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The design of soil nailed structures to AS4678

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Presentation Layout

- Introduction
- Soil Nailing in AS4678
- Design Process

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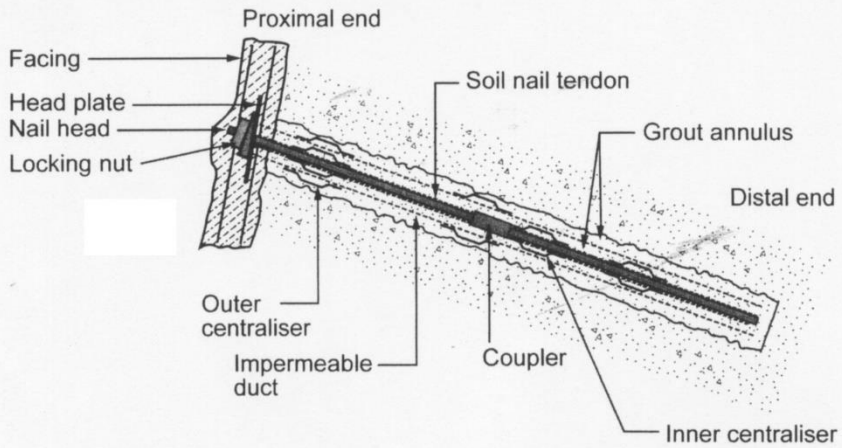
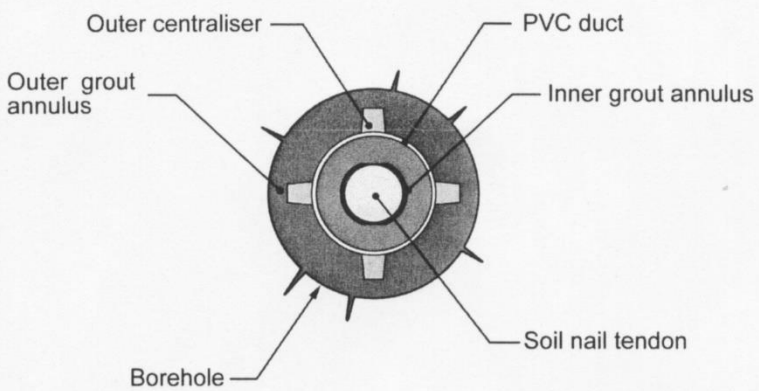
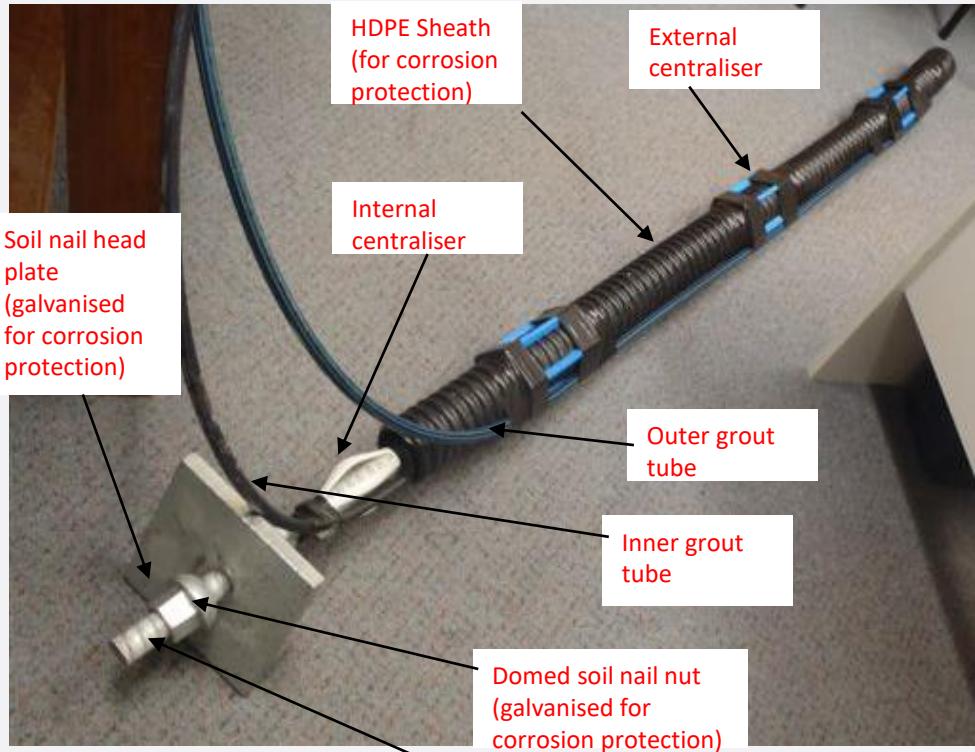
Soil Nail – Main Components





Section through soil nail

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



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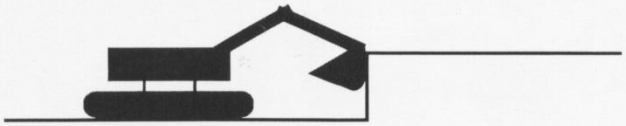
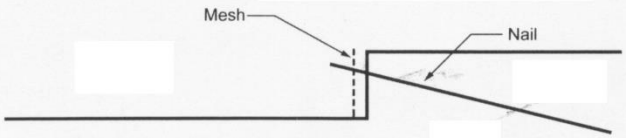
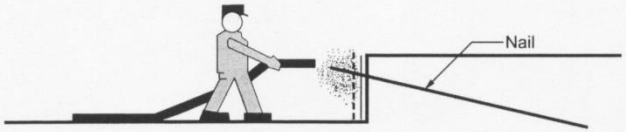


1 Excavation of appropriate lift height

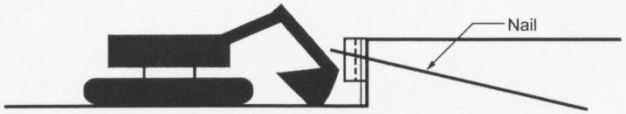
2 Drilling nail hole



3 Installation of nail, mesh and fixing assemblies



4 Application of sprayed concrete facing



5 Excavation of next lift

Reinforcing the soil

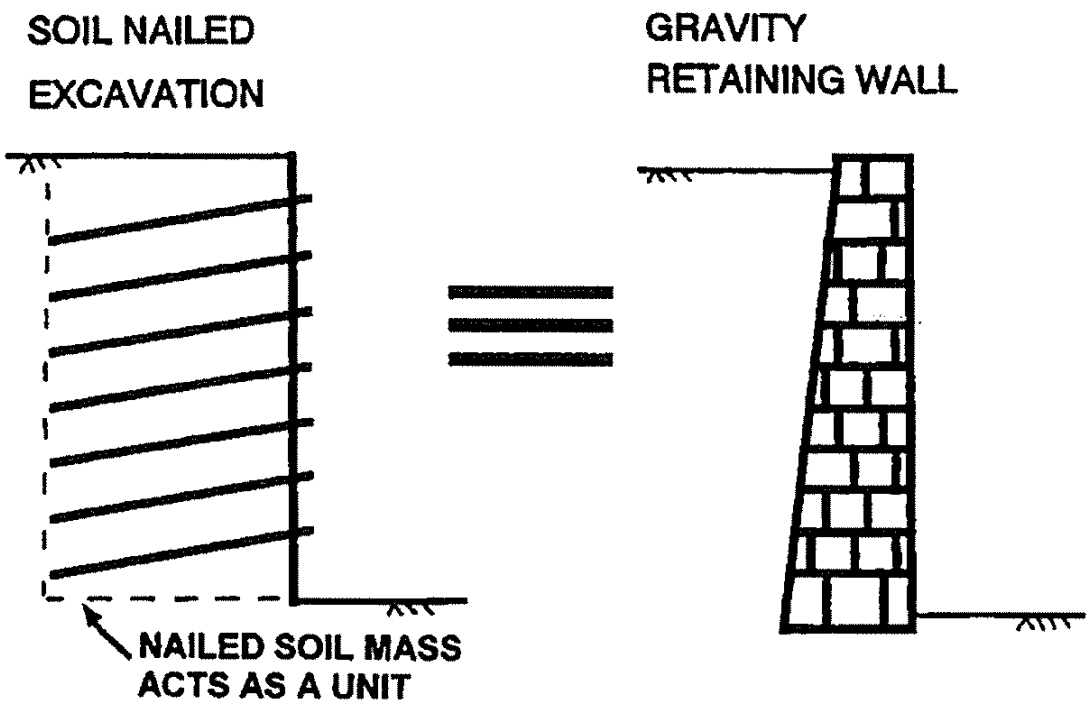


FIG. 1. Analogy between Soil-Nailed Excavation and Gravity Retaining Wall [after Stocker et al. (1979)]

How soil nails work

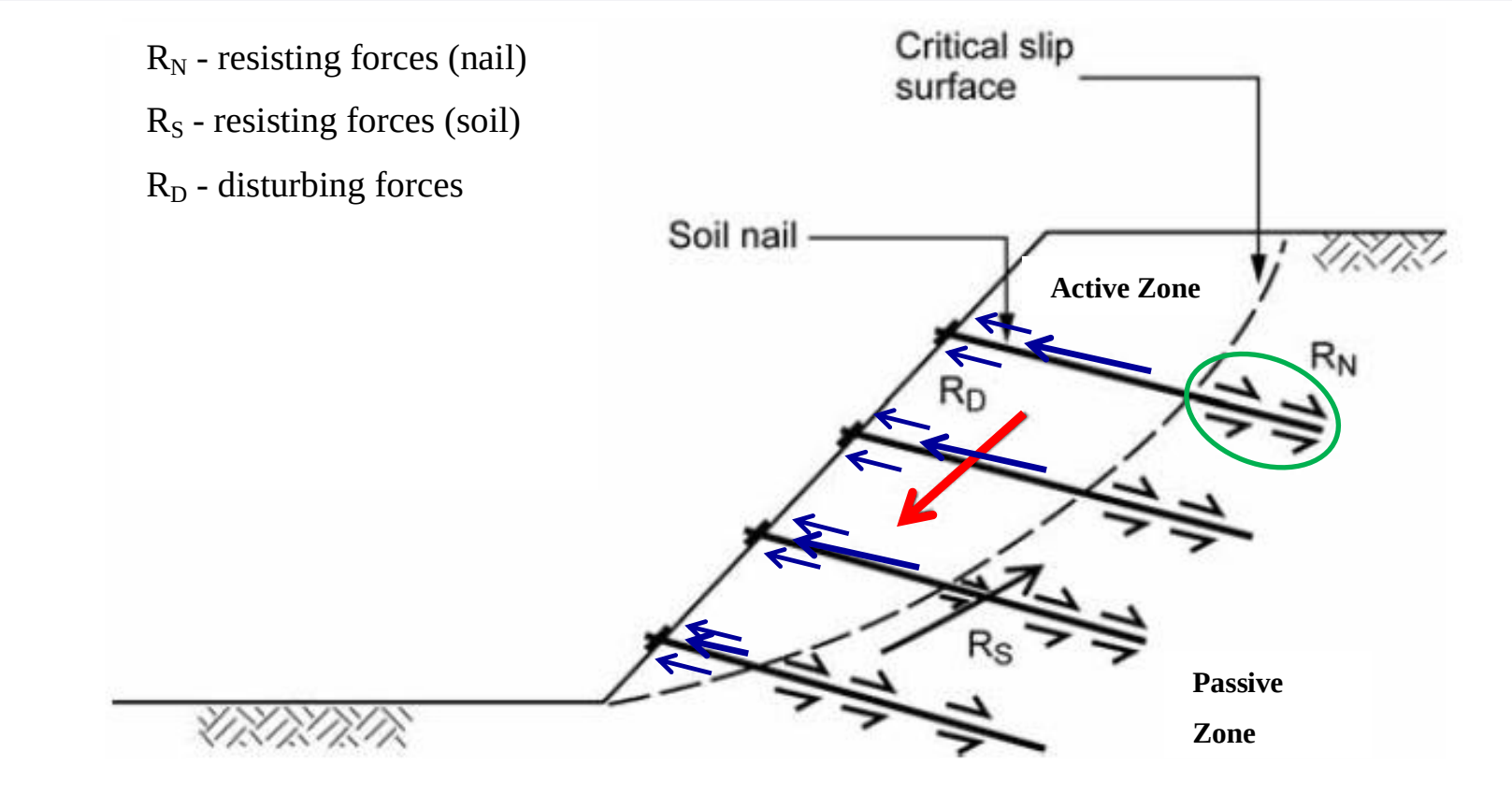


Figure 2.13 Forces Acting on a Potential Sliding Zone for a Nailed Slope (Phear *et al.*, 2005)

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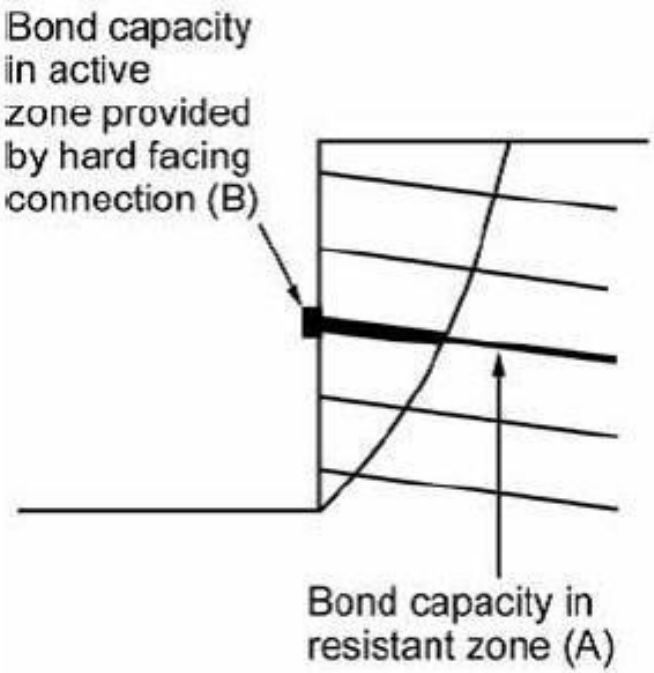
How soil nails work

