GEOTECHNICAL ENGINEERING IN THE DESIGN OF STRUCTURES:

Reinforced soil structures

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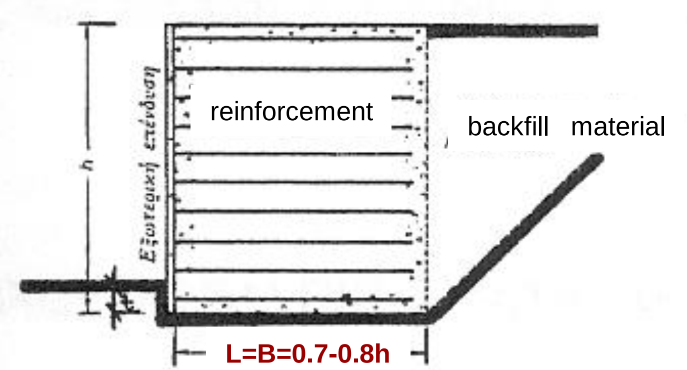
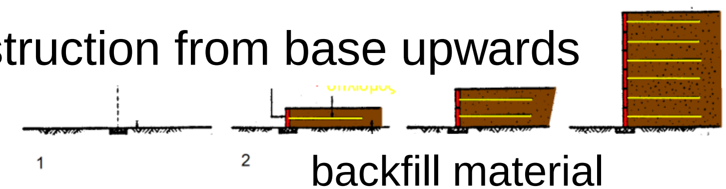
REINFORCED EARTH

- Reinforced earth _ Reinforced earthfill wall

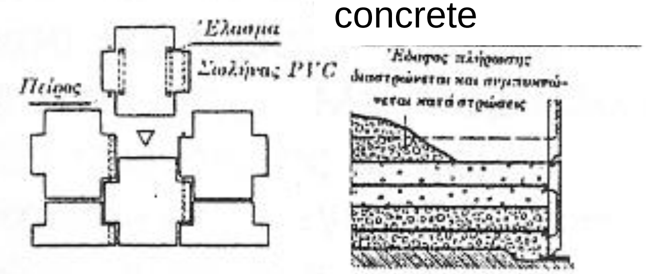


construction from base upwards

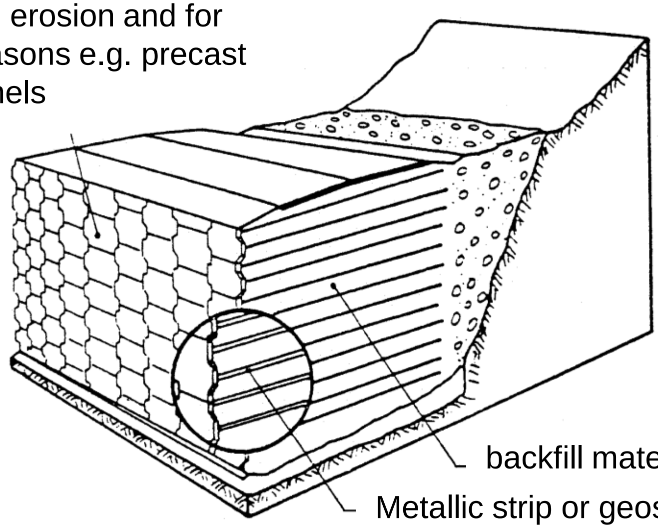


backfill material

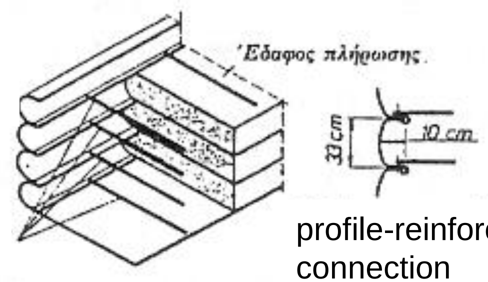
Face from prefabricated concrete



facing to provide local support, prevent local erosion and for aesthetic reasons e.g. precast concrete panels



