Design of Nail Head for Use of Soil Nails in Mitigation of Open Hillslope Landslides

GEO Report No. 360

V.S.F. Kong, R.C.H. Koo & D.S. Chang

Geotechnical Engineering Office
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Preface

In keeping with our policy of releasing information which may be of general interest to the geotechnical profession and the public, we make available selected internal reports in a series of publications termed the GEO Report series. The GEO Reports can be downloaded from the website of the Civil Engineering and Development Department (http://www.cedd.gov.hk) on the Internet.

Raymond WM Cheung
Head, Geotechnical Engineering Office
December 2022

Foreword

This Technical Note presents a review on the design of nail head for use of soil nails in mitigation of open hillslope landslides based on Geoguide 7 and GEO Report No. 175. The study was carried out by Mr V.S.F. Kong and Dr R.C.H. Koo and later by Dr D.S. Chang under my direction and the supervision of Ms P.F.K. Cheng and later by Ms L.L.K. Cheung. Useful comments were received on circulation of the draft and are incorporated as appropriate. The Drafting Unit of the Landslip Preventive Measures Division 2 assisted in formatting this report. All contributions are gratefully acknowledged.

H.W. Sun
Chief Geotechnical Engineer/LPM 2

Abstract

This Technical Note presents a review on the design of nail head for use of soil nails in mitigation of open hillslope landslides based on Geoguide 7 and GEO Report No. 175. Geoguide 7 provides recommendation on sizing soil-nail head for slopes steeper than 45° from numerical modelling results presented in GEO Report No. 175. This study extends the numerical modelling for the design of soil-nail head on gentle slopes, which is particularly relevant for the use of soil nails in mitigation of open hillslope landslides on natural terrains in Hong Kong.

Based on the findings of this study, recommendations pertaining to the sizing of soil-nail head for use of soil nails in gentle slopes, in particular for use of soil nails in mitigation of open hillslope landslides are made for rational and cost-effective design solutions, together with enhanced sustainable measures against shallow landslides and surface erosion.

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1 Introduction

Geoguide 7 (GEO, 2017) presents recommendation on sizing of soil-nail head for design of soil nails on slopes steeper than 45° based on findings of numerical modelling using the computer program *FLAC*, as reported in GEO Report No. 175 (Shiu & Chang, 2004).

The gradient of natural hillside, in particular hillsides susceptible to open hillslope landslides (OHL) is relatively gentler than man-made cut slopes. The design guidelines given in GEO Report No. 138 (Ho & Roberts, 2016) for mitigation of OHL hazards include the use of soil nails to increase the margin of safety against slope instability for the top 2 m of the hillslope. In these cases, the required soil nail forces as well as the required bearing capacity of the nail head are much smaller than that for the typical design of soil nails in upgrading of steep man-made slopes. Apart from sizing of the soil-nail head using the method recommended by the UK Department of Transport (DOT, 1994), the direct application of soil-nail head sizes presented in Table 5.7 of Geoguide 7 often leads to excessive excavation for forming very sizeable soil-nail heads on hillslopes. As a result, it may cause unnecessary impact on the environment and hamper buildability, cost-effectiveness and efficiency in the use of soil nails for mitigating OHL hazards with gentle slope angles (i.e. less than 45°).

In this study, numerical analyses are carried out using the computer program *FLAC* to assess bearing capacity of the soil-nail head on gentle slopes. The proposed method is verified for a steep slope with slope angle of 55° by comparing the bearing capacity based on the sizes of soil-nail heads recommended in Geoguide 7. The bearing capacity for the soil-nail heads calculated based on the proposed method in this study corresponds to the recommended soil-nail head sizes as given in Table 5.7 of Geoguide 7 and tally generally with the allowable tensile capacity of the soil nail steel bars.

2 Numerical Modelling

2.1 Numerical Model and Parameters

In this study, numerical analyses have been carried out using a two-dimensional finite difference computer program, Fast Lagrangian Analysis of Continua (*FLAC*) Version 7.0 to study the bearing capacity plastic mechanisms of the soil underneath a nail head due to tensile force developed in the soil nail. *FLAC* uses an explicit time-marching method to solve equations of motion and stress-strain relations and to determine the equilibrium stress conditions under applied boundary conditions. As a standard verification of *FLAC*, which is presented in its User Manual, the bearing capacity and plastic mechanism of strip and circular footings has been studied by applying a constant downward velocity to the area representing the footing. The numerical approach adopted in this study in modelling the bearing capacity of soil-nail head on slopes is essentially similar to that adopted in Geoguide 7, but to adopt the approach of applying constant velocity perpendicular to the soil-nail head as used in the *FLAC* verification exercise instead of direct application of a normal force on the soil-nail head as adopted by Shiu & Chang (2004).

The slope is represented by a plane-strain model with unit thickness and with three slope angles of θ considered: 30°, 35° and 40°. The width of the soil-nail head is given by dimension, w (400 mm, 500 mm or 600 mm) in the model. Results of the calculated bearing capacity using the plane-strain model are proportional to the width of the soil-nail head. An illustrative example of *FLAC* model adopting θ = 35° and w = 600 mm is presented in Figure 2.1. The ground is represented by an elasto-plastic soil model with Mohr-Coulomb perfectly plastic yield criteria, which are characterised by effective stress shear strength parameters c' and ϕ'. Side boundaries of the geometry adopt vertical roller and the bottom boundary is full fixed. Boundary effects to the soil-nail head in the model were checked and were considered to be minimal for the computational results. The grid size is refined at regions close to stressed areas to cater for large variation of stresses. Initial stresses of the slope are obtained by switching on gravity and achieving equilibrium in the calculation.

