2nd Earth Structures and Retention Conference

Soil nail testing

Chris Bridges

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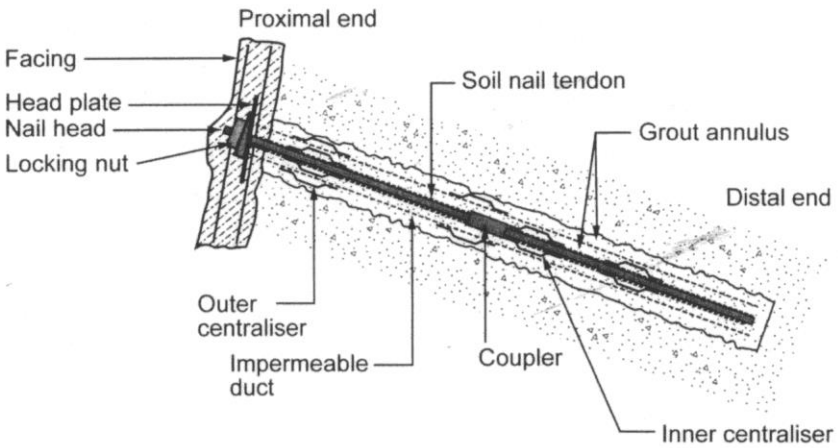
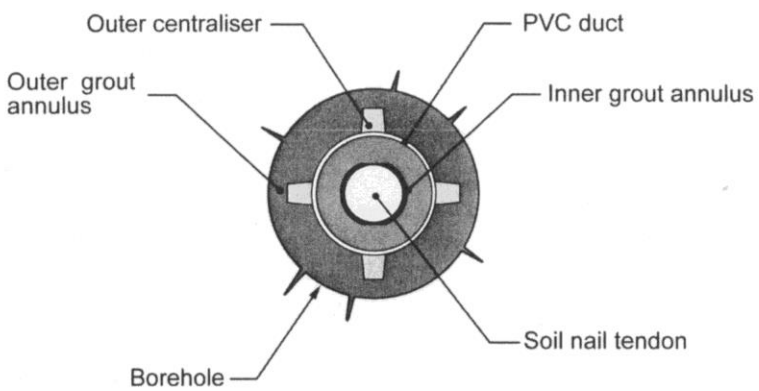
Introduction

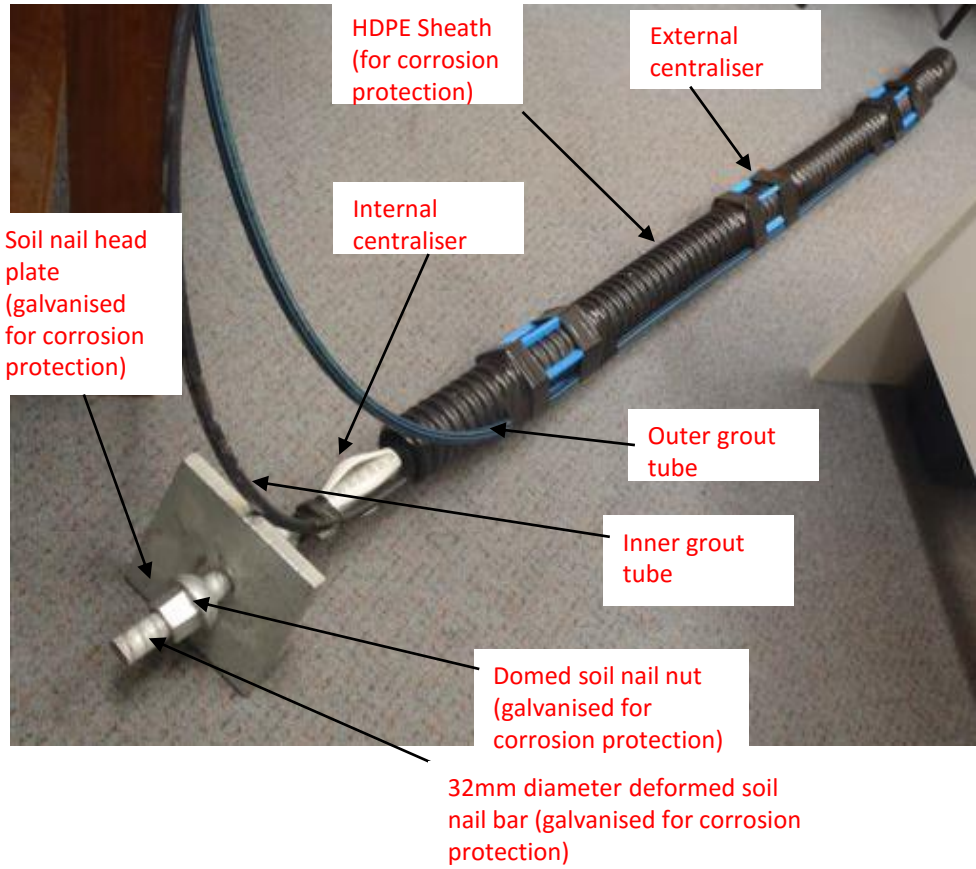
Soil Nail – Main Components





Section through soil nail

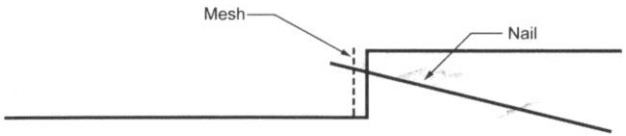
Note: Other systems may use flexible facing and/or may not use grout, impermeable duct or couplers



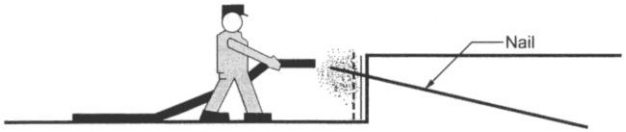
Construction Sequence

1 Excavation of appropriate lift height

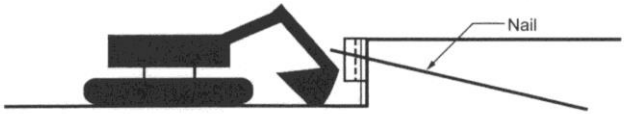
2 Drilling nail hole



3 Installation of nail, mesh and fixing assemblies



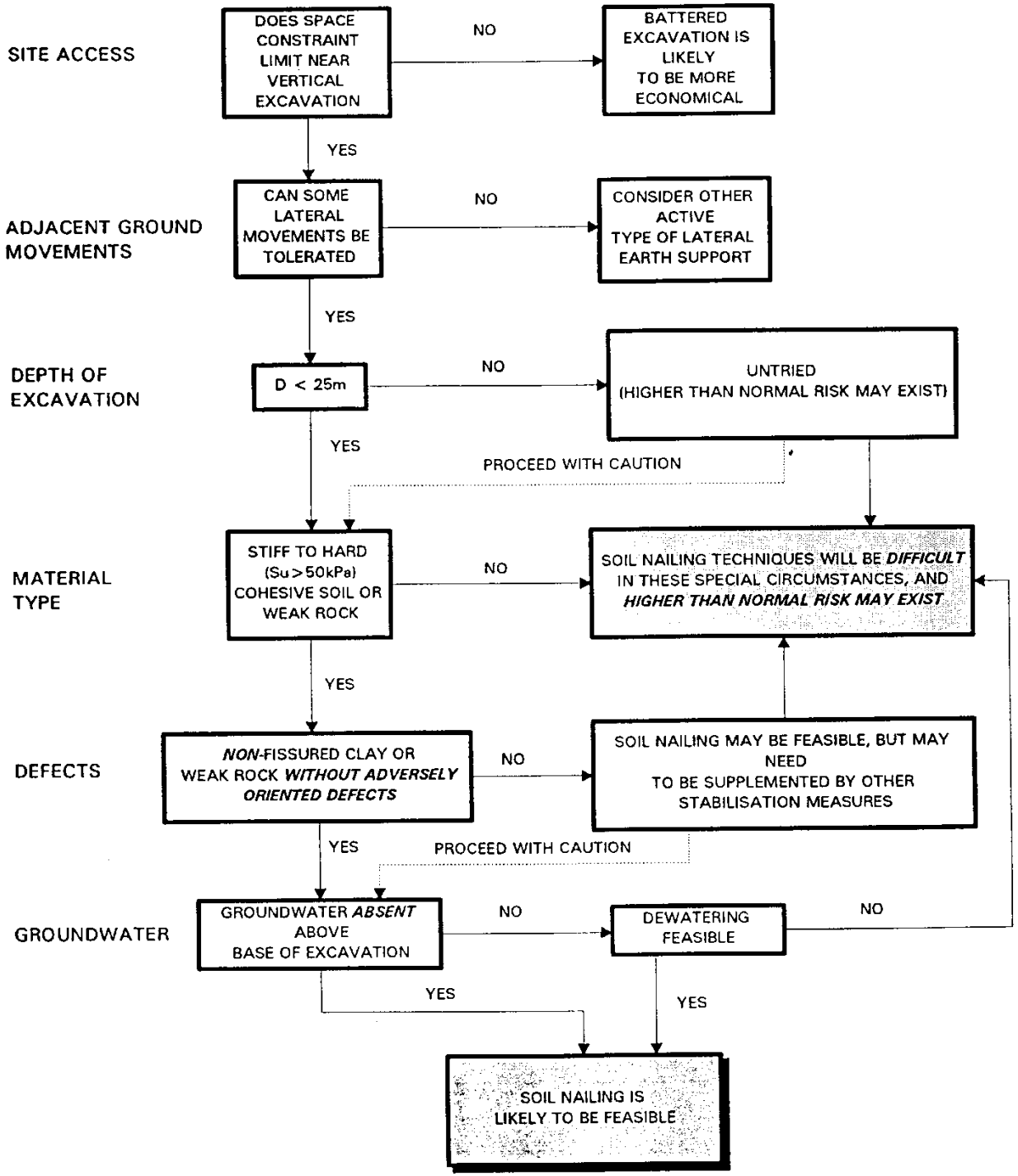
4 Application of sprayed concrete facing



