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Construction and Testing of Self-Drilled Soil Nails – a case study

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Abstract

Current standards and best practice guidance recognise that testing of self-drilled hollow bar soil nails can be problematic as conventional packers and debonded lengths cannot be constructed. As a result, this provides difficulty in testing and confirming the ultimate bond resistance within the passive zone of a soil nailed slope, and thus the design soil nail lengths.

This paper provides a summary and review of the various testing procedures adopted for a soil nail construction project in Scotland. The practical design considerations, and their validation through the installation and testing of 49 sacrificial test nails, are detailed. The construction issues associated with the nail installation and testing are also outlined and discussed in the light of the results obtained using different testing approaches.

The aim of this case study is to report on the experiences with installation and testing of hollow bar soil nails. The objectives is to develop an initial data base of available soil-grout bond strength of hollow bar soil nails based on the several practical installation procedures used on this project and to establish areas for improvement of installation, testing and quality control in order to perform comparable pullout tests on self-drilled hollow bar soil nails.

Keywords

Geotechnical Engineering, Field testing and monitoring, Anchors and anchorages

1. Introduction

Soil nailing is a form of slope stabilisation in which fully grouted steel or polymeric reinforcement bars are installed into the slope face of *in situ* ground, whether natural soil or existing fill, thus creating a reinforced block of soil. An appropriate facing system can then be constructed to stabilise the surface of the soil, thus completing the construction of the soil nailed slope. The use of soil nailing in slope stabilisation has grown rapidly in the UK since the mid-1990s (Phear et al, 2005).

Traditionally, soil nails comprise a solid steel tendon installed into a pre-drilled hole and then grouted. Self-drilled hollow bar soil nails have been developed relatively recently and offer significant advantages over the use of the traditional solid bar system (GEO, 2008) such as:

- installation into loose or collapsing soils without the need for casing to support the drill hole using the grout as a drilling fluid, and
- increased nail capacity due to the grout permeating the adjacent soil and increasing the bond diameter, both of which lead to increase in production rates and time savings for the contractor (Porterfield et al 1994, Phear, 2005, GEO, 2008).

This system allows relatively small lightweight rigs to be able to install the soil nails within most ground conditions much quicker than the traditional construction method, which not only reduces the construction time and the overall cost of the system, but also reduces the health and safety implications of mobilising heavy plant to an already failed or unstable slope.

Conversely, the disadvantages of such a system include:

- a need for proper controls of grout flush to ensure integrity of bond length, i.e. problematic in voided or very loose ground,
- a requirement for more attention to workmanship and supervision to ensure that the quality of the constructed nails does not suffer and
- difficulties in pull-out testing if use of the hollow bar system is attempted for testing which is considered in this paper.

Depending on the objectives, various forms of soil nail testing can be specified **Design investigation testing** can be undertaken prior to the soil nail design in order to ascertain the ultimate bond resistance of each stratum, its variability with depth, and the potential influence of groundwater on the bond resistance (i.e. testing within the same soil stratum above and below the groundwater table). In this type of test, a sacrificial test nail is constructed with a specified bonded length and is subsequently tested to failure using load test equipment appropriate for anticipated loads and bond resistances (Lazarte et al 2003; Phear et al 2005). **Suitability (pullout) testing** is traditionally undertaken immediately prior to or during the soil nail construction works to verify the ultimate nail pullout capacity assumed in the design and, thus, the soil nail lengths. These tests require construction of sacrificial test nails with a specified bonded length which is typically (Phear et al., 2005) achieved by partial grouting of the distal

1 end of the drill hole in order to mimic the length of the nail within the passive zone of the slope
2 which is determined within the design. The pull-out load applied to the test nail should equal the
3 working load determined within the design, multiplied by a partial factor typically in the range of
4 1.5-2.0 (Phear et al., 2005; BS 8006-2, 2011). An acceptable test, thus verifying the soil nail
5 lengths determined within the design, is where the creep rate at the pull-out load is less than
6 0.1% of the bond length of the test, often 2 mm per log cycle of time (Phear et al., 2005; BS
7 8006-2, 2011) as the test length is often the lower 2m of the nail (GEO 2008). **Acceptance**
8 **testing** can be undertaken on working nails to demonstrate satisfactory soil nail performance at
9 the design load. This test is undertaken on fully grouted production soil nails and is not suitable
10 to verify the lengths determined within the design or confirm the ultimate bond resistance of any
11 strata. This type of test is primarily to confirm that the installation methods give satisfactory
12 displacement results at the working load and is not discussed further in this study.
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20 For both pullout (suitability) and design investigation tests the successful formation of the
21 bonded length is critical (Richards 2010, Gomez 2008). With solid bars, the drill hole is formed
22 using 'open hole' techniques (Phear et al 2005) and progressed to the base of the bonded
23 length before a steel bar is inserted and grouted to a specified length of the distal end of the
24 hole (bonded length, Figure 1), with a packer or bond isolator and a debonding sleeve installed
25 to retain the grout (debonded length, Figure 1); However, this technique is not suited for self-
26 drilled soil nails as, by their very nature, their installation does not allow packers and debonded
27 lengths to be constructed (Cadden et al 2010), and alternative methods of installation or testing
28 have to be sought (Phear et al 2005). The introduction of BS EN 14490 in 2010 and the code of
29 practice for soil nail design (BS 8006-2) in 2011 do not provide any clarity on how testing of self-
30 drilled soil nails should be undertaken, and rely on the designer's knowledge and experience of
31 the ground conditions at the site (Richards 2010, Littlejohn and Bruce 1977) and the impact on
32 the soil nail construction and testing to confirm the test procedure to satisfy the design
33 assumptions.
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43 Published literature (Phear et al 2005, Cadden et al 2010, Lazarte 2011) suggests subtracting
44 the pullout capacity of a fully grouted test nail installed in the active zone from the pullout
45 capacity of a fully grouted test nail installed to the specified design length which would give the
46 pullout capacity of the bonded length within the passive zone. This solution is promoted as the
47 most effective for testing hollow bar self-drilled soil nails based on the experience of the
48 specialist supply and testing contractors (DSI 2008). This technique can be misleading
49 especially where longer nails are used with nails passing through different soil strata and most
50 of the current design methods require bond stress data for each stratum.
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56 The aim of this case study is to report on the experiences with installation and testing of hollow
57 bar soil nails, investigating the effects on the optimisation of the design. The objectives are to
58 analyse case study data in order to determine the characteristic grout-soil bond strength to be
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1 used to verify the design, to analyse the test nail construction considerations and effects such
2 as productivity, and to raise awareness of the need for standardised testing approach with
3 designers and contractors.
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6 **2. Methodology**