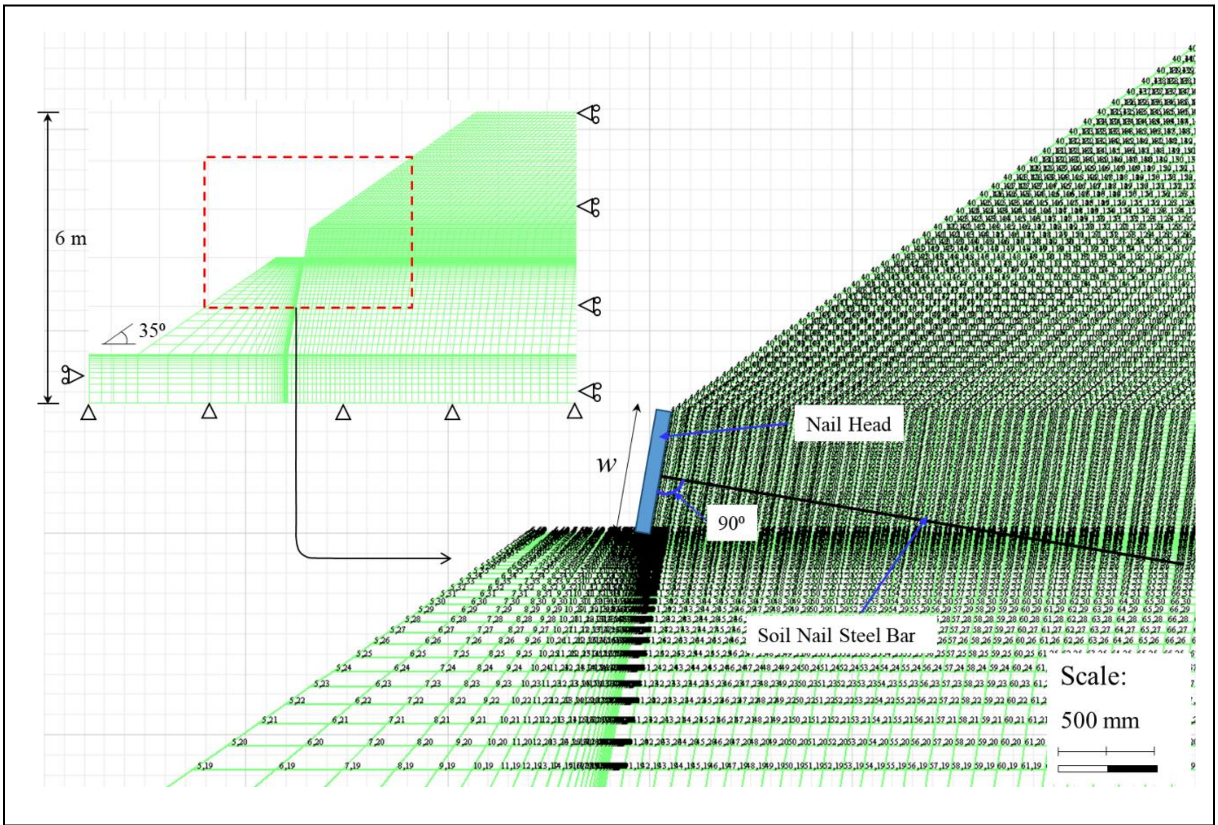


Figure 2.1 Modelling of Soil-nail Head on an Infinite Slope in *FLAC*

2.2 Determination of Bearing Capacity of Soil-nail Head on Slopes

For general instability of slopes, the potential unstable soil mass, i.e. the 'active zone' tends to move downwards along a sliding surface under concentrated shearing at the base of the unstable mass. Given the low flexural stiffness of soil nails, the unstable soil mass is primarily supported by tension developed in the soil-nail steel bars. Under the tensile force in the nail due to development of deformation of the 'active zone', the bearing capacity of the soil underneath the soil-nail head is mobilised. Soil-nail heads should be designed to provide an adequate bearing capacity against shear failure of the ground underneath the soil-nail head assuming structural capacity of the soil-nail head is satisfied. In this study, the modelling of the development of bearing pressure is through the application of a constant velocity for the soil-nail head relatively to the slope mass in the direction of the soil nail.

After reaching equilibrium stress distribution under the initial boundary conditions, a constant velocity is applied on the soil-nail head. The maximum bearing capacity of the ground underneath the soil-nail head is determined when the reaction to the soil-nail head reaches a plateau upon further displacement. Example of a load-displacement curve and a plot of plastic points at the termination of loading are shown in Figures 2.2 and 2.3 respectively for a 600 mm soil-nail head on a 35° slope with effective stress shear strength parameters c' = 2 kPa, and ϕ' = 34°. With the applied constant velocity of the soil-nail head, a plateau in bearing pressure behind the soil-nail head is reached under a steady state condition. The region in plastic stress state (indicated by plastic points) agrees well with that of the plastic mechanism for bearing capacity of spread footing on slope as presented in Murthy (2002) and Terzaghi et al (1996).

Applied velocity at 4.0×10^{-6} m/s was generally adopted in this study, except for models with notable large fluctuation of unbalanced forces. For those models, the applied velocity was reduced down to 8.5×10^{-7} m/s. These values are sufficiently small for obtaining stable solutions of the steady state plastic bearing capacity of the soil behind the model soil-nail head. The modelling loading rate effect on the calculated bearing capacity of soil-nail head has been checked by reducing or increasing the loading rate by 5 times. The difference of the results is within 5%. The influence of the loading rate to the calculated bearing capacity of the soil-nail head is minimal in this study.