5 Excavation of next lift

Applications

- construction of new slopes and retaining walls
- construction of temporary works
- upgrading existing slopes with inadequate stability
- the renovation of old retaining structures


SITE ACCESS
DOES SPACE CONSTRAINT LIMIT NEAR VERTICAL EXCAVATION
NO
BATTERED EXCAVATION IS LIKELY TO BE MORE ECONOMICAL
YES
ADJACENT GROUND MOVEMENTS
CAN SOME LATERAL MOVEMENTS BE TOLERATED
NO
CONSIDER OTHER ACTIVE TYPE OF LATERAL EARTH SUPPORT
YES
DEPTH OF EXCAVATION
D < 25m
NO
UNTRIED (HIGHER THAN NORMAL RISK MAY EXIST)
YES
PROCEED WITH CAUTION
MATERIAL TYPE
STIFF TO HARD (Su > 50kPa) COHESIVE SOIL OR WEAK ROCK
NO
SOIL NAILING TECHNIQUES WILL BE DIFFICULT IN THESE SPECIAL CIRCUMSTANCES, AND HIGHER THAN NORMAL RISK MAY EXIST
YES
DEFECTS
NON-FISSURED CLAY OR WEAK ROCK WITHOUT ADVERSELY ORIENTED DEFECTS
NO
SOIL NAILING MAY BE FEASIBLE, BUT MAY NEED TO BE SUPPLEMENTED BY OTHER STABILISATION MEASURES
YES
PROCEED WITH CAUTION
GROUNDWATER
GROUNDWATER ABSENT ABOVE BASE OF EXCAVATION
NO
DEWATERING FEASIBLE
NO
YES
YES
SOIL NAILING IS LIKELY TO BE FEASIBLE

Suitability

Soils that are self supporting soil for a short period, over typical excavated depths of 1.0m to 1.2m

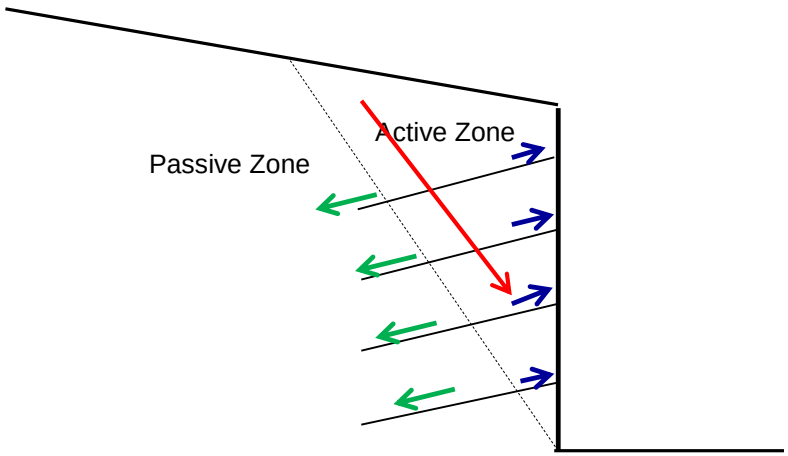
- Stiff or better clays
- Cemented sands
- Weathered rock
- Dry

Soil Nail Walls are not such a great idea in water charged sands and silts

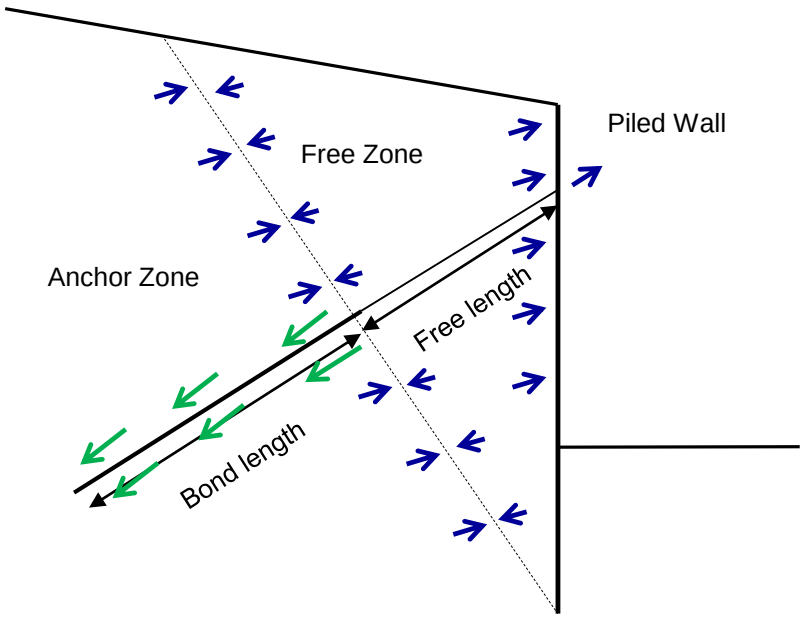
(They also can't be expected to have a 2 weeks stand up time)

Soil nailing and ground anchors

Soil nails

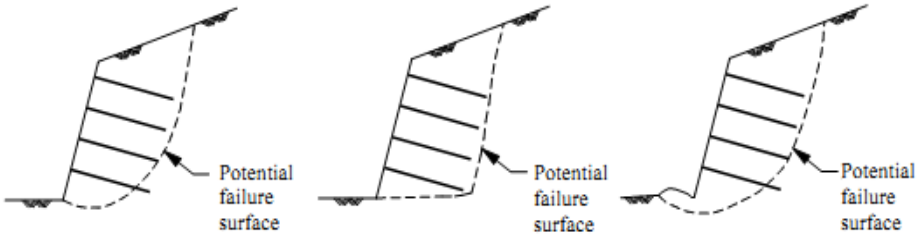


Ground anchors

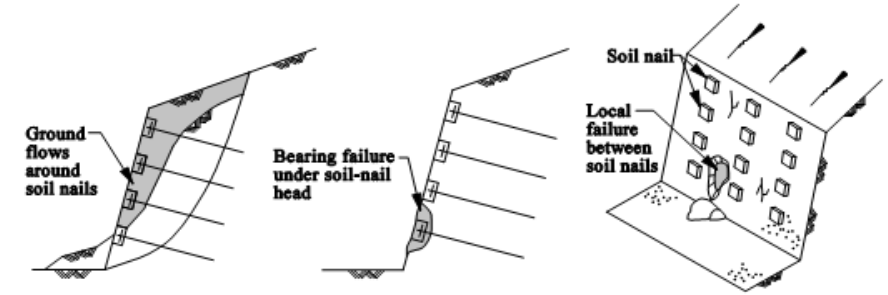


Modes of failure

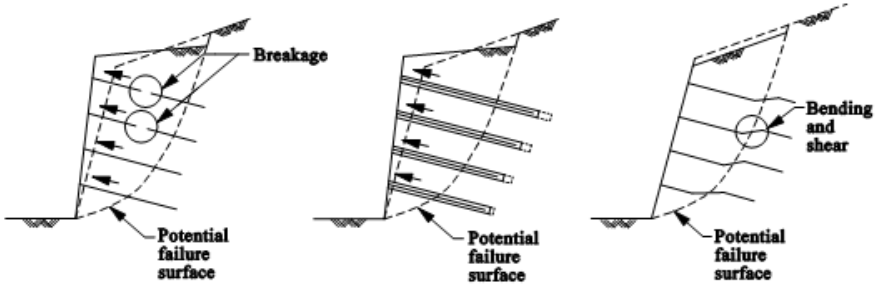
External Stability



(a) Overall Stability Failure (b) Sliding Failure (c) Bearing Failure

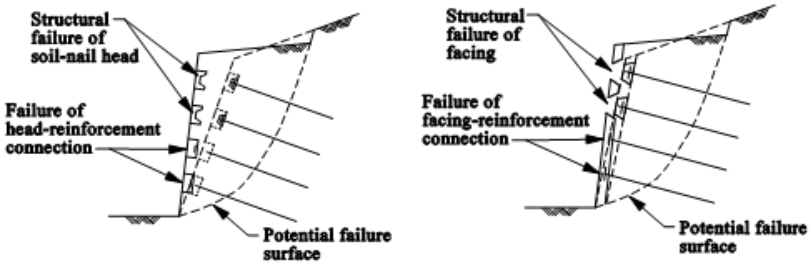


(a) Failure of Ground around Soil Nails (b) Soil-nail Head Bearing Failure (c) Local Failure between Soil Nails