Face from metal profiles



reinforcement

profile-reinforcement connection

backfill material

Metallic strip or geosynthetic reinforcement



Geotextiles: polypropelene, polyester fabric….filtering

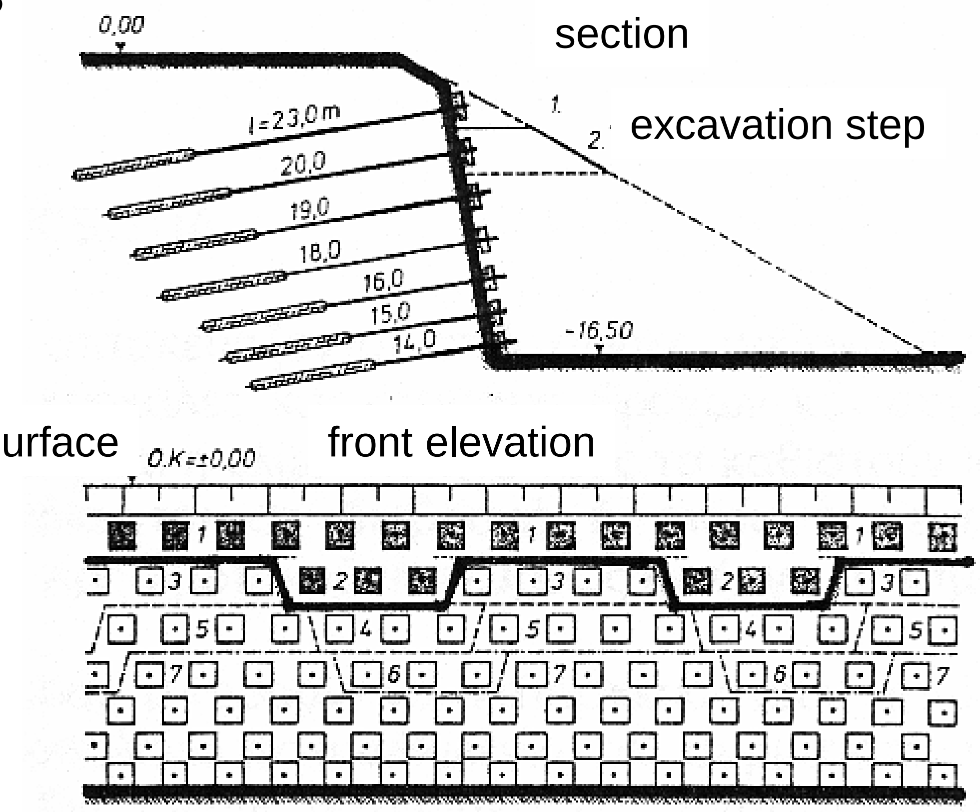


Geogrids: tensar uni-axial, biaxial, triaxial


Geomemrane liners: waterproofing

RETAINING WALLS

- Construction of reinforced *in-situ* walls using soil nailing



➪ existing slope is steepened e.g. motorway widening

Reinforced earthfill structures

Soil nailing

- Built on natural soil
- Built from top down reinforcing the soil in situ
- Nails under tension transfer forces deepper in the soil mass
- Conventional retaining wall withstands earth pressures
- Soil nailed wall relies on length and density of nails to

to resist earth pressuresby mobilising skin friction

Wall construction sequence-soil nailing

- Excavation of a shallow depth of soil in front of the wall~1-2m
- Installation of a row of soil nails
- Fill the hole with grout
- Remove surface water. A filter fabric on the ground surface before applying the shotcrete provides drainage behind facing
- Installation of reinforcing mesh and the facing
- Wall is formed top downwards by a sequence of the above steps
- Completed structure

REINFORCED SOIL STRUCTURES

Reinforced earthfill structures

1. Widening of embankments, embankments on soft foundations, bridge abutments, retaining walls
   - easy and rapid construction
   - suitable frictional backfill material required
   - non corrosive backfill material

Soil nailing

2. Reinforced in-situ soil structures. Retaining walls, excavation stability to tunnel portals and adjacent slopes, slope stabilisation of cuttings
   - cheap, flexible, small mobile quiet construction equipment
   - soil with some natural degree of cohesion required
   - dewatered excavation face-unsuited for excavation in soft clay