7 **2.1 Site description**

8 Self-drilled hollow bar soil nails were used in a recent slope stabilisation project in Scotland. The
9 site in Stonehaven is predominately located around the former trunk road (Bervie Braes Road),
10 and includes the adjacent coastal slope (Bervie Braes). The 40m high coastal slope in
11 Stonehaven has a history of instability (typical mechanisms include failures within the weak near
12 surface soils combined with occasional shallow groundwater, or perched water at times of
13 heavy rainfall, and over-steepened ground profiles; Currie et al 2009) which has resulted in the
14 closure of the former trunk road bisecting the slope. The road runs sidelong and generally
15 northwest-southeast across the Braes. The slope stabilisation works were limited to the slope
16 below the road ('Lower slope' on Figure 2a; Mickovski 2014b).
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24 The angle of the lower slope ranges between 25° and 30°, while the upper slope angle varies
25 between 30° and 35°. Ground investigations (Currie et al 2009) showed that the soil on the
26 lower slope typically consisted of vegetated topsoil (around 0.2m thick), overlying Raised Beach
27 Deposits comprising weak silts and silty sand with discrete soft cohesive layers with thickness
28 ranging from 1.5m to 5.0m. This stratum is underlain by medium dense glacial sands and stiff
29 cohesive Glacial Till with thickness of up to 20 m which, in turn, overlies the sandstone bedrock
30 (Figure 2b).
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37 The groundwater regime within the Braes consists of a shallow perched groundwater table
38 which exists due to the presence of the discrete cohesive layers within the Raised Beach
39 Deposits. A deeper groundwater table is present perched upon the stiff cohesive Glacial Till
40 (Mickovski 2014b).
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44 **2.2 Soil Nail Design**

45 Soil nailing, as means of improving the safety of the slope against failure, was the preferred
46 method of stabilisation selected after public consultation between the Local Authority and the
47 local residents following an options assessment (Currie et al 2009). Self-drilled hollow bar soil
48 nails were preferred to solid bar soil nails given the perceived associated lower construction
49 costs (mainly savings in construction time, Samtani and Nowatzki, 2006) and the limited budget
50 available for the works (Mickovski et al 2013, Mickovski 2014b).
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57 The soil nails were designed in general accordance with CIRIA guidance (Phear et al, 2005;
58 prior to BS 8006-2 (2011)), specifically using the effective stress method (Method 4) detailed
59 therein, considering the expected ground conditions at the site and the available information.
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1 The design load for each soil nail was determined based on the pullout resistance of the nail-
2 grout continuum from the soil and the working loads were determined by factoring the ultimate
3 pullout load with an appropriate factor of safety. Soil nail lengths of between 7 m and 24 m,
4 placed at 1.5 m horizontal and 1.0 m vertical spacing, were required to provide the necessary
5 resistance to shallow and deep seated (active zone of up to 10 m depth) slope failures.
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9 A 'soft facing', consisting of a buried reinforced concrete soil nail head, bio-degradable matting,
10 and a light metallic mesh, was selected given the site conditions and the project aesthetic
11 requirements (Mickovski et al 2013, Mickovski 2014a). The concrete nail head, designed to
12 DMRB HA 68/94, was envisaged to provide long term stability of the slope by transfer of the soil
13 load back to the soil nails bond length and also to provide shallow surface stability between the
14 nails. The bio-degradable jute mat and a light metallic mesh formed part of the facing to help
15 prevent surface erosion and support establishment of vegetation which, in turn, would provide
16 resilience of the structure in the long term (Norris et al. 2008, Mickovski 2014a,b).
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23 **2.3 Construction and testing**

24 Sacrificial test nails (BS14490:2010), were evenly distributed throughout the lower slope to
25 verify the design assumptions (e.g. bond strength, pullout capacity) and assess nail
26 performance across the site. All test nails in this study comprised a 38 mm external and 19 mm
27 internal diameter (753 mm² cross-sectional area), galvanised steel bars in 3 m long sections,
28 ,coupled together using galvanised steel couplers to achieve the design length and progressed
29 using a sacrificial bit drilling a 100 mm diameter hole. The access to the test nail locations was
30 cleared of vegetation and the drilling rigs were positioned at each location ensuring the safety
31 and stability would be maintained during the construction (Figure 3). The nails were tested by
32 application of pullout load in stages (BS14490:2010, Phear 2005; GEO 2008) either until either
33 the required pullout resistance or the design yield strength of the bar was reached. Test failure
34 was defined as the pullout load at which either (i) the creep movement (>0.1mm) continues after
35 a one hour hold period or (ii) the total movement exceeded 0.1% of the bonded length of the bar
36 (Phear 2005).
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46 **2.3.1 Long Nail / Short Nail (LN/SN) test**

47 With solid bar installation the normal procedure is to form the borehole using normal drilling with
48 water or air-foam or similar, then insert the bar and grout up the distal end (ground anchor) or
49 the full length (soil nail). No other area of the bar is grouted or in contact with the surrounding
50 soil, as it is the working bond between the soil and grout that provides the pull-out resistance
51 and thus stabilising the slope. The hollow bar nails generally use grout as a flushing medium
52 which may cause difficulties for testing because, even if a debonding sleeve over the free length
53 is used, grout will exist both inside and outside the sleeve and bar couplers may well be bigger
54 than the available sleeve, preventing pull-out movement during the test. To over-come these
55 difficulties, a 'long nail / short nail' test method was initially adopted in accordance with
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1 published guidance (Phear et al 2005) and the contractor method statement based on
2 recommendations from a specialist testing sub-contractor (DSI, 2008). A total of 56 nails (more
3 than 3% of the number of permanent nails; Phear et al 2005) were installed using an Atlas
4 Copco ROC 460 rig into the Raised Beach Deposits, Glacial Till and Gravels. The 28 short nails
5 (Figure 4) were installed using air flush due to high groundwater to the boundary between the
6 active and passive zones, as determined within the design, and the remaining 28 long nails,
7 reflecting the design length of the working nails at each location, were installed using air flush to
8 full design depth thus allowing the bond resistance from the passive zone alone to be
9 theoretically determined from pullout tests as:
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15 **Bond resistance from the passive zone = pullout resistance of the long nail – pullout**
16 **resistance of the short nail**
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21 The pullout load of the short nail in the pair was added to the design load of the long nail before
22 the long nail was tested for pullout under this new, combined load. It should be noted that the
23 active and passive zones are functions of particular limit equilibrium analyses and the key issue
24 during testing (BS 14490:2010) was to de-bond the heads of the nails 1 m from the reaction
25 frame to ensure that local boundary effects did not result in overestimating the bond strength.
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30 *2.3.2 Investigation Tests*

