National Highways technical staff and the supply chain to determine what issues had arisen with the use of soil nails on the Strategic Road Network (SRN). The feedback was that soil nail slopes were often located in critical locations where failure may pose a significant risk to the network and that defects and failures had occurred previously.

1.2 Soil Nail use in the UK

In the early-1990s the use of soil nails began to be accepted as a viable alternative to more traditional techniques in the UK. At that time there were two competing approaches to the installation of soil nails, driven nails and the more commonly encountered drill and grout. Driven nails were typically installed using a pneumatic launcher, but this technique appears to have fallen out of use, in the UK at least, although it does appear to persist in at least parts of the USA. Pneumatic launching of soil nails is typically not considered suitable for use on the SRN; however, it is noted that this technique has been used successfully in the past.

In parallel with the emergence of these two techniques a robust debate was conducted in the UK technical literature regarding the mechanism of soil nail reinforcement. Myles & Bridle (1991) argued for the importance of nail bending stiffness. This was crucial to the viability of slender driven nails with a relatively small circumference and consequentially small contact area and frictional pull-out resistance. Where driven nails are used the relatively small surface area of each nail generally results in a higher density of nails than for an equivalent drill and grout soil nail design. Drill and grout nails have a relatively large circumference and a consequentially higher contact area and pull-out resistance.

Experimental work showed that the axial tensile stress in a nail is activated prior to any significant shear stress (Jewell, 1990a; Pedley et al., 1990a, 1990b). This evidence supports the theoretical approach proposed by Jewell & Pedley (1990a, 1990b, 1991) who concluded that bending stiffness was of marginal significance in soil nailing. While there was no clear resolution to this debate in the technical literature it is perhaps telling that subsequent design guidance took the axial tensile stress approach to soil nail design.

Subsequent work by Jewell and Pedley (1992) demonstrated that only a small proportion of the maximum shear strength of a nail can be mobilised. The whole soil mass will be close to failure before the limiting shear strength of the nail is reached (BRC, 1994). This is because the small strains deforming the soil mass are efficiently transmitted across the bond between nail and soil thereby creating tensile stresses in the nail.

Currently there are two main installation techniques used in the UK which are both a drill and grout technique; these are ‘Bored and grouted’, and a type inserted using a displacement technique (referred to herein as ‘Self-drill’).

2 Issues Identified

A series of site inspections of soil nail slopes in-situ along with a review of case histories and consultations was undertaken between May 2021 and January 2022 to establish the prevalence, nature, condition and setting of soil nails on the SRN. This research phase, along with more general experience, has highlighted a number of issues relating to soil nails. Details of the site inspections and case histories are presented by Duffy-Turner et al. (2022). The ages of these soil nail installations range from seven to 31 years.

The issues identified from the research phase are highlighted in the following sections.

2.1 Ground conditions

As part of a soil nail design, it is imperative that the ground conditions are understood as not all situations are conducive to a soil nail system (see Section 3.2). For example, high plasticity soils are not recommended for soil nailing due to the seasonal shrink swell movements that are likely to occur.

The excavation of the slope should give a good opportunity to review the ground conditions as the face is exposed. If the soil type or groundwater levels are not as expected the design should be reassessed in light of the new observations; however, it is important when reassessing the design that each aspect of the soil nail system is reviewed.

A problem with the ground conditions was encountered on the A21 at Lower Haysden where a failure of the soil nail slope occurred following construction (see Figure 1).

Figure 1: Failure of a soil nail slope after construction with bulging between the nails, A21 Lower Haysden (from Balfour Beatty Mott MacDonald, 2013)

The embankment fill had a higher sand content than at other locations on the A21 and as such the spacing of the nails was increased due to the higher soil shear strength. However, the final trimmed surface of the embankment was more irregular than at the other A21 sites due to the more granular nature of the soil which meant the facing did not have intimate contact with the surface as required by the design and was unable to be adequately tensioned. Therefore slumping between the nails occurred as the face was unsupported and the cohesion in the soils was lower than had been assumed elsewhere (Balfour Beatty Mott MacDonald, 2013). A hard facing i.e. a steel mesh with separator and gabion style finish or sprayed concrete, would have been more appropriate for these ground conditions.

2.2 Slope excavation

The general recommendation for a new cut soil nail slope is to construct the slope incrementally (see Section 4.2) allowing the soil nails to become progressively loaded as excavation induced movements occur (BSI, 2011). This approach is not popular with contractors as the production rates of excavation, nail installation and facing installation are different leading to sub-optimal efficiency. However, over-excavation can give rise to an increased risk of instability during construction and may adversely affect the temporary and long-term stability of the cut.

In some instances, soil nail slopes on the network have been over-excavated which has led to failure of the slope prior to the installation of the nails (Figure 2).

Figure 2: Failure of a full height slope excavation prior to installation of the soil nails, A1 Dishforth to Barton Improvement (from Carillion/Morgan Sindall JV, 2018)

This happened on the A1 Dishforth to Barton Improvement Scheme where full height, rather than benched excavation was undertaken due to run off issues from the upper slope (Carillion/Morgan Sindall JV, 2018). The installation of the nails was out of sequence with the excavation of the slope and the excavations were left unsupported (un-nailed/faced) for significant periods of time with one particular slope left only partially nailed and faced over the Christmas break which ultimately failed (Figure 3). The failures were characterised by a series of shallow slips and flow slides and along with the excavation issues identified above there were also major issues with drilling and grouting, low volume water flow/seepage and installation of the facing (see Sections 2.3, 2.4 and 2.5 below). The original design and construction of the soil nail slopes were undertaken as a subcontract to the main works. Following these issues AECOM, who hadn't been involved in the original design and construction, carried out a forensic investigation into the problems encountered. A short section of vertical excavation can be undertaken successfully (as it was as part of the re-nailed at the A1 Cataractonium Cutting), but it requires good coordination between all the parties to ensure that the time between excavation and installation of the tensioned facing is kept to a minimum number of hours. This would require assessment as part of the temporary works design.

Figure 3: Failure of a slope which was left partially nailed and partially faced over an extended period, A1 Dishforth to Barton Improvement (from Carillion/Morgan Sindall JV, 2018)

2.3 Drilling and grouting

It is essential that the drilled hole can be kept open between drilling and grouting; however, there are a number of issues that can occur in relation to drilling of the soil nails and these differ depending on which technique is used (see Section 4.3). Some of the main issues associated with drilling are related to the grout and the placement of the tendon within the hole. The use of centralisers is integral to the performance of the soil nail system and achieving a continuous grout annulus around the tendon (see section 4.4). The failure to use centralisers has, on occasion, led to the tendon lying on the base of the borehole (Figure 4) which reduces the grout cover to the tendon. Grouting is important to provide contact between the soil nail and the ground so a reduction in grout cover can affect the frictional resistance and bond strength.

The contention between the need for centralisers and the potential for such devices to damage self-drilling nails and to impede grout placement was raised during the A21 Tonbridge to Pembury Scheme (WSP, 2019). It was identified that centralisers had not been installed although these were required within the specification provided in the Strengthened Earthwork Appraisal Form (WSP / Parsons Brinckerhoff, 2015). The specialist contractor on site argued that the centralisers had the potential to damage the galvanization on the tendon during the repeated withdrawal of the soil nail to clear arisings. A technical note was produced by the consultant on site which stated that due to the potential for the galvanization to be damaged, the design life of the soil nails could potentially be reduced from 60 years to 42 years if centralisers were used and the galvanization compromised (WSP / Parsons Brinckerhoff, 2017). This was accepted by National Highways and the remaining soil nails were installed with centralisers but accepting the design life of the soil nails may be reduced if damage was to occur.

Figure 4: Self-drilled soil nail lying on the base of the borehole due to failure to use centralisers. This reduces the grout cover for corrosion protection and potentially reduces the bond strength (image the authors)

On the A1 Dishforth to Barton Scheme at Cataractonium Cutting there were a number of issues observed with the newly constructed slopes (see sections 2.2, 2.4 and 2.5 for further details of the failures). Due to concerns regarding the quality of the workmanship, a number of nails were extracted from the cuttings (Figure 5). Out of the four nails extracted, three had either no centralisers present or centralisers in positions considered unacceptable. These three soil nails had limited grout coverage (between 0% and 30% intact coverage). In comparison the soil nail which had the centralisers present in acceptable positions had 93% intact grout coverage (Carillion/Morgan Sindall JV, 2018). During the re-nailing all the centralisers were secured with cable ties to the ridges in the nails and physical pull tests along the bar axis was carried out to confirm fixture. This prevented the centralisers from sliding along the bar during installation.

Another issue identified on the A1 Dishforth to Barton Scheme was that no tremie pipe was inserted to the back of the soil nail bore. It is not known if this was just on specific boreholes or if a tremie was not used on any of them; this may account for the lack of grout on the tendons when they were extracted.

Figure 5: Extraction of soil nail as part of the forensic investigation. The nail was pulled out of the slope with a load greater than required by the acceptance tests (image provided to Coffey by AECOM in 2017)

If there is potential for the bore to become unstable prior to the installation of the soil nail and grout, it is necessary to use casing to hold the bore open until the grouting is completed. If hole collapse does occur there is the potential for insufficient grout cover and/or grout bulbs to be formed during introduction of the grout into the hole. Putting in less grout than the theoretical required volume is an indication of hole collapse prior to grouting. The technical note produced by WSP (WSP / Parsons Brinckerhoff, 2017) states that if bulbing occurs it may benefit pull out performance. Whilst this is broadly true there is the issue of the bulb invalidating the frictional nature of the design by introducing an anchor block and the formation of grout bulbs should therefore be avoided.

2.4 Water

For most soil types, soil nails should be installed in a dry excavation (considering both groundwater and surface water flows). There have been numerous issues identified on the SRN where the water within a slope has not been properly identified and or controlled during the design and construction of the soil nail system.

A common mistake that has been raised is that in some designs it is assumed that the water table will drop to the base of a newly formed cut and therefore drainage provision has either not been included in the design or the provision has been inadequate. This can cause major disruption during construction when the short-term stability of the slope is dependent upon the pore pressures within the slope; however, it can also become an issue for long term stability.

On the A1 Dishforth to Barton Scheme a number of issues were identified that caused the uncontrolled outflow of surface water and groundwater within the soil nailed slopes in the Cataractonium Cutting and led to localised instability (Carillion/Morgan Sindall JV, 2018). These led, along with other contributing factors (see sections 2.2 and 2.5), to failure of the slopes. These issues included:

- Low volume water flow/seepage through the slope face, softening exposed materials (see Figure 6).
- Persistent seepage of groundwater through and over the upper slopes and discharging over the crest.
- Run off from the upper slope was not accounted for in the design.
- The unexpected presence of historic coarse stone drainage grips which channelled water into the slopes.
- Presence of a perched water table.
- Severing of original stone filled counterfort trenches.
- Incised ditches and channels present at the base of archaeological remains which channelled water into the slopes.

Figure 6: Seepages present on the cutting face at Cataractonium Cutting (image provided by National Highways)

In 1995 on the M1 Widening Scheme at Junction 21/21a an 80m section of soil nailed slope became waterlogged causing the facing panels to bulge which ultimately led to failure of the panels over a length of approximately 30m (Figure 7). The facing comprised a 300mm thick cage with topsoil located between the front and back mesh. It had been assumed that the topsoil between the meshes would have sufficient stiffness to ensure a degree of composite action between back mesh, soil and front mesh. When the panels were removed it was evident that water was seeping from the cutting face above the top row of nails. This was concluded to have been from a high perched water table established after a high intensity rainfall event and led to saturation of the topsoil in the facing. Rather than transferring shear between the meshes as designed for, the topsoil acted as a dense fluid (which cannot carry or transfer shear), and the mesh which was clipped together as a series of panels was not capable of withstanding the significant deformations (GIBB, 1996). The failure at this location was related only to the facing panels; the soil nails and head plates were found to be intact during subsequent investigations.