(d) Tensile Failure of Soil Nails (e) Pullout Failure at Ground-grout Interface (or Grout-reinforcement Interface) (f) Bending or Shear Failure of Soil Nails

Internal Stability

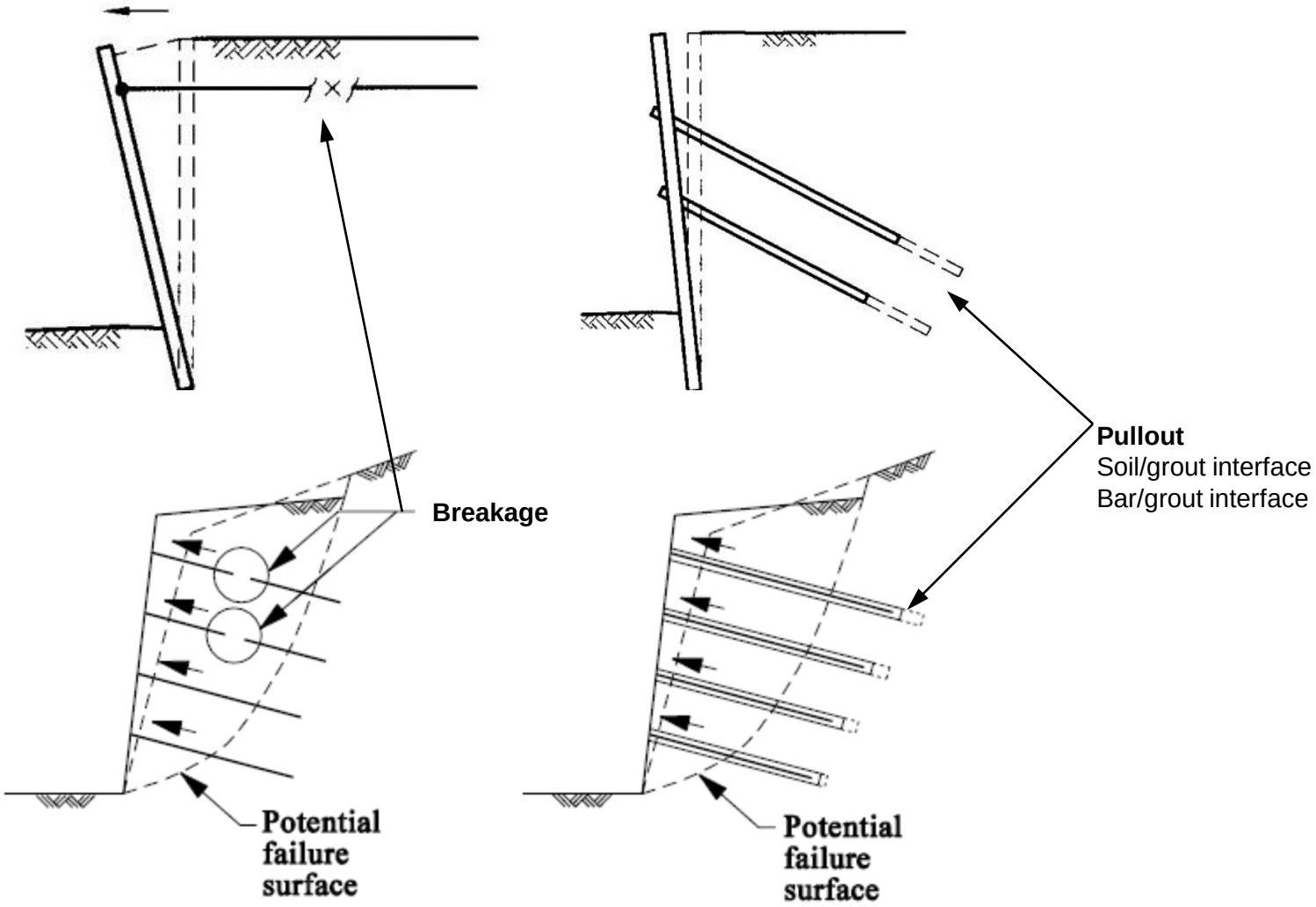


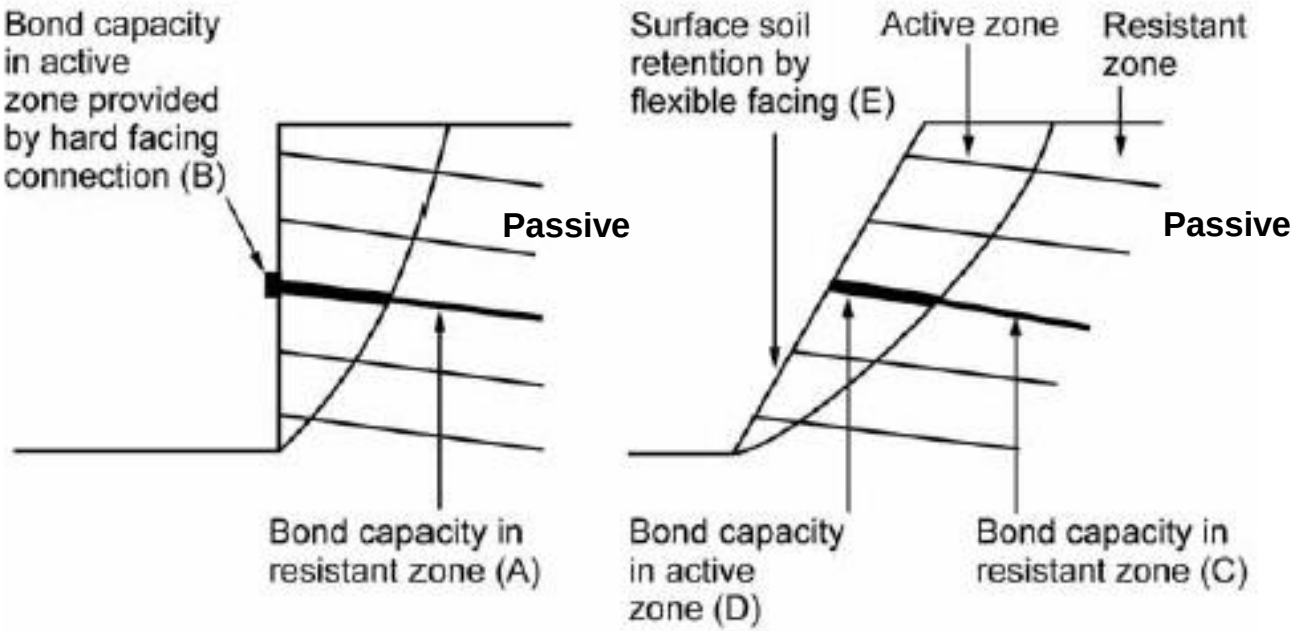
(g) Structural Failure and Connection Failure of Soil-nail Head (h) Structural Failure and Connection Failure of Facing

Anchor & Soil Nail failure - internal

Ground Anchors

Soil Nails





Wall or slope stabilisation with hard facing

Slope stabilisation with flexible facing

Major components of load transfer	Major components of load transfer
• bond capacity in the resistant zone (A) • plate bearing capacity to transfer load from facing structure (B) • strength of facing structures to retain active soil (B)	• bond capacity in the resistant zone (C) • bond capacity in the active zone (D) • surface soil retention by flexible facing (E)
Minor components of load transfer	**Minor components of load transfer**
• bond capacity in the active zone • bond capacity to the hard facing structure	• plate bearing capacity to supplement bond capacity of the active zone

Design codes and standards

AS4678-2002 Earth Retaining Structures (VicRoads)

BS8006:1995 - Strengthened/ reinforced soils and other fills (QLD TMR)

BS8006:2011-2 - Strengthened/ reinforced soils and other fills (QLD TMR)