31 Additional test nails (ATNs) were installed to a variety of depths within the Glacial Till in the
32 areas where the testing of the initial short nail / long nail system proved inconclusive or where
33 the tested nails failed in pullout. Fourteen ATNs, installed using the same rig as in SN/LN test,
34 were progressed using water flush to the full design depth before a set volume of grout was
35 pumped into the open hole, grouting a known bonded length. The test load was derived as the
36 design load multiplied by a factor of safety of 1.5 (BS14490:2010)
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42 Another seven nails were drilled using a KLEMM KR904 rig to a variety of depths in the Glacial
43 Till, where the majority of the design bond lengths are located. The holes were progressed
44 using water flush and casing through the Raised Beach Deposits and Glacial Sands and
45 Gravels before the nail bars were then inserted to full depth and a known volume of grout was
46 pumped into each of the holes. This rig was used for this purpose because of its capability to
47 case and control the size of the bore and volume of grout pumped.
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52 The aim of the investigation tests was to determine the bond resistance per metre length of the
53 bonding strata thus a shorter bond length was required to ensure that the nail would pull out and
54 therefore provide a result. All 21 investigation nails were tested to failure (defined as in LN/SN
55 test) such that the ultimate bond resistance of the Glacial Till per metre run could be determined
56 and compared to the results of LN/SN test when verifying the design.
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2 **3. Results**

3 **3.1 Installation**

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5 Test preparation included excavating a bench into the slope cleared of vegetation which, due to
6 the size of the reaction frame which was dependent on the expected loads, involved excavation
7 of approximately 2 m³/nail. This excavation was carried out for each nail which, in the case of
8 LN/SN setup where both nails are installed at close proximity, involved sizeable localised
9 excavation. The size of the excavation was exacerbated by the slope angle and the inclination
10 of the nail which meant the bench cut in the slope had to be at 70°.
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16 After the test location was prepared, the drilling rig was secured in place and the nails were
17 installed as per Section 2.3. The nail installation time ranged between 14 and 75 minutes for the
18 LN/SN nails and ATNs, and was approximately 6 minutes for the KLEMM nails.
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22 Due to the size and the weight of the reaction frame, which depended on the test loads which,
23 in turn, depended on the chosen test method, the transportation to and from each test location
24 across the slope was difficult, involved a combination of manual and plant labour, and lasted
25 between 20 and 60 minutes depending on the transport distance and location on the slope.
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29 **3.2 Testing**

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31 The pullout tests were carried out using standard () testing equipment (BS14490:2010, Phear
32 2005) including a 400 kN capacity, 200 mm diameter, hydraulic jack and displacement
33 transducers with 0.01 mm precision (Figure 5). The test duration was dependent on the pullout
34 load and it ranged between 25 minutes (failure recorded at relatively low loads) and 175
35 minutes (design yield load for the steel bar reached) per nail. The total nail testing duration on
36 the project was 60 days which included installation, setup and pullout testing.
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41 **3.3 Test results**

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43 Fifty-three of the 56 (28 pairs) nails installed using the SN/LN method were tested and the
44 results are shown in Table 1. Typical pullout behaviour of a pair of long and short nails is shown
45 on Figure 6a. It can be seen that satisfactory results on the nail resistance to pullout in relation
46 to the design load were obtained for 49% of the installed (26 nails, 13 pairs). The results of the
47 testing were termed 'inconclusive' where the short nail pulled out at a higher load than the long
48 nail, short nail pulled out at a relatively high load in relation to the design yield strength of the
49 steel bar, or where the long nail failed and the short nail did not. In all of these cases (9 nail
50 pairs or 33% of the total tested) the nails did not fail in pullout but, due to the nature of the tests,
51 the interpretation of the results was difficult. Five nail pairs failed because the difference
52 between the pullout resistance of long and short nail was lower than the design load.
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Table 1. Results of the pullout tests on LN/SN testing system. The resistance to pullout of the grouted short nail length is subtracted from the one of the long nail to derive the resistance of the bonded length. Remarks: N/A and (*) denote inconclusive tests where the short nail pulled out at a higher load than the long nail or short nail pulled out at a relatively high load in relation to the design yield strength of the steel bar i.e. where the interpretation of the result was difficult due to the nature of the test; (**) denotes design verification failure. GSG = Glacial Sands and Gravels, GT = Glacial Till.

Test nail	Grouted length of short nail [m]	Pullout resistance of short nail [kN]	Additional grouted length of long nail [m]	Pullout resistance of long nail [kN]	Pullout resistance of bonded length [kN]	Bonding Strata	Remarks
TN11	8.8	340	11.2	not tested		GSG & GT	N/A
TN13	7.6	310	9.4	360	50	GSG & GT	**
TN14	8.6	210	11.4	360	150	GSG & GT	*
TN15	8.2	100	11.8	160	60	GSG & GT	**
TN16	8	290	10	350	60	GSG & GT	**
TN17	8.6	90	11.4	250	160	GSG & GT	
TN18	12.2	290	11.8	not tested		GT	N/A
TN19	13	260	11	140		GSG & GT	**
TN20	10	150	14	310	160	GT	
TN21	11.8	300	12.2	280		GT	**
TN22	9.2	360	8.8	360		GSG & GT	*
TN23	11.2	190	12.8	340	150	GT	
TN24	12.4	290	11.6	360	70	GSG & GT	*
TN34	10	80	2	350	270	GT	
TN35	5.25	40	4.75	360	320	GSG	
TN25	6	220	9	360	140	GT	*
TN26	10	360	2	360		GT	*
TN28	10	360	2	not tested		GT	N/A
TN29	3	30	7	130	100	GT	
TN31	6	80	9	360	280	GT	*
TN32	4	130	6	180	50	GSS & GT	
TN51	9	30	2	190	160	GSG & GT	
TN52	9	80	2	120	40	GT	**
TN53	5.5	70	1.5	170	100	GSG	
TN54	9	140	2	250	110	GT	
TN55	5.25	40	1.75	110	70	GSG	
TN56	9	130	2	290	160	GSG & GT	
TN57	5	70	2	120	50	GSG	

The results of the investigation tests carried out to clarify the inconclusive results of the SN/LN tests are shown in Table 2. Typical behaviour of different types of additional test nails is shown on Figure 6b.

Table 2 Results of the investigation tests. Remarks: (*) denotes inconclusive tests where the design load \leq pullout load \leq combined test load, i.e. where the interpretation of the result was difficult due to the nature of the test; (**) denotes design verification failure. GSG = Glacial Sands and Gravels, GT = Glacial Till.