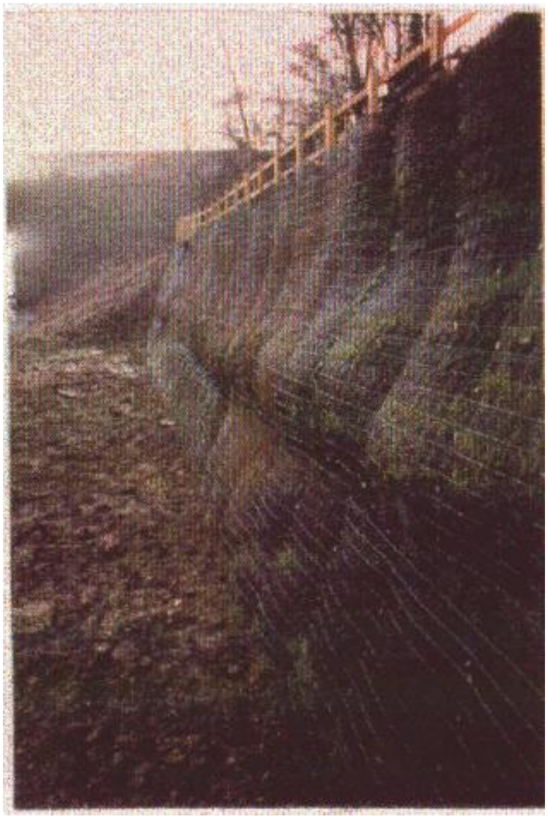


Figure 7: Failure of facing panels on a soil nailed slope, M1 Rapid Widening Scheme (from GIBB, 1996)

In 2016 on the A21 Tonbridge to Pembury Scheme a 20m section of a partially soil nailed slope at Castle Hill failed following a period of heavy rainfall (Figure 8). Following investigations, it was concluded that water was flowing down the access track into a manhole and then entering the slope via a BT duct along the crest. This led to softening and collapse of the slope.

Figure 8: Failure of a partially soil nailed slope during construction, A21 Tonbridge to Penbury (from WSP, 2019)

2.5 Facing

Where soil nails are used to stabilise a slope, they do not stabilise the surface soil. This is done by the nail head plate (see Section 2.6) and the slope facing (see Section 3.4 for more details). There are three main types of facing: soft, flexible and hard. The correct facing should be selected based on site specific conditions otherwise the facing may be subject to failure.

The failures seen on the A1 at Cataractonium Cutting (described in previous sections) also had problems with the installation of the facings with the three slopes (SNS1, SNS2 and SNS3) originally constructed using a Geobrugg Greenax steel wire mesh facing. The slopes were subject to slumping failures (Figure 9) and localised crest slope regression.

It was concluded a general lack of tension in the facing system allowed progressive deformation to take place. This included:

- Lack of tension in the mesh when applied to the slope.
- Lack of crest and toe facing-mesh tie-in for significant periods of time.
- Damage to the mesh at the toe of the slope.
- Nuts left loose and not fully engaged to tie the nail head and mesh together.

A discussion with the Geotechnical design lead who undertook the forensic investigation of the Cataractonium cutting failures (Roberts. P, personal communication, 25 February 2022), suggests that the flexible facing used on these slopes was unable to be adequately tensioned as per the manufacturer’s specification, due to the presence of the soil nails already installed on the slope i.e. once the facing was draped over and the nail threaded through the mesh aperture: that is, it is not possible to adequately tension the mesh with the nail head in place. As the performance of the facing is dependent upon the facing system being in tension the selected facing type was possibly not appropriate; however, the sequencing of construction at the Cataractonium cutting was not as recommended by Phear et al (2005) and did not allow for the facing to be installed and tensioned incrementally (Figure 28) between subsequent rows of nails. Following the failures of the facing, the manufacturer Geobrugg were consulted regarding use of the Greenax steel wire mesh. At this time Geobrugg raised concerns that the

Greenax steel wire mesh would not be able to withstand the forces it was being put under and that normally it is only recommended for slopes with gradients up to between 40° and 45° (personal communication – email from S. O. Rourke to A. Scholefield, 11 April 2017, 15:56pm), where it is understood that cut slopes in the Cataractonium Cutting were cut to 55° (Carillion/Morgan Sindall JV, 2014).

Figure 9: Slumping of the soil nail slope (SNS2) causing deformation of the facing at Cataractonium Cutting (image provided by National Highways)

The original facing systems were condemned during the works and replaced by a 450mm thick stone-filled mattress facing system with double layer structural mesh backing for SNS1 and SNS2 and a PVC-coated steel wire mesh with incorporated 3D erosion control mat facing system for SNS3 (Carillion/Morgan Sindall JV, 2018).

On the A42 to the northeast of Ashby-de-la-Zouch the slope adjacent to an emergency layby has been soil nailed and faced with concrete cloth straps/planks on a 1m grid and infilled with a black geogrid (Figure 10). This soil nail slope is believed to be around 30 years old which is one of the oldest on the SRN. The face was observed to be bulging with the concrete straps heavily bowed, especially the ones in vertical alignment. The geogrid located behind the concrete cloth straps was brittle and broke apart with light pressure suggesting this may be suffering from UV deterioration.

Figure 10: Facing of a soil nail slope comprising concrete cloth straps/planks with a small aperture black geogrid, A42 northeast of Ashby-de-la-Zouch (image the authors)

2.6 Nail heads

The nail head plate should be designed and specified in conjunction with the soil nails and slope facing to act as a complete soil nail system to adequately resist any driving forces and loads upon it. The nail head plate should be correctly sized to prevent bearing failure and to promote soil arching thereby reducing local instability in between soil nails (Phear et al., 2005). Inadequate design or construction can lead to punching failure of the facing (Figure 11).

There is an issue of the potential trip hazard, and the related spike-injury hazard, caused by soil nail heads being left proud of the surface. In reality this should not be an issue if (1) the nail heads are correctly trimmed once installed and as (2) soil nailed slopes are unlikely to be at an angle that allows for foot-based inspection other than from the top and/or bottom of the slope. It is assumed that engineers undertaking inspections of earthworks with soil nails will have an appropriate risk assessment which should identify the potential trip and spike hazard; however, if soil nails are located in an area accessible to the public, this is something that should be considered. A project in Scarborough involved soil nailing slopes adjacent to a highway which was easily accessible to the public. To prevent the risk of the potential trip and spike hazard a geocell was installed on the slope over the soil nails and facing and infilled with topsoil (Figure 12).

Figure 11: Mesh soil nail slope facing where slope movement forces have caused punching failure of the soil nail mesh facing. After failure the face plate is approximately 600mm behind the facing (image the authors)

Figure 12: Geocell installed on a soil nailed slope and infilled with topsoil to prevent a trip and spike hazard in a publicly accessible area (image the authors)

On a slope along the A628, the lower row of nails, immediately adjacent to the layby, presented trip and fall hazard. Vehicle impact with the protruding nail heads was also a possibility (see tyre tracks in Figure 13). Nails on the first row were uncapped (Figure 14), while some of the nails on the second row were capped (Figure 15). Historic Google Maps imagery showed that caps were present on the lower two rows and on the netting dowels following construction in 2012, with the majority having been lost in the interim; presumably either intentionally (whether by the operator or vandalism) or possibly through weather-related issues (i.e. high winds). The head plates and locking nuts at this location were observed to be loose and both the plate and nut were able to be moved by hand.

Figure 13: Soil nails installed in cutting adjacent to layby on the A628 to the East of Manchester (image the authors)

2.7 Corrosion

During the site investigations no soil nail tendons were exposed apart from at the nail head. The different sites all had nail heads which showed signs of corrosion where the bar had been cut and these were accompanied by varying degrees of grout loss from within the soil nail annulus, typically ranging from no/slight loss through to full loss (Figure 14).

Figure 14: Soil nail heads on the A628 east of Manchester showing varying amounts of grout loss from within the nail head (image the authors)

One site, the A628 east of Manchester (SGM ID 6312), had caps present on some of the soil nail heads (see Section 2.6). Where the cap was present, the nail beneath it appeared to have been covered by a galvanizing paint and in these instances no corrosion or grout loss was observed on the nail head.

Figure 15: Soil nail heads on the A628 east of Manchester with rare caps present. The image on the right shows the condition of the nail head beneath a cap indicating no corrosion or grout loss (image the authors)

Barley & Mothersville (2005) reported on a series of observations and exhumations that have been undertaken on soil nails both internationally and in the UK. These were based on case studies in Japan and Hong Kong (Shiu & Cheung, 2002), Singapore (Barley & Kiat, 2002) and the UK. In Japan 10-year-old soil nails were exposed from nine sites as part of investigatory work by Tayama et al. (1996). Partial uniform and pitting corrosion were observed on some of the nails. The maximum pit depths were 5.8mm for the steel bars without galvanization and 0.84mm in one soil nail with galvanization (it is unknown how many nails were galvanized). Heavy corrosion was also observed at locations behind the concrete nail heads. The causes of corrosion at these sites were thought to be due to shortage of grout at the crown of the grout column and inadequate grout cover in deeper areas (grout cover ranged from 7mm to 30.6mm). In Hong Kong two sacrificial soil nails (bare steel) were installed in 1988 as part of a soil nail stabilised retaining wall (Watkins, 1987). In 1997 the sacrificial soil nails were exposed and for one of the nails, the grout annulus was intact, and no corrosion was observed on the steel bar. The other nail showed voids in the grout annulus, indicating the grouting work was not caried out properly. This led to pitting corrosion up to 3mm on the bar indicating a corrosion rate of about 0.3 mm/year. Observations of the upper one metre of a few grouted soil nails in Singapore (Barley & Kiat, 2002) showed the presence of surface rust, but no evidence of deep pitting after a 15-year service life.

The test data reported by Shiu and Cheung (2002) indicated that the rate of corrosion of both steel and zinc decreases with time with an initial rapid loss over the first two years followed by a progressive decrease in the corrosion rates.

The approach to corrosion losses was raised in the original phase of the project (Duffy-Turner et al., 2022). Corrosion losses over the life of the structure are generally about 2mm to 3mm which coincides with the height of the ridges on the nail surface that provide most of the bond at the nail-grout interface. As the nail is relying on this bond, the implication that only the ridges corrode may well be flawed as corrosion is likely to occur over the entire nail profile; the remaining question will be what that process does to the bond between the nail and the grout and further investigation is likely to be required.

2.8 Other issues

Other issues that have been identified are addressed in the following sections.

2.8.1 Other construction activities

Following an inspection in 2011 of a soil nail embankment on the M23 Gatwick Spur Junction 9 to 9a, it was observed that one soil nail was missing, two were damaged (Figure 16) and a further one needed the head plate and nut to be tightened (Balfour Beaty Mott MacDonald, 2011). In addition to the damage to the soil nails, the galvanized mesh was disturbed around the damaged nails. Earlier in 2011 a scheme had been completed to install a safety barrier for the full length of the M23 Gatwick Spur. It is understood that a Geotechnical Report was not prepared for the safety barrier works as it was assumed by the consultant that it was not required based on the guidance in HD 22/08 Management Geotechnical Risk (HE, 2008). National Highways understood this to be a non-compliance and requested a Non-Conformance Report to be raised. Discussions with National Highways Area 4 team indicate that the installation of the safety barrier damaged the soil nails although nothing was reported at the time of the barrier installation.

2.8.2 Vegetation

During the site inspections in 2022 the soil nail cutting at M6 Junction 10 (Northern carriageway) was observed to have vegetation growing out of the slope and causing damage to the mesh facing (Figure 17). Currently this is not causing too many concerns but as the trees grow this will put more stress upon the mesh and subsequently the head plates and nails.