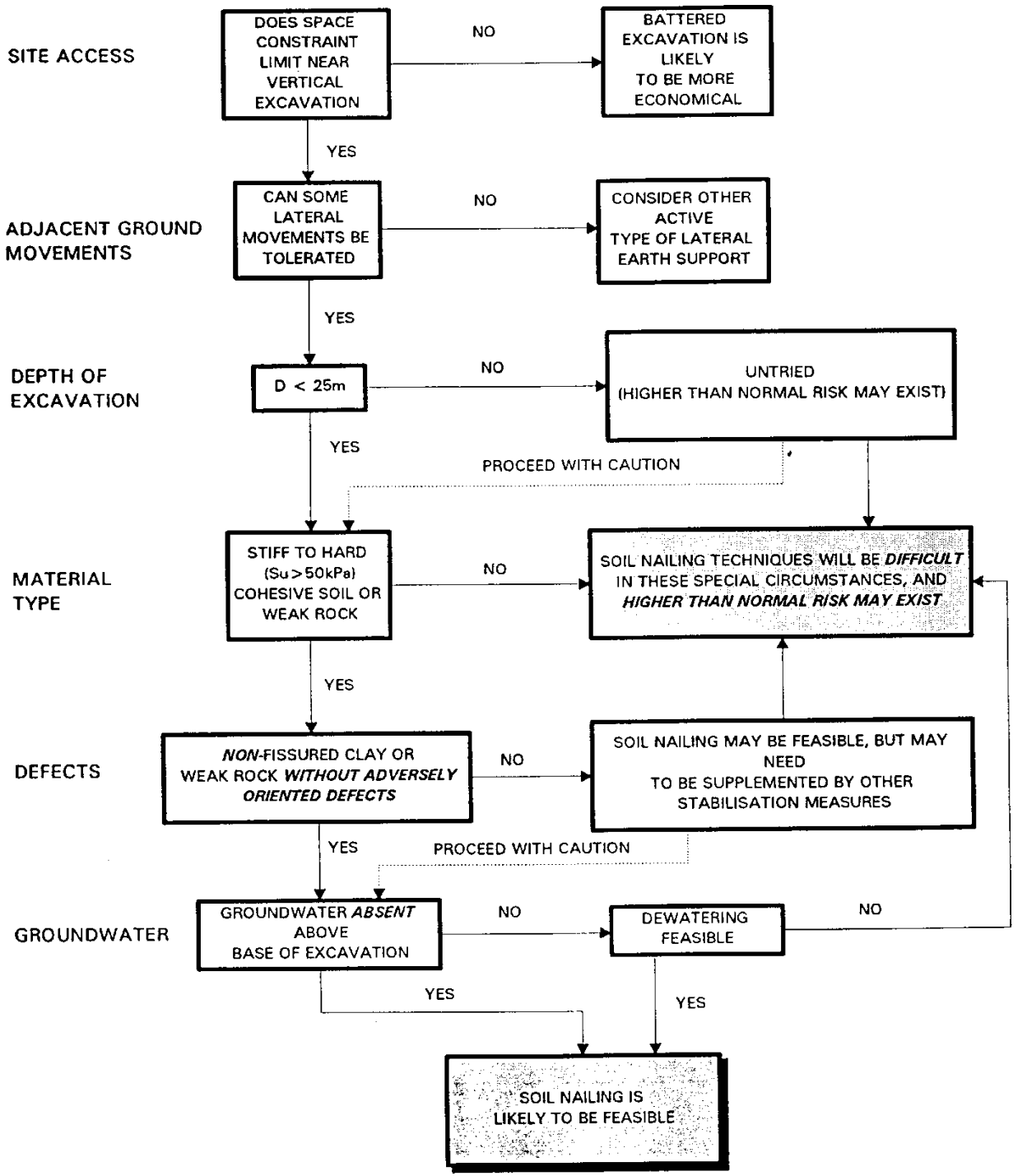
Soil nailed wall



Wall or slope stabilisation with hard facing

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)
Minor components of load transfer
• bond capacity in the active zone • bond capacity to the hard facing structure

Soil Nailing – Is it suitable?



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Advantages & Disadvantages

Advantages

- construction flexibility
- cost
- environmental/aesthetic considerations
- Complex excavation geometry
- Faster relative to other lateral support systems
- Permits top-down construction
- Can be used in situations with limited access

Disadvantages

- temporary conditions (cut must stand vertically)
- Groundwater
- clay soils
- land issues
- Corrosion
- ground movement
- Untried for depths beyond about 25m
- Not suitable for deep seated failures

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AS4678 - 2002

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- **Design Considerations – Limit States**
  - Strength - Must consider all critical conditions during the excavation/nail installation process
  - Serviceability – must include movements during excavation
  - External Stability
  - Internal Stability
- **Design Loads – load combinations & factors**
- **Design Factors – factors on material properties & uncertainty**

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- Structures <15m
- Face angle <90°, >70°
- “Uncomplicated”

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AS 4678 – 2002

- Informative Guidelines only
- Appendix C of AS4678
- Design principle is similar to Reinforced Soil Walls
- Appendix C refers back to Appendix B – Ground anchors

AS 4678—2002
(Incorporating Amendment No. 1)

AS 4678

Australian Standard™

Earth-retaining structures

Accessed by LEIGHTON CONTRACTORS PTY LTD on 02 Oct 2007

Standards Australia

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Design Process

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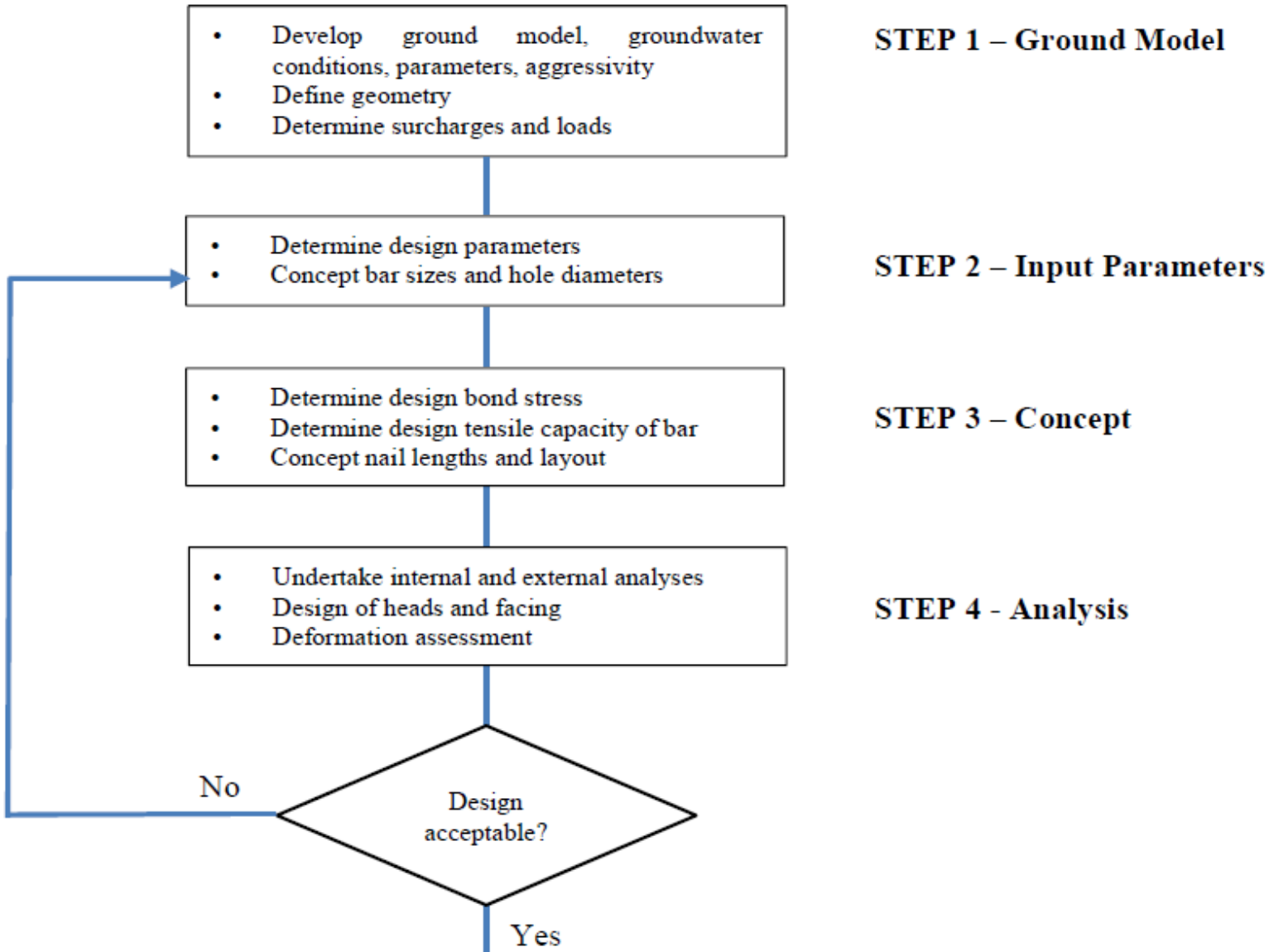
Design Process



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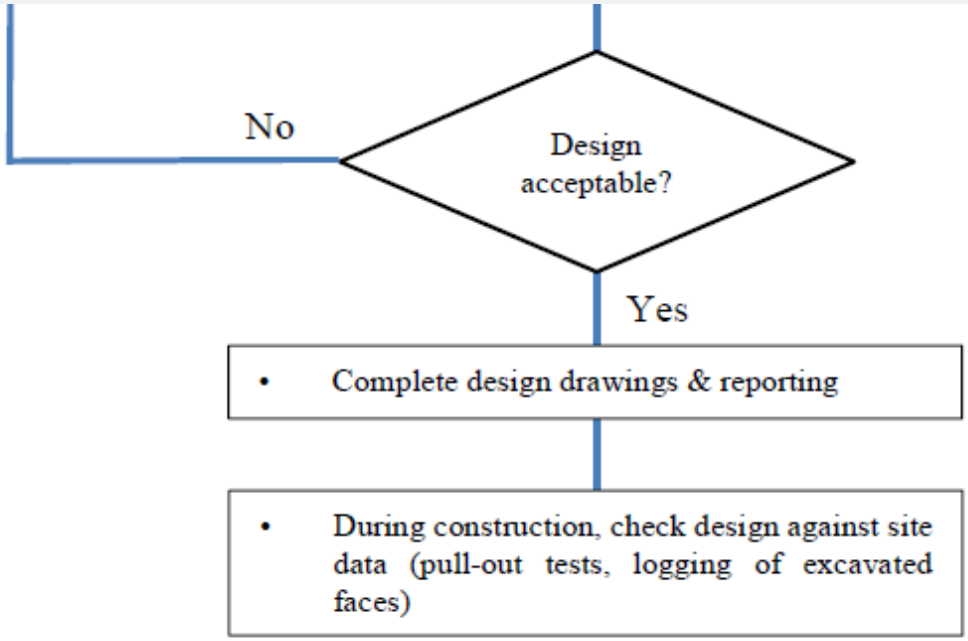
Design Process



STEP 5 – Final Design

STEP 6 – Construction Verification

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Step 2 – Input parameters

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Soil Properties – Uncertainty Factors

ϕ^* = design angle of internal friction of soil (deg.) (= $\tan^{-1}(\Phi_{u\phi}\ (\tan\phi'))$;

c^* = design value of cohesion of soil (kN/m^2) (=$c'\ \Phi_{uc}$);

TABLE 5.1(A)

MATERIAL STRENGTH AND SERVICEABILITY UNCERTAINTY FACTORS FOR SOIL (based on peak values of c' and ϕ')

Soil or material uncertainty factor		Soil or fill conditions			
		Controlled fill		Uncontrolled fill	In situ material
		Class I	Class II		
Strength	$\Phi_{u\phi}$	0.95	0.90	0.75	0.85
	Φ_{uc}	0.90	0.75	0.50	0.70
Serviceability	$\Phi_{u\phi}$	1.0	0.95	0.90	1.00
	Φ_{uc}	1.0	0.85	0.65	0.85

TABLE 5.1(B)

MATERIAL STRENGTH AND SERVICEABILITY UNCERTAINTY FACTORS FOR SOILS (based on c_u and Φ_u)

Soil or material uncertainty factor		Soil or fill conditions			
		Controlled fill		Uncontrolled fill	In situ material
		Class I	Class II		
Strength	$\Phi_{u\phi}$	0.0	0.0	0.0	0.0
	Φ_{uc}	0.6	0.5	0.3	0.5
Serviceability	$\Phi_{u\phi}$	0.0	0.0	0.0	0.0
	Φ_{uc}	0.9	0.8	0.5	0.75

terials defined by the term 'other fill' are used, then the partial factors to be used will
e type and quality of the fill materials. In no case shall the partial factor be greater than
tors for Class 1 'controlled fill'.

gth parameters c' and ϕ' are effective strength parameters. Appendix D gives information
olume and residual strength parameters.

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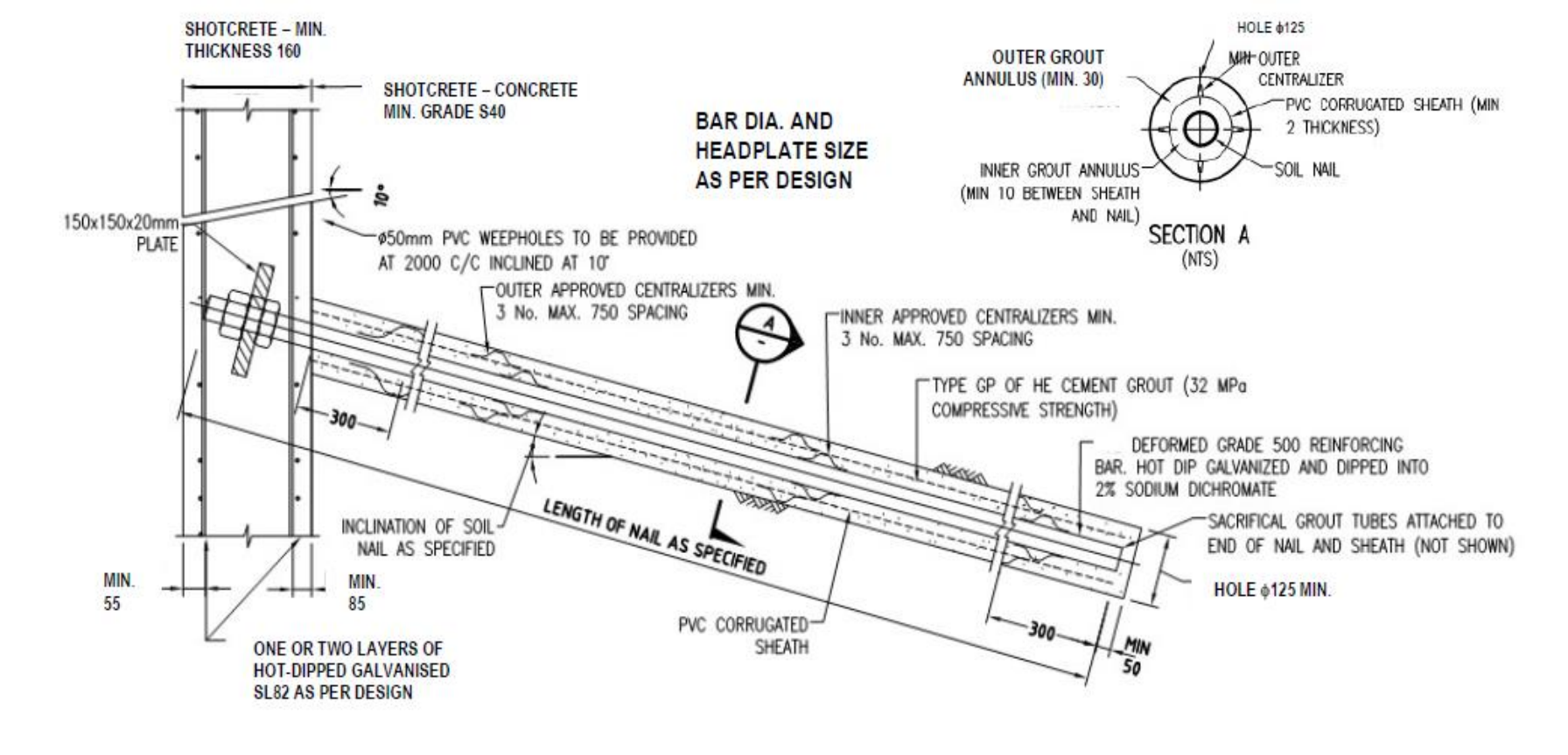
Bar size and hole dia.