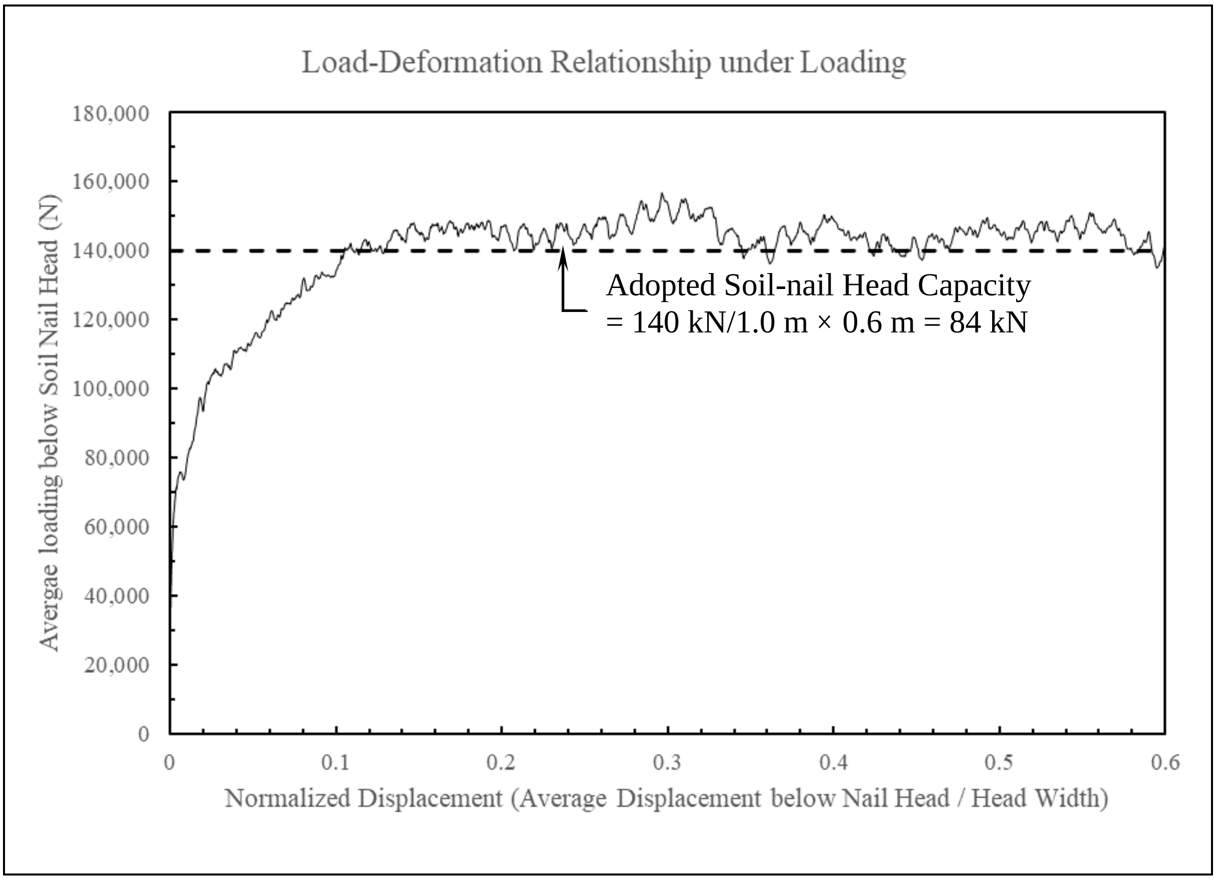


Figure 2.2 Typical Result of Load-displacement Curve of a 600 mm Soil-nail Head

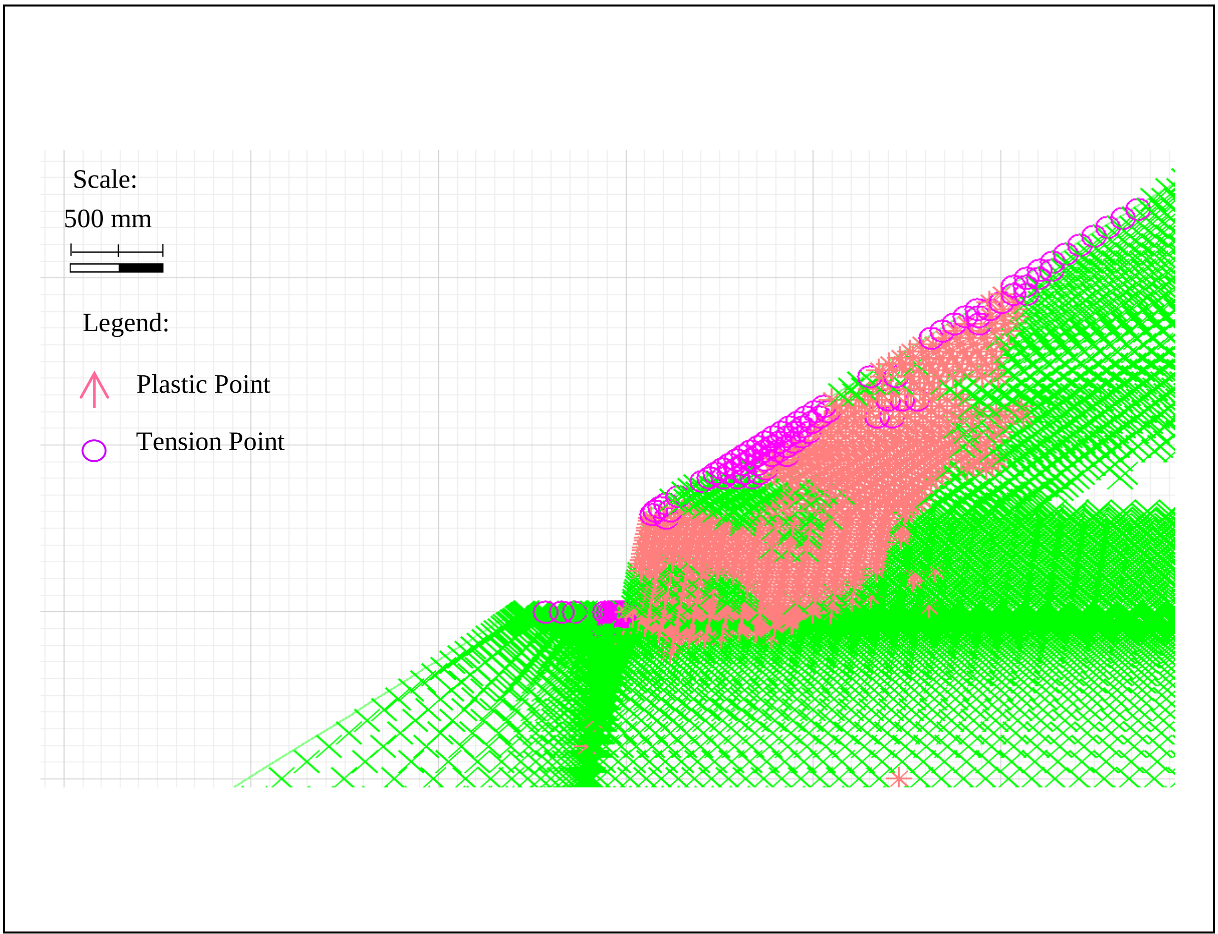


Figure 2.3 Typical Result of Plastic Points at the Termination of Loading

2.3 Verification of the Proposed Method

To verify the numerical modelling approach adopted in this study, a numerical model is set up for a 55° steep slope. Effective stress shear strength parameters c' = 4 or 8 kPa, and ϕ' = 36° are adopted with a view to match selected results presented in Geoguide 7. The bearing capacity of the soil underneath the soil-nail head is calculated following the approach presented in Section 2.2 and the results are summarised in Table 2.1.

Sizing of soil-nail heads recommended in Geoguide 7 assumes that the bearing capacity of the soil-nail head is sufficient to support full allowable tensile capacity T_0 of the soil-nail steel bar (Shiu & Chang, 2004):

$$T_0 = f_m A_s \quad \text{(1)}$$

$$f_m = 0.55 f_y \leq 0.23 \text{ (kN/mm}^2\text{)} \quad \text{(2)}$$

Where f_y is the characteristic strength of high yield bar, and A_s is the cross-sectional area of the steel bar. The maximum allowable nail force for 25 mm, 32 mm and 40 mm diameter reinforcement are 113 kN, 185 kN and 289 kN respectively.

The bearing capacity for the soil-nail heads calculated based on the proposed method in this study corresponds to the recommended soil-nail head sizes in Geoguide 7 and tally generally with the tensile capacity of the soil-nail steel bars as summarised in Table 2.2.

Table 2.1 Calculated Bearing Capacity of Soil-nail Head on a 55° Slope

Soil-nail Head Size (mm)	Bearing Capacity of Soil Underneath Soil-nail Head (kN)	
	$c' = 4$ kPa, $\phi' = 36°$	$c' = 8$ kPa, $\phi' = 36°$
400	125	205
600	200	315

Note: c' and ϕ' are the effective stress shear strength parameters of the soil.

Table 2.2 Comparison of Calculated Bearing Capacity of Soil-nail Head on a 55° Slope Corresponds to the Soil-nail Head Size Recommended in Geoguide 7

Effective Stress Shear Strength Parameter, c' (kPa)	Bearing Capacity of Soil Underneath Soil-nail Head (kN)		
	$d = 25$ mm $w = 400$ mm	$d = 32$ mm $w = 600$ mm	$d = 40$ mm $w = 600$ mm
4	125 > 113 required	200 > 185 required	-
8	205 > 113 required	315 > 185 required	315 > 289 required

Notes:
(1) d is the diameter of the nail reinforcement.
(2) w is the width of the soil-nail head.
(3) The size of the soil-nail head modelled in the numerical model is the same as that proposed in Geoguide 7 (viz. $w = 400$ mm for $d = 25$ mm and $w = 600$ mm for $d = 32$ and 40 mm).
(4) Effective stress shear strength parameter $\phi' = 36°$.