Figure 16: Soil nail protruding from the face directly below a safety barrier post which was installed at a later date, M23 Gatwick Spur (from Balfour Beaty Mott MacDonald, 2011)

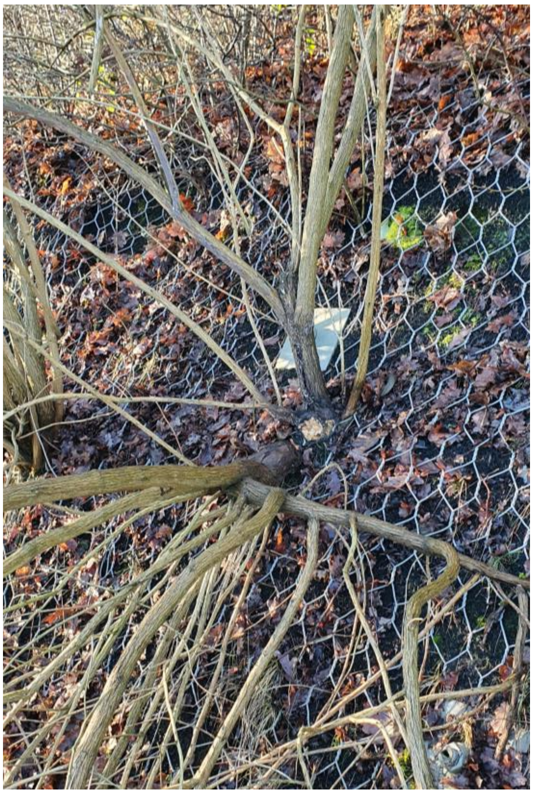


Figure 17: Vegetation growing through the mesh on the soil nail slope at M6 Junction 10 (image the authors)

2.8.3 Missing soil nails

On the A42 to the northeast of Ashby-de-la-Zouch the soil nail slope inspected in 2022 was observed to have infrequent soil nails missing from the bottom row (Figure 18). There were no signs of the missing nails in the hole or any indication of what may have happened to them (there are no design or construction details relating to this slope, but it is assumed they were originally installed). All the other nails present on the slope appeared to be secure.

Figure 18: Missing soil nail from a slope adjacent to an emergency layby along the eastbound carriageway of the A42 (image the authors).

2.8.4 Nail grout interface

During the initial phase of the SGM project it was highlighted that there may be an issue between the nail/grout interface relating to the presence of calcium zincate forming. This issue was brought to the forefront following loss of bond between the grout and the nail at the Cataractonium Cutting and the development of a white substance on the tendon which was observed following an extraction test during the works. The tendon was later sent to Newcastle University where it was subject to testing as part of a Masters dissertation project (Otchere, 2018) using X-ray powder diffraction (XRD) (Roberts. P, personal communication, 25 February 2022). Otchere (2018) identified that the calcium hydroxy zincate was found on all the samples of bar tested and this was the anticipated corrosion product formed during the initial reaction between the hydroxides in the cement grout and the zinc passivation layer with a by-product of hydrogen gas released during this process.

Also identified by the XRD on all the samples was the presence of calcium carbonate which was determined to be the source of the white stains on the bar.

Figure 19: Presence of white substance on the soil nail tendon following pull out of the soil nail at the Cataractonium Cutting (image provided by AECOM).

Langill (2001) suggests that reactions between the grout and galvanized reinforcement bars are only of concern during the initial curing stages when the grout mix is still wet. As the concrete surrounding the tendon is curing it is very alkaline, typically with a pH of around 12.5. The wet concrete can react with the zinc which passivates the coating by the precipitation of a protective layer of calcium hydroxy-zincate (Ca[Zn(OHbl $2H_20$)]). A by-product of this reaction is the production of hydrogen gas which can weaken the bond between the bar and the grout (CRSI, 2016). Langill (2001) also suggests that where a wet concrete mix has a pH greater than 13.5, there is a significant increase in the reaction between the galvanised bar and the grout and that the use of these components should be avoided without the use of chromate.

The American standard ASTM A767-19 (2019) has a requirement that galvanized reinforcement requires chromate passivation immediately after galvanizing which prevents the reaction from occurring. The most common method of treatment is to quench passivate the galvanized steel in a low concentration of sodium dichromate (CRSI, 2016). In 2003 the European Commission issued a directive [2003/53/EC] stating that to protect human health (particularly from contact dermatitis), the use of cement containing more than 2 ppm chromium VI (hexavalent chromium) should be restricted where it is possible that products can come into contact with the skin. This was incorporated into UK health and Safety Legislation in 2005 although it is unknown if there was a date for implementation by manufacturers.

Otchere (2018) determined that the reduction of chromium to less than 2ppm in the cement has affected the performance of the grout when it comes to the nail / grout interface.

The phenomenon observed at Cataractonium Cutting has not been highlighted as being an issue at any other site within works on the SRN; however, it is unlikely this would be identified if testing was not specifically undertaken for the production of calcium hydroxy-zincate but with the reduction in chromium from UK legislation in 2005, and no chromate passivation included on the galvanization as in the USA, it is plausible that these reactions are occurring.

2.8.5 Soil nail testing

Issues surrounding the testing of soil nails, whether of in-service (production) nails or sacrificial nails, were raised in the original phase of the project (Duffy-Turner et al., 2022). These essentially highlight that when the notional pull-out resistance of the full nail length exceeds the tensile strength the nail, the bond could not be fully tested without failure of the tendon (typically at a nail length of around 5m or more). In addition, it was noted that the notional design pull-out capacity is less than the true capacity which is limited by the tensile strength of the tendon. This assumes that the testing load is transferred progressively and completely to the nail behind the face rather than being distributed along the nail with an emphasis on the part of the nail close to the face, initially in the active zone. Progressive failure, or debonding, then moves the zone in which the loads are focussed along the nail towards the resistant zone. In this way the full load capacity of the nail tendon should not be reached – this ties in with the comments from Jewell & Pedley (1992) referred to in the introduction to this Information Note (see Section 1.2).

3 Design

3.1 Standards

Soil nails are part of a system which includes the tendon, the nail head and the slope facing, all of which interact to form a slope retention system. The SGM category (SNAL) for Soil Nails does not differentiate between the different types of flexible or rigid facing, for example, mesh or sprayed concrete. It is important to note that the retention system could not function without the head and facing elements, the latter of which, for example, prevent surface failure when properly designed and constructed. These facing elements also fall into their own separate SGM categories, SMEH (mesh) and SHOT, (shotcrete or sprayed concrete). Guidance for the facing elements is indicated, but this has not been researched extensively for this Information Note, rather soil nail systems as a whole.

Table 1 summarises the level of information from the available documentation.

This document does not go into detail on the design process for soil nails; however, it does give a brief summary of the general steps involved. Detailed information on the design and specification of soil nails is available in BS 8006 Part 2 (2011) and also by Phear et al. (2005). British Standards are also available for specification of elements of the facing components, for example sprayed concrete, BS EN 14487:2005 *Sprayed concrete - Part 1: definitions, specifications and conformity*.

Details of construction considerations are given in BS EN 14490 (2010b).

HA 68/94 (HA, 1994) gave design methods for the reinforcement of highways slopes by reinforced soil and soil nailing techniques; however, this was withdrawn in 2017 and has not been replaced. This is likely due to the issue of the updated BS 8006-2:2011.

The main steps involved in the detailed design of soil nailed slopes are set out in flow charts by Phear et al. (2005) and these are re-presented in Figure 20. It is to be noted that the BS 8006 for Soil Nail Design (BSI, 2011) was released after the CIRIA guide by Phear et al. (2005); however, the process given in the diagram is still applicable and relevant.

3.2 Use of Soil Nails

Typical applications of soil nails include the stabilisation of new cuttings, steepened embankments or existing slopes, where the ground is excavated at an angle steeper than that at which stability can be maintained. When soil nails are used in a remedial situation, the arrangement of the nailing may be very different to that in a preventative one as a specific failure mode will most likely need to be addressed.

Soil nails may also be used in existing retaining structures such as stone, brick or concrete walls, particularly those that have suffered serviceability failure. One of the key considerations in these cases is the connection of the nails to the existing structure and the load transfer at this point to prevent pullout of the nails or damage to the structure.

Table 1: Matrix of relevant documentation available for Soil Nails

Level of information provided: Background (red) | Marginal (amber) | Comprehensive (green)

Publisher	Document number and title	Relevant to: Design SNAL	Specification SNAL	Construction SNAL
BSI	BS 6031:2009 Code of practice for earthworks	Background	Background	Background
BSI	BS 8006-2:2011+A1:2017 Code of practice for strengthened/reinforced soils Part 2: Soil nail design.	Comprehensive	Comprehensive	Comprehensive
BSI	BS EN 14487:2005 Sprayed concrete - Part 1: definitions, specifications and conformity	Background	Marginal	Marginal
BSI	BS EN 14490:2010 Execution of special geotechnical works - soil nailing	Marginal	Comprehensive	Comprehensive
BSI	BS EN 1997-1:2004+A1:2013a Eurocode 7: Geotechnical design - Part 1: General rules	Marginal	Marginal	Marginal
CIRIA	CIRIA (Perry et al., 2003b) C592 Infrastructure embankments - condition appraisal and remedial treatment	Background	Background	Background
CIRIA	CIRIA (Phear et al., 2005) C637 Soil Nailing best practice guidance	Comprehensive	Comprehensive	Comprehensive
CIRIA	CIRIA (Donovan et al., 2020) C794 Grouted anchors and soil nails: inspection, condition assessment and remediation.	Background	Background	Background
HE	DMRB Vol 4 Section 1 Part 2 CD 622 Managing geotechnical risk	Background	Background	Background
ICE	ICE (Burland et al., 2012) Manual of geotechnical engineering	Marginal	Marginal	Marginal
NR	NRL3CIV071 (Network Rail, 2011) Geotechnical Design	Background	Background	Background
TRL	TRL 380 (Murray, 1993) Development of specifications for soil nailing	Marginal	Marginal	Marginal
TRL	TRL 537 (Johnson et al., 2002) Soil nailing for slopes	Marginal	Marginal	Marginal
USFHA	US Federal Highway Agency Manual for design and construction monitoring of soil nail wall (Byrne et al., 1998)	Comprehensive	Comprehensive	Comprehensive

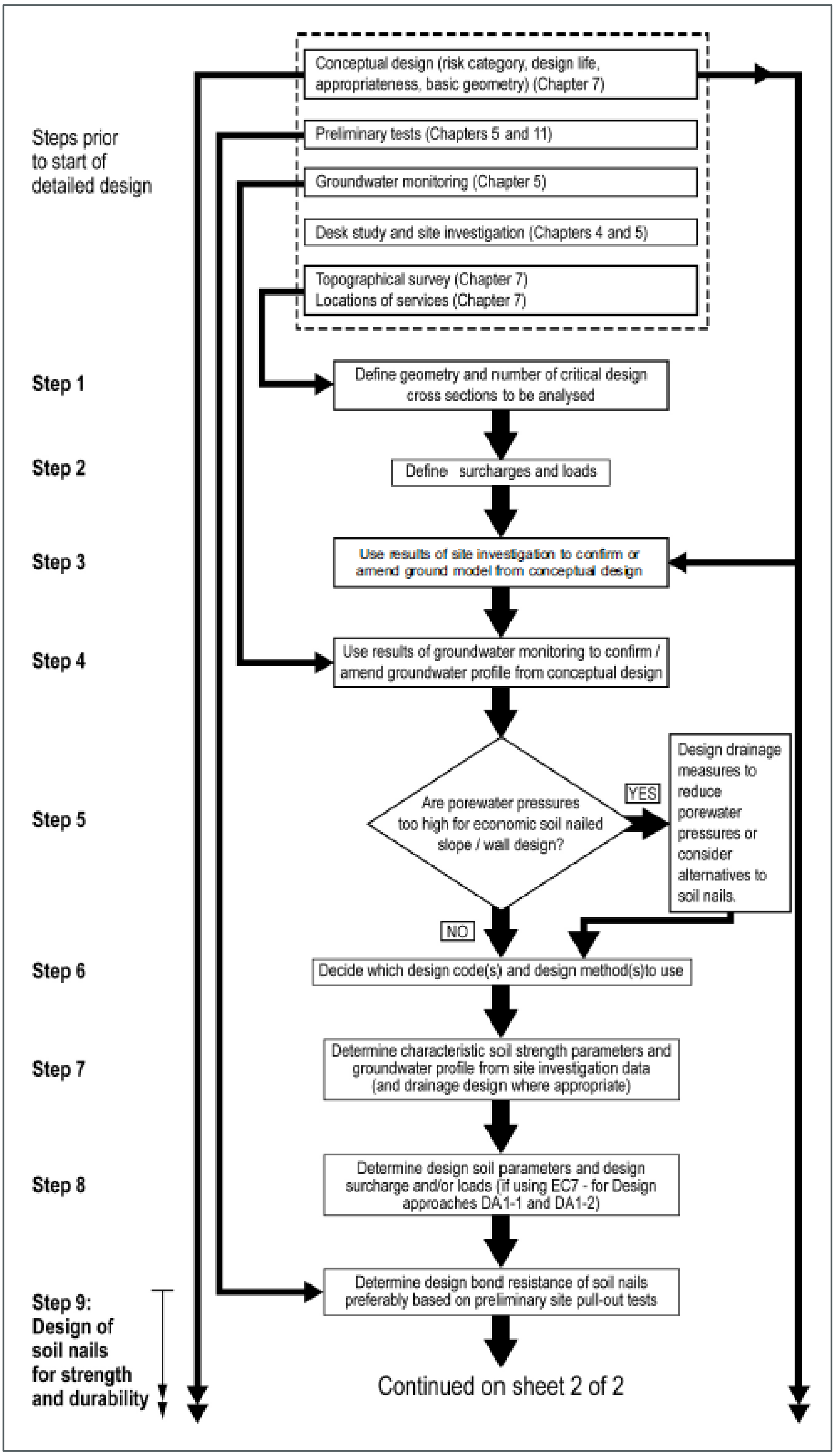


Figure 20: Flow chart for typical detailed design process (from Phear et al., 2005)