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Step 3 - Concept

Nail spacing, length and inclination

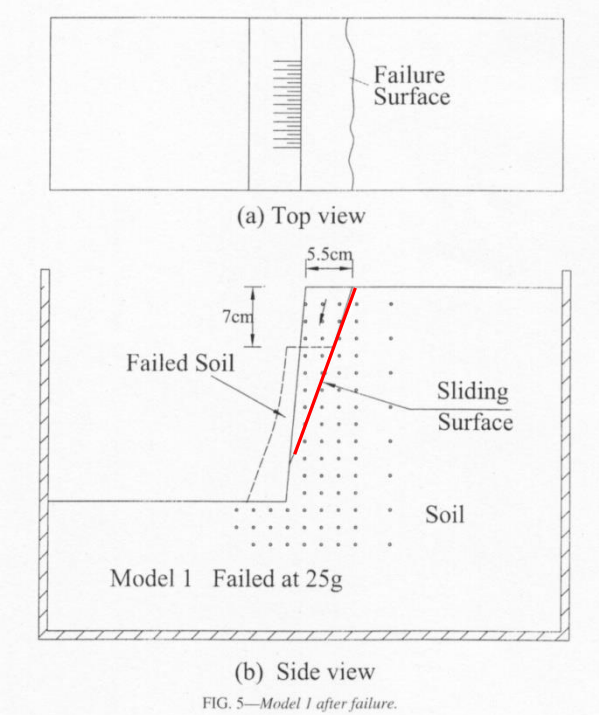


FIG. 5—*Model 1 after failure.*

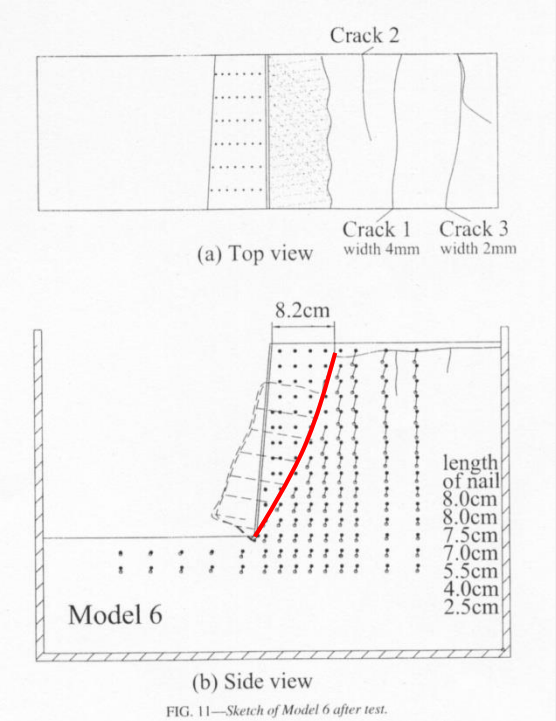


FIG. 11—*Sketch of Model 6 after test.*

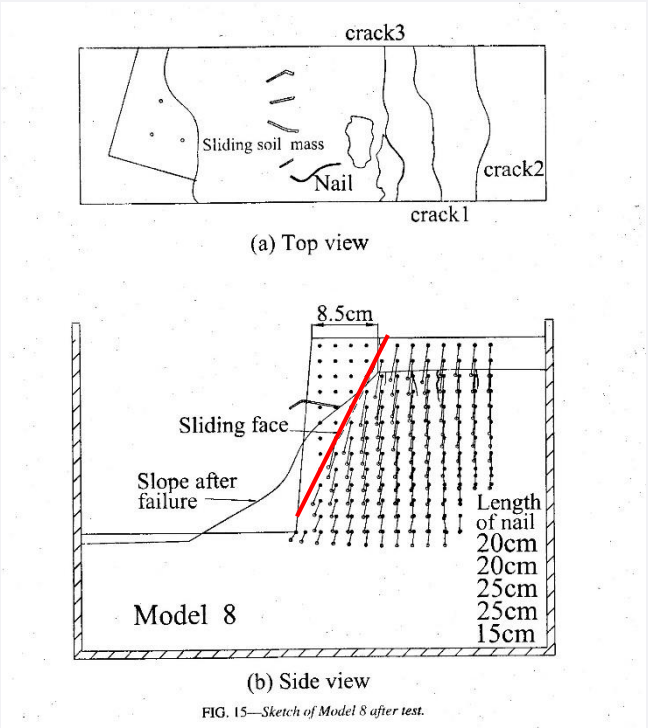


FIG. 15—*Sketch of Model 8 after test.*

MODEL 1

No soil nails

Planar failure

MODEL 6

- Short soil nails
- L/H = 0.32
- Block failure

MODEL 8

- Long, widely spaced soil nails
- L/H = 1
- Planar failure

Ref.: Zhang et al, 2001

Nail spacing, length and inclination

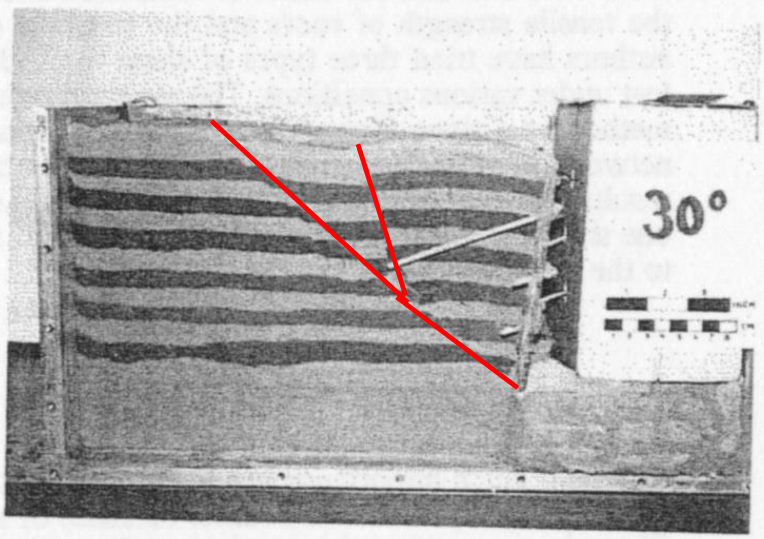


Figure 5. Test 4 - 30^0 nail inclination

TESTS 1-4

L/H = 0.67 (incl. 0-30 deg)

Closely spaced

Two-part wedge: no difference in failure with nail inclination 0-30 deg.

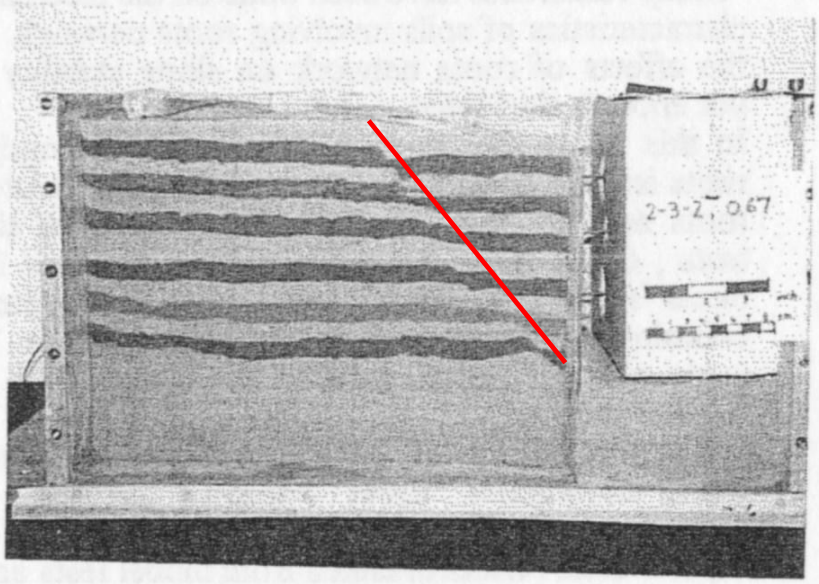


Figure 6. Test 5 - Reg. nails with 2-3-2 spacing

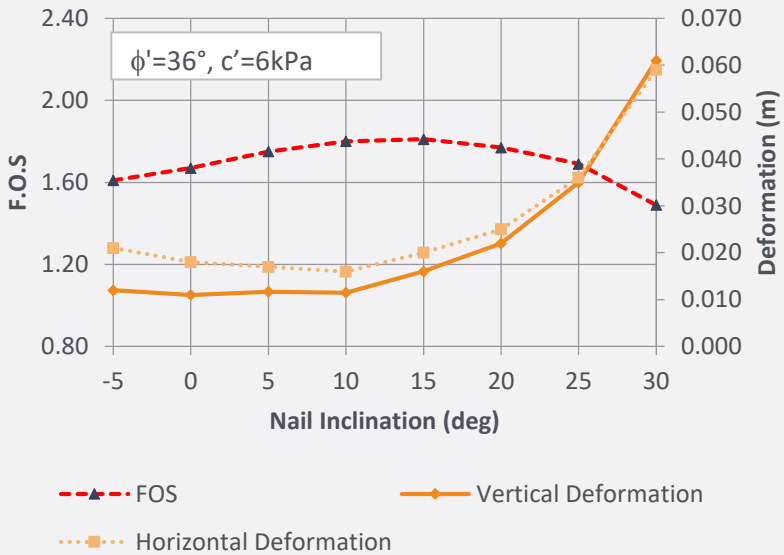
TESTS 5-7

- L/H = 0.67 & 1.0
- Widely spaced at 0 deg inclination
- Planar failure

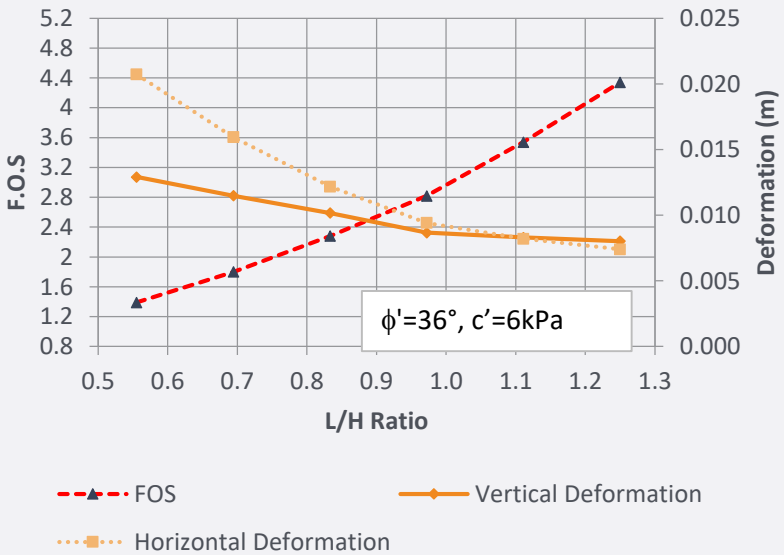
Ref.: Vucetic et al, 1996

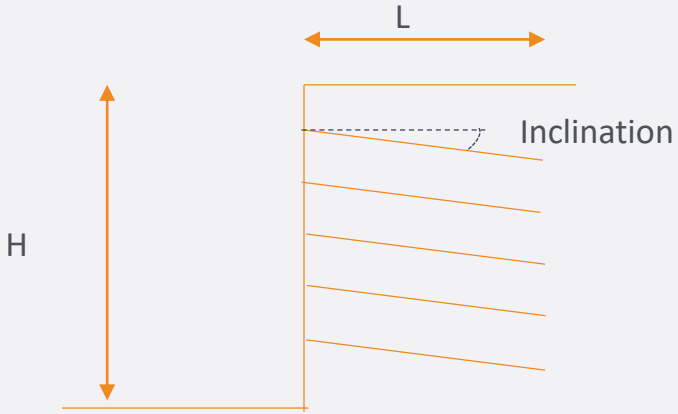
Nail spacing, length and inclination

Factor of safety for different soil nail inclinations (90° wall face angle)



Factor of safety for different L/H ratios (90° wall face angle)





Nail spacing, length and inclination

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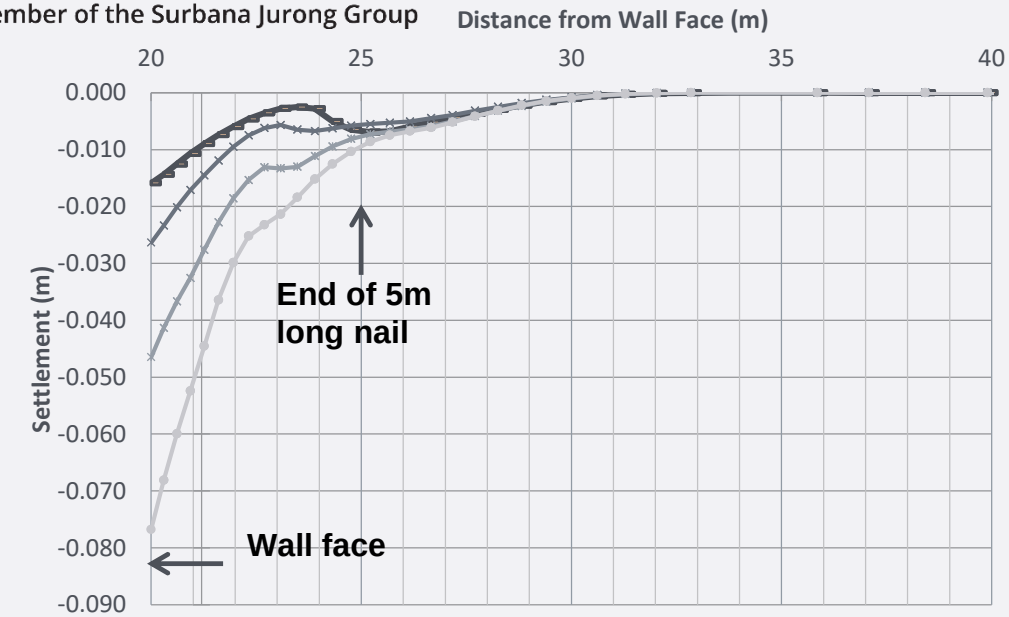