Test nail	Installed length [m]	Bonded length [m]	Failure Load [kN]	Design Verification Load (kN)	Bonding Strata	Remarks
TN12	20	5.5	120	180	GSG & GT	*
ATN10	20	9.7	155	155	GSG & GT	
ATN11	20	9.7	230	165	GSG & GT	
ATN12	20	9.7	150	150	GSG & GT	
ATN14	20	5.5	70	180	GSG & GT	**
ATN5	13.5	5.5	220	195	GT	
ATN7	24	8.3	140	195	GT	*
ATN8	15	8.3	300	130	GSG & GT	
ATN13	24	6.9	210	205	GSG & GT	
TN27	15	2.8	55	80	GT	*
TN30	15	2.8	45	80	GT	**
ATN1	12	5.5	70	70	GT	
ATN3	15	2.8	35	110	GT	**
ATN9	11	7.5	220	60	GT	
KLEMM1	24	5.5	70	N/A	GT	
KLEMM2	24	5.5	80	N/A	GT	
KLEMM3	24	6.9	110	N/A	GT	
KLEMM4	21	2	190	N/A	GT	
KLEMM5	18	2	80	N/A	GT	
KLEMM6	15	2	90	N/A	GT	
KLEMM7	12	2	80	N/A	GT	

It can be seen that satisfactory results on the nail resistance to pullout in relation to the design load were obtained for 57% of the installed ATNs. The results of the testing were inconclusive in 21% of the ATNs where the nail pulled out at a higher load than the design load but lower than the combined test load. The remaining 3 ATNs failed as their resistance pullout was lower than the design load. However, it should be noted that the bonded length of the failed nails was shorter than the design bonded length and the potential resistance of the full design bonded length was calculated as the product of the bond resistance per metre length from the tests and the length of the design bond.

4. Discussion

The results of this study showed similarities and differences between the methods, as well as between this case study and the published literature. While the general installation of the test nails was very similar between the methods used in this case study (the difference being the use of different flush material), the success of the specific installation method depended on the

1 ease of access and health and safety considerations. Test nail installation with each rig type
2 included disturbance of the slope and the superficial soil deposits in terms of rig access and
3 establishment of safe system of work. The access with the lightweight rig was more flexible as
4 the rig could be positioned almost precisely on the desired location although this was done at
5 the cost of damage to the existing vegetation and exacerbated erosion due to trampling during
6 setup and installation. The heavier KLEMM rig could not operate on the slope and required
7 much more elaborate and robust safety system. Only relatively light rigs could operate on a long
8 slope where long reach or heavier rigs reported in the literature (Cadden et al 2010) could not
9 be used, but these rigs have a limitation with depth that can be reached and type of soil strata
10 that can be penetrated. The designer needs to consider the access to test nail locations and
11 balance the testing schedule against the potential outcomes of the testing. Furthermore, the
12 designer needs to consider the health and safety implications of specifying different tests and, in
13 this respect, the LN/SN method may be further unsuitable due to the need for manual
14 excavation and handling of heavier equipment.
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23 In terms of test nail installation technique, air flush was considered to create voids within the soil
24 which then get easily filled with grout and contribute towards 'bulbing' which, while beneficial for
25 the overall nail capacity (Cadden 2010, Lazarte 2011), creates problems for pullout testing of
26 fully grouted longer nails (e.g. higher pullout capacity necessitating heavier testing equipment
27 and more slope disturbance). That is why water flush was used for the ATNs and KLEMMs that
28 only aimed at determination of pullout capacity per specified bonded length, but the efficiency of
29 this technique could not be assessed with certainty because the bonded lengths in these cases
30 were shorter than those used in long/short nail pairs in order to limit the slope disturbance and
31 heavy testing equipment. Grout flush could not be used to grout distal parts of the test nail only
32 because of the issues noted in Section 2.3.1, i.e. the alternative methods, as postulated by
33 Phear (2005), were used to produce a hole for soil nail bar to be grouted along bonded length
34 only. Problems arising from drilling with water flush in areas of high groundwater tables would
35 be envisaged and further research is needed in assessing the efficiency of different installation
36 types in different soil types.
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46 Current codes and testing guidance rarely cover the testing preparation which includes
47 benching into the slope and setting up the reaction frame. In this case study this element was
48 one of the most time consuming and disruptive to the soil on the slope. The excavation for the
49 reaction frame and the associated backfill were significant and, due to the length and access
50 constraints on the slope, had to be carried out in large part manually. This approach worked
51 relatively well on the shallow natural slope in this case study but may be an issue on steeper
52 slopes with soft soils, high groundwater level and/or failures occurring when access and
53 excavation angles would be limited and temporary support may be needed. More attention will
54 have to be paid on this aspect of test nail installation in the future as part of the overall nail
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1 testing methodology. It may be necessary to design and specify tests that would require
2 minimum excavation and produce minimum disturbance to the soil on the slope.
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5 The results of the testing methods used showed large percentage of inconclusive results and a
6 small number offailures of design verification due to the testing method (including the testing
7 setup) adopted by the contractor, which may have not been suitable for the encountered ground
8 conditions (e.g. high groundwater and saturation). The calculated pullout stress based on the
9 tests carried out (Figure 7) shows, however, similar trends and values across the different
10 methods.
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15 The values obtained in the tests correspond to the values reported in the literature for drilled
16 nails (Lazarte et al 2003, Phear et al. 2005, Littlejohn and Bruce 1977, Porterfield et al 1994),
17 albeit the published results do not distinguish between self-drilled and traditionally installed
18 nails. It should be noted that the values shown correspond to average interpreted bond strength
19 along the bond length of the nail, and may not be representative of larger, localized values
20 within the bonded zone (Littlejohn and Bruce 1977, Cadden et al 2010). As reported in the
21 literature (Phear et al 2005, Lazarte et al 2003), shorter and relatively stiffer soil nails showed
22 higher pullout resistance per metre bonded length than the longer, more flexible nails. It is likely
23 that this is the result of a simultaneous mobilisation of bond strength along the entire length of
24 the short nail as opposed to progressive mobilisation of soil-grout shear strength in the longer
25 nails (Frank and Zhao 1982, Gomez et al 2008) which leads to lower average bond strength in
26 identical soil formations.
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35 The ATN method of installation contains assumptions on the installation such as forming the
36 bond length into an entirely homogenous material with a high proportion of grout dissipating into
37 the surrounding soil (DSI 2008). Given the fact that the majority of the nails in this case study
38 were designed for a bonded length in Glacial Till, it was not likely that a high percentage of the
39 pumped grout would dissipate into the surrounding soil. The ATN grouted lengths quoted in
40 Table 2, have been determined by calculation assuming no dissipation of grout in the Glacial Till
41 (i.e. the bonded portion of the nail is a cylinder with a diameter equal to the bore diameter and
42 height equal to the bonded length of the nail) by means of which it was assured that a
43 conservative assessment of bond resistance is made.
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51 A comparison of the resistance of the bonded length back-calculated using a conservative
52 estimate of the pullout resistance (40 kPa, Figure 7), with the design bond resistance shows a
53 margin of safety of between 1.08 and 2.68 for all additional nails (ATNs and KLEMMs). This
54 justifies the design, bearing in mind that partial factors of safety (BS EN 1991, 2009; BS EN
55 1997-1, 2007) were used to derive the design bond resistance but also shows that the utilisation
56 factor may be very low for a relatively large number of nails. If the Eurocode 7 (BS EN 1997-1,
57 2007) philosophy is used and the design is based and optimised through testing verification, it
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1 may be more cost effective to carry out design verification tests on production nails using
2 conservative estimate of the bond resistance from case studies or published research which
3 would have to be developed for self-drilled hollow bar nails. However, it should be noted that
4 both our and values in the literature correspond to the undrained bond strength which is higher
5 than the effective bond strength during the service life of the nail (Phear et al 2005). Further
6 research will be focussed on the comparison of the measured bond strength and the design
7 bond strength in order to define a realistic partial factor of safety.
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12 The experience during this case study was that the specifics of nail installation and testing
13 depended on the testing loads which ultimately depended on the adopted testing method. The
14 higher testing loads due to long, fully grouted nails necessitated larger excavation for a larger
15 testing rig as well as longer time for testing and more robust safe method of working. The risk of
16 inconclusive tests was also higher due to potential 'bulbing' (Cadden et al 2010) and interaction
17 between short and long nails installed relatively closely together. The longer testing time meant
18 prolonged exposure of the excavated soil to the elements and trampling leading to erosion.
19 Longer tests posed a risk of slowing down the progress of the production nails and verification
20 and optimisation of the design where it was based on the results from testing (Murray 1993).
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25 It is considered that pull-out testing using sacrificial solid bar soil nails during the ground
26 investigation stage would be a realistic way of progressing a design if the use of hollow bars is
27 being considered for the working nails. In this way the actual pull-out resistance of the nails from
28 different soil types across a site would be determined before the design stage, with the soil nail
29 lengths being optimised during the design based on actual pull-put data instead of theoretical
30 working bonds and overburden pressures. This would remove some of the reliance of the
31 design on pull-out testing during construction of hollow bar working nails, with a reduced
32 number of pull-out tests being required during construction.
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42 Published literature (Cadden et al 2011) details different methods of hollow bar nail installation
43 before testing but these methods involve complicated plant and operations which requires
44 skilled work and specialist plant and it may be impractical on sites where a large number of nails
45 are to be installed and tested. However, the above study does highlight the difficulties the
46 industry around the world is experiencing trying to determine an appropriate testing method for
47 hollow bar soil nails.
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52 In order to improve the testing process of self-drilled hollow bar nails it may be better to test
53 shorter grouted nail lengths only which correspond to the design bonded lengths, i.e. grouting
54 the passive zone of the nail into the soil type expected for the production nail bond length. This
55 approach would depend on the bonded length assumed or calculated in the design and on the
56 local soil conditions. However, testing of a sufficient number of nails of different bonded lengths
57 in each expected soil material and analysing the results in terms of 'cautious estimate' (BS EN
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1 1997: 2009) of bond resistance (per metre bonded length or for the nail assuming cylindrical
2 bond) would decrease the potential errors and provide, at least statistical, evidence of validity of
3 the design assumptions. In this case, a better control of the actual grouted length and grout
4 quantities would be needed bearing in mind the potential grout permeation within the adjacent
5 soil. In our case the grout intake could not be controlled for each nails due to the fact that grout
6 pumps on site provided grout to several nails that were installed concurrently across the slope.
7 To avoid the need for the above, the hole could be progressed using a traditional method of
8 drilling, with or without casing, and installing the nail tendon after a set amount of grout has
9 been placed in the distal end of the hole. If a solid bar is used in this process, providing the hole
10 diameter is the same as for the hollow bar nail, a packer could be also installed which will
11 improve the control of bonded length while producing results on the bond strength comparable
12 to hollow bar nail. With this approach, the installation and testing time will be shortened (one
13 nail vs short-long nail pairs; shorter bond length would mean smaller testing setup and shorter
14 testing time) which can be of great benefit where an already failed or unstable slope is to be
15 stabilised in an area of high risk. Additionally, this approach can potentially provide an
16 opportunity to correlate the bond strength of traditionally installed solid bar nails and self-drilling
17 hollow bar nails, recognised as a common design problem (Cadden et al 2010).