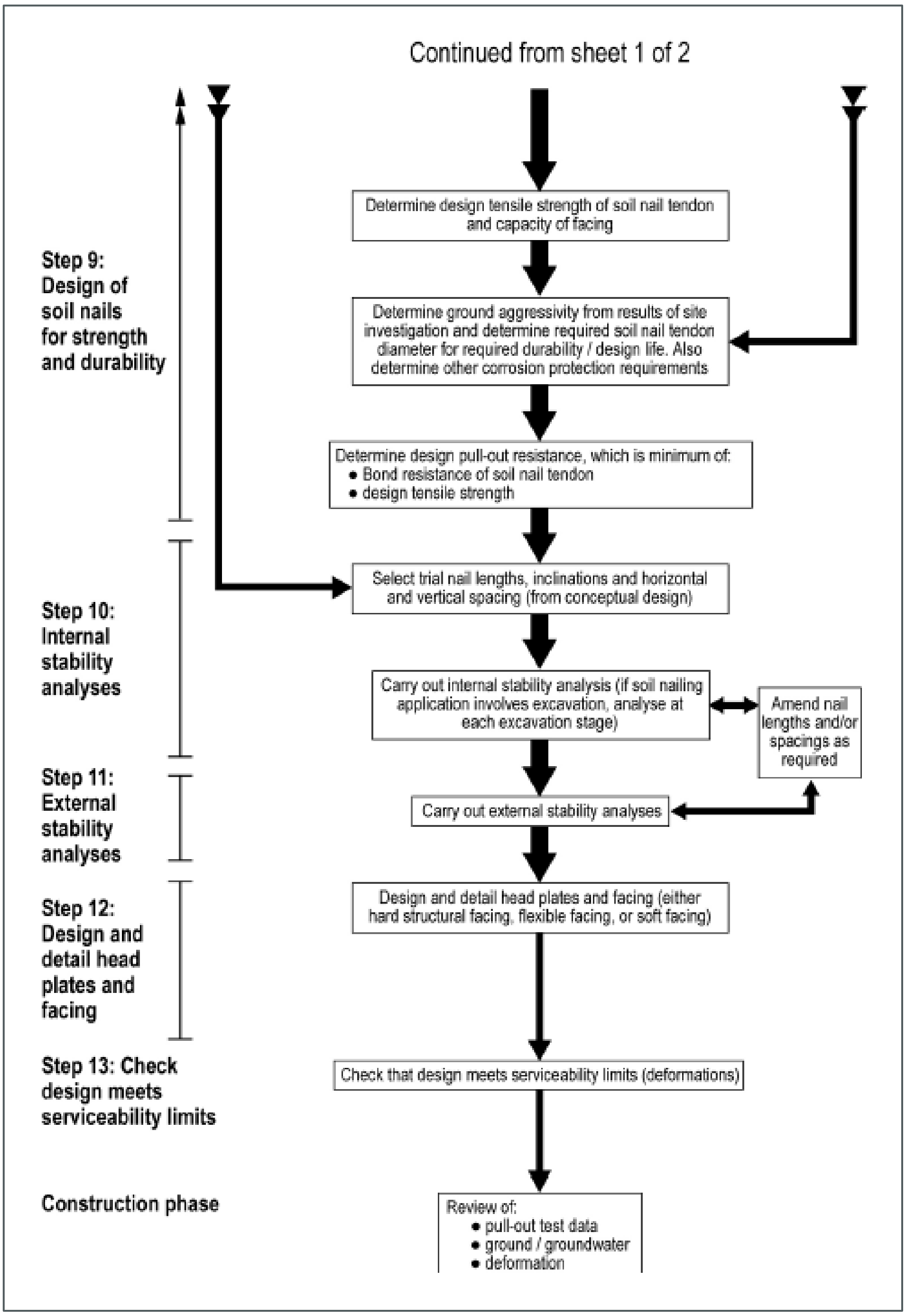


Figure 20 (Continued): Flow chart for typical detailed design process (from Phear et al., 2005)

Whether soil nails are the appropriate solution for an application will be highly dependent upon the exiting ground conditions and Table 2 gives guidance on the best suited and less suitable ground conditions for soil nailing. The knowledge of less suitable ground conditions has been recognised since at least the 1980s when the French National Project CLOUTERRE (1991), conducted between 1986 and 1990, provided comprehensive guidance on this subject. The CLOUTERRE report observed that soil nail techniques do not adapt well to the following situations:

- Where sands have no cohesion.
- Where the stability of the excavation cannot be guaranteed.
- In very plastic, clayey and sensitive soils particularly where there is relatively low unit skin friction.
- In swelling clays or soils that are frost susceptible due to high forces that could develop.
- In soils known to be highly aggressive; and,
- In areas where the water table is higher than the nailing.

The design of soil nails and facing becomes more onerous as the slope angle increases and in the case of vertical or near vertical soil nailed structures, the use of these should be very carefully considered, as often the crest of such slopes is close to existing structures or foundations where ground movement might be critical (BSI, 2011).

3.3 Components

A typical soil nail element comprises a number of components, some of which are required to carry structural loads while others are needed to ensure durability over the design life (BSI, 2011). The key components are shown in

Figure **21** and include the following:

- Tendon – this is the main component for transferring axial load along the length of the soil nail.
- Head plate and locking nut – these are used to transfer load between the tendon and facing.
- Protective ducts, sheaths and coatings – these may be used to improve durability of the soil nail.
- Grout annulus – this is designed to provide intimate contact between the soil nail and the ground.

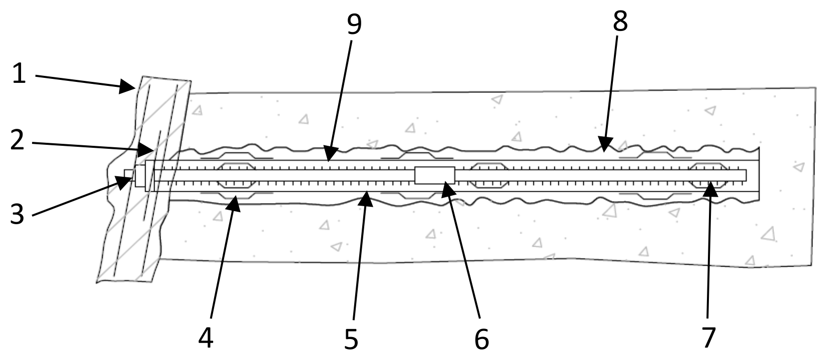
The tendon is generally composed of either uncoated steel, coated steel, austenitic stainless steel or fibre composite materials (BSI, 2011). The uncoated steel is typically carbon manganese steel. The coated steel usually comprises either galvanised steel reinforcing bar, or epoxy (or other) coated steel reinforcing bar. Typically, the galvanised steel is more robust as it does not depend on the adhesive coatings of other types. Coated steel is quite susceptible to damage during transportation and installation (Section 2) and galvanised coatings especially corrode in even mildly acidic conditions. Stainless steel tendons are generally resistant to corrosion; however, they can be susceptible to chlorides within the environment. Fibre reinforced plastic tendons comprise stiff strong fibres embedded in a resin matrix. The type selected will be dependent upon factors including strength, stiffness, thermal and electrical requirements (Phear et al., 2005), with glass fibre being the most widely used.

Table 2: Summary of ground conditions best suited and less well suited to soil nailing (after Phear et al., 2005).

	Ground conditions best suited to soil nailing	Ground conditions less suitable to soil nailing	Possible measures to improve the suitability of ground conditions
Material to be nailed	Firm to stiff, low-plasticity clays	Soft cohesive and organic soils prone to creep deformation	None can improve these soils sufficiently for soil nailing
		High plasticity or highly frost-susceptible soils and rocks	Provide adequate protection against wetting and drying
	Well-graded soils having a cohesive matrix such as some glacial tills, provided that cobbles and boulders do not obstruct nail installation Fine to medium sands and silty sands with some apparent cohesion Medium-dense to dense sands and gravels with some apparent cohesion	Loose, clean sands and gravels with little or no apparent cohesion	Pre-grouting or ground-freezing to improve temporary stability. Limit excavation heights/lengths
	Weathered rock without adverse joint orientation	Weathered rock with adverse joint orientation or voids	
	Engineered fills comprising selected natural or uniform, non-aggressive materials that have been carefully placed and well compacted to achieve characteristics similar to those of the natural soils described above	Non-engineered fills, particularly those containing variable, aggressive and/or degradable constituents that are prone to collapse and differential settlement (and obstructions)	Excavate, sort reusable material and replace (unlikely to be cost-effective) If fill constituents are suitable, ground improvement methods may be used to reduce the risk of collapse settlement, such as grouting, vibro-stone columns and dynamic compaction
Groundwater conditions	Above the groundwater table with a dry excavated face	Below the water table	Temporary and permanent dewatering
		Artesian groundwater at depth	Should be accommodated within the design, both in terms of internal and external stability
		Perched water or groundwater seepage through granular soils or pockets	Temporary dewatering and permanent drainage measures to ensure long term stability of the slope or wall
Underlying ground conditions and geological features	Underlying conditions and geological features that do not compromise the stability and performance of the soil nailed structure	Adverse underlying ground conditions and geological features such as: • pre-existing slip surfaces or adverse jointing • soft, compressible layers unless strengthened before soil nailing • voids such as solution features or mining cavities	Possible measures will depend on nature of the adverse conditions/ features and must be assessed on a site-specific basis

3.4 Soil nail slope facing

Most soil nailed slopes and structures will have a facing element and the selection of the appropriate facing will be dependent upon structural considerations (i.e. disturbing forces) and aesthetic considerations (i.e. requirement for vegetated faces). The selection of an appropriate facing is fundamental to the performance of the soil nailed slope. The selected facing will provide lateral confinement for the retained soil between nail head locations. If the facing does not adequately stabilise the surface of the slope between the soil nails, this can lead to progressive shallow failure of the slope (Phear et al., 2005). This is described in further detail in Section 3.5 below.