2.4 Ultimate Bearing Capacity of Soil-nail Head on Gentle Slopes

A parametric numerical study is conducted to determine the bearing capacity of the soil underneath the soil-nail head by varying effective stress shear strength parameters, slope angle and soil nail inclination. A range of combinations of effective stress shear strength parameters (i.e. c' = 2 kPa, 4 kPa, 6 kPa, 8 kPa, 10 kPa and ϕ' = 34°, 36°, 38°, 40°) based on the recommendations in Geoguide 7 is adopted. Typical soil nail inclinations at 10° and 20° have been selected. The numerical results for bearing capacity of soil-nail head sizes of 400 mm, 500 mm and 600 mm on slopes with combinations of c' and ϕ' are shown in Tables 2.3, 2.4 and 2.5 respectively. The recommended values as shown in Tables 2.3, 2.4 and 2.5 are based on the results of the numerical study with the assumed geometrical and geological conditions and modelling consideration on size effect to benchmark with Geoguide 7. Although the bearing capacity of soil-nail head developed in this study is for mitigation of OHL hazards, it could be also applicable to other gentle slopes with similar geological and hydrogeological conditions.

Tables 2.3, 2.4 and 2.5 indicate that the soil-nail head size and soil effective shear strength parameters are the most salient parameters for soil-nail head bearing capacity. The bearing capacity of the soil underneath soil-nail head increases with the increase of soil-nail head size and soil effective stress shear strength parameters. The bearing capacity of a 600 mm nail soil-head is approximate 25% to 70% larger than that of a 500 mm soil-nail head, and 60% to 200% larger than that of a 400 mm soil-nail head. The bearing capacity is also related to slope angle, with lower bearing capacity for gentler slopes. This is because the overburden pressure for the passive soil wedge above the soil-nail head is lower for gentle slope. The inclination of the soil nail plays a notable effect on development of bearing capacity. A steeper inclination results in a higher bearing capacity. This is because the mobilised plastic shearing zone at failure is larger for a larger inclination. However, if the nail inclination is larger than 20°, the bearing pressure of the soil-nail head may decrease because the tensile force of the nail may not be fully mobilised (Shiu & Chang, 2005).

Table 2.3 Calculated Ultimate Bearing Capacity of 600 mm Soil-nail Head on Gentle Slopes

Ultimate Bearing Capacity of 600 mm Soil-nail Head (kN)

30°≤ Slope Angle < 35°
Nail inclination = 10°

Cohesion (c')	Friction Angle (ϕ') 34	36	38	40
2	75 (56)	90 (68)	105 (79)	120 (90)
4	93 (70)	108 (81)	126 (95)	141 (106)
6	108 (81)	123 (92)	144 (108)	168 (126)
8	120 (90)	141 (106)	159 (119)	186 (140)
10	138 (104)	156 (117)	180 (135)	198 (149)

30°≤ Slope Angle < 35°
Nail inclination = 20°

Cohesion (c')	Friction Angle (ϕ') 34	36	38	40
2	81 (61)	99 (74)	120 (90)	138 (104)
4	102 (77)	120 (90)	141 (106)	165 (124)
6	120 (90)	138 (104)	162 (122)	186 (140)
8	135 (101)	153 (115)	180 (135)	204 (153)
10	150 (113)	174 (131)	198 (149)	225 (169)

35°≤ Slope Angle < 40°
Nail inclination = 10°

Cohesion (c')	Friction Angle (ϕ') 34	36	38	40
2	78 (59)	96 (72)	114 (86)	138 (104)
4	102 (77)	120 (90)	141 (106)	165 (124)
6	120 (90)	141 (106)	156 (117)	180 (135)
8	138 (104)	153 (115)	186 (140)	210 (158)
10	150 (113)	171 (128)	201 (151)	225 (169)

35°≤ Slope Angle < 40°
Nail inclination = 20°

Cohesion (c')	Friction Angle (ϕ') 34	36	38	40
2	84 (63)	105 (79)	126 (95)	156 (117)
4	111 (83)	132 (99)	153 (115)	180 (135)
6	135 (101)	156 (117)	180 (135)	207 (155)
8	150 (113)	174 (131)	204 (153)	234 (176)
10	168 (126)	192 (144)	219 (164)	252 (189)

40°≤ Slope Angle < 45°
Nail inclination = 10°

Cohesion (c')	Friction Angle (ϕ') 34	36	38	40
2	78 (59)	96 (72)	117 (88)	144 (108)
4	105 (79)	126 (95)	150 (113)	180 (135)
6	129 (97)	153 (115)	180 (135)	207 (155)
8	147 (110)	174 (131)	201 (151)	237 (178)
10	165 (124)	195 (146)	219 (164)	252 (189)

40°≤ Slope Angle < 45°
Nail inclination = 20°

Cohesion (c')	Friction Angle (ϕ') 34	36	38	40
2	84 (63)	105 (79)	129 (97)	159 (119)
4	114 (86)	138 (104)	162 (122)	195 (146)
6	138 (104)	165 (124)	195 (146)	231 (173)
8	162 (122)	192 (144)	225 (169)	252 (189)
10	186 (140)	213 (160)	246 (185)	288 (216)

Notes:
(1) Effective stress shear strength parameter c' is in kPa, and ϕ' is in degree (°).
(2) Ultimate bearing capacity of soil-nail head with its back parallel to slope surface are given in brackets (Section 4 and CEDD Standard Drawing No. C2106/7 refer).

Table 2.4 Calculated Ultimate Bearing Capacity of 500 mm Soil-nail Head on Gentle Slopes

Ultimate Bearing Capacity of 500 mm Soil-nail Head (kN)

30°≤ Slope Angle < 35°
Nail inclination = 10°

Cohesion (c')	Friction Angle (ϕ') 34	36	38	40
2	45 (34)	55 (41)	65 (49)	78 (58)
4	58 (43)	68 (51)	80 (60)	93 (69)
6	70 (53)	78 (58)	90 (68)	108 (81)
8	80 (60)	90 (68)	105 (79)	120 (90)
10	88 (66)	100 (75)	118 (88)	133 (99)

30°≤ Slope Angle < 35°
Nail inclination = 20°

Cohesion (c')	Friction Angle (ϕ') 34	36	38	40
2	58 (43)	70 (53)	85 (64)	103 (77)
4	75 (56)	93 (69)	108 (81)	128 (96)
6	90 (68)	108 (81)	128 (96)	148 (111)
8	105 (79)	123 (92)	140 (105)	165 (124)
10	118 (88)	135 (101)	160 (120)	183 (137)

35°≤ Slope Angle < 40°
Nail inclination = 10°

Cohesion (c')	Friction Angle (ϕ') 34	36	38	40
2	50 (38)	63 (47)	73 (54)	85 (64)
4	65 (49)	78 (58)	90 (68)	103 (77)
6	78 (58)	90 (68)	105 (79)	118 (88)
8	88 (66)	103 (77)	120 (90)	135 (101)
10	100 (75)	115 (86)	130 (98)	153 (114)

35°≤ Slope Angle < 40°
Nail inclination = 20°

Cohesion (c')	Friction Angle (ϕ') 34	36	38	40
2	60 (45)	75 (56)	88 (66)	108 (81)
4	78 (58)	95 (71)	110 (83)	135 (101)
6	95 (71)	113 (84)	133 (99)	158 (118)
8	115 (86)	133 (99)	155 (116)	185 (139)
10	130 (98)	150 (113)	175 (131)	205 (154)