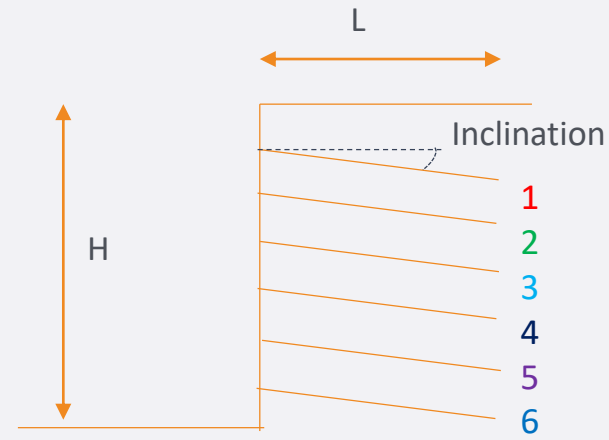

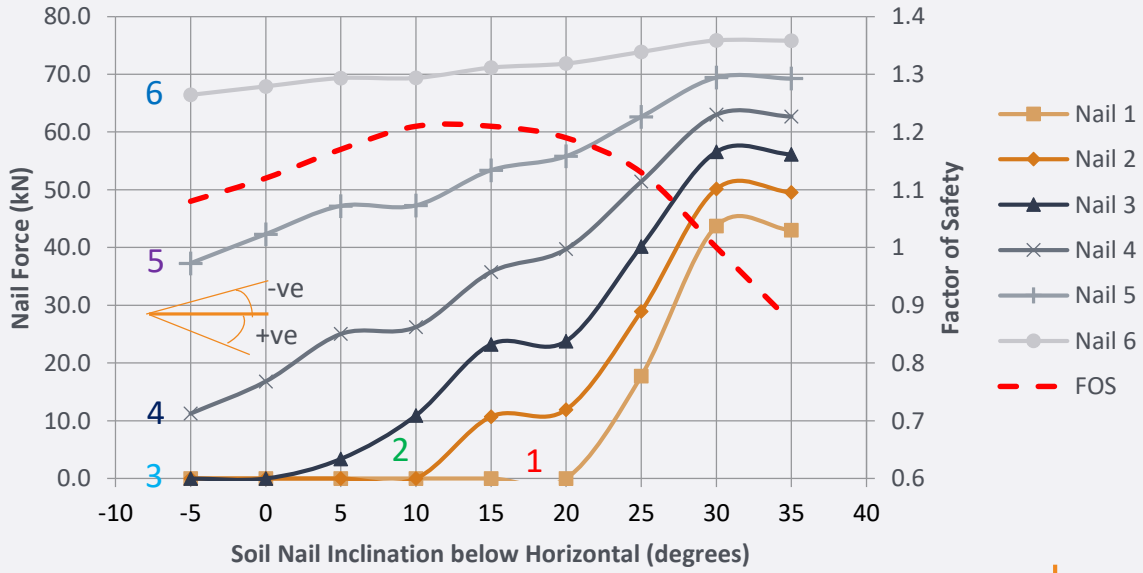

Effect of soil nail inclination on nail force
(Nail 1 is top row of nails)

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Nail Spacing

- Closer spaced nails provide greater internal stability
- Wide spacing of nails can effect internal stability
- Soil nail spacing should not exceed 1 nail per 6m^2 of hard facing or 1 nail per 2m^2 to 4m^2 of flexible facing otherwise the soil nailed structure will not act as a reinforced mass (CIRIA C637)
- Max. spacing – typically 1 - 2m

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Nail Length

- Short nails at bottom provides less stability – likely pullout
- Shorter nails at top, longer at bottom provides “excellent” stability but shorter nails at the top will increase deformations (Shui & Chang, 2005)
- As L/H increases, deformations decrease – no additional effect when L/H>1
- Short nail lengths can effect external stability – thin gravity wall
- Length of Nails - 0.8 - 1.2H (Clouterre)
- Soil nail lengths above 15m should be avoided due to drilling difficulties and greater deformation required to mobilise tensile capacity.

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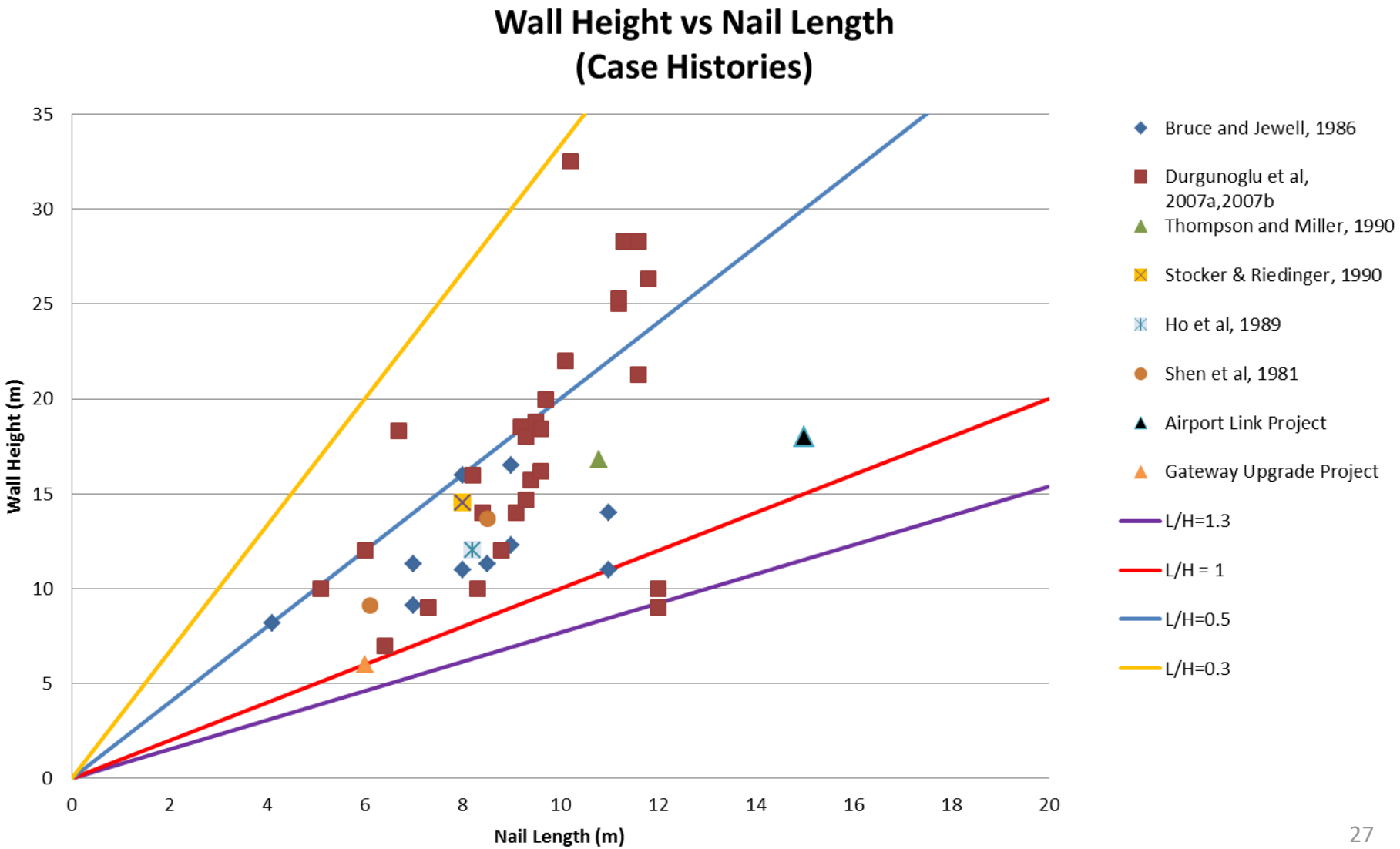

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Nail Inclination

Nail inclination between 0 and 20 deg does not appear to affect stability

>20 deg then rapid increase in wall deformation

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Preliminary Sizing

The following relationships were derived by Bruce & Jewell (1987):

Length Ratio = Length of soil nail / Excavation height (L/H)

Bond Ratio = (Hole Dia. x L) / Nail Spacing

Strength Ratio = $(\text{Nail Dia.})^2$ / Nail Spacing

Nail Spacing = horizontal spacing x vertical spacing (m^2)

Performance Ratio = $\frac{\text{Outward Movement}}{\text{Excavation height}} = \frac{\delta}{H}$

	Length Ratio	*Bond Ratio*	*Strength Ratio(10^{-3})*	*Performance Ratio*
Granular soil	0.5-0.80	0.3-0.6	0.4-0.8	0.001-0.003
Morraine / Marls	0.5-1.0	0.15-0.20	0.1-0.25	-

Marl – mix of calcium carbonate & clay

Morraine – glacial debris (silt thru to boulders)

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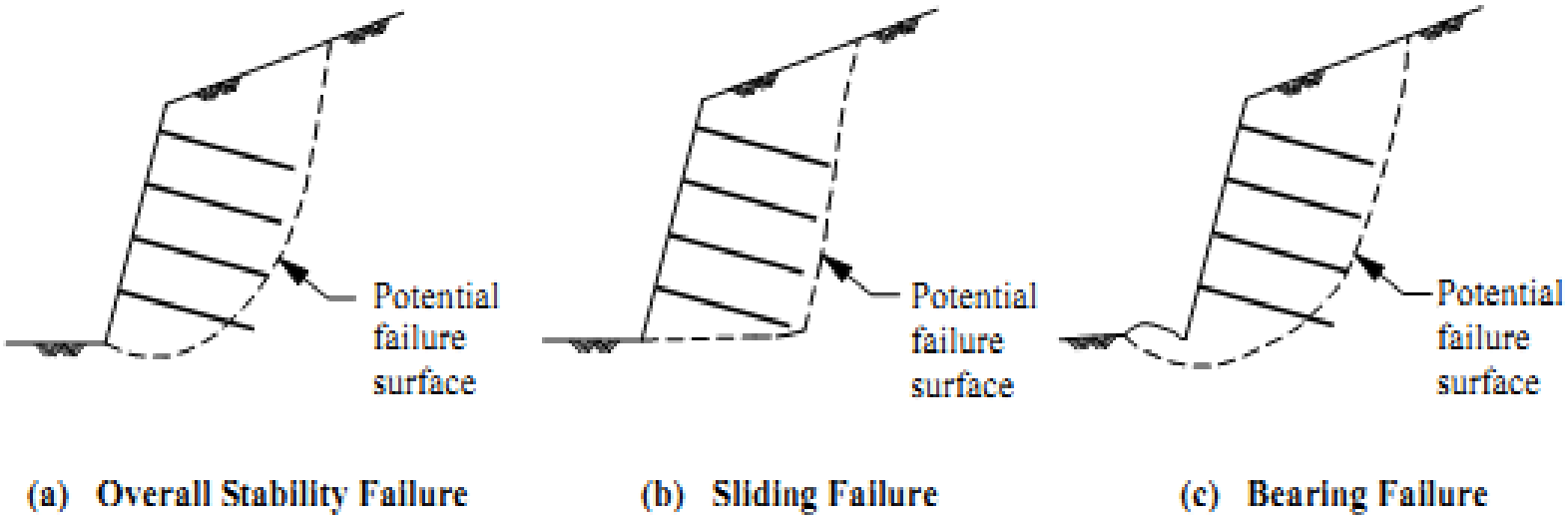
Step 4 - Analyses

External Stability - Modes of Failure



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

External Stability

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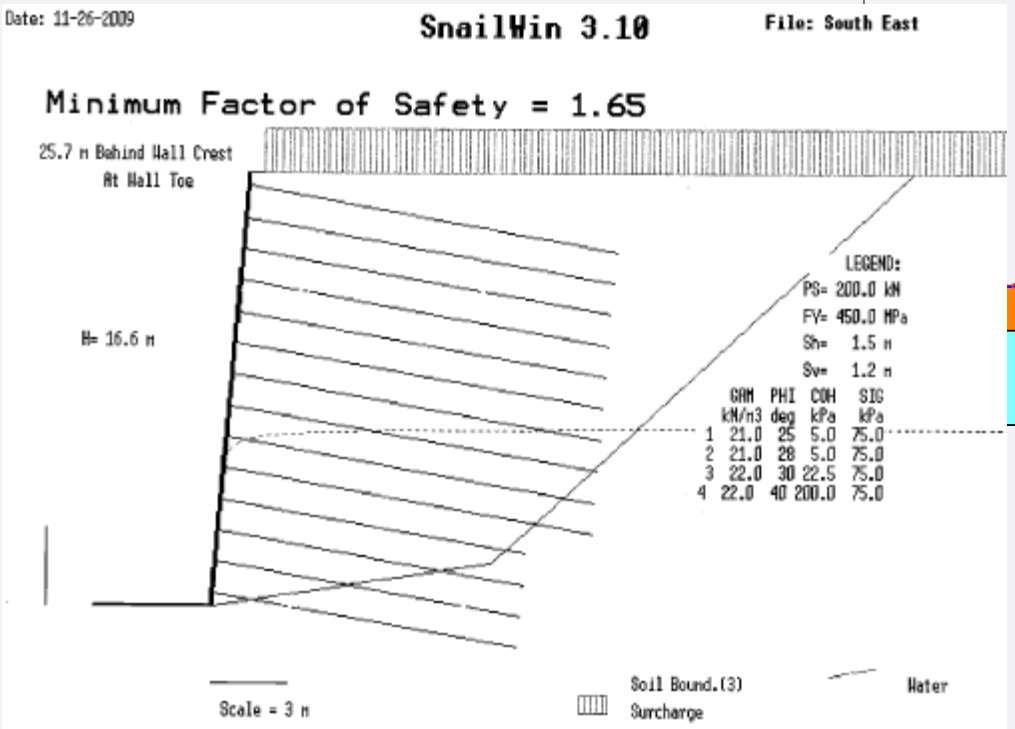
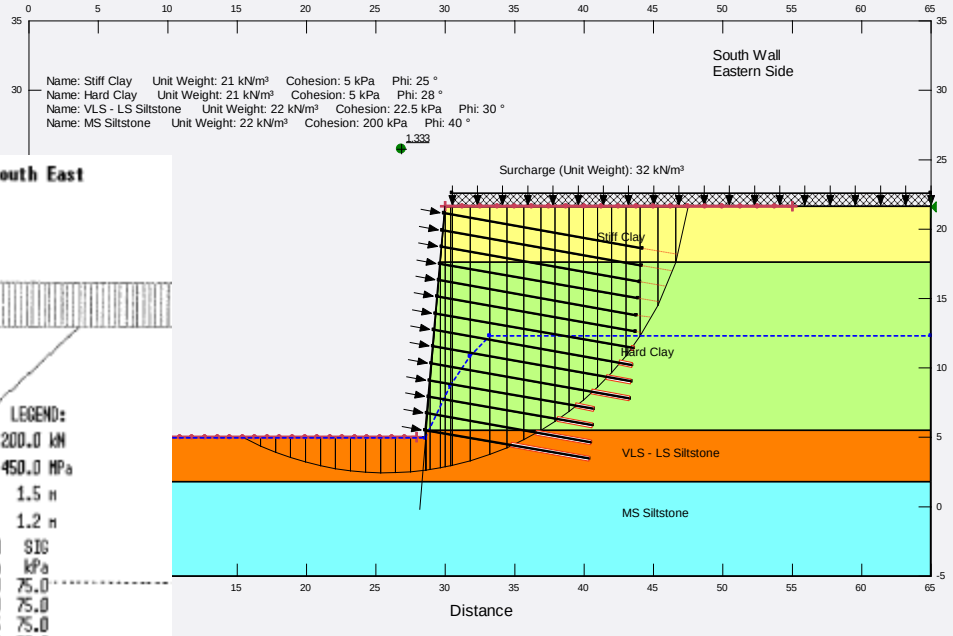
Stability Analyses