NOTE: Other systems might not use all the components included in the diagram

1. Facing
2. Head plate
3. Locking nut
4. Outer spacer
5. Duct
6. Coupler
7. Inner spacer
8. Grout annulus
9. Reinforcing element

Figure 21: Extract of possible components of soil nail system, pre-bored and grouted, shown with rigid facing (after BSI, 2011)

There are three main types of facing:

- Soft facings – used for slopes that are typically less than 45° and are mainly used in a short-term role to protect the slope surface whilst vegetation establishes. Soft faces typically comprise geosynthetic materials or light metallic mesh.
- Flexible facings – provide long term stability of the face of the soil nailed slope by supporting the slope in between the soil nails and transferring the load from the soil to the soil nails (BSI, 2011). A flexible facing allows some movement of the soil slope. Typically metallic materials are best for flexible facings due to the likelihood of punching failures through geosynthetic materials.
- Hard facings – perform the same function as flexible facings but with less deformation and these are typically used where steep or vertical slopes are required. Hard faces are typically concrete (i.e. sprayed concrete, in-situ concrete or concrete panels).

3.5 Nail spacings and facings

The design of the soil nailing system needs to consider both the design of the nails and also the design of the facing. Where soil nails are used to stabilise a slope (new or existing), they do not stabilise the surface soil (Phear et al., 2005). The stabilisation of the surface soils is achieved through the use of head plates and/or the facing.

In order to prevent overstressing of nails locally and the risk of progressive failure, nail spacings should be limited such that each nail is capable of withstanding the loads to which it is subjected locally. However, the horizontal and vertical spacings need to be close enough that the soil nailed ground behaves as a coherent reinforced soil block rather than as individual elements. Maximum horizontal and vertical nail spacings are typically in the range of 1.0m to 2.0m (Phear et al., 2005).

The spacing of nails is clearly important in terms of ensuring that sufficient axial tensile resistance is provided in order to ensure that global stability conditions are met. However, an upper limit on spacing may also be implied by the erosional stability of the soil between the nails and this includes the effects of the facing system, that is applied to the face.

When considering the spacing of nails there is an issue when designing to the British Standards. Typically soil nail design is undertaken using a limit equilibrium approach and computer software, often part of a slope stability analysis programme, is used to run the analysis. The issue is that with using the slope stability software the steep slopes (i.e. the slope face) will generally have a factor of safety less than unity for shallow failures. In the analysis shallow can be defined within most programmes by either adopting a limited weight or minimum depth of failure surfaces to be considered. This will then automatically assume that the shallow failures will be supported by the facing. The term shallow is not defined by either Phear et al. (2005) or BS 8006-2 meaning that the Designer needs to use subjective judgement on what would be considered shallow; 'shallow' failures may therefore not be assessed within the limit equilibrium analysis.

For small slopes of less than a few metres there is typically an overlap between the deep and shallow analysis; however, for larger slopes there is a potential that some failure surfaces with a factor of safety less than unity are not taken into account i.e. being missed on the slope stability analysis for deeper slips and unaccounted for in the facing design which typically considers failures within the first 1m of the slope. This happened at the Cataractonium Cutting on the A1 and led to significant movements of the facing. An example of this analysis is given in **Figure 22** and highlights the slip circles with a Factor of Safety less than unity from both the deep and shallow stability analyses. The purple dashed line indicates the limit of soil considered within the facing design from a two-part edge analysis; however, it shows that due to the deeper slips (up to 3m deep) with a factor of safety equal to or less than unity, the forces will be greater on the facing than designed for. This could lead to significant deformation and failure of the slope surface.

Most early soil nailed slopes were constructed using hard facings such as sprayed concrete; however, more recently they have moved towards flexible facing types which are typically more cost effective but can have issues with its ability to resist the loads imparted by the nail heads and head plates.

Pokharel et al. (2011) undertook finite element modelling and subsequent physical testing to observe the difference between using a flexible facing design and a rigid concrete facing on a soil nail slope constructed of high plasticity clay. Both the model and physical test showed significant deformations using flexible facing with the vertical deformations from settlement being more responsible for overall failure than the horizontal deformations. Also assessed was the component of facing tension; this revealed a limitation inherent to the use of flexible facings in that for small angles between the nail force and the slope facing (Figure 23), the tension in the facing must be very large to develop a significant retention force.

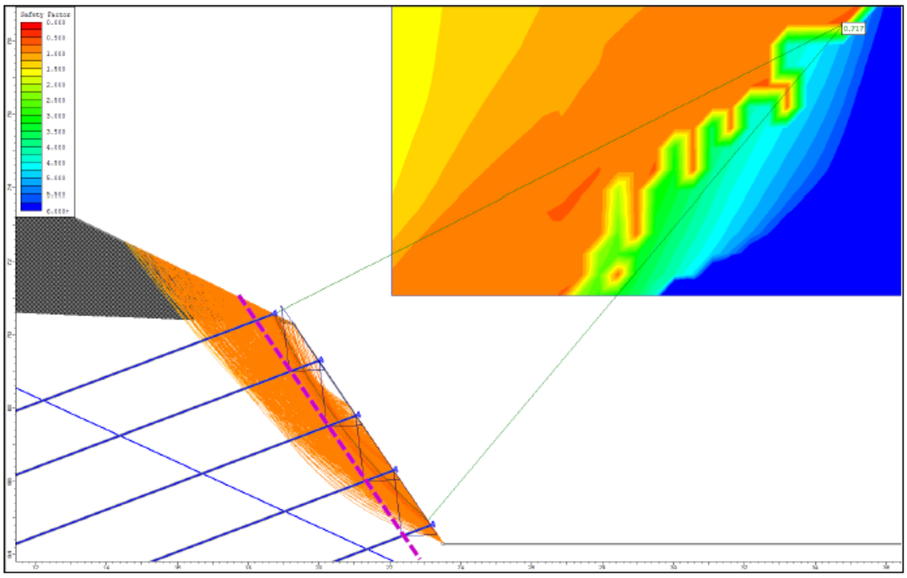


Figure 22: Slip circles with a factor of safety equal to or less than unity from an example soil nailed slope (from Coffey, 2017)

To develop a significant retention force, a number of steps can be taken:

- Mechanically pretension the slope facing.
- Shape the wall face prior to installation of the facing so that angle α (Figure 23) is greater than 0. A face shaped this way would cause the membrane tension to increase when the nuts were tightened on the soil nails.

Pokharel et al. (2011) recommended that based on the results from the testing (both model and physical), the use of flexible facings for clay slopes be limited to non-critical structures where large vertical and horizontal deformations are acceptable; however, they have been used successfully where the design, construction and construction sequencing is undertaken appropriately.

It is important that an appropriate opportunity is sought to review and revise the soil nail design process as it pertains to facings and that the outcomes are incorporated in appropriate standard(s).

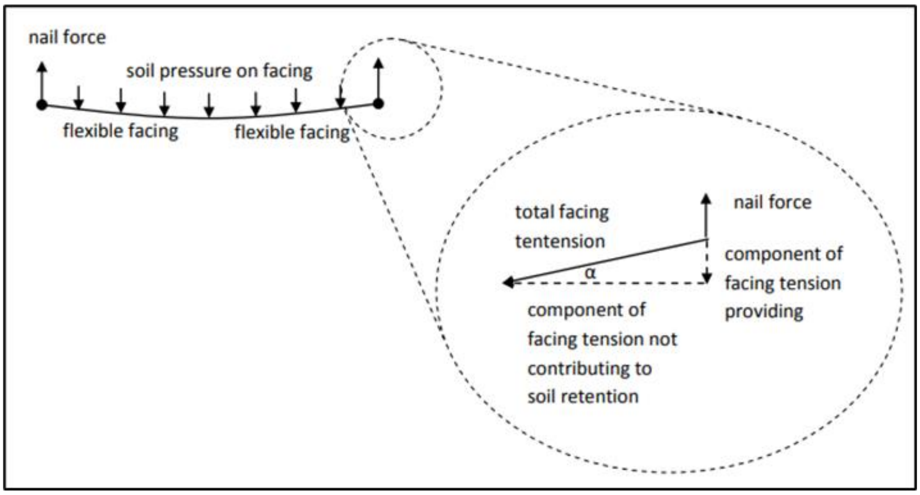


Figure 23: Two-dimensional plan view of force components in flexible facing (Pokharel et al., 2011)

3.6 Drainage

It is essential that the water regime at the site including groundwater table, local perched water in granular soils, existing drainage (channels and pipes) and the location of any underground flow path is fully accounted for in a soil nail design.

The soil nail slope should be fully protected against water ingress, especially where a rigid facing is used, as failure to do so can result in undesigned loads on the facing causing it to split or rupture. Ingress of water through a soil nailed slope can also lead to an increase in corrosion, especially in aggressive environments (see Section 3.7), (CLOUTERRE, 1991).

The design should consider the nature of any drainage required to ensure design assumptions related to groundwater and pore-pressures can be met during the design life of the slope (including in the temporary case during construction) (BSI, 2011). Drainage requirements can vary depending on whether it is groundwater or surface water related, but techniques can include sub-horizontal drains, weepholes, changes in profile and installation of other systems to collect and channel the water away. Figure 24 presents typical types of drainage for soil nailed slopes.

When considering the construction of drainage on a soil nail slope it is important to consider the sequencing of installation. The slope face drainage and any sub-surface drains (i.e. horizontal) should be installed after each excavation stage (see Section 4.2). This is primarily due to issues with access following excavation of the full slope; however, it will also assist with releasing the build-up of water pressures during excavation, construction and ongoing performance.

Drainage should also be provided to the slope face and this is especially important in the case of hard facings (i.e. sprayed concrete) where the slope face will be inaccessible following construction. This could be in the form of geocomposite strip drains which are placed behind the hard facing (Figure 25).

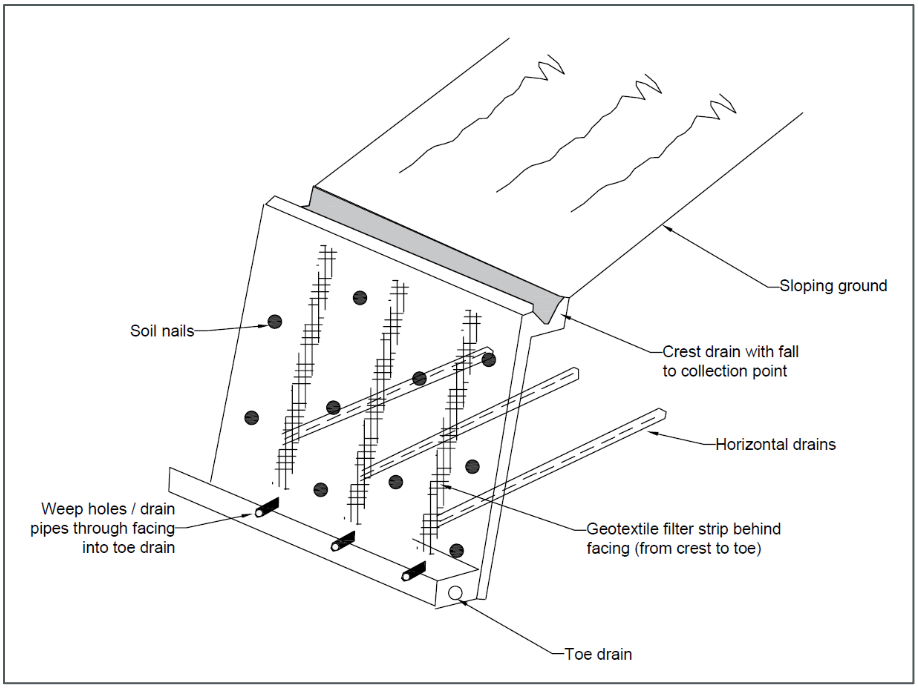


Figure 24: Typical types of drainage for a soil nailed slopes (after Phear et al., 2005)

Figure 25: Geocomposite strip drains being installed on the slope face prior to construction of the facing on the M42 (image the authors)

3.7 Corrosion

3.7.1 General

The durability of a soil nail tendon and its associated components may be highly variable and is primarily influenced by the aggressivity of the ground into which it is placed. Barley & Mothersville (2005) concluded that the lifespan of soil nails can vary from only a few months to potentially more than 120 years depending on the type of system provided, the aggressivity of the ground and the external environment. To understand how degradation can occur over the life of the nail it is imperative to understand the potential changes in the ground conditions over the life of the design such as increased permeability due to slope movements and change in aggressivity.