18 From this case study, it became apparent that both the designer and the contractor need to
19 consider the wider aspects of nail testing and be flexible during the construction process. The
20 designer had to consider the access to test nail locations and balance the testing schedule
21 against the potential outcomes of the testing, while the contractor had to be flexible to match the
22 installation and testing techniques to the requirements of the design specification (Mickovski et
23 al 2013). In the future, the designer and contractor could benefit from additional detail on self-
24 drilled hollow bar nails installation and testing in the current codes of practice as suggested
25 previously in the literature (Cadden et al 2010). Empirical results from case studies could be
26 collated to form basis of Best Available Techniques document covering all aspects of self-drilled
27 hollow bar soil nail testing from scoping to interpretation of results.

28 **5. Conclusions**

29 A number of installation and testing methods for hollow bar soil nails were tried with variable
30 success as part of a slope stabilisation project in Scotland. The hollow bar nails were quicker to
31 install than the solid bar nails and their use could save time and labour on the project. The most
32 time consuming part of the process was the preparation for testing which involved excavation of
33 large volumes of soil and disturbance to the slope. The test setup was dictated by the testing
34 method and the bonded length of the nail which ultimately affected the success of the test. The
35 LN/SN method proved sufficient for verification of the design assumptions in the half of the
36 tests, the other half of the tests being inconclusive (the design did not fail but the interpretation of
37 the results was impossible) due to the encountered ground conditions and the assumptions that
38 had to be made for this method. To verify the design for the inconclusive results, additional