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Nail Tension Forces

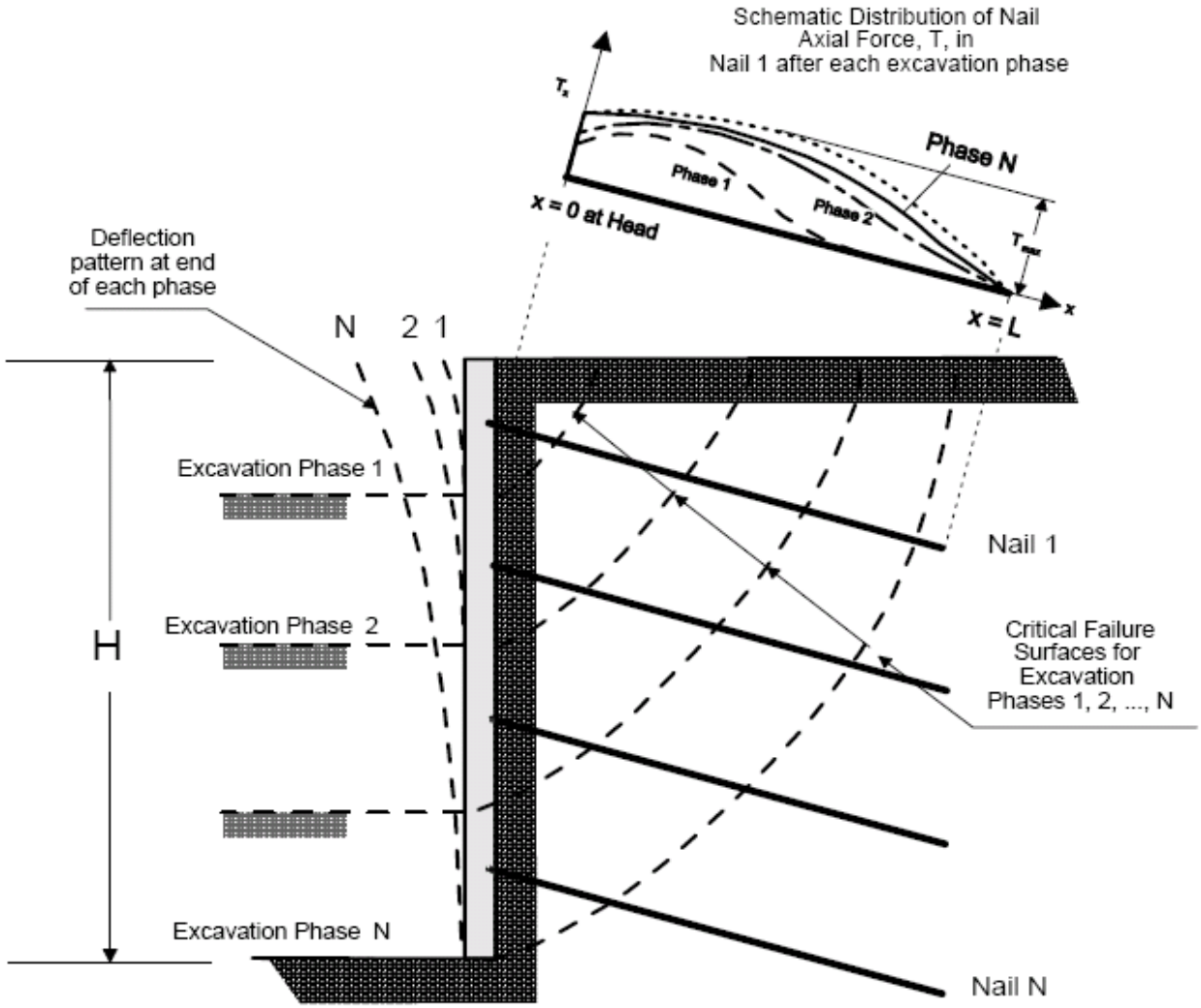
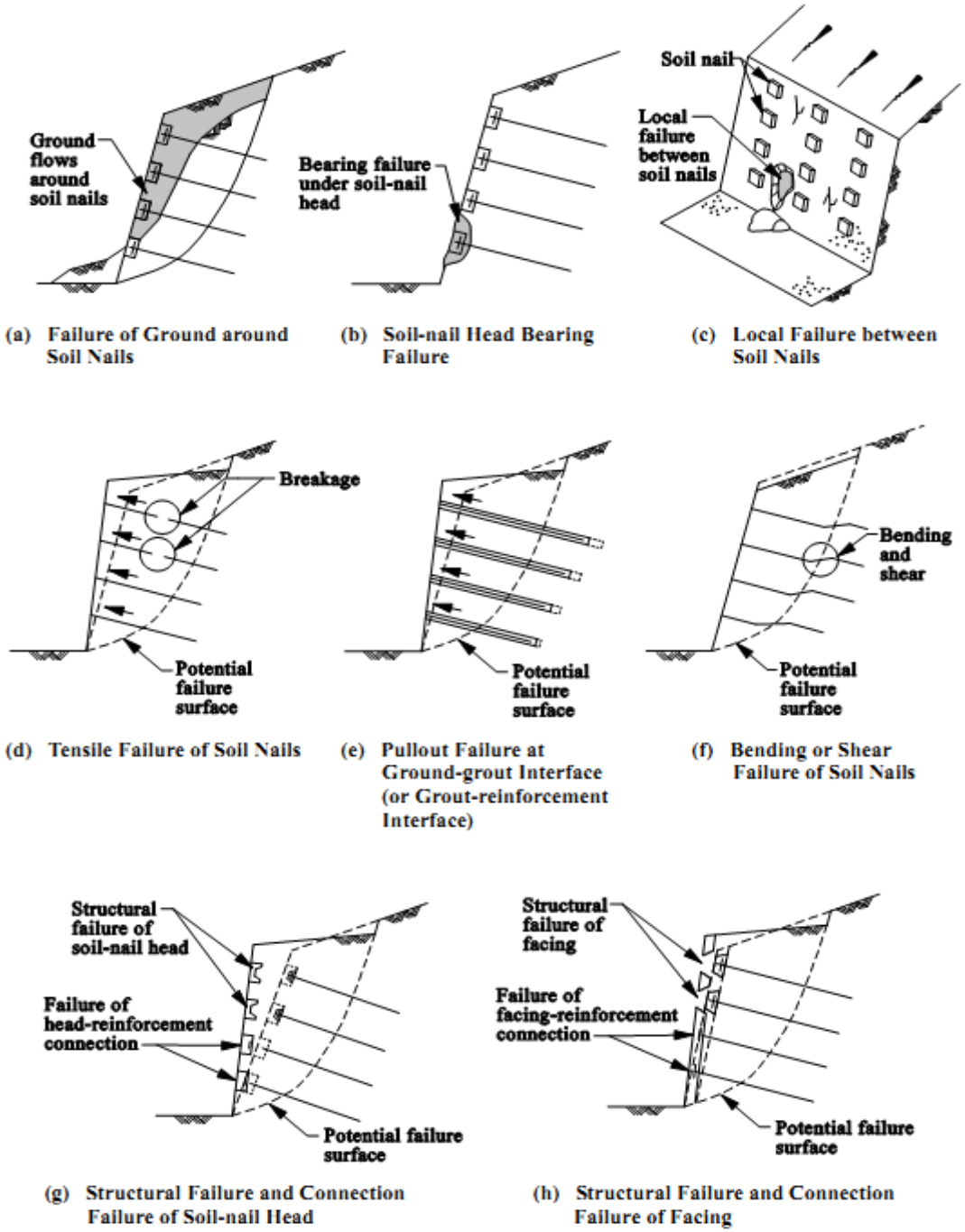


Figure 5.1: Potential Failure Surfaces and Soil Nail Tensile Forces.

Modes of 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

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

(h) Structural Failure and Connection Failure of Facing

Internal Stability

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Soil Nailing – Internal Stability

- Soil nail pull-out (grout-ground bond)
- Nail failure (i.e. tensile failure of nail)
- Pull-out of connection to facing material

Design pull-out capacity (AS4678)

$$T^* = \Phi_n . \Phi_b . \pi . D . L_f . \tau_u$$

Where:

Φ_n	=	Structure classification design factor (Table 5.2)
	=	0.9-1.1;
Φ_b	=	Bond reduction factor (Table B2) = 0.7;
D	=	Diameter of grout hole (m);
L_f	=	Fixed length (m);
τ_u	=	Design grout/ground resistance (bond stress) (kN/m^2).

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Bond Stress

- Effective stress design methods
- Pull out tests
- Empirical values

Design bond stress (effective stress design method)

$$\tau_u = (c^* + \sigma'_v \tan\phi^*) \ (kN/m^2)$$

where:

σ'_v	=	effective vertical stress at the mid-depth of nail behind the failure surface;
ϕ^*	=	design angle of internal friction of soil (deg.);
c^*	=	design value of cohesion of soil (kN/m^2).

Pull-out tests

$$\tau_u = P_{ult} / \pi DL \quad \text{(kPa)}$$

where:

P_{ult}	=	pull out resistance from pullout test (kN)
D	=	diameter of grout hole (m)
L	=	grouted length of soil nail (m)

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Pull-out tests

$$\tau_u = P_{ult} / \pi DL \xi \Upsilon_p \quad \text{(kPa)}$$

where:

P_{ult} = pull out resistance from pullout test (kN)

D = diameter of grout hole (m)

L = grouted length of soil nail (m)

ξ = correction based on test results

Υ_p = partial factor (1.25 temp, 1.5 perm)

Table 8.5 *Correction factors for pullout test results to obtain characteristic values*

Number of pullout tests	1	2	3 or more
ξ based on mean of test results	Not applicable	1.35 [1]	1.30 [1]
ξ based on lowest test results	Not applicable	1.25 [1]	1.10 [1]
ξ based on test result	1.50 [1]	Not applicable	Not applicable

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Empirical Values

Apply a factor on ultimate of 0.5 - 0.66

Typical values of ultimate bond stress for various materials in the Sydney region are given below:

Material	Ultimate Bond Stress (kPa)	Material	Ultimate Bond Stress (kPa)
Residual soil	50 – 75	Class V Sandstone	150
Class V Shale	75 – 100	Class IV Sandstone	250 – 800
Class IV Shale	150		

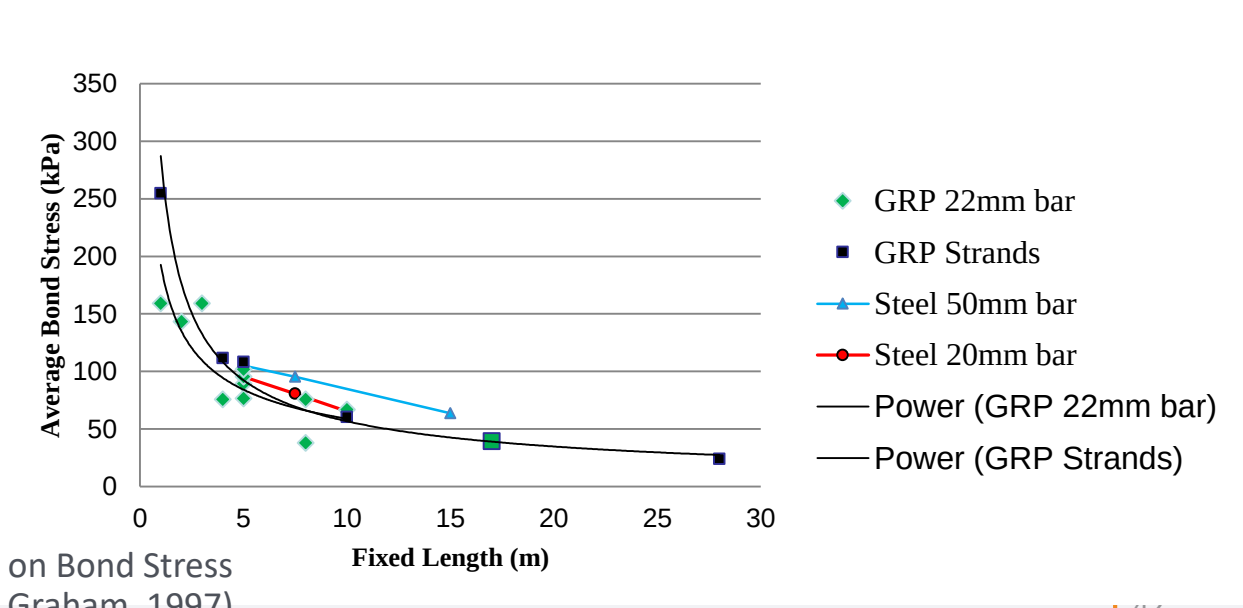
See also:
FHWA Geotechnical Engineering Circular No. 7 – Soil nail walls (2003)
CIRIA C637 Soil nailing – best practice guidance (2005)

Values should be confirmed by pull-out testing.

Design pull-out capacity

- Pull-out resistance is usually assumed to be uniform along the length of the nail.
- This is reasonable if nails are short and stiff (dia. of bar >20mm, bond length <5m)
- For more elastic nails (eg. fibre-composite nails) the ave. bond stress reduces when bond length >3m

CIRIA Report C637



Effect of Fixed Length on Bond Stress (Barley and Graham, 1997)

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Nail tensile capacity

Bar strength (tension capacity) can be determined from equation B4(1) in AS4678-2002

$$T = \Phi_k \Phi_n \Phi_t f_p A_p \quad (kN)$$

where:

Φ_k = Importance category reduction factor (Table B1) = 0.8 (perm.) - 0.9 (temp);

Φ_n = structure classification design factor (Table 5.2, AS4678) = 0.9 - 1.1

Φ_t = Material reduction factor (Table B2) = 0.9;

f_p = Tensile strength of nail (kN/m^2);

A_p = Cross sectional area of nail (m^2).