3.7.2 Durability and degradation

The ground is a complex chemical environment that can vary considerably both on a regional and a local scale at any particular site (Phear et al., 2005). This can have a detrimental effect on the durability of the soil nail system if the conditions are not understood and designed for accordingly. The many adverse environmental conditions that may affect soil nails include:

- relatively homogeneous soils with low salt content and benign water condition;
- partially saturated soils or zones with fluctuating groundwater levels;
- strata with differing chemical composition and differences in water or gas content;
- saturated clays with low oxygen content and high sulfate content;
- sea water or saline ground conditions; and,
- contaminated soils.

Detailed assessment for degradation risk for both buried and exposed components should be undertaken in accordance with BS EN 14490:2010 (BSI, 2010b) and BS 8006-2:2011 (BSI, 2011).

The corrosivity of the atmosphere should also be considered especially with regards to the exposed components of the soil nail system such as the head plate, nail head and facing and any lengths of nail that may be exposed behind walls that have been stabilised using soil nails. The soil nails through the retaining wall along the A628 (Figure 26) were designed to include corrosion protection of a sacrificial nail thickness, a minimum grout coverage around the nail tendon and a hot dip galvanized steel coating (Halcrow, 2013). As is obvious from the image, the nail tendon does not have the required minimum grout coverage in the section through the wall which may lead to corrosion of the bar. In this case a soil nail installed within an impermeable duct may have been a more appropriate solution to guarantee the inner protection layer remains intact.

De-icing agents used to limit snow and ice on the SRN have the potential to accelerate the corrosion of soil nail systems, especially the exposed components but also the near surface elements. For permanent structures exposed to de-icing salts, Lazarte et al. (2015) suggests that in regions where de-icing salts are used, the top 2.5m of soil behind a soil nail wall should be assumed to contain a higher concentration of chlorides based on limited studies of reinforced earth walls. These corrosion rates have not been directly measured for soil nail slopes and as these effects have been less than fully investigated, further work may be needed in this area. Facings are likely to be subject to de-icing agents and, in order to achieve the required durability for the design life of the soil nail system, steel facing materials are likely to require corrosion treatment such as plastic coating. The majority of the sites inspected as part of this project had a plastic coating on the facing mesh; however, head plates and nail ends were typically exposed. Further investigation and guidance are called for that is directly associated with soil nails.

Figure 26: Soil nail installed through pre-existing block wall along the A628 to the east of Manchester. The tendon is not encapsulated in grout through the wall and therefore may be susceptible to corrosion (image the authors)

3.7.3 Achieving design life

The required design life for a particular situation may be achieved by different methods or a combination of methods (BSI, 2010). The following approaches are commonly applied to metallic reinforcement:

- A cover of appropriate concrete, grout or mortar;
- sacrificial thickness allowance;
- surface coating (e.g. galvanisation);
- corrugated duct with grout;
- stainless steel; or,
- a combination of the above.

The most common method of isolating the tendon is by using grout around the nail. As identified in Section 2 the grout cover to tendons is not always complete due to factors such as the soil nail not being properly centralised (Figure 4), where there has been a partial hole collapse, for example and also where soil mass movement has led to cracking of the grout column (Barley & Mothersville, 2005). This leads to the question, if grout cover cannot be guaranteed, should it be used to contribute to corrosion protection? This is the view WSP (WSP/Parsons Brinkerhoff, 2017) took when producing their technical note for the A21 Tonbridge to Pembury Scheme.

> *"The grout body does not contribute to corrosion resistance as BS 8006-2:2011 states, "it is inevitable that the grout surrounding a steel tendon in the ground will crack due to axial movement." Therefore, grout cover is not taken as corrosion protection measure and other methods of corrosion resistance have been provided".*

However, notwithstanding the loss of grout or any cracking, using grout is not ineffective as a means of protection since the alkaline environment (pH 9.5 to 13.5) due to the grout can maintain the steel in a passive condition providing there is no water flow through the crack (BSI, 2011).

The typical outcome of most degradation assessments would be that if steel nails are used these should be provided with additional protection either as a coating (Section 3.4) or by using additional section thickness that may be regarded as sacrificial within the life of the nail (BSI, 2011). However, it is to be noted that using a sacrificial thickness is not recommended for high-risk permanent structures (BS EN 1997-1:2004, Category 3) and should be limited to low-risk structures (BS EN 1997-1:2004, Category 1) and where soil conditions are not aggressive (Barley & Mothersville, 2005 and BSI, 2011).

In the case of high-risk categories or when the nail tendons are particularly long or heavy (these are often synonymous), consideration should be given to using double corrosion protection (Barley & Mothersville, 2005). This should also be considered where a longer design life may be required i.e. in the case of a structure where a design life of 120 years would be required.

Figure 27 presents a summary of soil nailing systems and how they can be used relating to different categories of risk. Based on these recommendations from BS 8006-2, self-drilled nails (coated or uncoated) should not be used in a highly corrosive environment unless only a low-risk category 1 structure (BSI, 2004) is planned, and it is unlikely that they could achieve a design life greater than 60 years in any case.

3.8 Specification

The specification fulfils two main functions; the first being that the intention and function of the design transfers to the construction, and the second being that the detailed construction does not compromise the design. In essence the specification is the bridge between the design and construction.

In the context of soil nails, the design is well established but there are issues regarding the need to ensure that the designed corrosion protection is provided and that this it is not compromised by, for example, the nails resting in the bottom of the borehole.

Type of Soil Nail	Category of Risk								
	Low Risk			Medium Risk			High Risk		
	T or P in SCE	T in HCE	P in HCE	T or P in SCE	T in HCE	P in HCE	T or P in SCE	T in HCE	P in HCE
Steel directly in soil	R	R	NR	R	NR	NR	NR	NR	NR
Coated steel directly in soil	R	R	R	R	R	NR	NR	NR	NR
Steel surrounded by cement grout	R	R	R	R	R	NR	R	NR	NR
Self drilled steel surrounded by cement grout	R	R	R	R	R	NR	R	NR	NR
Coated steel surrounded by cement grout	R	R	R	R	R	NR	R	NR	NR
Self drilled coated steel surrounded by cement grout	R	R	R	R	R	NR	R	R	NR
Polyester composite surrounded by cement grout	R	R	R	R	NR	NR	R	NR	NR
Vinylester composite surrounded by cement grout	R	R	R	R	R	R	R	R	NR
Stainless steel surrounded by cement grout	R	R	R	R	R	R	R	R	NR
Self drilled stainless steel surrounded by cement grout	R	R	R	R	R	R	R	R	NR
Steel surrounded by grouted impermeable ducting	R	R	R	R	R	R	R	R	R
Coated steel surrounded by grouted impermeable ducting [A)]	R	R	R	R	R	R	R	R	R
Stainless steel surrounded by grouted impermeable ducting [A)]	R	R	R	R	R	R	R	R	R
Steel surrounding by pregrouted double impermeable ducting [A)]	R	R	R	R	R	R	R	R	R

Key

T = Temporary (< 2 years)
P = Permanent (> 2 years)

SCE = Slightly corrosive environment [B)]
HCE = Highly corrosive environment [B)]

R = Recommended
NR = Not Recommended

[A)] System particularly suitable for heavy or long nails for permanent works where one of the two protective layers may become damaged during handling or installation.
[B)] As defined in BS EN 14490:2010

Figure 27: Summary of recommendations for different soil nailing systems in relation to different categories of risk (after BSI, 2011)

3.9 Technical approval

The procedures, documents and certification for a soil nailed slope shall be in accordance with DMRB CD 622 'Managing Geotechnical Risk'. This allows the geotechnics risks to be clearly identified through all the phases of work including options, development of design, construction and handover to the operations team.

In accordance with CD 622 a Special Geotechnical Measures Form (SGMF) can be used by agreement between the Designer's Geotechnical Advisor (DGA) and the Overseeing Organisation's Geotechnical Advisor (OOGA). If an SGMF is used, then this should include its own certificate. In particular the serviceability performance of potentially flexible SGMs such as soil nail solutions, requires careful consideration and reporting.

In some instances, a soil nail slope would be classified as a structure and this depends on the facing type, the height of the slope and the angle of the slope. CG 300 'Technical approval of highway structures' states the following criteria for classification as a structure:

- Reinforced/strengthened soil/fill structure, with hard facings where the effective retained height is greater than 1.5m.
- Reinforced/strengthened soil/fill which is an integral part of another highway structure.

CG 300 also states that strengthened soil where hard facings are not provided and the face inclination exceeds 45 degrees, can require structural technical approval at the behest of the Overseeing Organisation. This is typically decided through a joint discussion between the Overseeing Organisation's Geotechnical and Structural Advisor.

4 Construction

4.1 Procurement

During the consultation in Phase 1 of this project (Duffy-Turner et al., 2022) a comment was made about *poor quality control, particularly in the context of lowest price tenders and self-certification, with poor and inappropriate site supervision by drillers incentivised to install nails rapidly and a lack of the required construction records.*

An additional problem with procurement is the compartmentalising of full schemes into packages for design and construction in which case the main scheme designers do not have input into certain elements and therefore things can get missed in translation.

The authors broadly agree with these sentiments and, indeed, both recognise and highlight the link between the separate issues of lowest price, self-certification and poor quality. However, it is also recognised that the issue of lowest price is one that is often outside the control of the Overseeing Organisation's Geotechnical team.

4.2 Sequencing

The sequencing of construction for a soil nail slope will be determined by whether it is a new cut slope or an existing slope.

New cut slopes should normally be constructed incrementally with each increment consisting of a phase of excavation to a stable level, followed by a phase in which soil nails and facing are placed in the new cut face (BSI, 2011). Phear et al. (2005) provide a typical construction sequence for soil nailing of new excavations; however, the facings should typically be installed prior to the installation of the head plates and nuts. In some cases where a rigid facing is used i.e. sprayed concrete, the nail head may be covered by the facing in which case the facing will succeed the installation of the nail head. Numerous studies (CLOUTERRE, 1991; Murray, 1993; Woods & Brady, 1995) suggest spreading a thin protective concrete layer on the face immediately after earthworks are completed to limit the risk of local failure and erosion of the exposed soil surface; however, this practice has fallen largely out of favour with the popularity of self-drilled soil nails which would be unable to bore through such a layer. This technique of providing initial additional stability to the excavated face should not be discounted but is only likely to be used for shotcrete facing applications.

It is recommended that a typical construction sequence be as follows:

- Prepare the working platform.
- Excavate to appropriate depth (typically 1.5-2.5m per step).
- Install the nails and the drainage
- Install the facings.
- Fix the head plates and nuts to the nails.
- Excavate the next step.

Existing slopes would typically follow the same construction sequence; however, only local trimming/excavation will be required unless, for example, the works are part of carriageway widening, and it is unlikely that steps/benching will be needed.

A basic construction sequence is given in Phear et al. (2005) and is presented in Figure 28.