40°≤ Slope Angle < 45°
Nail inclination = 10°

Cohesion (c')	Friction Angle (ϕ') 34	36	38	40
2	50 (38)	63 (47)	75 (56)	95 (71)
4	70 (53)	83 (62)	95 (71)	118 (88)
6	83 (62)	98 (73)	115 (86)	135 (101)
8	98 (73)	113 (84)	133 (99)	153 (114)
10	113 (84)	128 (96)	150 (113)	173 (129)

40°≤ Slope Angle < 45°
Nail inclination = 20°

Cohesion (c')	Friction Angle (ϕ') 34	36	38	40
2	60 (45)	75 (56)	90 (68)	108 (81)
4	80 (60)	95 (71)	115 (86)	138 (103)
6	100 (75)	120 (90)	138 (103)	163 (122)
8	118 (88)	135 (101)	160 (120)	193 (144)
10	133 (99)	160 (120)	183 (137)	218 (163)

Note:
(1) Effective stress shear strength parameter c' is in kPa, and ϕ' is in degree (°).
(2) Ultimate bearing capacity of soil-nail head with its back parallel to slope surface are given in brackets (Section 4 and CEDD Standard Drawing No. C2106/7 refer).

Table 2.5 Calculated Ultimate Bearing Capacity of 400 mm Soil-nail Head on Gentle Slopes

Ultimate Bearing Capacity of 400 mm Soil-nail Head (kN)

30°≤ Slope Angle < 35°
Nail inclination = 10°

Cohesion (c') \ Friction Angle (ϕ')	34	36	38	40
2	26 (20)	32 (24)	36 (27)	44 (33)
4	34 (26)	40 (30)	46 (35)	54 (41)
6	40 (30)	48 (36)	56 (42)	64 (48)
8	48 (36)	54 (41)	64 (48)	72 (54)
10	54 (41)	62 (47)	72 (54)	82 (62)

30°≤ Slope Angle < 35°
Nail inclination = 20°

Cohesion (c') \ Friction Angle (ϕ')	34	36	38	40
2	30 (23)	36 (27)	42 (32)	52 (39)
4	38 (29)	46 (35)	54 (41)	62 (47)
6	46 (35)	54 (41)	62 (47)	74 (56)
8	54 (41)	62 (47)	72 (54)	84 (63)
10	62 (47)	70 (53)	80 (60)	92 (69)

35°≤ Slope Angle < 40°
Nail inclination = 10°

Cohesion (c') \ Friction Angle (ϕ')	34	36	38	40
2	30 (23)	36 (27)	42 (32)	50 (38)
4	38 (29)	46 (35)	52 (39)	62 (47)
6	46 (35)	54 (41)	62 (47)	72 (54)
8	54 (41)	62 (47)	72 (54)	80 (60)
10	60 (45)	70 (53)	80 (60)	92 (69)

35°≤ Slope Angle < 40°
Nail inclination = 20°

Cohesion (c') \ Friction Angle (ϕ')	34	36	38	40
2	32 (24)	40 (30)	46 (35)	56 (42)
4	42 (32)	50 (38)	60 (45)	72 (54)
6	52 (39)	60 (45)	70 (53)	82 (62)
8	60 (45)	70 (53)	80 (60)	92 (69)
10	68 (51)	78 (59)	90 (68)	104 (78)

40°≤ Slope Angle < 45°
Nail inclination = 10°

Cohesion (c') \ Friction Angle (ϕ')	34	36	38	40
2	45 (34)	58 (43)	69 (52)	81 (61)
4	63 (47)	75 (56)	87 (65)	102 (77)
6	75 (56)	90 (68)	105 (79)	120 (90)
8	90 (68)	102 (77)	123 (92)	138 (104)
10	102 (77)	117 (88)	135 (101)	156 (117)

40°≤ Slope Angle < 45°
Nail inclination = 20°

Cohesion (c') \ Friction Angle (ϕ')	34	36	38	40
2	48 (36)	60 (45)	75 (56)	90 (68)
4	69 (52)	81 (61)	99 (74)	114 (86)
6	84 (63)	99 (74)	117 (88)	141 (106)
8	99 (74)	117 (88)	132 (99)	156 (117)
10	114 (86)	129 (97)	150 (113)	177 (133)

Note:
(1) Effective stress shear strength parameter c' is in kPa, and ϕ' is in degree (°).
(2) Ultimate bearing capacity of soil-nail head with its back parallel to slope surface are given in brackets (Section 4 and CEDD Standard Drawing No. C2106/7 refer).

3 Stabilisation Forces by Soil Nails for Mitigation of Open Hillslope Landslides

Using soil nails as structural support, the stabilisation forces required for mitigation of OHL hazards can be obtained by limit equilibrium slope stability analysis. In this study, limit equilibrium calculations have been conducted for a homogenous infinite slope with different slope angles and soil shear strengths. The groundwater table is taken to be 1.0 m below the slope surface. The postulated failure plane for potential slope instability is assumed to be located 2 m below the slope surface, which is in line with the generalised design objectives for mitigation of OHL hazards as detailed in GEO Report No. 138 (Ho & Roberts, 2016). An application of soil nail forces to the unstable slope mass following 2.0 m vertical and horizontal spacing is adopted to bring up the factor of safety to a minimum value of 1.4.

Table 3.1 summarises the required stabilisation forces for an infinite slope with slope angle of 35° and 40° under different effective stress shear strength parameters. It clearly demonstrates that even the smallest nominal 25 mm diameter soil-nail steel bar will be oversized purely based on structural capacity consideration. It also shows that the bearing capacity of a 400 mm, 500 mm or 600 mm soil-nail head is capable of producing the reaction required at the upper end of the soil nails with notable margin of safety. It is considered rational for designers to assess the required stabilisation forces for soil nails at different spacing and to provide soil-nail heads with sufficient bearing capacity for the required stabilisation forces for the different portions of the hillside to account for the variation in slope conditions, including possibly more shallow failures. The required nail forces for mitigation of landslides on other types of hillside catchments (i.e. topographic depression and channelized debris flow) may also be relatively small provided that no adverse hydrogeological, geological and topographic features are present.

Designers should specify soil-nail head with sufficient ultimate bearing capacity as presented in Tables 2.3, 2.4 and 2.5 to counteract the required stabilisation force of soil nail with a minimum factor of safety of 1.2, based on the following considerations:

(1) a factor of safety of 1.2 on calculated plane-strain bearing capacity for the required stabilisation force of a soil nail in view of the inherent uncertainty with mobilisation of shear strength in the relatively small volume of groundmass involved in providing the bearing pressure to the soil-nail head, despite the actual bearing capacity of soil-nail head would be higher if three-dimensional effect is considered;

(2) the required stabilisation forces of soil nails are assumed to be fully transferred to the nail heads by ignoring the friction developed by grout-soil bond of the length of the soil nail in the active zone;

(3) a safety margin against the slope stability has been considered in assessing the required stabilisation forces of soil nails; and

(4) the bearing capacity failure of soil-nail head is not common in nailed slopes.

Nevertheless, a larger soil-nail head might be warranted in particular situations in respect of adverse hydrogeological and geological conditions.