Facing

Facing can comprise:

- Individual plates or pads
- Mesh
- Shotcrete facing with steel mesh or steel fibre reinforcement
- Vegetation

Flexible facing provides similar overall stability to rigid facing, but more localised deformation

Facing type (based on case studies) –

- face angle ≥70°= hard
- face angle ≤70°= flexible

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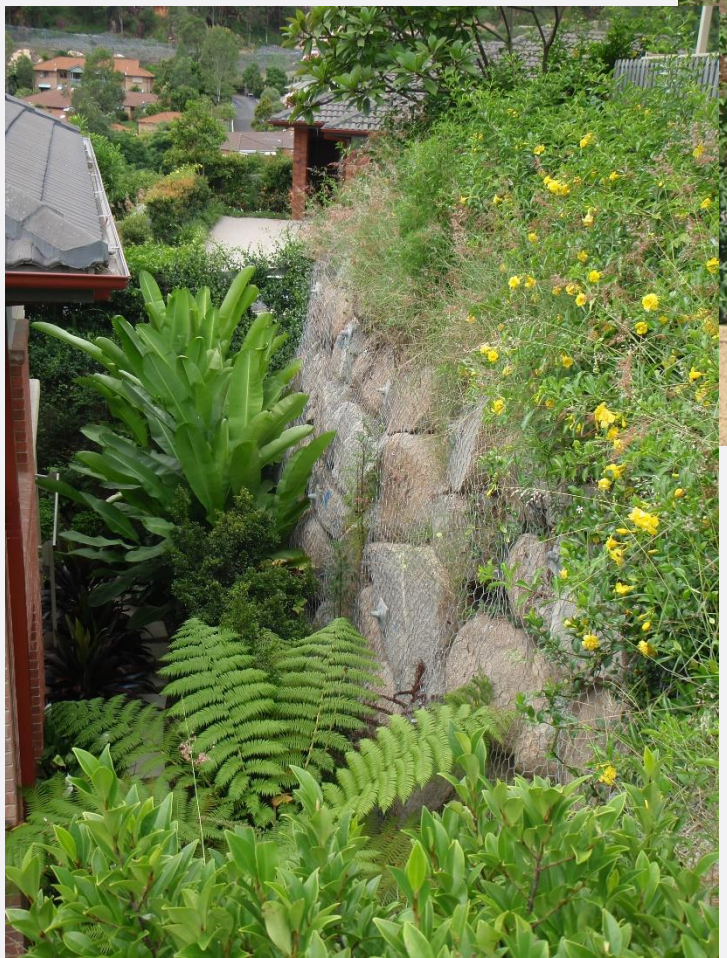

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Vegetated Slope Works

July 2001

August 2001

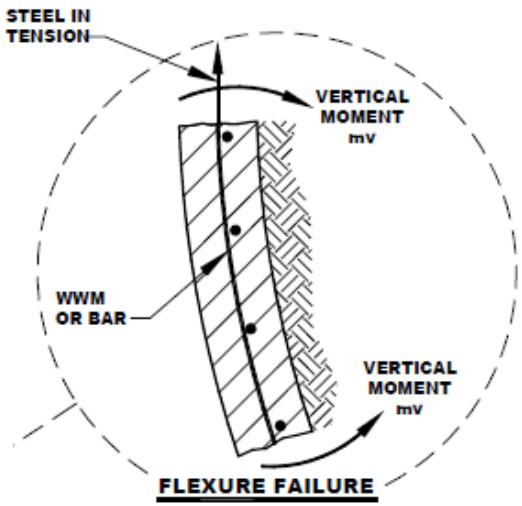
June 2001

September 2002

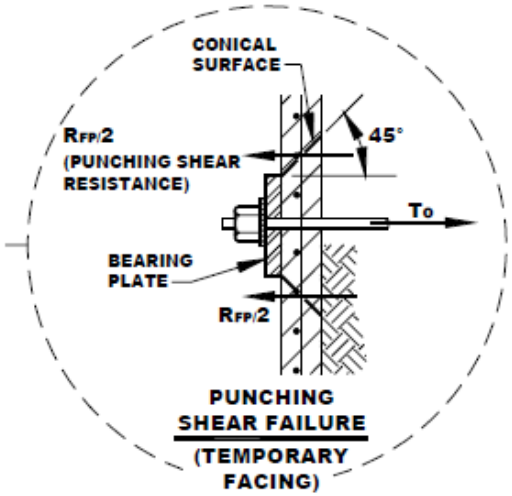
April 2003

Facing

1. FHWA approach
2. FHWA Modified Approach (CIRIA C637)
3. Clouterre



- Shotcrete can be applied in one of two layers (a temporary layer and a permanent layer). Typical temp thickness is 75mm with a single layer of mesh
- Shotcrete thickness for a soil nailed wall is generally > 150mm (MRTS03 – 160mm)
- Shotcrete thickness for a slope 75-100mm (MRTS03 – 120mm)
- Shotcrete thickness generally governed by min. cover to steel requirements



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Soil Nailing - Serviceability

Serviceability limit state of soil nailed structure is similar to RSW.

Remember – movement is required to generate resistance. Therefore beware of existing structures on top of proposed cut.

Where special concrete facings are used, any excessive deformation of the facing may constitute a serviceability limit state.

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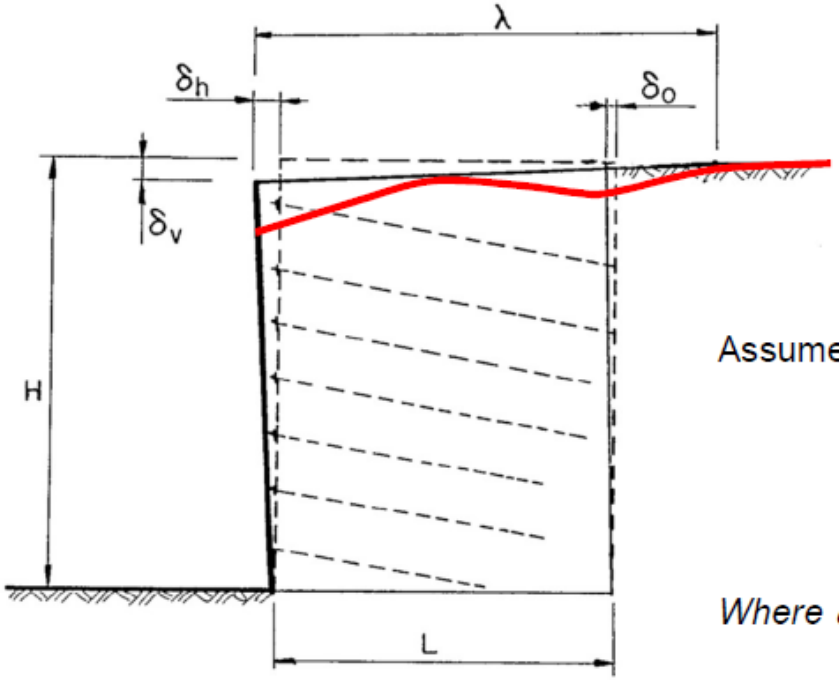

Typical settlement profile (exaggerated)

Assumed that

$\delta_v \approx \delta_h$

$\delta_0 = k(1\text{-}\tan\phi')H \approx \delta_h/10$

$\lambda = H\ (1\text{-}\tan\alpha)\ k$

Where α = initial wall face angle from vertical

Vertical or horizontal deformation	*Weathered Rock / Stiff Soils*	*Sandy Soils*	*Clayey Soils*
$\delta_v = \delta_h$	H/1000	2H/1000	3H/1000
δ_o		4H/1000 to 5H/1000	
k	0.8	1.25	1.5

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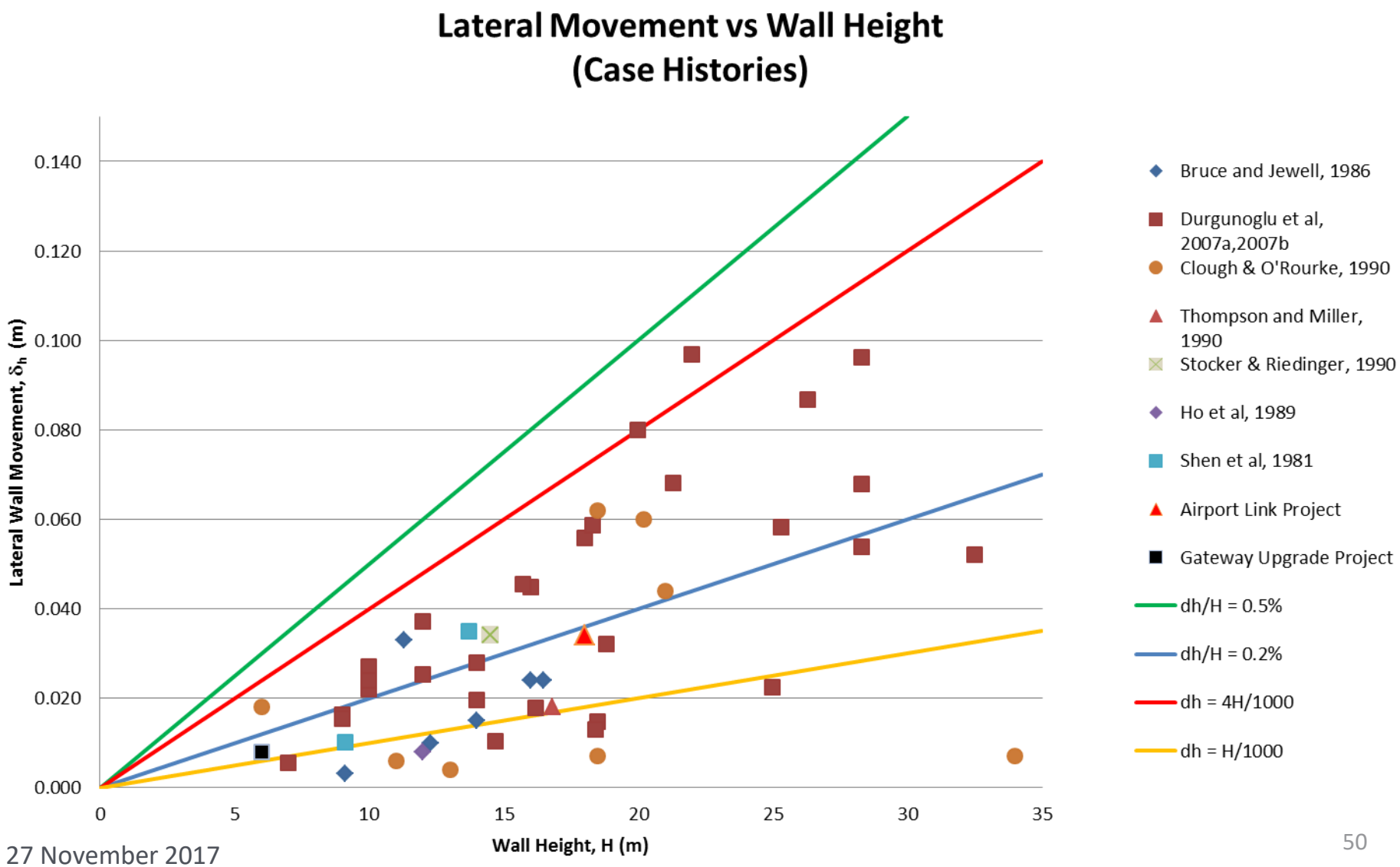
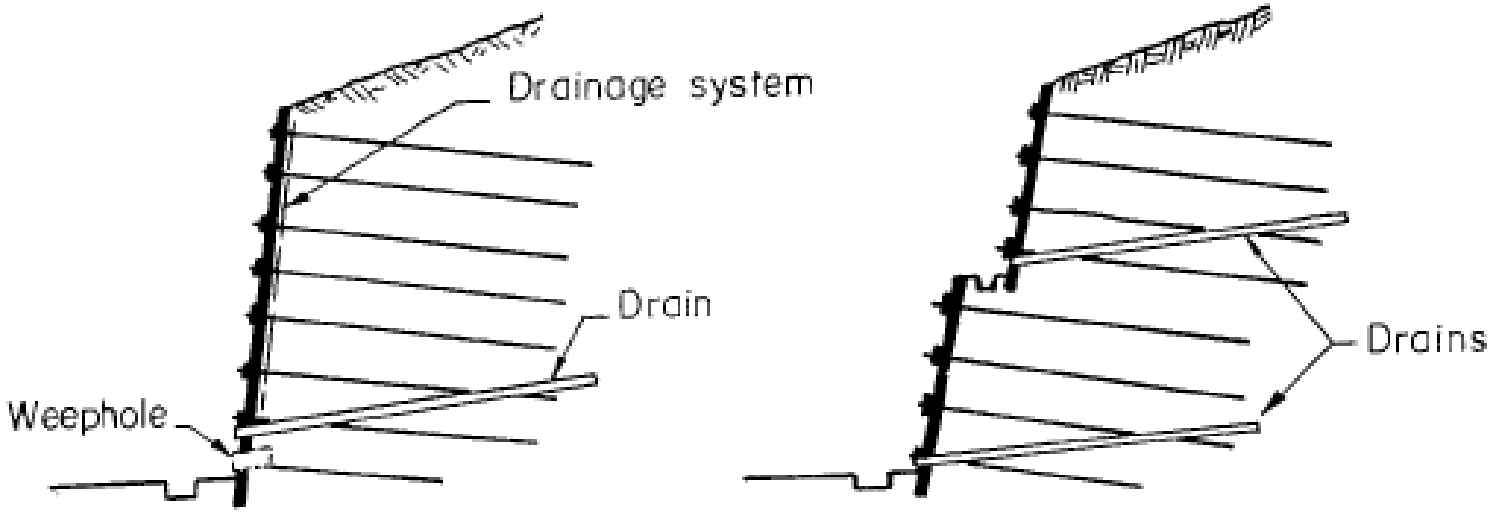
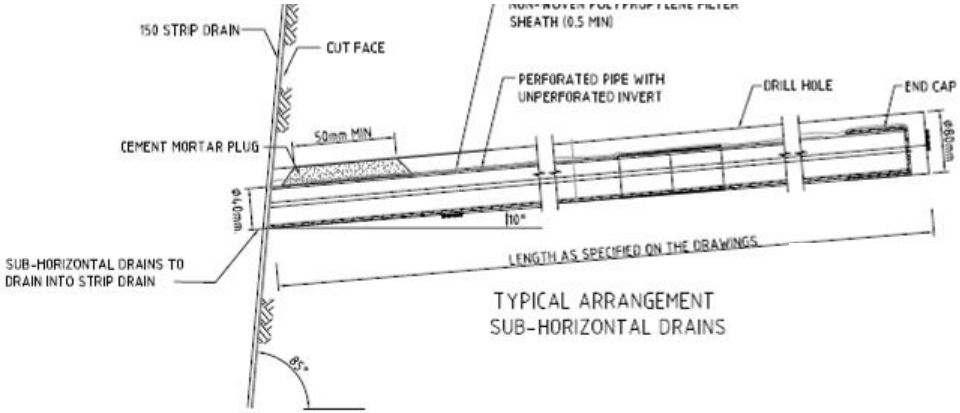
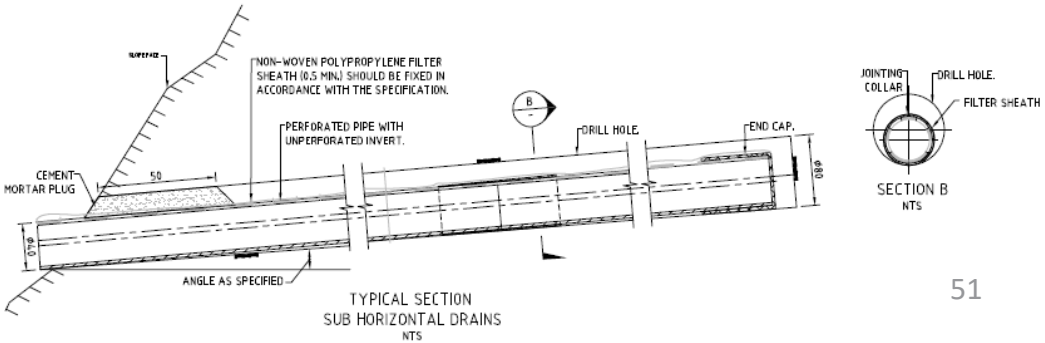
Soil Nailing - Serviceability