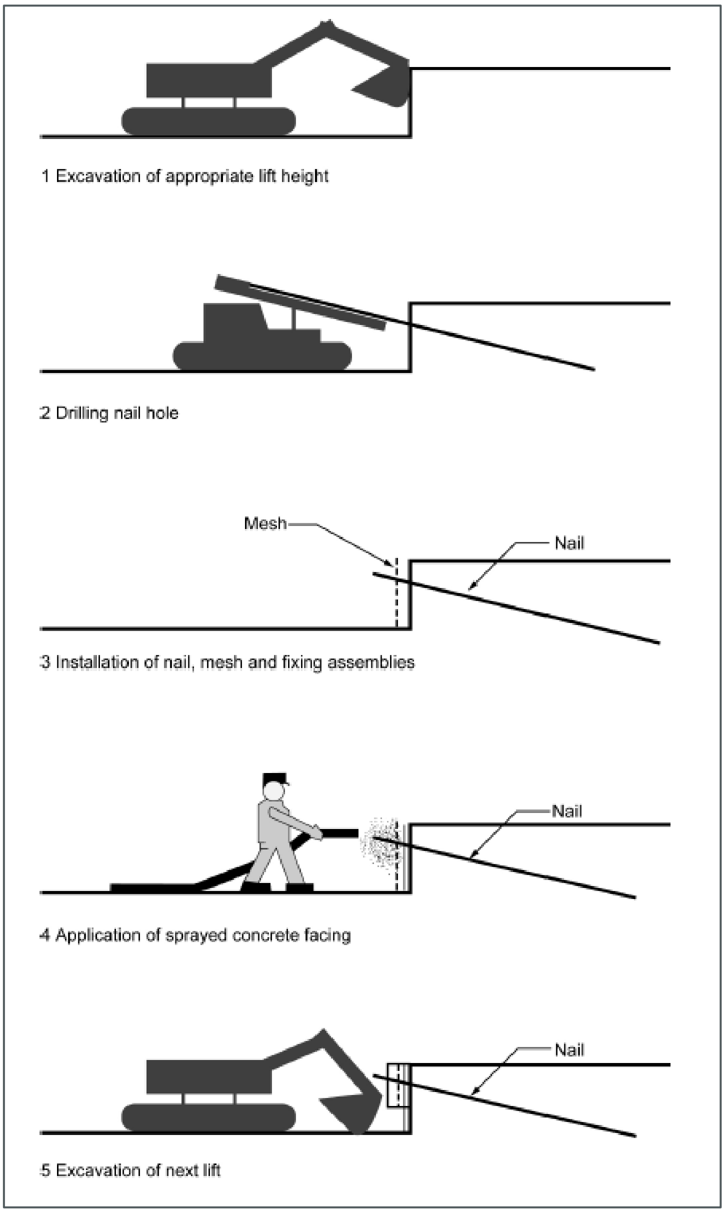


Figure 28: A typical construction sequence for a soil nailed slope constructed using excavation with a sprayed concrete facing (from Phear et al., 2005)

4.3 Installation method

There are two main installation techniques used in the UK and these are traditional Bored and grouted nails and Self-drill nails. A third technique, driven nails, was prevalent in the 1990s; however, it is typically no longer used in the UK as the nails generate less bond with the soil and have a lower degree of corrosion protection.

Placing bored and grouted soil nails entails the use of a drilling technique to open a hole into which the tendon and grout are placed. This hole may be unsupported (where soils exhibit sufficient cohesion) or supported by temporary casing (Phear et al., 2005). Drilling can include such techniques as augering, rotary or rotary percussive. Once the hole has been created centralisers should be used at regular intervals to provide the required cover of grout (see Section 4.4). Without adequately spaced centralisers the soil nail tendon can lie on the base of the drilled hole with little or no grout cover, and/or cover may be reduced at the top of the nail bore (see Figure 4).

Self-drill soil nails are currently the mostly commonly used type in the UK, due to restrictions with installation time and cost. In this system, the soil nail bar itself is used to transfer the energy from the installation plant to a sacrificial drill bit. The soil nail bar is hollow and grout is injected down the bar as the hole is drilled. This technique combines the placement of the reinforcement and grouting in a single pass, without the need for a casing. The grout is used as the flushing medium to remove cuttings and also to maintain the bore stability (Arup/AECOM, 2020).

When first introduced soil nails were generally constructed in sequence with each hole drilled, and the nail placed and grouted before moving on to the next hole to repeat the sequence. This practice was adopted to remove the need for the holes to be cased as it limited the potential for hole collapse. Even partial hole collapse can make the placement of the soil nail (tendon and centralisers) impossible.

Currently, construction often takes a batch approach to soil nail construction with a sequence of holes drilled prior to the nails being placed and grouted. Self-drilled nails, using a grout flush, were introduced to allow the batch construction process to operate without undue hole collapse. The method employed a light (thin) grout drilling fluid to provide support to the hole walls during drilling by means of hydraulic support and to create a surface cake to provide temporary support to the hole walls. This would be followed by the installation and permanent grouting part of the batch process began.

However, in addition to batch construction, current practice often uses air flush drilling methods. While this may work with the sequential process, with the batch process this leaves the walls unsupported both during drilling and after until the installation and grouting process begins. The time that holes are left unsupported can often be 24 hours or even more, affording ample opportunity for partial hole collapse that may impair the installation of the soil nail. It is recommended that the time between drilling and installing the soil nails should be limited to four hours to lower the risk of hole collapse.

It is recommended that in the case of batch construction drilling should be limited to one row at a time and only grout flush should be allowed as it will assist in stabilising the bore and assist with the formation of a continuous annulus. This is especially important in weaker or more granular soils. If grout flush is not considered to be suitable for a site, then consideration should be given whether to case the hole to prevent collapse. A detailed assessment of the ground conditions by the designer would be required to make this decision.

4.4 Soil nail centralisers

Centralisers are used in a soil nail system to ensure that the tendon is placed in the centre of the hole to maximise the likelihood of there being a continuous and adequate grout annulus; this helps to maximise the resulting corrosion protection afforded by the grout annulus. Such corrosion protection is particularly important as the use of factory-produced grouted-and-sleeved double-corrosion protected nails that were common in the 1990s has largely fallen out of favour and been replaced by single-corrosion protected galvanised and/or epoxy coated nails. While the former are protected by galvanisation, a layer of grout, a plastic tube and the outer layer of in-situ grout the latter have only the galvanisation and/or epoxy coating and a single, albeit thicker if properly centralised, layer of grout.

The specification for soil nails demands the use of centralisers and Phear et al. (2005) state.

> *"Centralisers (also known as spacers) installed at centres not greater than about 2–3m along the soil nail tendon are essential to maximise the likelihood of there being a continuous grout annulus."*
>
> and
>
> *"Centralisers need to be installed in accordance with the manufacturer's instructions at appropriate centres along the nail. They need to be sufficiently robust to withstand the installation process".*

However, manufactures' responses to enquiries regarding centralisers are denying the need for such fittings (see Section 2.3).

Galvanized coating has shown good resistance to abrasion damage; however, it is still possible (WSP / Parsons Brinckerhoff. 2017). Defects in the coatings can often be detected by inspection on site and if caught early enough can be treated using a setting fluid or epoxy resin (Barley & Mothersville, 2005).

Phear et al. (2005) and BS 8006-2 both state that centralisers should be made of a non-corrodible material having no deleterious effect on the tendon itself and the use of metals dissimilar to the tendon should be avoided. It is recommended that all metal should be avoided in a centraliser to reduce the risk of damage to the tendon.

Discussions internally with National Highways indicate that centralisers should be used on their schemes with all drill and grouted soil nails (bored and grouted, and self-drill).

There are two potential means of modifying current practice to ensure that the corrosion protection is adequate – either by moving away from the batch process and reverting to the sequential approach of construction, or by ensuring that when batch construction is used, a light grout drilling fluid is used to ensure that the hole walls are supported through the drilling process and also during the period between the completion of the hole and the placement and grouting of the nail. Some soils in which the hole walls are particularly prone to collapse may need to be constructed in sequence and with a grout drilling fluid.

4.5 Changes to design during construction

It is essential that the designer visit site during construction to verify the ground conditions.

At each level of excavation the ground conditions should be assessed against the design. If the soil type or groundwater levels are not as expected the design should be reassessed in light of the new observations. It is important when reassessing the design that each aspect of the soil nail system (soil nails, facing and drainage) is reviewed to ensure compatibility is still achieved.

4.6 Testing of soil nails

Testing of the soil nails should be carried out at various stages of the design and construction to ensure that the design conditions and the performance requirements are met. There are two different types of tests for soils nails; sacrificial nail tests and production nail tests and both of these have different purposes (Table 3) and requirements (BSI, 2010).

Table 3: Type and purpose of soil nail (after BSI, 2011)

	Sacrificial Nail Test	Production Nail Test
Purpose of test	To verify the ultimate soil nail to ground bond resistance used in the design: a) the bond used in the passive zone; b) the bond used in the active zone; c) the bond along the entire length of the nail.	To demonstrate satisfactory soil nail performance at a load designated by the designer. The test is performed on the entire length of the nail.
When tested	Before, during or after production works.	During or on completion of production works.
Type of nail used	Sacrificial	Production
Action taken in case of non-compliant test result	Review soil nail installation method and/or consider alternative soil nail length and layout.	Consult designer for action to be taken and approval to continue.
Comments	If necessary, the test should be done at each different soil layer.	Caution should be exercised when testing production nails not to overstress the nail to grout bond or cause damage to corrosion protection. When a structural facing is used the test nail should be debonded within the zone of influence of the facing.

The sacrificial nail tests should be done in advance of the main construction works and these are usually undertaken before detailed design to ensure the results are incorporated into the design of the soil nail system. When installing the production nails it is imperative that they are installed by the same construction methods as those used in the sacrificial nail tests. This also applies to the ground conditions. If either the construction method or ground conditions are different than originally tested for, additional sacrificial nail tests should be undertaken to ensure the design requirements can be met.

Soil nail testing needs to take cognisance of the zone where the resistance of the nail (nail bond) is utilised behind the anticipated failure plane. This can be done by sleeving (debonding) the part of the nail in the potential failure mass.

4.7 Supervision and construction quality assurance

Adequate and competent personnel for construction and supervision should be provided to ensure that construction follows both the design and specification requirements.

As soil nails cannot readily be inspected non-destructively once they are installed, it is difficult to verify that the work has been done as it should be (P Roberts, Personal Communication, 2020 - 2022). This coupled with the fact that the construction supervision is carried out by the drilling supervisor and that often nail installers are on price rate (i.e. they are paid more for installing more nails in a shift), means quality can slip and go unrecorded (i.e. centralisers not effectively used, length of nail not measured, or no allowance made for the section of nail proud of the slope facing).

Construction quality assurance records should be kept and provided to the Overseeing Organisation throughout the construction process and for SGMs the records of the auditing process should be captured in the Geotechnical Feedback Report (GFR). In light of the above issues regarding quality control it is also recommended that the Overseeing Organisation should maintain an independent set of quality records for all activities.

4.8 Construction acceptance

Observations on the SRN and of the wider UK infrastructure portfolio have found the self-certification process to be suboptimal. A move to cease Contractor self-certification and revert to a more conventional designer-led certification scheme in order to ensure quality of execution of Works is strongly advised.

It is important that snagging is undertaken (and completed) prior to the contractor leaving the site and that the Works Examiner is afforded adequate opportunity to formally accept the work undertaken prior to the contractor leaving the site. In many instances these activities will need to be planned and executed prior to removing traffic management.

Acceptance once site access is restricted (i.e. once the road is fully operational) is rarely an acceptable option as access without Traffic Management is at best limited and at worst of unacceptably high health and safety risk. It is recommended that provision for early inspection be built into the contract along with the potential consequential withholding of all or part of the contractor’s final invoice if the works are deemed unacceptable.

5 Operations and maintenance

5.1 General

Earlier and more extensive operational and maintenance geotechnical input to Major Works should be undertaken in order to ensure specification compliance, acceptability for use and handover to the operator.

The effective implementation of this recommendation along with moving away from contractor self-supervision and certification increases the likelihood that Works are built correctly first time and greatly reduces the risks associated with future defects and deterioration. This becomes even more critical in the light of predicted climate change which is expected to exacerbate geotechnical asset deterioration.

5.2 Inspection

Soil nail slopes/structures, dependent upon its classification during the Technical Approval stage (see Section 3.9), shall be inspected and maintained in accordance with the DMRB, particularly CG 302 As-built, operational and maintenance records for highway structures, CS 450 Inspection of highway structures, CS 459 The assessment of bridge substructures, retaining structures and buried structures and CS 641 Managing the maintenance of highway geotechnical assets.

In 2020 CIRIA released a new guide 'C794 - Grouted anchors and soil nails: inspection, condition assessment and remediation' (Donovan et al., 2020) which was written to address industry needs.

In undertaking any inspection, condition assessment or remediation of a soil nailed structure, it is necessary to address the whole system, including soil nails, facing and drainage.

Dononvan et al. (2020) reference the guidance on inspection and monitoring available in BS 8006-2:2011, BS EN 1490:2010, Phear et al. (2005) and Lazarte et al. (2015).