1 investigations using different installation methods were employed. The additional investigation
2 tests focussing on determining the strength of the bonded length were more successful
3 although there was a variation in the resulting values of bond strength.
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6 The potential for optimisation of the design lies in more detailed testing prior and during the
7 construction as well as adoption and verification of a bond resistance approach. To do this, it is
8 suggested to use solid bar nails for testing, provided the diameter is the same as for the working
9 nails, where only the bonded length of the nail is pulled out having successfully been separated
10 from the rest of the nail with a packer. Current design codes and codes of practice should be
11 updated to include testing methods applicable to hollow bar self drilled nails and partial factors
12 of safety specific to hollow bar self drilled nails based on empirical results and further research.
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21 for the support with the graphics preparation for publishing.
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2 **Figure captions**
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5 Figure 1 Schematic representation of bonded/debonded section of a test nail divided by a
6 packer or bond isolator. This arrangement allows pullout testing of the bonded length of the test
7 nail which lies in the passive zone of the slope.
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11 Figure 2 a) Site location plan. b) Typical geo-morphological logical cross section showing the
12 soil nail design. The soil nailing works (testing and production nails) were carried out on the
13 lower slope only.
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17 Figure 3 Test nail installation using a) ROC 460 rig and b) KR 960 rig. The access, safety and
18 stability were ensured using a steel rope and winch anchored at the road level.
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22 Figure 4 A schematic of the 'Long nail / Short nail' (LN/SN) testing system. The nails in the pair
23 have to be installed in close proximity of each other to minimise the potential of variation in the
24 soil properties but apart enough as to avoid interaction during testing.
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28 Figure 5 Test setup for the pullout testing of sacrificial nails. a) excavation (long and short nails
29 can be seen) b) testing frame installation on one of the nails of the pair c) pullout testing while
30 recording pullout force and displacement.
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34 Figure 1 Typical pullout behaviour of a) long (full line) and short (dashed line) nail of a pair
35 (TN20). b) ATN (full line; ATN12) and KLEMM (dashed line, KLEMM 7) nail. Bonded lengths
36 can be seen in Tables 1 and 2.
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40 Figure 7 Bond pullout stress for a) LN/SN tests; b) Investigation tests
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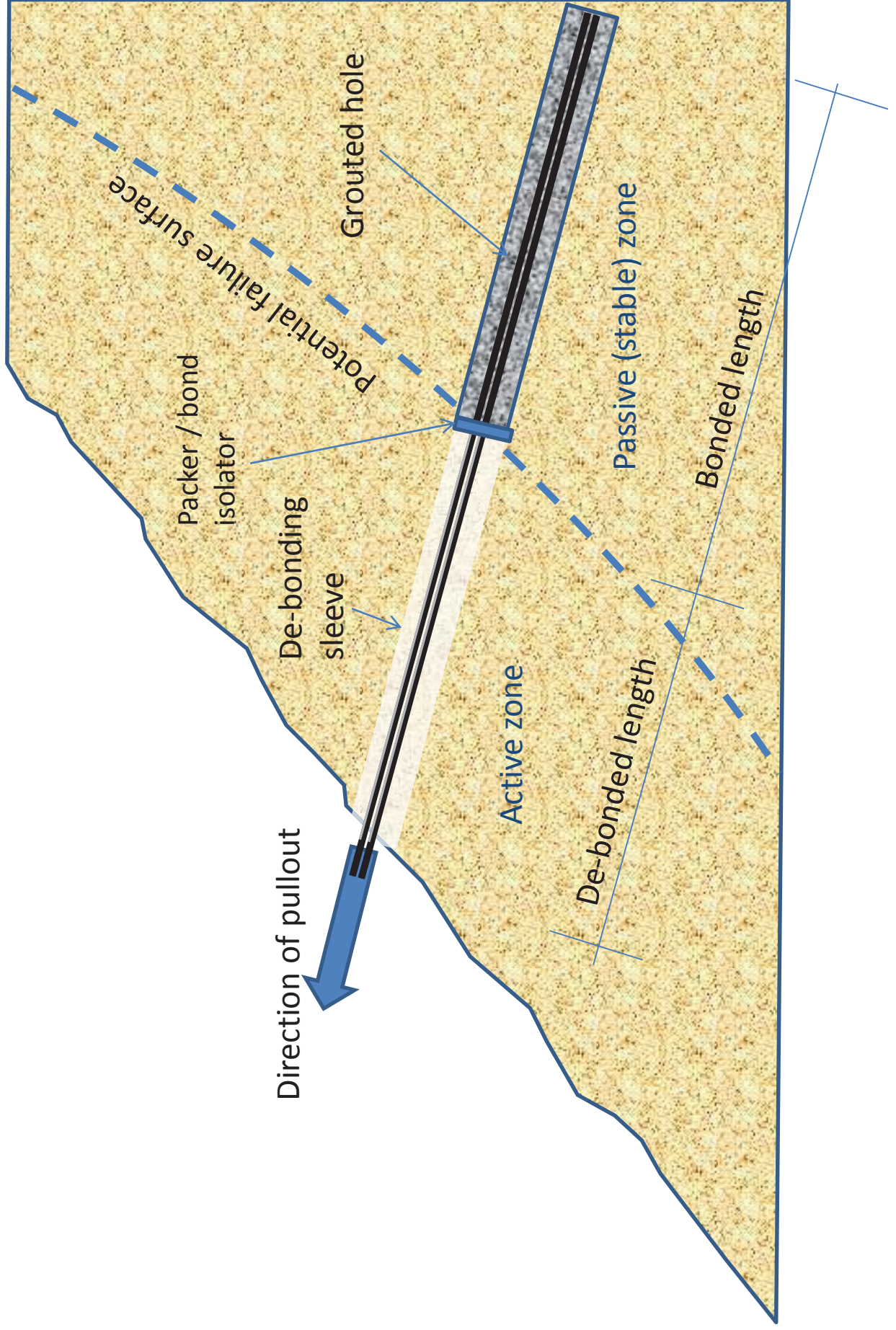
Table 1. Results of the pullout tests on LN/SN testing system. The resistance to pullout of the grouted short nail length is subtracted from the one of the long nail to derive the resistance of the bonded length. Remarks: N/A and (*) denote inconclusive tests where the short nail pulled out at a higher load than the long nail or short nail pulled out at a relatively high load in relation to the design yield strength of the steel bar i.e. where the interpretation of the result was difficult due to the nature of the test; () denotes design verification failure. GSG = Glacial Sands and Gravels, GT = Glacial Till.**