FHWA Geotechnical Engineering Circular No. 7 – Soil nail walls (2003/2015)

CIRIA C637 Soil nailing – best practice guidance (2005)

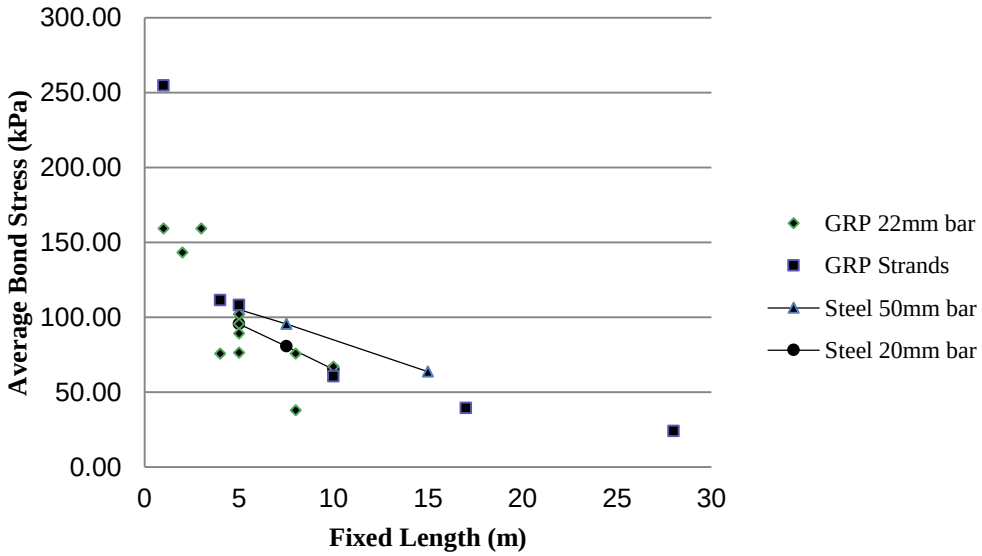
Traditional FOS approach – 1.5 on global, reduction factor of bond 1.5-2

Preliminary Sizing

Typical nail spacing, walls –	1m - 2m (1 nail per $1m^2$-$4m^2$ of face)
Typical lifts -	1.2m
Length of Nails -	0.8 - 1.2H

It is recommended that the soil nail length outside the anticipated failure surface should not exceed 5m, and bar diameters should be greater than 20mm (CIRIA). GRP should not exceed 3m.

Note: in soils nail lengths above 15m maybe difficult to achieve due to hole collapse.



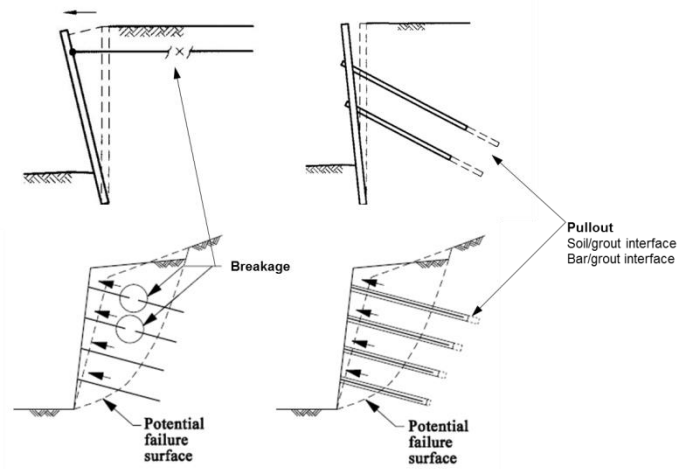
02
Soil nail testing

Soil nail testing

The primary method of testing soil nails *in situ* is by pulling the nail at the nail head.

There are 3 ways in which soil nails can fail due to internal stability:

- Tensile failure of the soil nail bar
- Failure between the grout and bar
- Failure between the grout and soil



The first two failure mechanisms are generally well defined but the capacity of the grout / soil interface is difficult to predict

Soil nail testing

Factors which can affect the grout / soil capacity include:

- Drilling technique
- Grouting method
- Ground conditions

It is, therefore, important to get site specific information via field tests on nails that are installed in the same way as the permanent (production) nails

Construction method	Soil type	Ultimate bond stress (kN/m^2)	Source
Augered	Loess	25–75	2
	Soft clay	20–30	1
	Stiff to hard clay	40–60	1
	Clayey silt	40–100	1
	Calcareous sandy clay	90–140	1
	Silty sand fill	15–20	1
Open hole	Non-plastic silt	20–30	2
	Medium-dense sand and silty sand/sandy silt	50–75	2
	Dense silty sand and gravel	80–100	2
	Very dense silty sand and gravel	120–240	2
	Stiff clay	40–60	2
	Stiff clayey silt	40–100	2
	Stiff sandy clay	50–100	3
Rotary-drilled	Marl/limestone	300–400	1
	Soft dolomite	400–600	1
	Weathered sandstone	200–300	1
	Weathered shale	100–150	1
	Weathered schist	100–175	1
	Basalt	500–600	1
	Silty sand	100–150	1
	Silt	60–75	1
Driven casing	Dense sand/gravel	180–210	3
	Sandy colluvium	70–150	3
	Clayey colluvium	40–75	1
Jet-grouted	Sand	380	1
	Sand/gravel	700	1

Tests

Two basic types of test:

- Sacrificial nail test
- Production nail test

The procedure of the test may vary depending on what you are trying to achieve

Types of test

Sacrificial

Design / Investigation

- Carried out before design starts to investigate the ultimate bond stress
- Test load usually a function of bar strength
- Typically optional

Suitability

- Carried out either before design starts our during construction to confirm the ultimate bond stress used in design
- Test load usually based on design or working load
- Typically one per material type

Production

Acceptance

- Carried out typically on a percentage of production nails
- Confirm satisfactory performance at working load
- Test load usually based on design or working load
- Typically fully grouted

Creep Test

- Typically carried out as part of another test, but can be carried out separately
- To determine susceptibility to creep