Drainage


Drainage system
Drain
Weephole
Drains


150 STRIP DRAIN
CUT FACE
SHEATH (0.5 MIN)
PERFORATED PIPE WITH UNPERFORATED INVERT
DRILL HOLE
END CAP
CEMENT MORTAR PLUG
50mm MIN
110°
SUB-HORIZONTAL DRAINS TO DRAIN INTO STRIP DRAIN
LENGTH AS SPECIFIED ON THE DRAWINGS
TYPICAL ARRANGEMENT
SUB-HORIZONTAL DRAINS


NON-WOVEN POLYPROPYLENE FILTER SHEATH (0.5 MIN.) SHOULD BE FIXED IN ACCORDANCE WITH THE SPECIFICATION.
PERFORATED PIPE WITH UNPERFORATED INVERT.
DRILL HOLE.
END CAP.
CEMENT MORTAR PLUG
50
ANGLE AS SPECIFIED
TYPICAL SECTION
SUB HORIZONTAL DRAINS
NTS
JOINTING COLLAR
DRILL HOLE.
FILTER SHEATH
SECTION B
NTS

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Drainage

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Conclusion

AS 4678 – 2002 can be used for soil nailing

But:

Lack of information and guidance in the standard limits its use

Clients specify different standards

And

NOTE: The following alternative design approaches to retaining walls may be used, provided the same design considerations and performance criteria as outlined in this Standard are satisfied:

(a) For walls other than reinforced soil walls, a global (lumped) geotechnical resistance factor may be used, rather than partial material design factors. No guidance is given in this Standard for the choice of global factors.

(b) A safe design of conventional retaining structures can also be achieved by analysing limit equilibrium conditions using the worst credible soil parameters. A factor of safety just exceeding 1 would be sufficient to prevent failure. However, if the chosen safety factor is also intended to limit displacements to a tolerable maximum, the lowest credible soil strength will need to be further reduced by dividing it by a partial factor. This approach is referred to as the Direct Assessment (Worst Credible Scenario) method. No guidance for this approach is given in this Standard.

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Thank you

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Construction Issues

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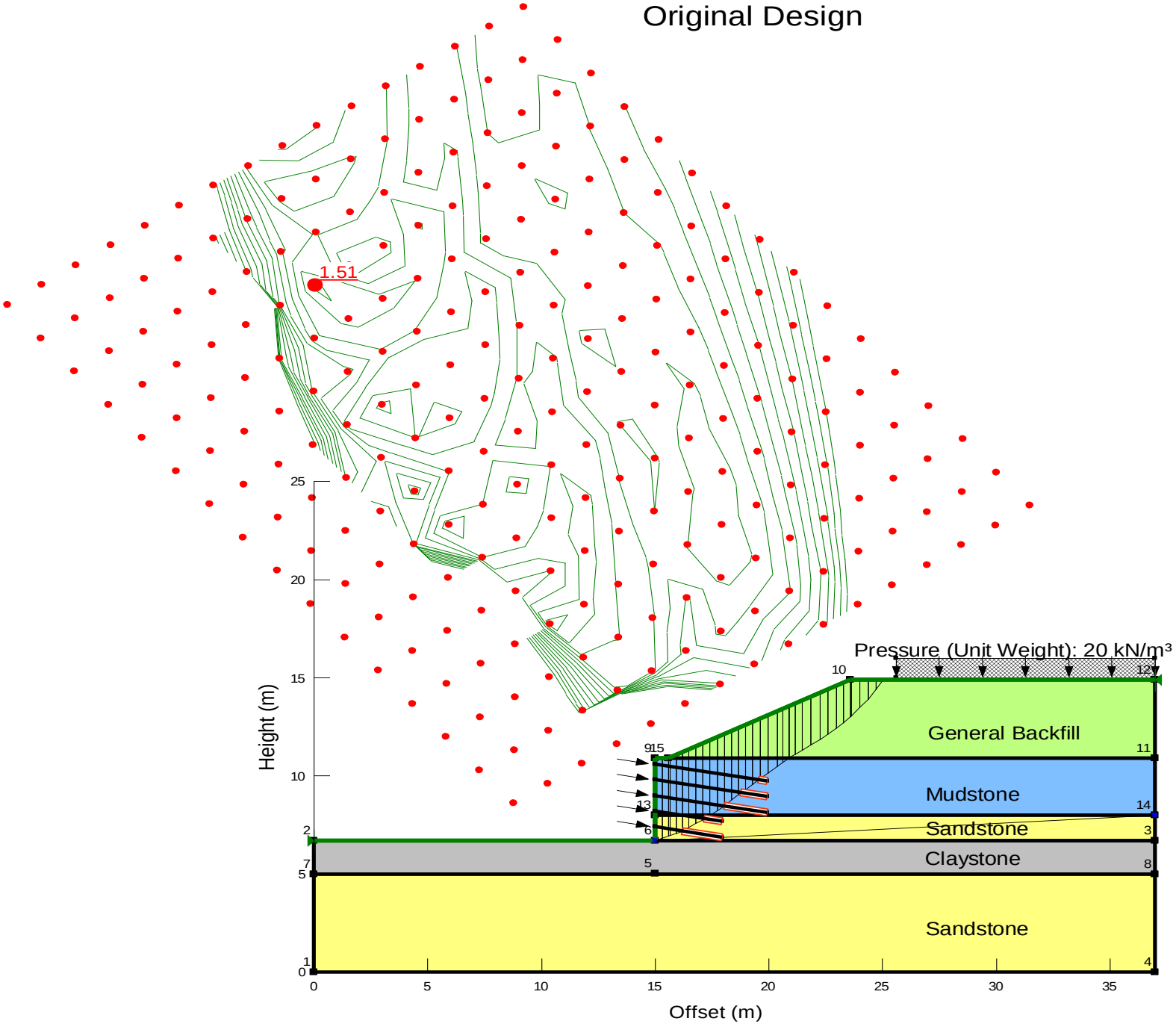
225m long wall – signs of distress during construction

Original Design



Name: General Backfill
Model: Mohr-Coulomb
Unit Weight: 19 kN/m³
Cohesion: 5 kPa
Phi: 30 °

Name: Claystone
Model: Mohr-Coulomb
Unit Weight: 21 kN/m³
Cohesion: 10 kPa
Phi: 40 °

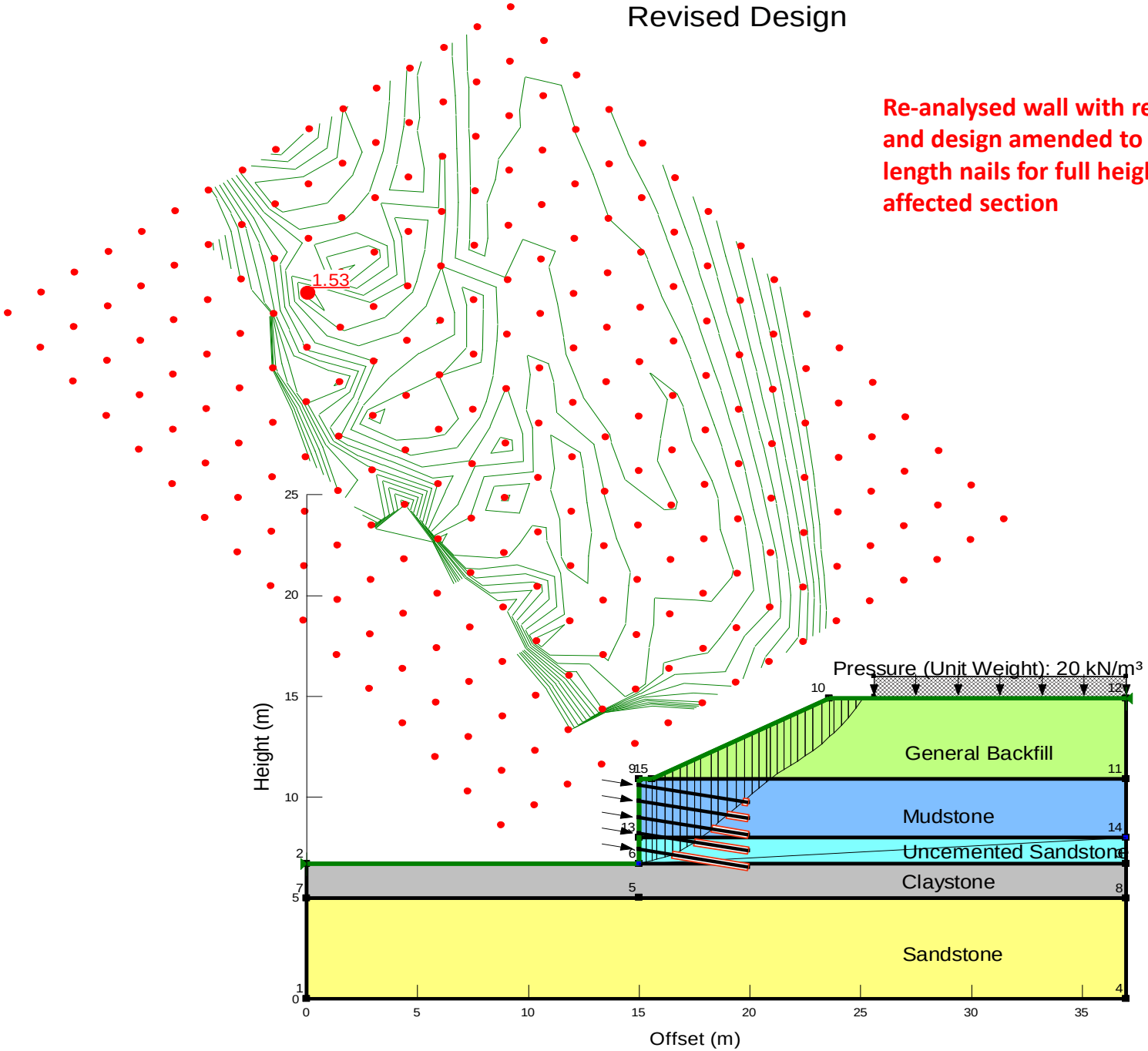
Name: Mudstone
Model: Mohr-Coulomb
Unit Weight: 21 kN/m³
Cohesion: 10 kPa
Phi: 42 °

Name: Sandstone
Model: Mohr-Coulomb
Unit Weight: 20 kN/m³
Cohesion: 2 kPa
Phi: 42 °

Directory: K:\Q1215 - LMI\Coffey\Design\Walls\RW08\

Revised Design

Re-analysed wall with revised ground model and design amended to incorporate same length nails for full height of wall over affected section



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Name: Mudstone
Model: Mohr-Coulomb
Unit Weight: 21 kN/m³
Cohesion: 10 kPa
Phi: 42 °

Name: Uncemented Sandstone
Model: Mohr-Coulomb
Unit Weight: 20 kN/m³
Cohesion: 0 kPa
Phi: 35 °

Name: Sandstone
Model: Mohr-Coulomb
Unit Weight: 20 kN/m³
Cohesion: 2 kPa
Phi: 42 °

Directory: K:\Q1215 - LMI\Coffey\Design\Walls\RW08\

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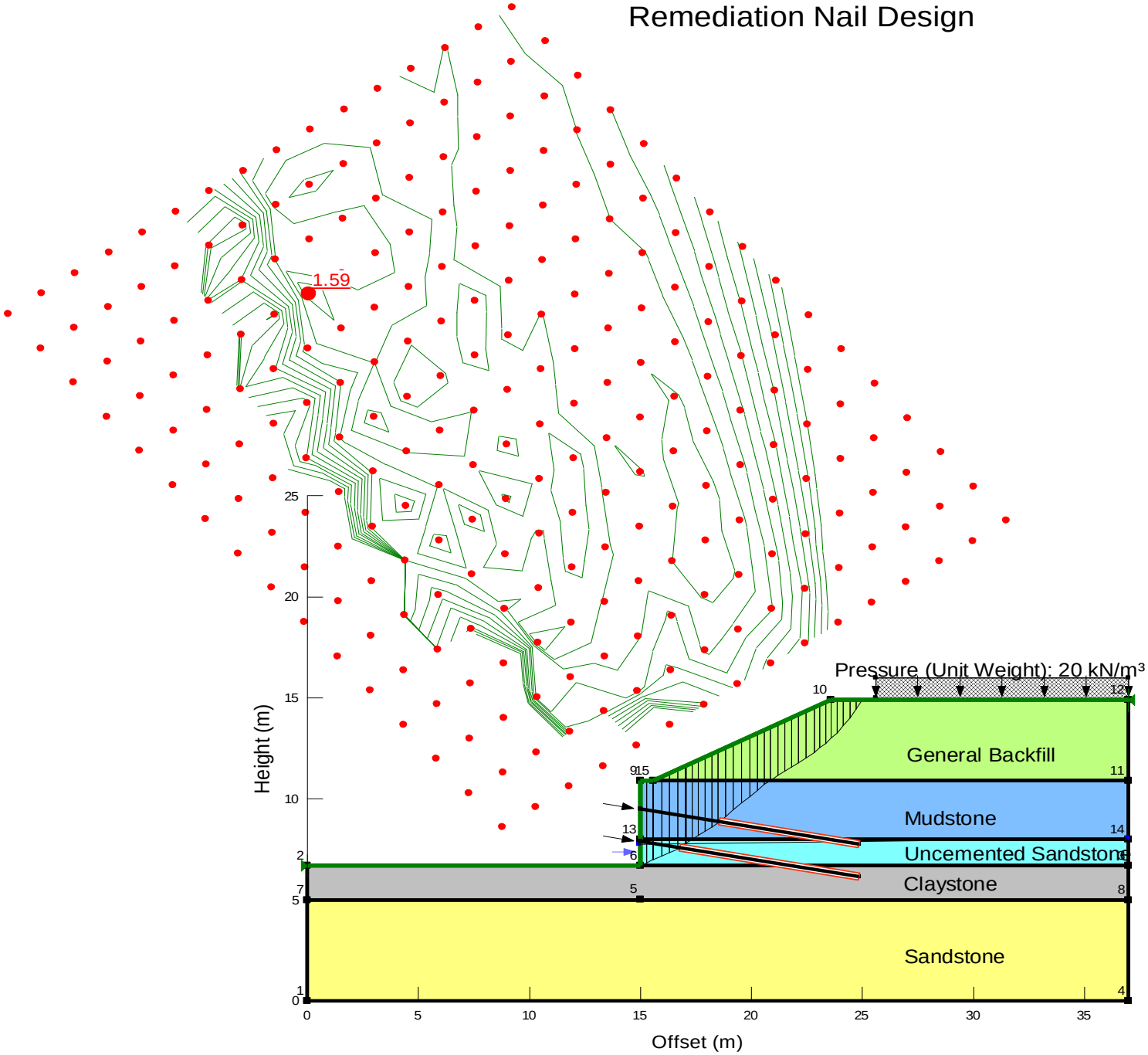
Remediation