Table 3.1 Summary of Required Stabilisation Forces for Soil Nails at 2.0 m Vertical and Horizontal Spacing for Bringing up the Factor of Safety to a Minimum Value of 1.4

Slope Angle	Required Allowable Tensile Capacity of Soil Nail (kN)	
	$c' = 4$ kPa, $\phi' = 36°$	$c' = 8$ kPa, $\phi' = 36°$
35°	39	18
40°	58	36

Note: c' and ϕ' are the effective stress shear strength parameters of the soil.

4 Soil-nail Head Details and Slope Surface Protection

Designers are recommended to give due consideration to ensure effective interaction between the soil-nail head and the ground for gentle slopes, such as natural hillsides (GEO, 2017). The typical details of recessed soil-nail head presented in CEDD standard drawing (Figure 4.1) are generally used for mitigation of OHL hazards to promote soft landscaping in current design practice. A separate *FLAC* model was set up to investigate the effect of different inclinations of the back of the soil-nail head, viz. parallel to slope surface, and perpendicular to the nail alignment, for the same model parameters (slope angle, soil effective stress shear strength parameters, soil nail inclination) as reported in Section 2. Table 4.1 summarises the ultimate bearing capacity of soil-nail head on a 35° slope with different effective stress shear strength parameters and inclinations of the back of the nail head (i.e. parallel to slope surface, or perpendicular to the nail alignment). The results show that the bearing capacity of the parallel-to-slope-surface scenario would be generally 25% less than that of perpendicular-to-nail-alignment scenario where the values of effective stress shear strength parameters are small (viz. $c' = 2$ kPa & 4 kPa and $\phi' = 32°$ and 34°). In this regard, if the back of the soil-nail head is parallel to the slope surface, it is recommended that the presented ultimate bearing capacity in Tables 2.3, 2.4 and 2.5 should be reduced by 25%. In other words, the ultimate bearing capacity presented in brackets in Tables 2.3, 2.4 and 2.5 should be adopted.

Apart from the typical details of soil-nail head proposed in Figure 5.6 of Geoguide 7 for gentle slopes, an enhanced soil-nail head details with its back perpendicular to the soil nail alignment as shown in Figure 4.2 is proposed to maximise the effectiveness of the soil-nail head and to promote the soft landscaping on gentle slopes as a good practice. The hessian bags and the fixing details are taken from existing standard soil-nail head details (Figure 4.1) to ensure integrity of the soil-nail head. Designers may adopt alternative details to suit specific site conditions and applications.

As suggested in Geoguide 7 (GEO, 2017), one of the key functions of soil-nail heads is to enhance local stability of the ground between soil nails. Adopting a smaller soil-nail head will leave greater area exposed, which can be susceptible to shallow instabilities or erosion. Recommendations on prevention of local instability as given in Section 5.6.5 of Geoguide 7, e.g. provision of erosion control mat on the slope surface may not be of direct relevance for gentle slopes, except for localised areas particularly vulnerable to surface erosion, e.g. presence of thin veneer of loose fill. To minimise potential for surface erosion, attention should be made to avoid having features that may induce concentrated surface flow. It is also important to prevent surface erosion by maintaining existing vegetation and planting additional vegetation as recommended in GEO Publication No. 1/2011 (GEO, 2011). For example, pit planting of shrubs staggered between the soil-nail heads are generally applicable. Bioengineering solutions presented in Campbell et al (2008) and GEO (2011) such as live stakes (Figure 4.3) should be considered as appropriate for reducing the rate or extent of hillslope deterioration and thereby the potential for erosion and shallow failures.

The use of design soil nail as mitigation measures to deal with surface erosion in thin layers of loose materials (e.g. fill) on gentle hillslopes should be avoided. Instead, designers may consider the application of bioengineering measures as discussed above and to adopt combined use of erosion control mats fixed with stainless steel pins if necessary for areas susceptible to concentrated surface runoff and erosion. Further work is recommended to collect experience in the applications of different solutions for mitigation of shallow landslides on gentle hillslopes and for development of prescriptive measures.

Table 4.1 Summary of Calculated Ultimate Bearing Capacity of 600 mm Soil-nail Head with Different Inclination on a 35° Slope

ϕ'	Calculated Ultimate Bearing Capacity (kN)					
	Back of Nail Head Parallel to Slope Surface			Back of Nail Head Perpendicular to Nail Alignment		
	c' = 2 kPa	c' = 4 kPa	c' = 6 kPa	c' = 2 kPa	c' = 4 kPa	c' = 6 kPa
34°	63	98	120	84	111	135
36°	81	114	141	105	132	156
38°	102	144	180	126	153	180

Note: c' and ϕ' are the effective stress shear strength parameters of the soil.

DIMENSION TABLE

NAIL HEAD SIZE (mm)	REINFORCEMENT
400 x 400	3B16 U BARS BOTHWAYS
600 x 600	3B16 U BARS BOTHWAYS
800 x 800	4B16 U BARS BOTHWAYS