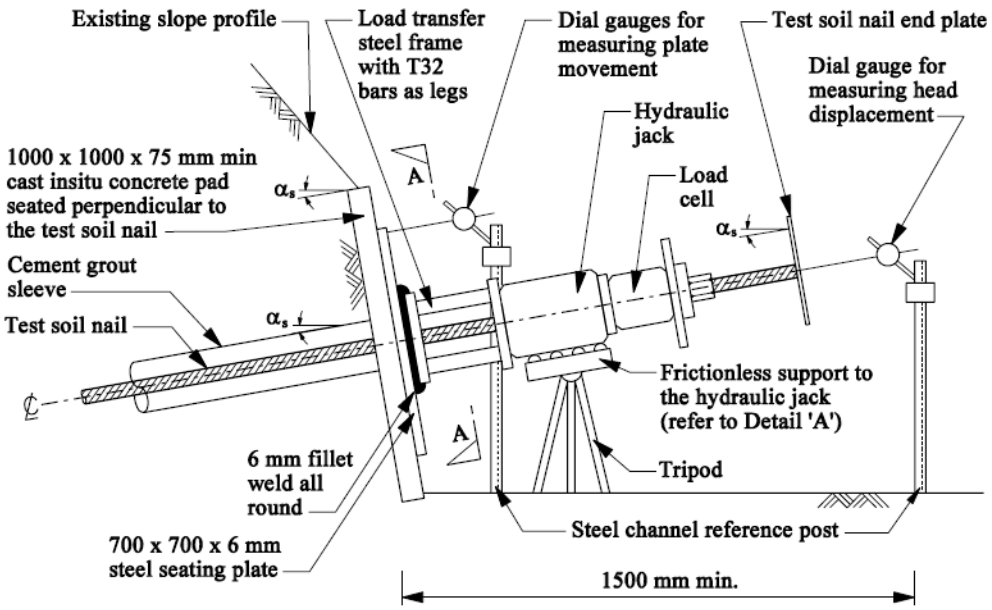
Sacrificial Tests

Pulling out the soil nail involves some risk


Sacrificial nail testing


Production nail testing

Testing setup



Testing setup

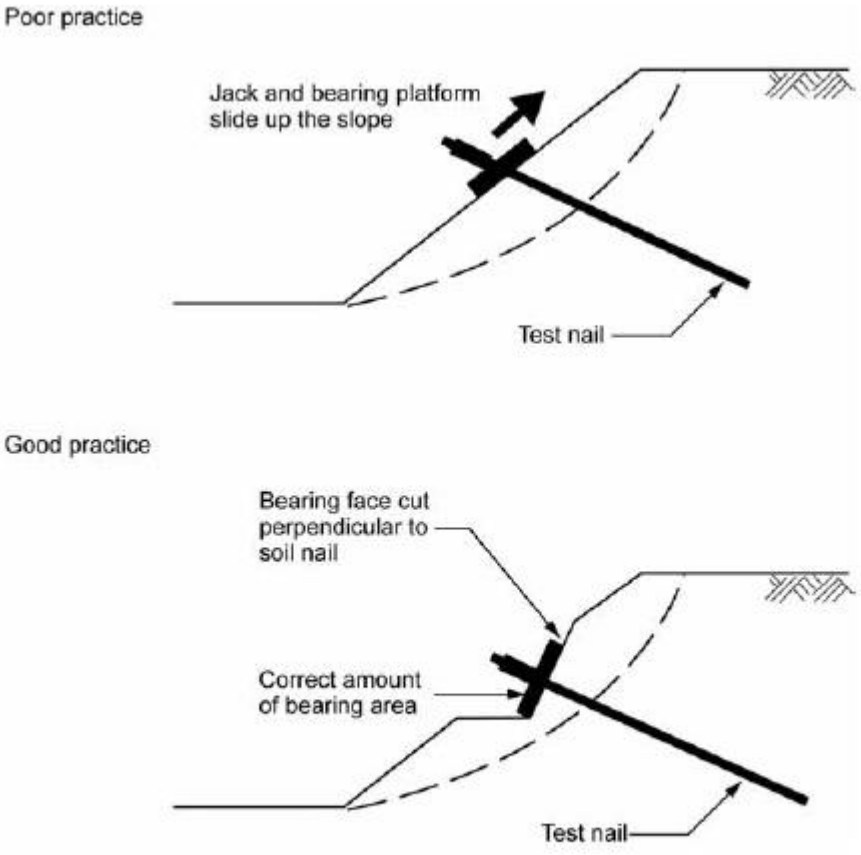


Figure 11.4 *Preparation of bearing face for soil nail testing (adapted from Dywidag Systems International Ltd, 2003)*

Testing setup

- Length of grouted zone
- Free (unbonded) length requirements
- No. of cycles
- Loading and unloading intervals
- Test load
- Period for holding load at intervals and test load
- How many tests
- Bar size (larger bar size than for production nails may be required to test full ultimate bond stress)
- Head arrangement

Specifications

Requirement	Reasoning
• Bedding-in load of 10%	• Alignment of equipment
• Load intervals equally distributed	• Good practice to apply the test load gradually
• Minimum elongation (a percentage of the elastic deformation of unbonded length – 80-100%)	• To confirm the unbonded length
• Maximum deformation of 2mm over log time (typ. 5min/50min or 6min/60min)	• If creep rate exceeds 2mm per log cycle of time additional load will lead to continuing grout body movements

Production testing requirements

Jurisdiction	Requirement
• QLD TMR (MRTS03)	• 3 Cycles, held for 60 mins, test load = 1.5 x working load • Tests: 1-50 nails – 3 tests, 51-100 nails – 6 tests, >100 nails – 6% of nails
• VicRoads (Section683)	• 1 Cycle, held for 240 mins, test load = 1.5 x design load, **sacrificial** • Tests per row, largest of: 5%, 2 nails, 2 nails per soil type, 2 per installation method
• NSW RMS (R64)	• 1 Cycle, held for 180 mins, test load = 1.5 x working load • Tests: 3% of nails, 50% top row, 25% middle row, 25% bottom row
• CIRIA C637	• 1 Cycle, held for 60 mins, test load = 1.1-1.5 x working load or = 1 x design load • *Tests:1-200 nails – 3-5 tests, >200 nails - 1.5%-2.5% of nails
• BS8006:2011 (BS EN 14990:2010)	• Test as per CIRIA C637 • *Tests: 2-3%, min 3-5 nails, 1 nails per soil type, 1 per excavation stage
• Hong Kong	• No test specified – **non-destructive testing only**

*** Based on risk**

Sacrificial testing requirements

Jurisdiction	Requirement
• QLD TMR	• No test specified
• VicRoads	• 1 Cycle, held for 240 mins, test load = 1.5 x ultimate bond stress, sacrificial • 3 tests per each type of soil profile
• NSW RMS	• 4 Cycles, held for 180 mins, test load = 2 x “design working load” or failure or 80% of the ultimate tensile strength, whichever is lower • Tests: 1% of nails, min 2 nails
• CIRIA C637	• Min. 2 Cycles, held for 60 mins, test load = 1.5-2 x design load • 1-2 tests per each type of soil profile, min. 3-6 tests
• BS8006:2011 (BS EN 14990:2010	• Test as per CIRIA C637 • *Tests: min 3-5 nails, 1-2 nails per soil type
• Hong Kong	• 3 Cycles, held for 60 mins, test load=90% yield strength of bar • Tests: 2% of nails, min 2 nails • Creep test can be carried out as 2nd cycle of the pullout test or separately. Test load = 1.5 x design bond stress

*** Based on risk**

Comparison Example

Analysis based on BS8006:2011
Working load: 34 kN
Design load: 115 kN
Ultimate bond stress: 100 kPa
Allowable Bar tensile capacity: 260 kN (AS2678)
90% yield strength: 360 kN
100mm grout hole

	QLD TMR	VICROADS	NSW RMS	BS8006:2011/ CIRIA C637	HK Geoguide 7
Production test load (kN)	51 (1.5 x working load)	172.5** (1.5 x design load)	51 (1.5 x working load)	38 – 51 (1.1-1.5 x working load)	Non-destructive testing
Time load held (min)	60	240	180	60	-
Sacrificial test load (kN)*	-	32/m of nail (1.5 x ult. bond stress)	230 (2 x design load)	172.5 – 230 (1.5-2 x design load)	360 (2m bond typical)
Time load held (min)	-	240	180	60	60

*Sacrificial load tests always have an upper limit based on bar strength.
**Sacrificial test

Failure Criteria – sacrificial nails

VICROADS	NSW RMS	BS8006:2011/ CIRIA C637	HK Geoguide 7
plot of nail head displacement with log time shall be linear or display a decreasing rate of creep	The creep rate is linear or decreasing, when plotted against the logarithm of time throughout Cycle 4		plot of nail head displacement with log time shall be display a decreasing rate of creep (creep test only)
creep rate shall be less than 2 mm per log cycle of time at the test load	total creep movement of less than 2 mm between the 6 and 60 minutes readings is measured during Cycle 4	creep rate shall be less than 2 mm per log cycle of time at the test load	creep rate shall be less than 2 mm per log cycle of time at the test load or 0.1% of bonded length
the movement of the steel bar head under the test load shall be less than 0.2% of the bonded soil nail length	total creep movement of less than 1mm between the 60 and 180 minutes readings is measured in Cycle 4		
total nail head displacement at the design load shall not exceed 12 mm beyond the theoretical elastic deformation of the free length plus one half of the bonded length		total nail head displacement at the test load shall be not less than the theoretical elastic deformation of the free length (CIRIA is 80%)	

Failed test?

	VICROADS	NSW RMS	BS8006:2011	CIRIA C637	HK Geoguide 7
Production	Review, revise and agree with Superintendent.	Test an additional 2 soil nails in the vicinity of the nonconforming soil nail and remove failed nail.	Consult designer for action to be taken and approval to continue.	Consult designer	N/A
Sacrificial	Revise the design and shall undertake further sacrificial testing	Repeat on replacement nail at own cost	Review soil nail installation method and/or consider alternative soil nail length and layout.	*Design/ investigation test:* Not applicable. *Suitability test:* Review the soil nail installation method, length, layout	Record test data

- QLD MRTS03 – not stated
- Client or contractors cost to replace and re-test?
- Failure due to ground conditions or poor workmanship?

03

What are some of the issues with soil nail testing?