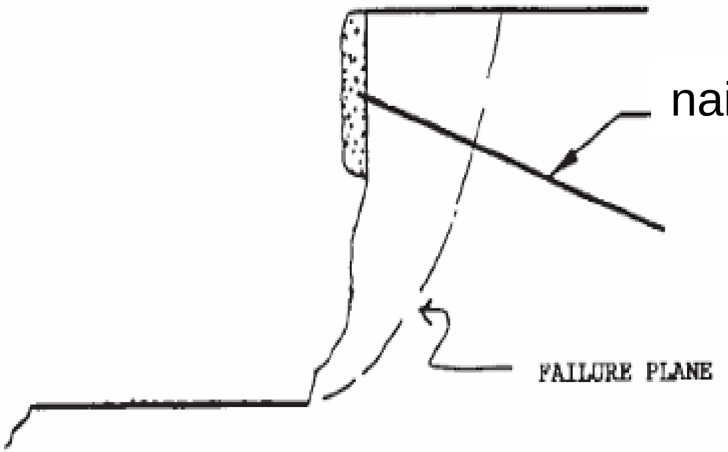
SOIL NAILING

- Clouterre (1991). “Soil nailing recommendations for designing, calculating, constructing and inspecting earth support systems using soil nailing”. ***Ecole Nationale des Ponts et Chausseès, Paris***. English translation (1993), US Department of transportation, FHWA-SA-93-026.

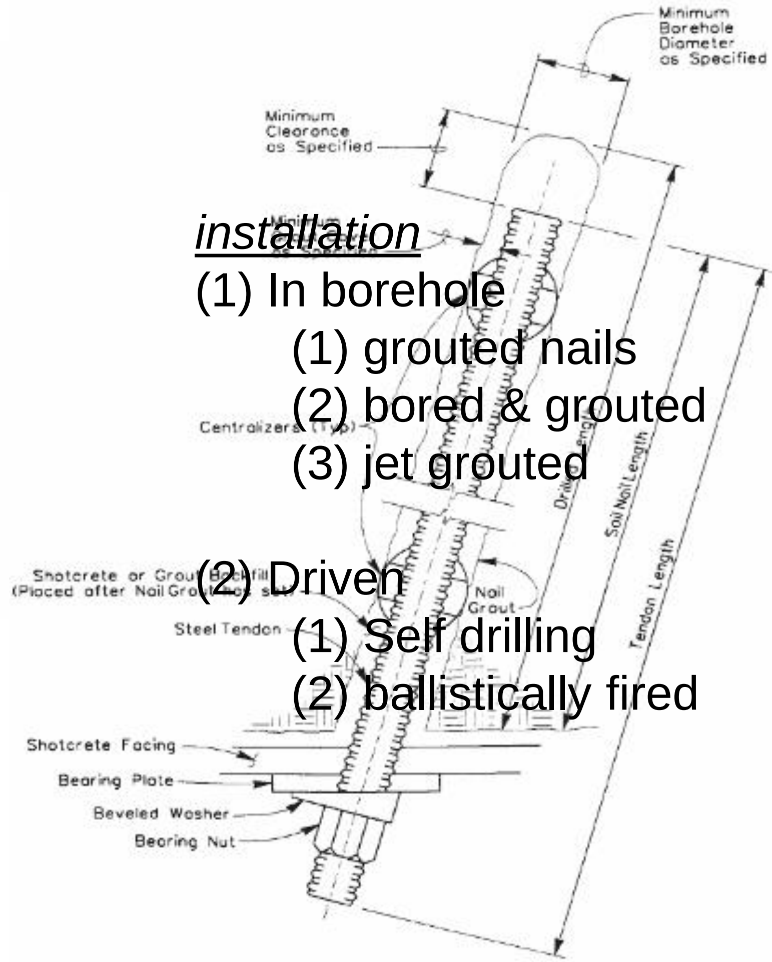
Construction of railway cutting in Versailles-Chantier,1974.