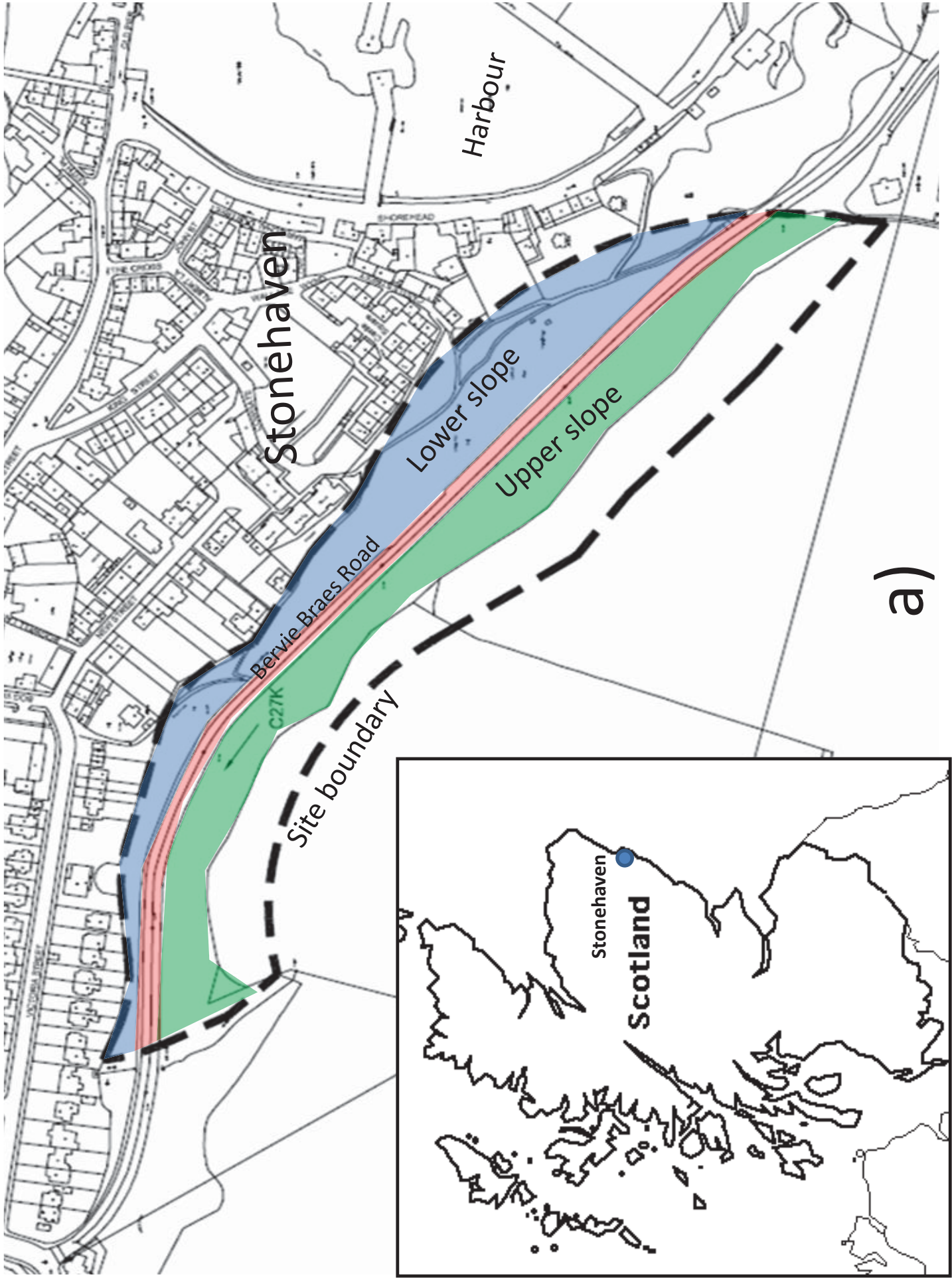
Test nail	Grouted length of short nail [m]	Pullout resistance of short nail [kN]	Additional grouted length of long nail [m]	Pullout resistance of long nail [kN]	Pullout resistance of bonded length [kN]	Bonding Strata	Remarks
TN11	8.8	340	11.2	not tested		GSG & GT	N/A
TN13	7.6	310	9.4	360	50	GSG & GT	**
TN14	8.6	210	11.4	360	150	GSG & GT	*
TN15	8.2	100	11.8	160	60	GSG & GT	**
TN16	8	290	10	350	60	GSG & GT	**
TN17	8.6	90	11.4	250	160	GSG & GT	
TN18	12.2	290	11.8	not tested		GT	N/A
TN19	13	260	11	140		GSG & GT	**
TN20	10	150	14	310	160	GT	
TN21	11.8	300	12.2	280		GT	**
TN22	9.2	360	8.8	360		GSG & GT	*
TN23	11.2	190	12.8	340	150	GT	
TN24	12.4	290	11.6	360	70	GSG & GT	*
TN34	10	80	2	350	270	GT	
TN35	5.25	40	4.75	360	320	GSG	
TN25	6	220	9	360	140	GT	*
TN26	10	360	2	360		GT	*
TN28	10	360	2	not tested		GT	N/A
TN29	3	30	7	130	100	GT	
TN31	6	80	9	360	280	GT	*
TN32	4	130	6	180	50	GSS & GT	
TN51	9	30	2	190	160	GSG & GT	
TN52	9	80	2	120	40	GT	**
TN53	5.5	70	1.5	170	100	GSG	
TN54	9	140	2	250	110	GT	
TN55	5.25	40	1.75	110	70	GSG	
TN56	9	130	2	290	160	GSG & GT	
TN57	5	70	2	120	50	GSG	

Table 2 Results of the investigation tests. Remarks: (*) denotes inconclusive tests where the design load \leq pullout load \leq combined test load, i.e. where the interpretation of the result was difficult due to the nature of the test; () denotes design verification failure. GSG = Glacial Sands and Gravels, GT = Glacial Till.**