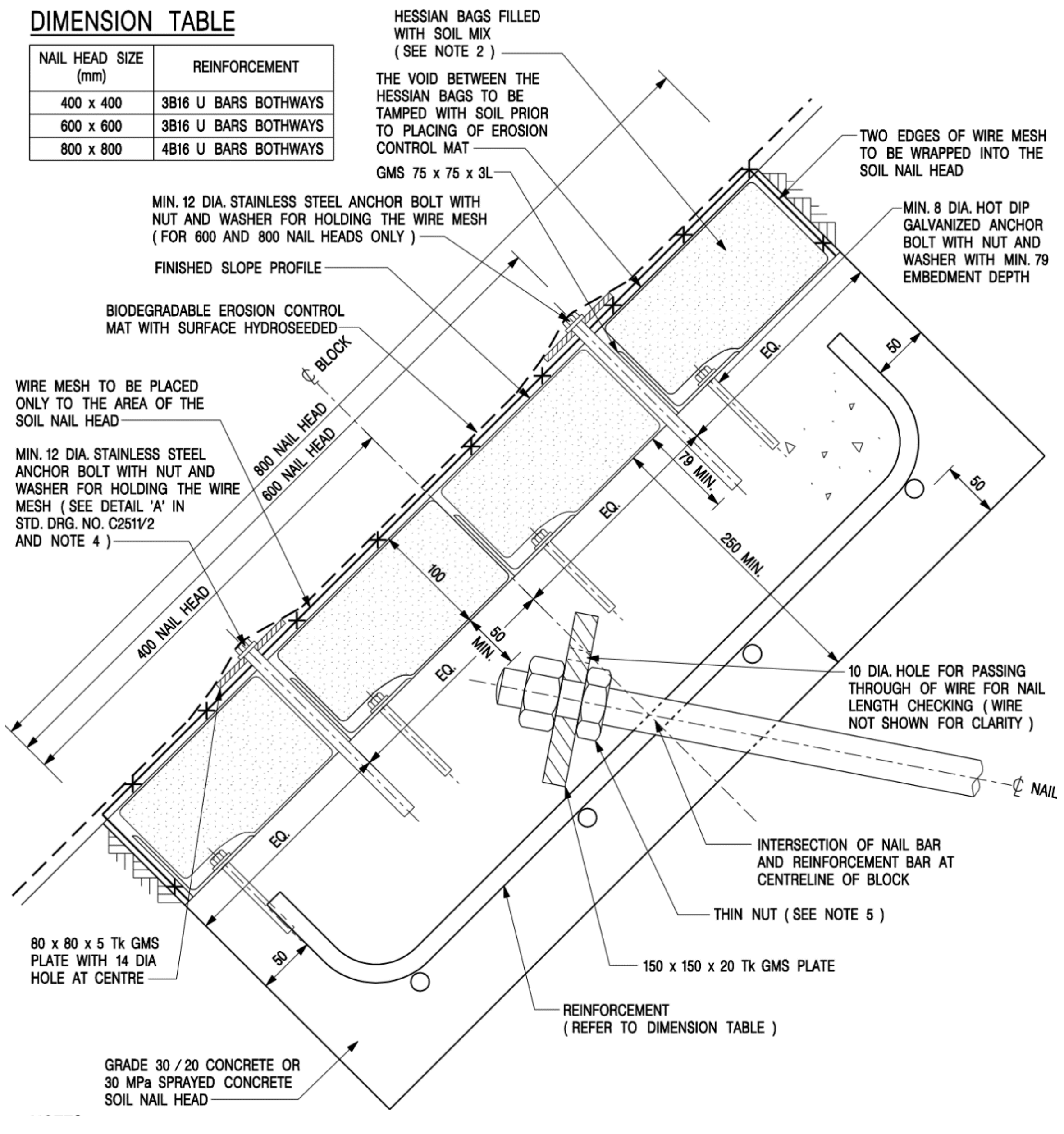
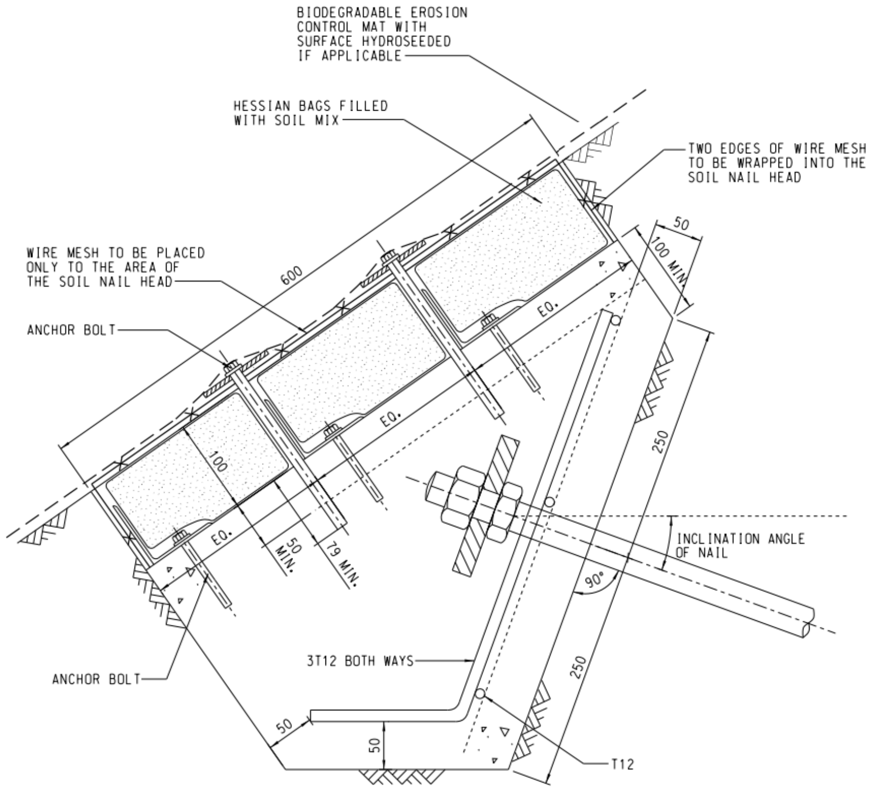
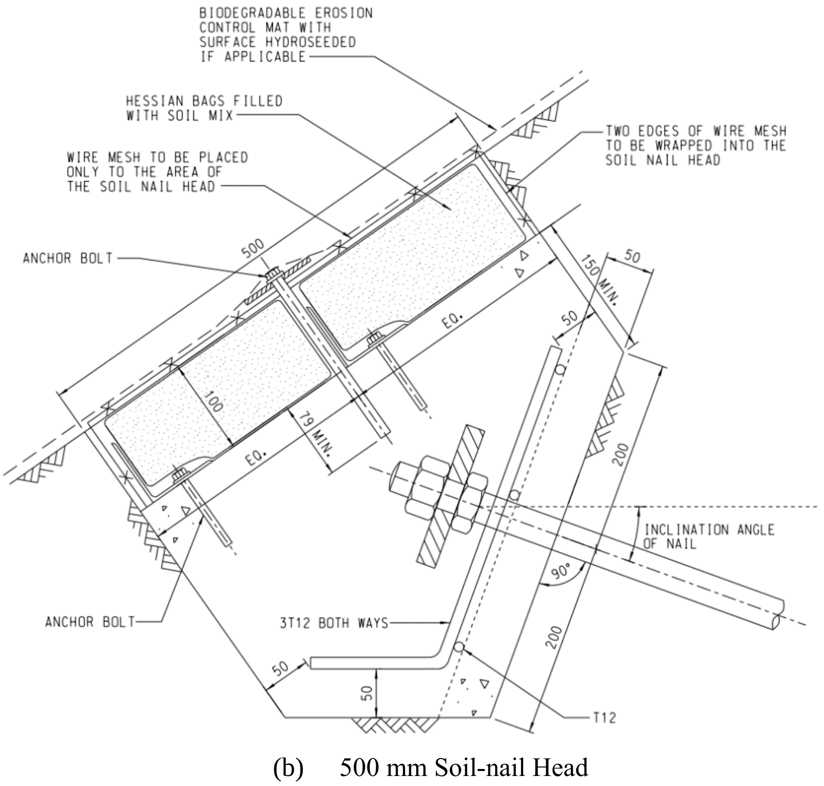


Figure 4.1 Typical Recessed Soil-nail Head Details for Hydroseeding Surface with Biodegradable Erosion Control Mat (Back of Nail Head Parallel to the Slope Surface) CEDD Standard Drawing No. C2106/7B