Testing issues

- Different requirements in different jurisdictions
- Generally derived from ground anchor testing
- Some are generic and do not take account of the site specifics
- Magnitude of test load is a function of the design method adopted
- Do not necessary take account of how soil nails behave
- Testing production nails can cause debonding in the active zone with detrimental effects

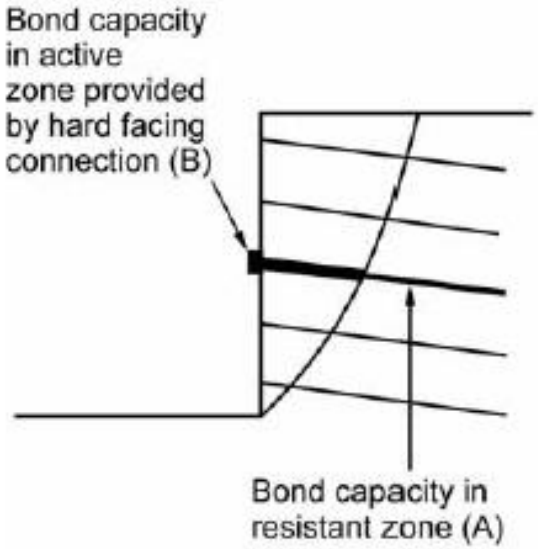
Soil nailing and ground anchors

Soil nails

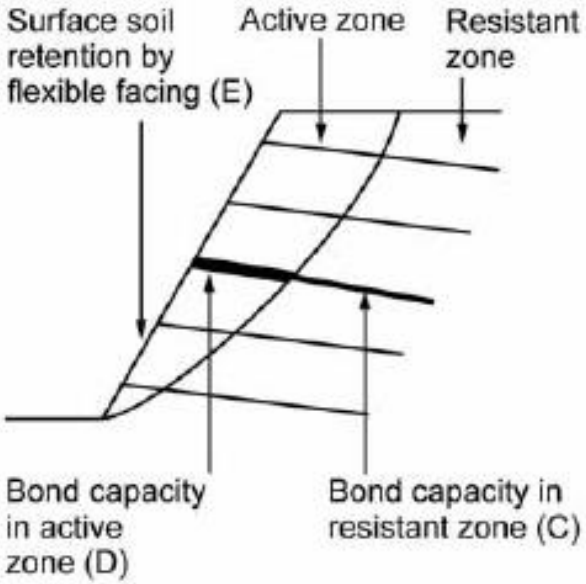
- Soil nails are not stressed and require an amount of movement to work
- Soil nails fully encased in grout
- Installed at a higher density than ground anchors so failure of one nail is not as critical. Construction tolerances not so high as soil nails work as a mass and not individual basis. Relatively low load per nail
- Soil nails have lower head loads which can be addressed with small headplates within a shotcrete surface
- Typically less than 15m
- Usually addressing shallow failure surfaces

Ground anchors

- Typically stressed (up to its design load) to inhibit structural movement
- Only grouted over fixed anchored length
- Lower density of anchors so single anchor failure critical – low redundancy. High loads per anchor
- Anchors are usually under high load which require substantial bearing structures at the head
- Usually long (15m-45m)
- Usually suitable for deep seated failure



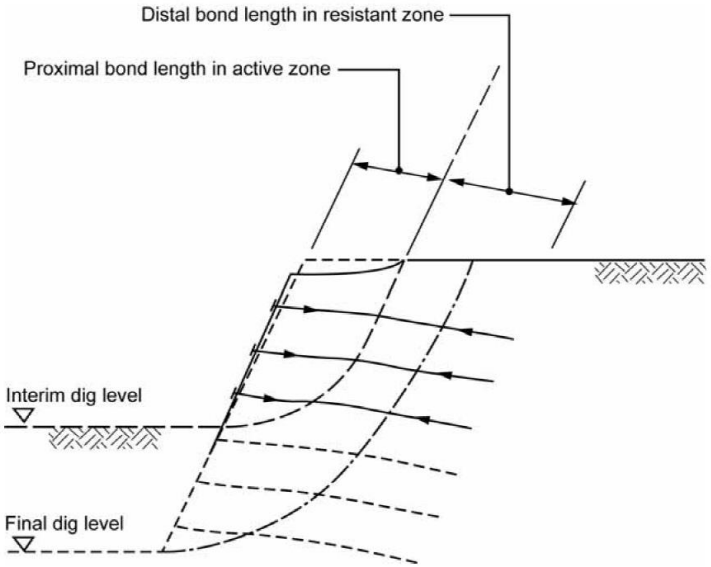
Wall or slope stabilisation with hard facing



Slope stabilisation with flexible facing

Major components of load transfer	Major components of load transfer
• bond capacity in the resistant zone (A) • plate bearing capacity to transfer load from facing structure (B) • strength of facing structures to retain active soil (B)	• bond capacity in the resistant zone (C) • bond capacity in the active zone (D) • surface soil retention by flexible facing (E)
Minor components of load transfer	**Minor components of load transfer**
• bond capacity in the active zone • bond capacity to the hard facing structure	• plate bearing capacity to supplement bond capacity of the active zone

- As the excavation proceeds the bond stress distribution along the soil /grout interface changes
- This means we need to make sure that testing is carried out within the active and passive zones



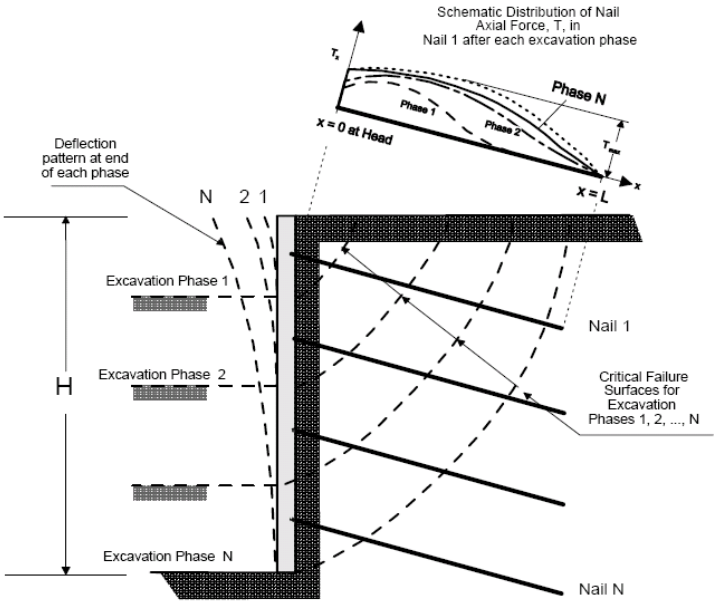
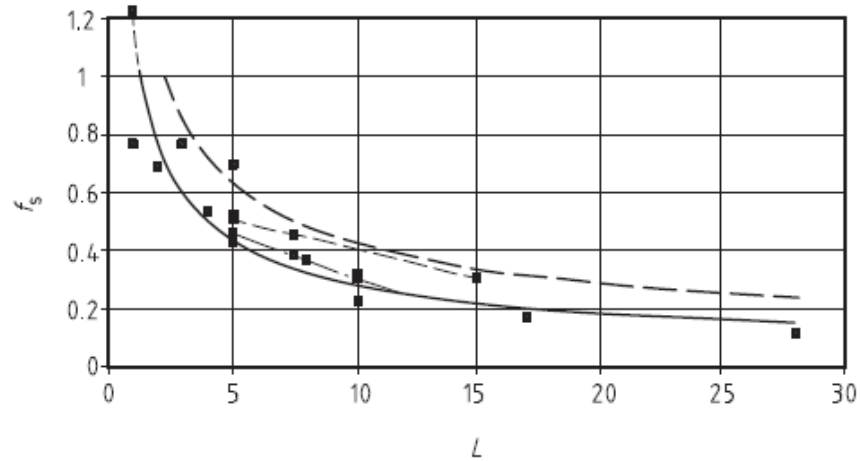


Figure 5.1: Potential Failure Surfaces and Soil Nail Tensile Forces.

Nail lengths

- The bond length of sacrificial nails often shorter than production nails

Figure 26 Effect of test length and axial stiffness on measured average bond



Key

GRP nails, $f_s = 1.19L^{-0.62}$

Anchors, $f_s = 1.60L^{-0.57}$

50 mm steel bar nails, $f_s = 0.61 - 0.02L$ $(15 > L > 5)$

20 m steel bar nails, $f_s = 0.61 - 0.3L$ $(10 > L > 5)$

f_s Efficiency factor

L Fixed length (m)

After Barley and Graham [18].

BS 8006-2:2011

Production Nails – to test or not to test?