Donovan et al. (2020) recommend that inspections of soil nail slopes should be at no more than five-year intervals. This is for at least the first 10 years after which the interval schedule can be revised based on working knowledge of the earthwork.

Inspection intervals should be determined by:

- Risk category of the structure/slope.
- Slope angle and height.
- Type of facing.
- Classification of soil (cohesive or granular).
- Level of groundwater and surface water risk.
- Ongoing performance and developing history of the structure/slope.

The guide also details the condition assessment which should typically be undertaken where soil nail slopes are showing signs of movement at the head or there is evidence of corrosion.

Inspection and maintenance requirements should be considered as part of the design both in terms of future operations and to be in accordance with the Construction (Design and Management) Regulation 2015. These considerations should be presented in the Geotechnical Design Report or the SGMF if used and include details such as any requirements for groundwater monitoring and presence of hidden parts.

Specific maintenance or ongoing monitoring requirements for a soil nailed slope shall be highlighted in the Geotechnical Feedback Report produced within six months of the end of the construction phase.

With regards to drainage installations, safe access for maintenance should be considered and clearly specified in the design, especially where new structures may be located in front of the soil nailed slope.

5.3 Competence

It is recommended that the inspection of SGMs should be certified by a Geotechnical Advisor in accordance with CD 622.

6 Decommissioning

There is no official guidance on the decommissioning of soil nailed slopes but there are two main reasons this would be undertaken:

1. The earthwork is coming to the end of its design life.
2. The road layout is being changed and no longer supports the existing slope.

Soil nails have been used in the UK predominantly since the early 1990s which means that the oldest soil nails on the network are likely to be around 30 to 35 years old (one approximately 31 years old was inspected along the A42 as part of this research project). Based on these ages the soil nailed earthworks are typically around halfway (or less) into their design life and this is similar for other infrastructure owners in the UK. As such, there are not many instances where soil nailed earthworks have been decommissioned and the ones that have tend to be associated with a change in road layout (i.e. road widening schemes).

Where a soil nailed slope requires decommissioning a Geotechnical Design Report (GDR) should be produced specifically for that purpose. This would require a managed geotechnical risk and should be compliant with CD 622.

The option selected for this is likely to be influenced by the requirement for the remaining earthwork. If the earthwork is to be completely removed, i.e. as part of carriageway widening, the removal becomes more of a safety issue for deconstruction; however, if the earthwork is to remain in place then additional in-situ reinforcement, including additional soil nails or other forms of reinforcement, could be placed to preserve and/or reinstate the stability of the slope.

If the earthwork is being completely removed a deconstruction sequence similar to below may be appropriate (Harms. J, personal communication, 08 June 2022):

1. Remove vegetation.
2. Clear any topsoil to identify nail heads locations.
3. Cut the bolts off the nail head and removed the head plate.
4. Remove any facing mesh reinforcement and clean/sort for recycling purposes.
5. Excavate earthwork (top down where possible), removing nail tendons and grout as they are encountered.
6. Run the nail tendons through rollers to remove grout surround if necessary.
7. Clean and sort steel for recycling purposes if possible.
8. Reuse soil/grout mix as earthworks fill in conventional manner where appropriate.

Where the soil nail slope is to remain in place there are a number of options which could be considered, and this would be dependent on the age of the slope (i.e. if it is at the end of its design life or if it is no longer required in its current form). Two are discussed below.

- If the slope is coming to the end of its design life, acceptance testing could be undertaken on a certain percentage of the nails and then additional nails could be installed in-between the old ones. The facing is likely to require replacing at this stage, especially in the case of reinforcing mesh which will be exposed to the environment.

- Where part of the slope is to remain (i.e. during a widening project) bullet points 1 to 4 from the sequence above could be followed and then a new retaining structure installed such as a sheet pile wall. Temporary works are likely to be required to ensure the stability of the face prior to installation of the new retaining structure. Whilst any remaining grout and tendons in the slope may provide additional support, these should not be accounted for in the design of the new retaining structure.

7 Conclusions and recommendations

7.1 General

Soil nails systems have many components including the facing, the head plates, the method of construction and corrosion as well as the nail itself. All these interrelate in the design, specification and construction.

While generalisations are fraught with difficulty the available information does seem to indicate that the overall design issues are generally well-understood but that, perhaps, there is room for improvement and updating of some of the design standards. This may suggest that designers are too dependent upon the standards and specifications.

Comments from the questionnaire survey (Duffy-Turner et al., 2022), appear to demonstrate that the resultant problems are clearly understood, with drainage/water issues leading to some sort of failure, but that the solutions appear almost exclusively to address the failure with little to no attempt to address the cause. Construction practices play a key role to the issues surrounding soil nails, whether that be a failure to sequence the construction, to properly install the nails or to complete the installation by tightening the face plate nuts.

What does appear to be clear is that the original design philosophy and construction approach applied to soil nails entailing the use of double-corrosion protection appears to have been lost. While it is appreciated that considerations related to economy are important the additional resilience afforded by such protection is considered to be important. In addition, the use of self-drilled nails has come to the fore. This raises many issues related to the durability of nails that may be damaged during installation, including by the centralisers that are vital to ensure that the nail is centred in the hole but which can, in turn compromise the ability of the grout to fill the annulus between the nail and the holes. This is particularly relevant when the hole is drilled uncased.

There is no compelling evidence that when properly designed, specified, constructed and maintained, including an appropriate inspection regime, Soil Nail SGMs cannot meet the required design life for either slopes (60 years) or for structures (120 years) of such SGMs. However, there is substantial evidence that in the UK, soil nail design, specification and construction is frequently not at a level that would promote longevity of this nature.

7.2 Major recommendations

Rules and guidance for work involving soil nails are presented by Phear et al. (2005) and BS 8002:2011; however, we have presented below our additional recommendations for where the design and standards are either lacking or consistently not followed during design and construction.

Recommendation 1: Structural applications with a hard facing and an effective retained height of more than 1.5m and slope applications in network critical locations should be double corrosion protected. Single corrosion protection should be used only for slopes, with flexible facings, in areas of lower network criticality.

Recommendation 2: It is important that an appropriate opportunity is sought to review and revise the soil nail design process as it pertains to the issue with facings as identified in Section 3.5 and that the outcomes are incorporated in appropriate standard(s).

Recommendation 3: During the review of soil nail facings (as per Recommendation 2), the use of flexible facings, specifically for clay slopes, should be considered further. When properly constructed these flexible facings have the ability to work well; however, poor construction can lead to large vertical and horizontal deformations which have been seen on numerous soil nail schemes.

Recommendation 4: The use of centralisers should be maintained in accordance with Phear et al. (2005) and BSI 8002:2011 to ensure a continuous grout annulus around the tendon. It is recommended that all metal should be avoided in a centraliser to reduce the risk of damage to the tendon.

Recommendation 5: It is recommended that in the case of batch construction drilling should be limited to one row at a time and only grout flush should be allowed as it will assist in stabilising the bore and assist with the formation of a continuous annulus. This is especially important in weaker or more granular soils. If grout flush is not considered to be suitable for site, then consideration should be given as to whether to case the hole to prevent collapse. A detailed assessment of the ground conditions by the designer would be required to make this decision.

Recommendation 6: The effect of de-icers on soil nail systems is an issue that has been less than fully investigated and further work may be needed. In the first instance this might take the form of estimates or modelling of the quantity of de-icers affecting SGMs both above and below road level, the associated acceleration of the corrosion rate and the consequential loss of stability. The results from such work could then inform the basis of decisions on whether more detailed and complex physical investigations and tests would be required to refine the understanding of such effects.

Recommendation 7: Facings are likely to be subject to de-icing agents and, in order to achieve the required durability for the design life of the soil nail system, steel facing materials are likely to require corrosion treatment such as plastic coating. The majority of the sites inspected as part of this project had a plastic coating on the facing mesh; however, head plates and nail ends were typically exposed. Further investigation and guidance are called for that is directly associated with soil nails.

Recommendation 8: It is recommended that the MCHW 1 should include a requirement that all reinforcing geosynthetic materials used as slope facing for soil nail slopes be fully protected against UV exposure. Further, such protection should not rely on the establishment, growth or persistence of vegetation that can be unreliable on steep slopes, particularly in the context of climate change.

Recommendation 9: Investigate further the potential for debonding at the nail grout interface due to the production of hydrogen gas from a reaction between the zinc galvanisation and the hydroxides in the cement grout. If this is a concern, as initial research may suggest, the use of any chromate passivation would need to be balanced against the risks of chromium to human health.

Recommendation 10: There is a need to ensure that the design and construction of soil nail systems on the SRN takes full account of the following issues:

- Programme for the works should take weather conditions into account as cutting into soil slopes in winter is not recommended.
- If the ground conditions are not as anticipated the soil nail system (soil nails, facings and drainage) needs to be reassessed to ensure that it is still acceptable. As part of this it is essential that the designer visits site during construction to validate the ground conditions.
- Ensure that the water conditions (ground and surface water) are completely understood prior to installation of the nails and ensure that drainage provision is a consideration from the outset.
- It is recommended that the time between drilling and installing the soil nails should be limited to four hours to lower the risk of hole collapse.
- Whilst not ideal, a short section of vertical excavation can be undertaken successfully but it requires good coordination between all the parties to ensure that the time between excavation and installation of the tensioned facing is kept to a minimum number of hours. This would require assessment as part of the temporary works design.
- If using bored and grouted soil nails, a tremie pipe should be inserted to the full depth of the borehole to ensure proper grout placement. The grouting should continue at low pressure until the grout emerges from the top of the hole. Where this is not possible due to the angle of the nail, hand packing of the end with stiff grout could be undertaken.
- Grout take must be recorded for assessment against the anticipated grout take as this will give an indication if a hole has not been completely filled due to a blockage or collapse of the hole.
- Ensure the facing is tensioned sufficiently in accordance with the manufacturer's specifications and installation guidance. If this is not possible then an alternative facing solution (i.e. hard facing) should be used.
- Ensure the galvanisation or epoxy coating on the tendons is checked on site for damage prior to installation of the soil nails and that damaged tendons are rejected.
- Maintenance of vegetation on soil nail slopes is required to prevent damage to the facing and nails by the growth of large shrubs and trees.

7.3 Overarching issues

Throughout this project, contractor self-certification has been raised and evidenced as one of the most significant issues that leads to poor construction. The issues may not be apparent at the time of construction and therefore may not be addressed by the designer or client, leading to subsequent poor performance and early-life failure of not only SGMs but other forms of construction. Indeed, this issue has been highlighted on other National Highways projects on which the authors have worked and in work for other infrastructure owners and operators both in the UK and overseas.

A high-profile example of this is found in the Earthworks Task Force Report (Mair, 2021) on the Carmont Rail Disaster, which notes in the context of water management, drainage assets and the associated risks that “There is very limited supervision of drainage work by [Network Rail], with a reliance on contractor self-certification”.

It is considered that a move to cease Contractor self-certification and revert to a more conventional client-led Construction Quality Assurance scheme in order to ensure quality of execution of Works is strongly indicated.

Also strongly indicated is, earlier and more extensive operational and maintenance geotechnical input to Major Works in order to ensure specification compliance, acceptability for use and handover to the operator.

The effective implementation of these two recommendations increases the likelihood that Works are built correctly first time and greatly reduces the risks associated with future defects and deterioration. This becomes even more critical in the light of predicted climate change which is expected to exacerbate geotechnical asset deterioration.

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Forensic Examination of Critical Special Geotechnical Measures: Soil Nails Information Note

The effective design, specification and construction of Special Geotechnical Measures (SGMs) is critical to the efficient operation of the National Highways Strategic Road Network (SRN). Given the required performance of the SRN in terms of resilience, reliability, redundancy and recovery it is essential that SGMs are themselves reliable in terms of performance and life; resilient to external conditions such as earthworks deterioration and extraordinary conditions (e.g. climate change). Around 100 different types of SGMs are used on the SRN and the early installations of some SGMs are approaching the end of their design life and the design, specification and application of many of these techniques is based on limited studies. This Information Note on Soil Nails is part of a series that reports on investigations of specific SGMs and makes recommendations on their future use.

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