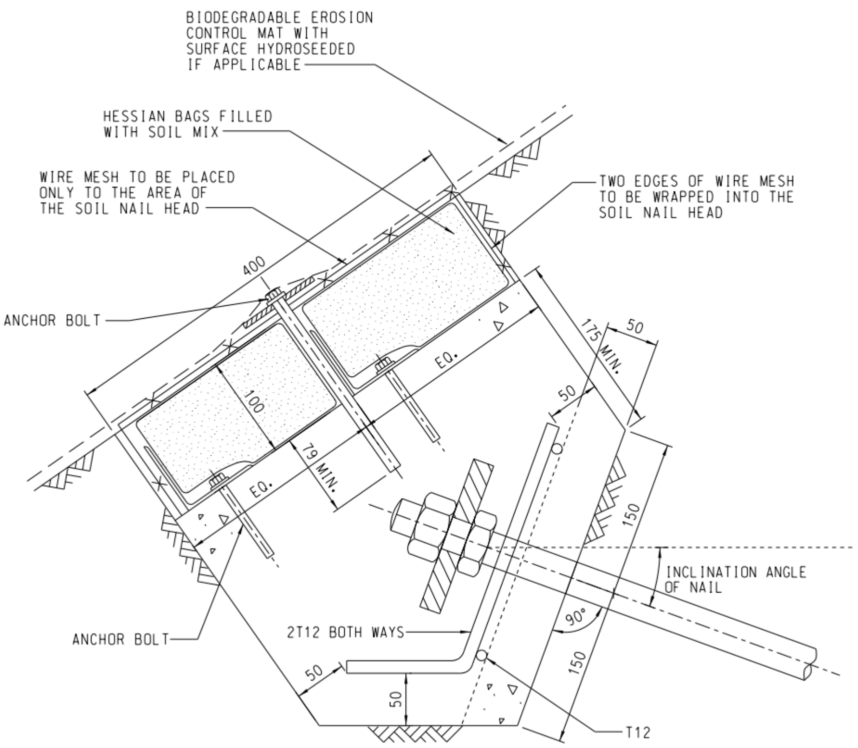


(a) 600 mm Soil-nail Head



(b) 500 mm Soil-nail Head

Figure 4.2 Enhanced Soil-nail Head Details for Soil Nails on Gentle Slopes (Back of Nail Head Perpendicular to the Nail Alignment) (Sheet 1 of 2)



(c) 400 mm Soil-nail Head

Figure 4.2 Enhanced Soil-nail Head Details for Soil Nails on Gentle Slopes (Back of Nail Head Perpendicular to the Nail Alignment) (Sheet 2 of 2)

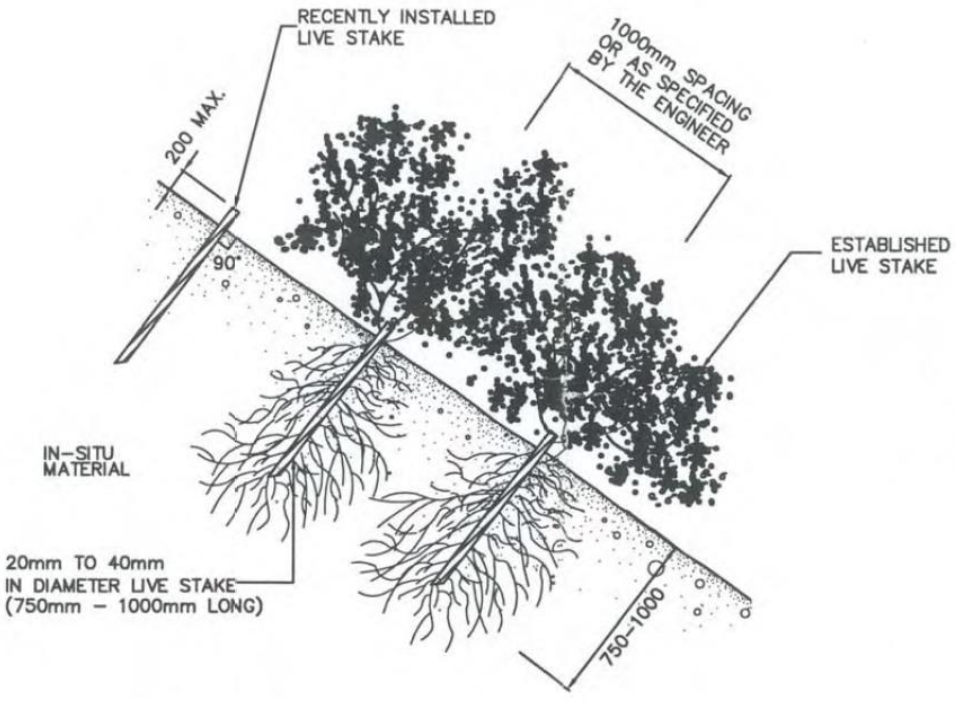


Figure 4.3 Details of Live Stake (Extracted from Sotir, 1996)

5 Recommendations and Conclusions

Geoguide 7 provides recommendation on sizing soil-nail head for slopes steeper than 45° based on findings from numerical modelling presented in GEO Report No. 175. Following the same modelling methodology, this study extends the numerical modelling using *FLAC* for the design of soil-nail head on gentle slopes, which is particularly relevant for the use of soil nails in mitigation of OHL hazards on natural terrains in Hong Kong. The key findings and recommendations are summarised in the following.

(1) The proposed method for calculation of bearing capacity of soil-nail head on gentle slopes in this study is essentially the same as that adopted for steep slopes as presented in Geoguide 7. Apart from adopting the lower bound bearing capacity equation proposed by the UK Department of Transport (DOT, 1994), ultimate bearing capacity of a 600 mm, a 500 mm and a 400 mm soil-nail head with its back perpendicular to the nail alignment as presented in Tables 2.3-2.5 of this report may be adopted. If the back of the soil nail head is parallel to the slope surface, the presented ultimate bearing capacity in brackets in Tables 2.3-2.5 should be used.

(2) The stabilisation forces required for mitigation of OHL hazards by using soil nails are generally lower than those required for steep man-made slopes.

(3) In general, a 400 mm, 500 mm or 600 mm soil-nail head would be adequate to conteract the stabilisation forces required for the soil nails to enhance general stability of relatively gentle slopes, in particular in mitigation of OHL hazards. This will greatly enhance buildability of the soil nail solution and promote sustainability to the environment as part of the natural terrain landslide mitigation works. Designers should specify soil-nail head with sufficient bearing capacity to counteract the required stabilisation forces of the soil-nail based on site-specific conditions and according to the ultimate bearing capacity values as recommended in para. (1) above, and with a minimum factor of safety of 1.2. The calculated bearing capacity of soil-nail head in this study is based on typical condition of gentle slopes. Designers should review the application if any adverse hydrogeological, geological and topographic features are present.

(4) An enhanced soil-nail head details with the back of the nail head perpendicular to the soil nail alignment has been proposed. This is to maximise effectiveness in mobilisation of the bearing capacity of the soil-nail head and to promote soft landscaping for gentle slopes. Designers should review

the structural adequacy of the reinforcement details if the application of the soil-nail head details is beyond the mitigation of OHL hazards following the generalised design objectives given in GEO Report No.138.

(5) Attention should be made to prevent concentrated surface runoff and to promote vegetation cover to prevent surface erosion of the ground between soil-nail heads. It is also important to prevent erosion by maintaining existing vegetation as recommended in GEO Publication No. 1/2011 (GEO, 2011). Planting of additional vegetation such as pit planting of shrubs and provision of bioengineering measures such as planting of live stakes (Figure 4.3) should be considered to enhance the robustness against potential shallow failure and soil erosion between soil-nail heads and to promote sustainability to the environment. For areas susceptible to concentrated surface runoff and erosion, designers may consider adopting combined use of erosion control mats fixed with stainless steel pins in addition to planting and bioengineering measures.

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