- **BS EN 14490:2010 9.3.2.4** If load tests are conducted on production nails, consideration should be given to downgrading the capacity, and additional nails may be installed to provide sufficient resistance and long-term stability.
- **BS 8006-2:2011 6.1.1** Due to the mobilization of the strain field in a test nail subject to a pull-out test being significantly different from production nails, pull-out tests on production nails should be avoided being confined to sacrificial nails only
- Where to test - Centrifuge modelling – lower row of nails critical

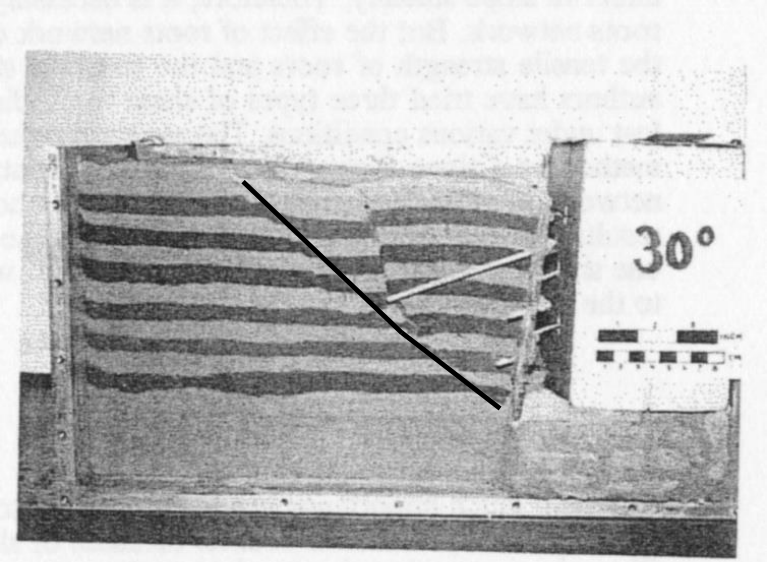


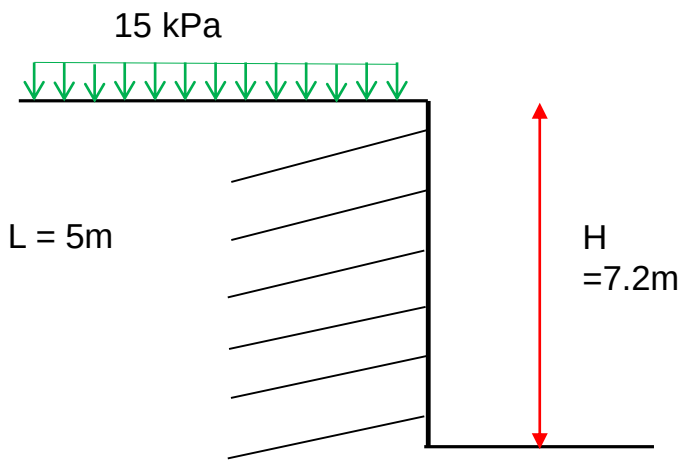
Figure 5. Test 4 - 30^0 nail inclination

Partial factors and factors of safety

System / Factor	FHWA (2003)	Clouterre (1991)	HA 68/94	BS8006: 1995 (Table 26)	BS8006-2: 2011 Set 1 (Table 5)	BS8006-2: 2011 Set 2 (Table 5)	Nordic Hand-book (2002)	CIRIA C637 (2005) (DA1-1) (Table 8.2)	CIRIA C637 (2005) (DA1-2) (Table 8.2)	Geoguide 7 (2008)	AS4679-2002 (Annex C) Case A	AS4679-2002 (Annex C) Case B	AS4679-2002 (Annex C) Case C
Load factors													
Soil weight	1.0	1.05/0.95	1.0	1.5	1..35	1.0	1.0	1.0	1.0	1.0	1.25	1.25/0.8	1
Dead surcharge	1.0	1.2	1.0	1.2	1.35	1.0	1.0	1.35	1.0	1.0	1.25	0.8	1
Live surcharge	1.0	1.33	1.0	1.3	1.5	1.3	1.3	1.5	1.3	1.5	1.5	0/1.5	0.4/0.7/1.0
Soil parameters													
tan f'	1.0	0.77-0.83	0.67-0.77	1	1.0	0.77	0.8	1.0	0.8	0.82	0.75-0.95	0.75-0.95	0.9-1.0
c'	1.0	0.61-0.67	0.67-0.77 <5kN/m^2	0.63	1.0	0.77	0.63	1.0	0.8	0.83	0.5-0.9	0.5-0.9	0.65-1.0
c_u	1.0	0.71-0.77	-	1.0	1.0	0.71	1.0	1.0	0.71	0.5	0.3-0.6	0.3-0.6	0.5-0.9
Soil nail pullout	2	1.4-1.9	1.0	1.3	1.1-1.7	1.5-2.25		1.25-2.0	1.25-2.0	1.5-2.0	1.3-1.6	1.3-1.6	1.3-1.6
Overall stability	1.35	1.125	1.0	1.0 or 1.25	1.0	1.0	1.0	1.0	1.0	1.0-1.4	1.0	1.0	1.0

Soil nailing – code comparison

Example wall



c' = 4 kPa
ϕ' = 36 deg
Ultimate bond = 100 kPa

Results

- Max. working load 34 kN
- Ave. working load 22 kN
- Max. design loads varied from 71 kN to 117 kN

- So it is important that the specifying authority recommend the use of one approach to maintain consistency – establish precedent

04
Conclusions

Testing

- Risk
- Body of data of similar soils / previous experience of the ground conditions
- Ground conditions – creep susceptible?
- Upgrade or new works / slopes or walls
- Site supervision

coffey

Table 2 — Suggested frequency of soil nail load tests based on density of nails and geotechnical structure category

Test type	Suggested Minimum Frequency of Load Tests	
	Sacrificial nail test	Production nail test
Geotechnical Category 1: negligible risk to property or life.	Optional	Optional
Geotechnical Category 2: no abnormal risk to property or life.	If no comparable experience of soil type: a minimum of three sacrificial nails with at least one sacrificial nail per soil type. Where direct experience exists then sacrificial nail tests are optional.	2 %, min. three tests.
Geotechnical Category 3: all other structures not in Category 1 or 2.	A minimum of five sacrificial nails with at least two sacrificial nails per soil type.	For number of nails: 3 %, min. five tests.

NOTE 1 Geotechnical Category of structure as defined in EN 1997.

NOTE 2 Test nails should be evenly distributed throughout the structure.

NOTE 3 The frequency of testing is a suggested minimum.

NOTE 4 Where sacrificial nail tests are carried out the number of production nail tests can be reduced on a pro-rata basis.

NOTE 5 For spacing, less then 0,8 m, a group test of four nails is recommended.

from BS EN 14490:2010

Problem soils

Cohesive soils

- Problematic
- Should not be installed in:
  - Organic soils
  - Consistency Index, Ic [= (LL-w / LL–PL)] < 0.9
  - LL > 50%
  - PI > 20%
- Saturated soft sensitive clays (undrained condition) – creep susceptible
- Insitu Su < 50kPa or remoulded Su < 25kPa are creep susceptible