But, after wall completed:

Wall still showed signs of movement

Extra nails 10m in length were recommended along 20m of the unstable section

Remediation Nail Design



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Model: Mohr-Coulomb
Unit Weight: 20 kN/m³
Cohesion: 2 kPa
Phi: 42 °

Directory: K:\Q1215 - LMI\Coffey\Design\Walls\RW08\

Spacers of inadequate strength

Damage to installed soil nail bars by excavator

Lack of experience of contractors staff

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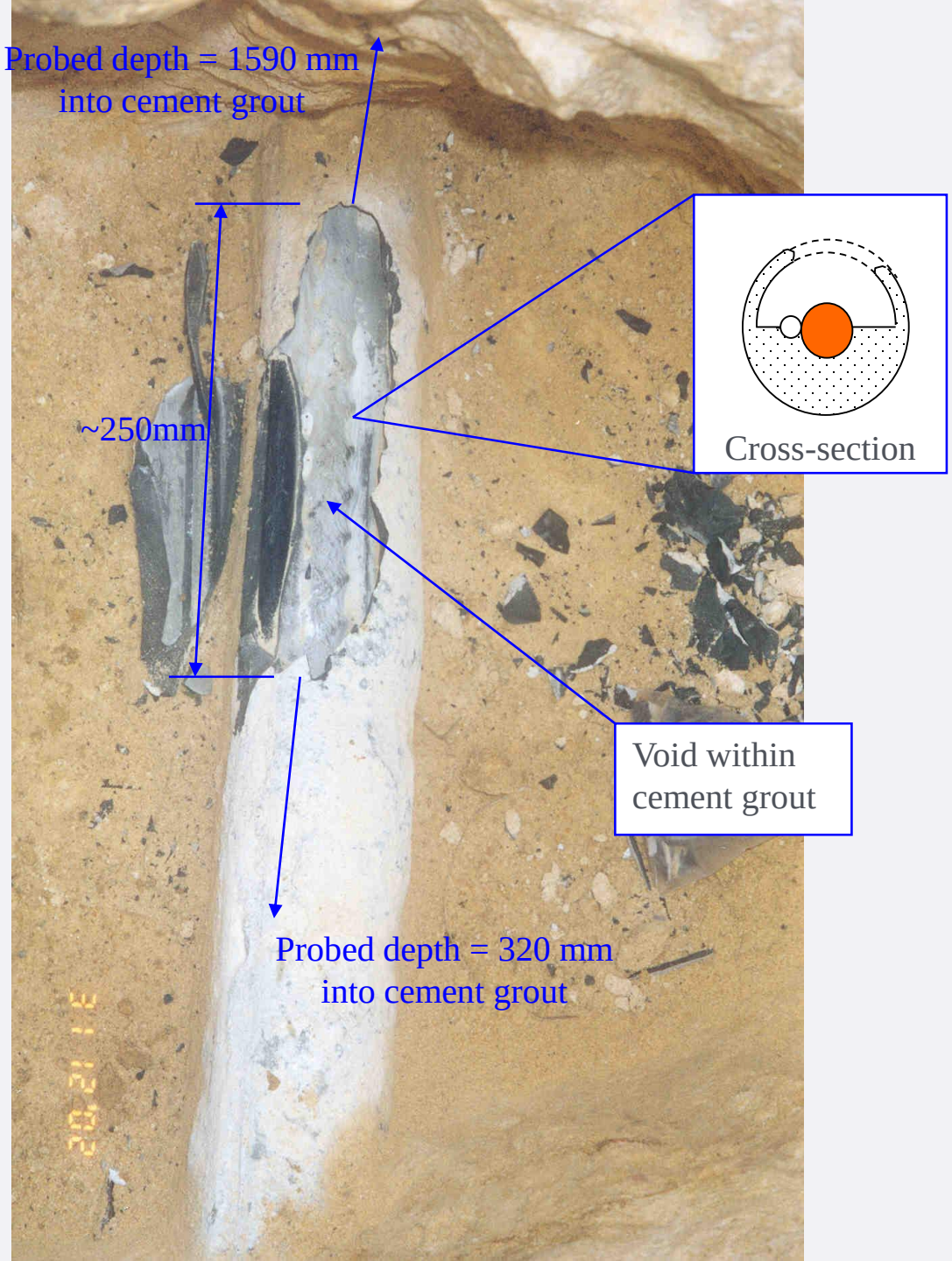
Soil Nail Failures

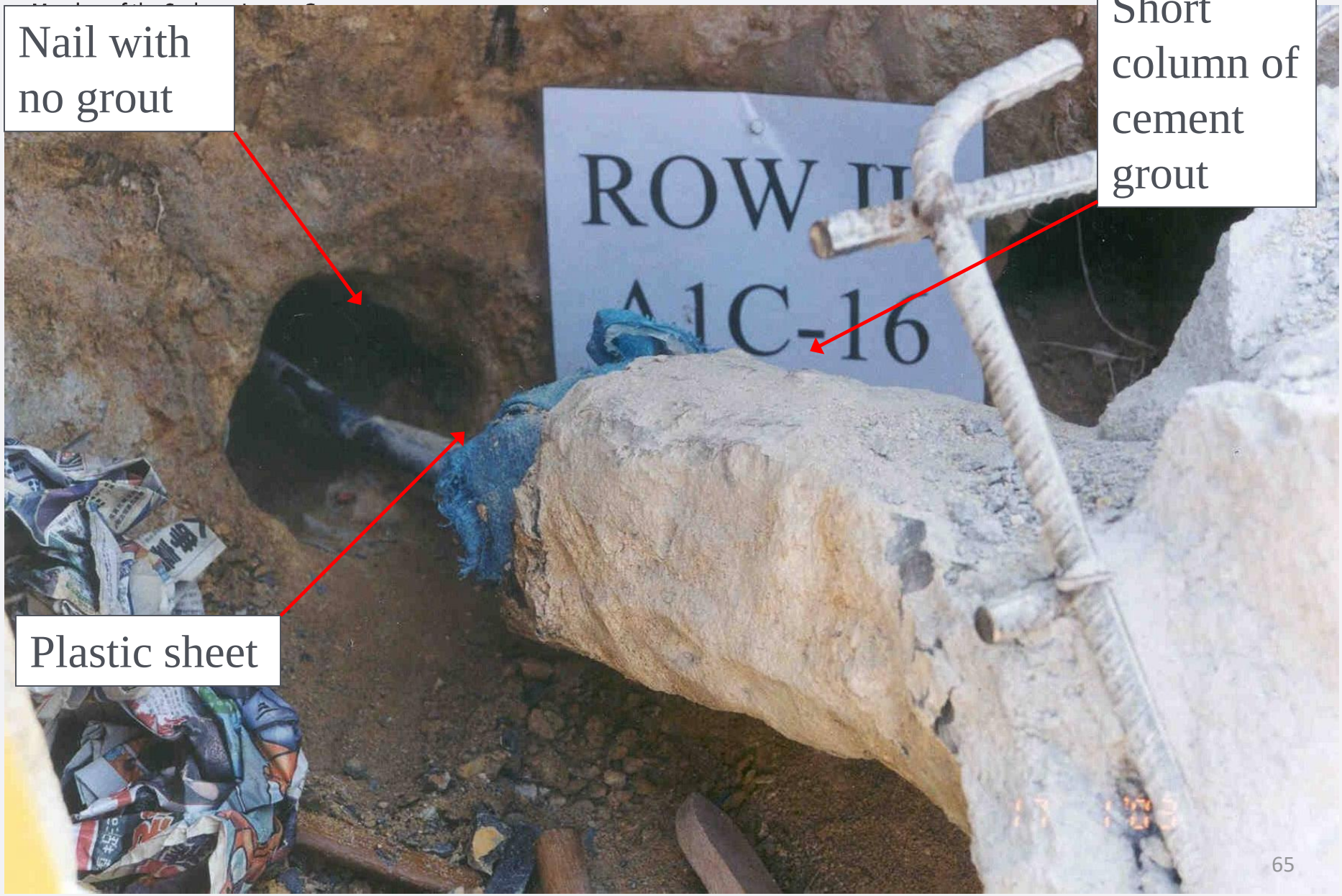
Soil nail facing failure

Grout cover cracked and peeled off from nail

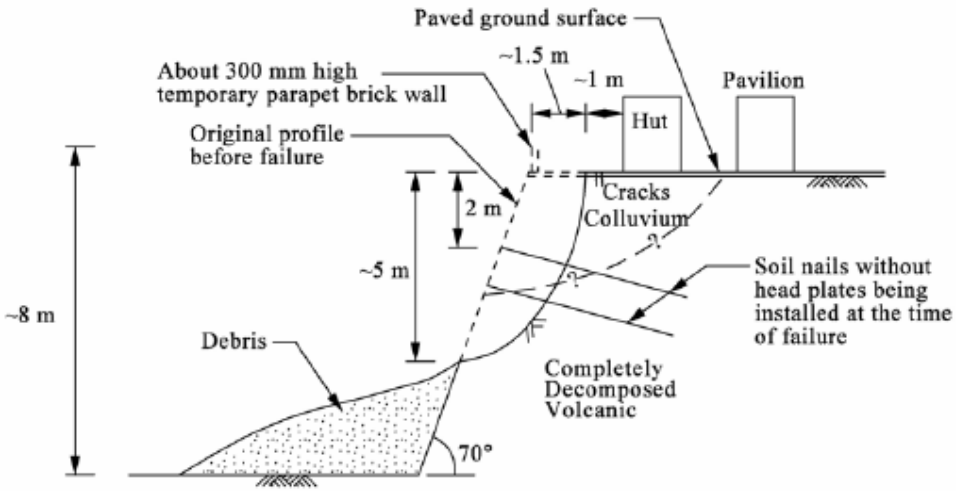
Ref.: Tan. & Chow, 2004

Soil Nail Failures




Nail with no grout
Short column of cement grout
Plastic sheet
ROW II
A1C-16

Soil Nail Failures



Slope failure prior to soil nail heads being installed during heavy rain

Cause of failure:

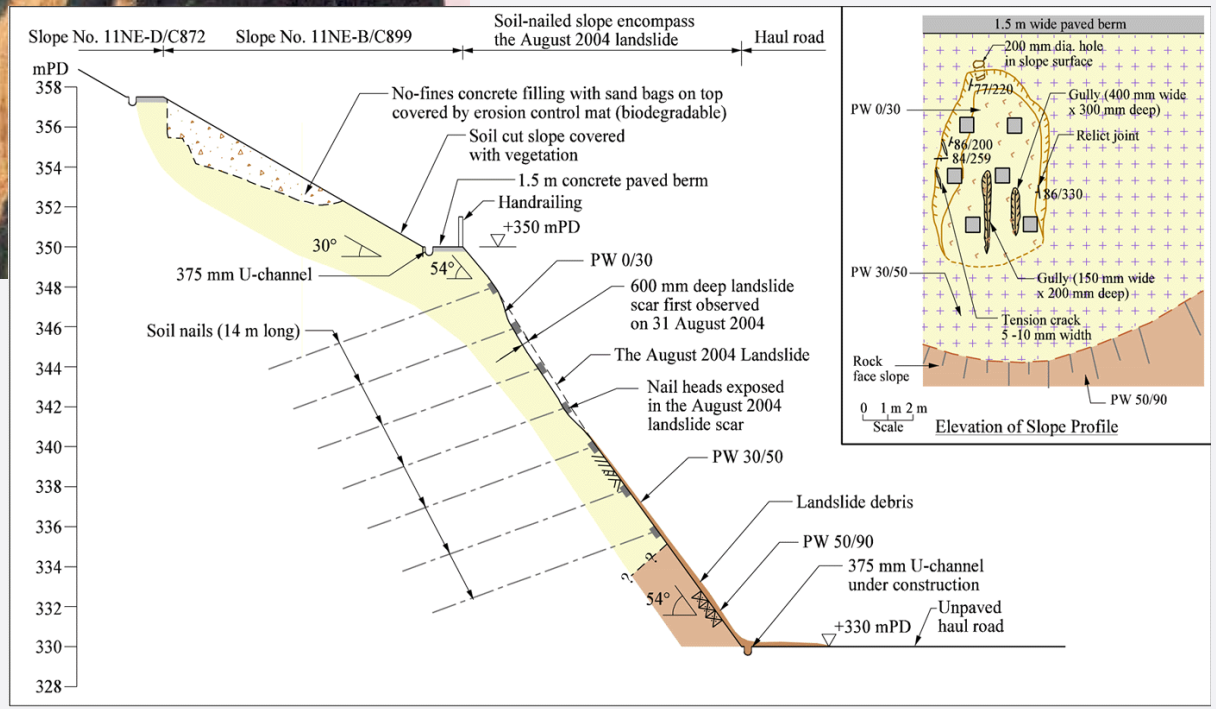
- Ingress of water

Assisted by -

- Upper row of nails too low below crest
- Wide nail spacing
- Lack of surface protection
- Poor construction of nails

Ref.: Sun & Tsui, 2005

Soil Nail Failures



6m^3 failure in Completely Decomposed Tuff

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Airport Link – Construction Issues

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)

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