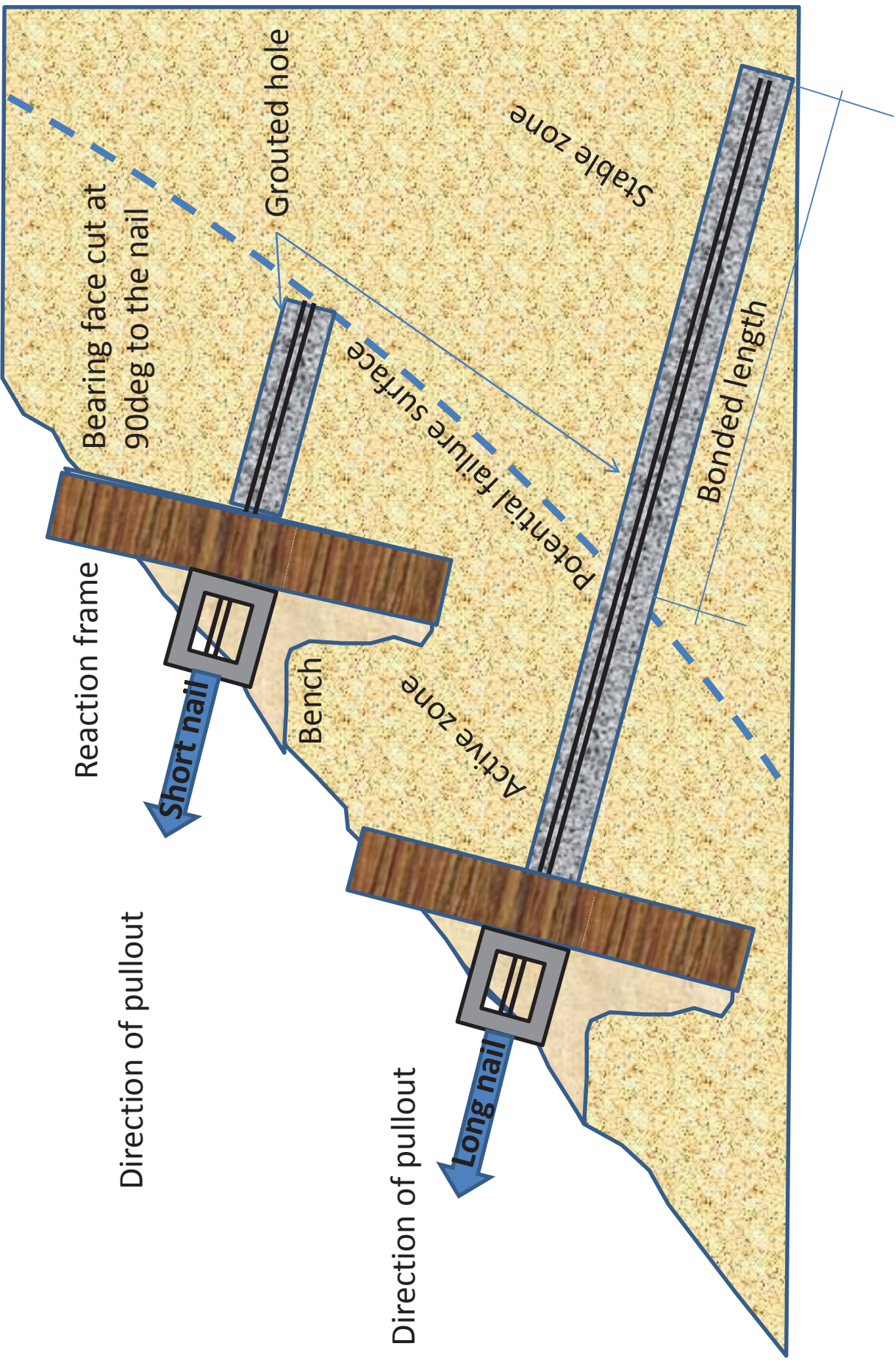
Test nail	Installed length [m]	Bonded length [m]	Failure Load [kN]	Design Verification Load (kN)	Bonding Strata	Remarks
TN12	20	5.5	120	180	GSG & GT	*
ATN10	20	9.7	155	155	GSG & GT	
ATN11	20	9.7	230	165	GSG & GT	
ATN12	20	9.7	150	150	GSG & GT	
ATN14	20	5.5	70	180	GSG & GT	**
ATN5	13.5	5.5	220	195	GT	
ATN7	24	8.3	140	195	GT	*
ATN8	15	8.3	300	130	GSG & GT	
ATN13	24	6.9	210	205	GSG & GT	
TN27	15	2.8	55	80	GT	*
TN30	15	2.8	45	80	GT	**
ATN1	12	5.5	70	70	GT	
ATN3	15	2.8	35	110	GT	**
ATN9	11	7.5	220	60	GT	
KLEMM1	24	5.5	70	N/A	GT	
KLEMM2	24	5.5	80	N/A	GT	
KLEMM3	24	6.9	110	N/A	GT	
KLEMM4	21	2	190	N/A	GT	
KLEMM5	18	2	80	N/A	GT	
KLEMM6	15	2	90	N/A	GT	
KLEMM7	12	2	80	N/A	GT	

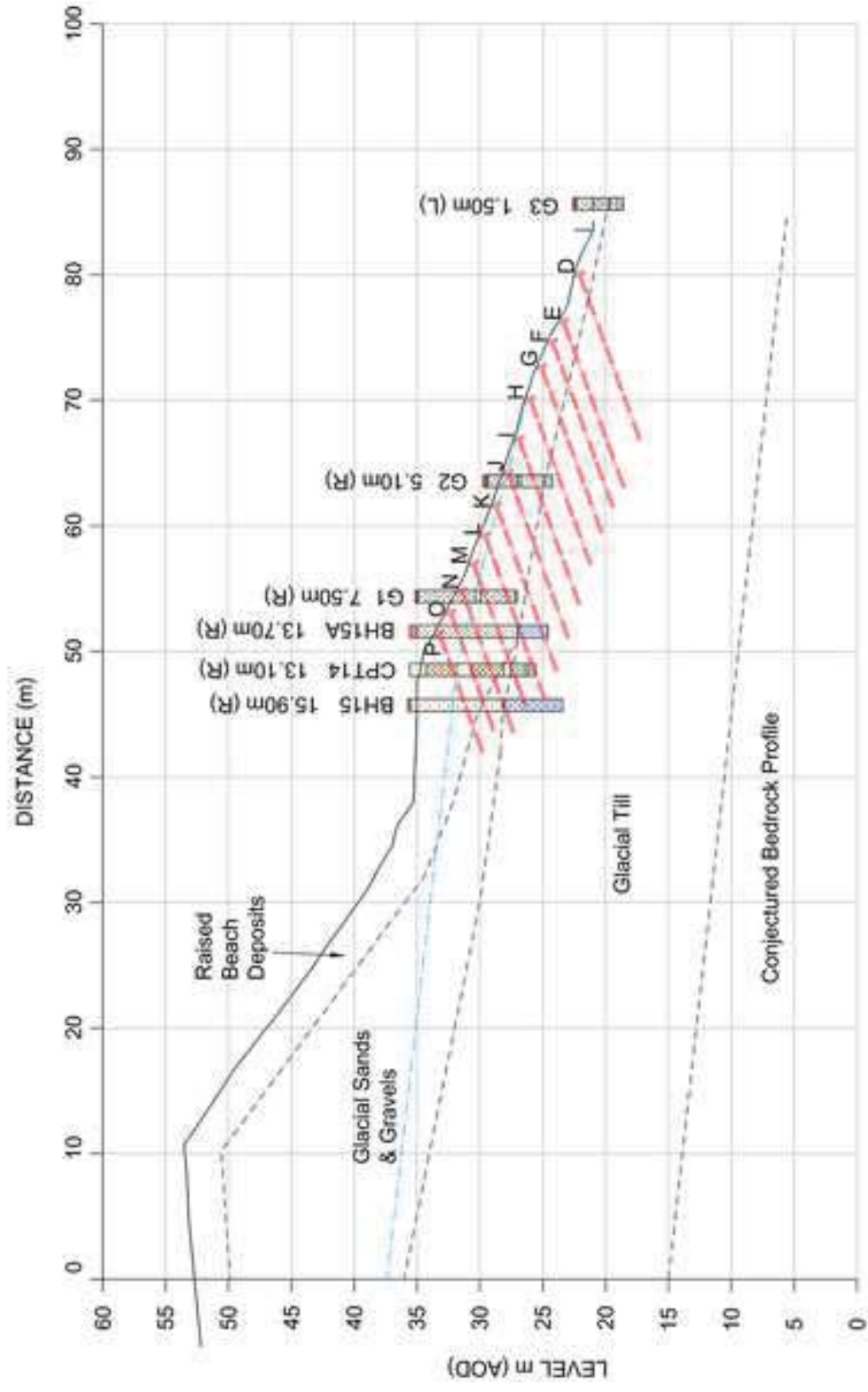
Figures 1, 2a, 4 in native format





a)





b)



a)



Figure 5a

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