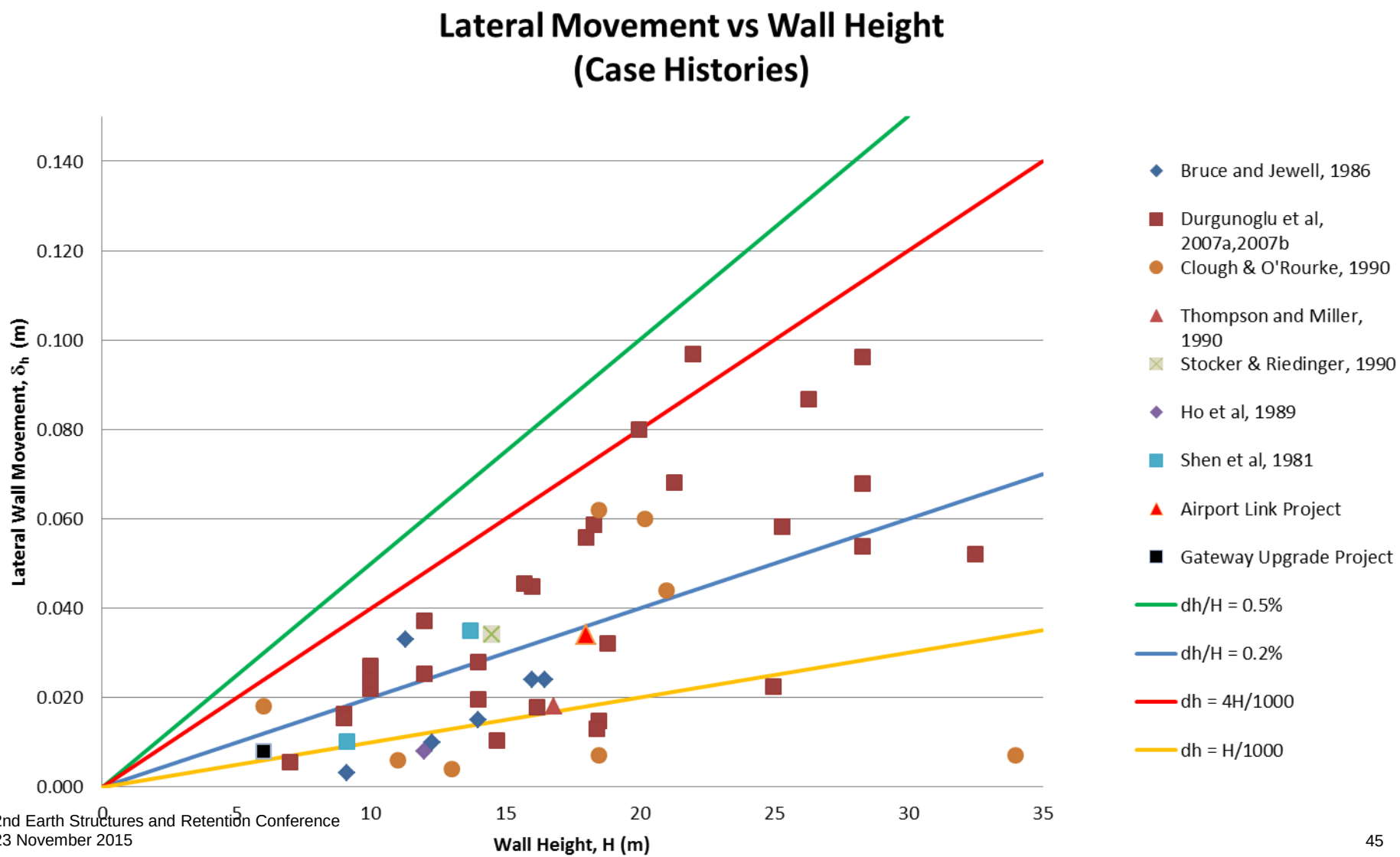
Non-cohesive soils

- Should not be installed where:
  - SPT <10
  - Rel. Density <0.3

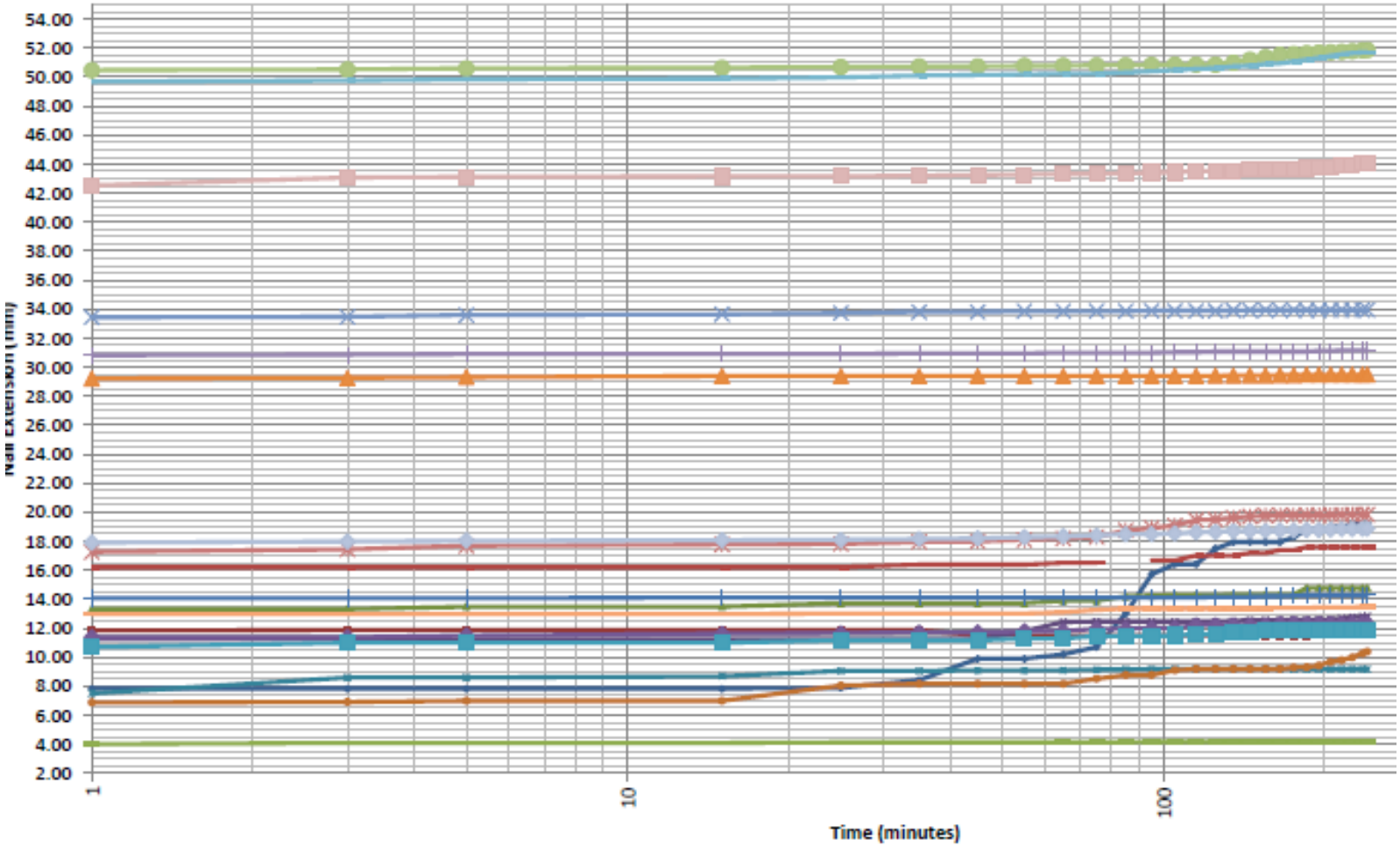
Other

- Corestones
- Fill
- Defects

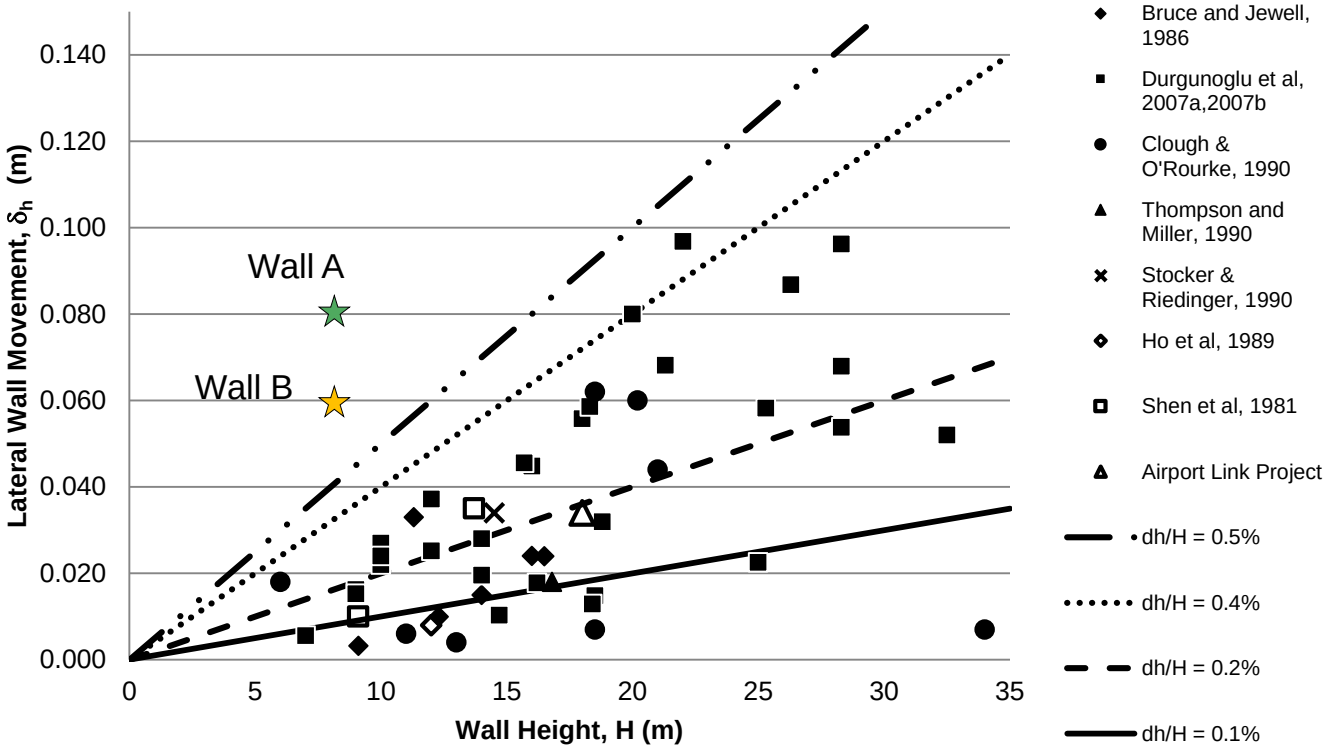
Factor of safety isn't everything!



Production nail test results – creep?



The effect of creep?



Soil nailing an existing slope

- Full-time supervision
- High risk to life
- Issues related to cube failures and productivity
- Maintained 6% testing of production soil nails

Conclusion

When specifying testing it should be site specific based on:

- Risk
- Body of data of similar soils / previous experience of the ground conditions
- Ground conditions – creep susceptible?
- Upgrade or new works / slopes or walls
- Site supervision

Remember soil nail testing of grout/soil capacity only examines one mechanism of failure and the testing needs to be backed up by adequate ground investigation and appropriate design.