- slope height 22m
- excavation cutting 1.4m
- reinforcement subhorizontal 30^0

SOIL NAILING



In soil nailing reinforcement can withstand tension and moment



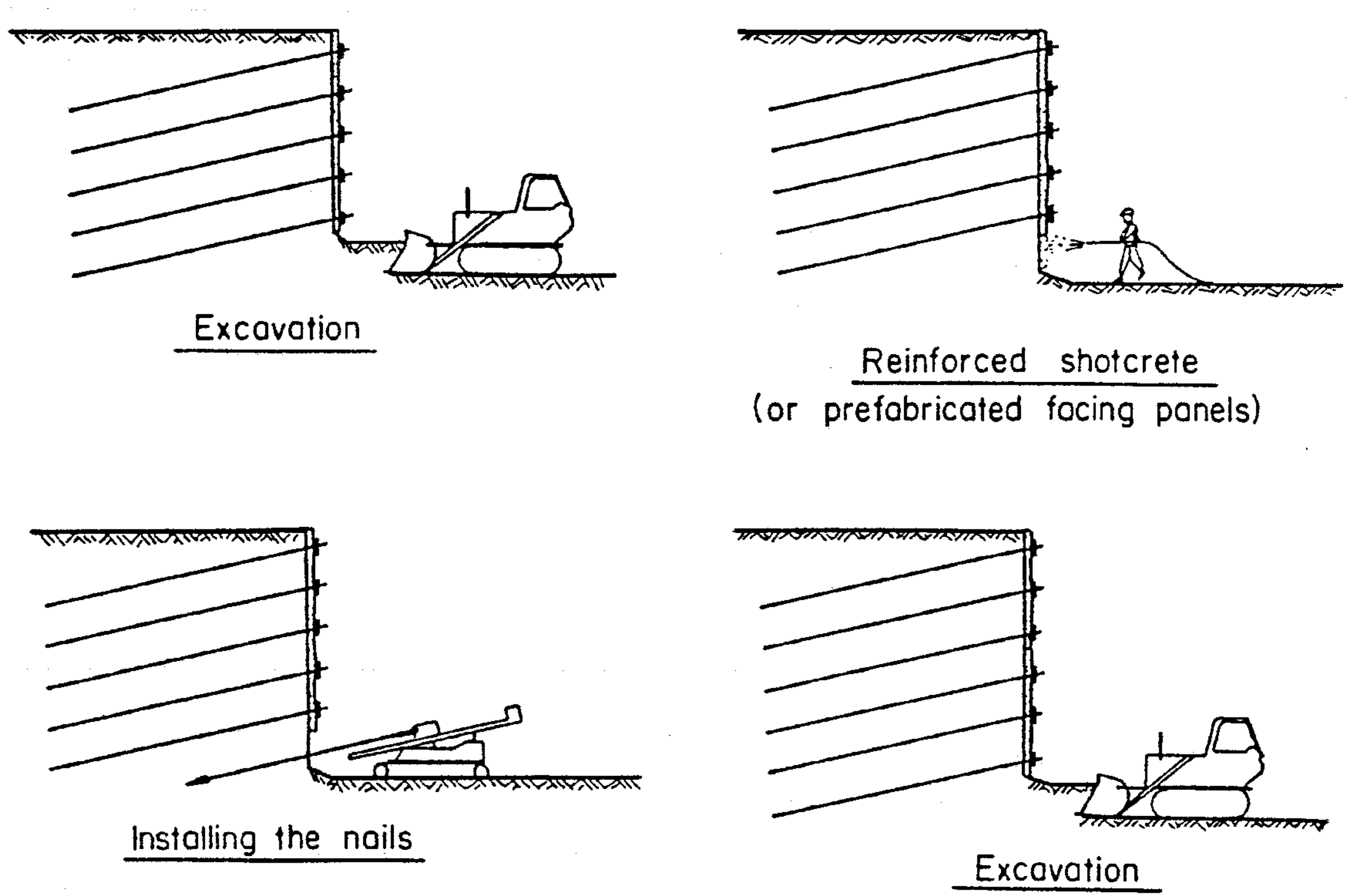
installation

(1) In borehole
- (1) grouted nails
- (2) bored & grouted
- (3) jet grouted

(2) Driven
- (1) Self drilling
- (2) ballistically fired

grouted nail

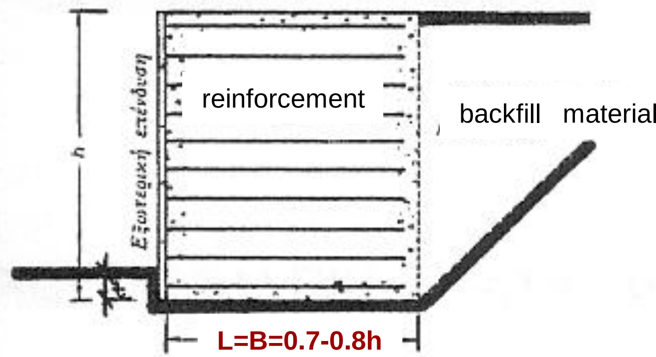
CONSTRUCTION SEQUENCE FOR REINFORCED IN-SITU WALLS USING SOIL NAILING



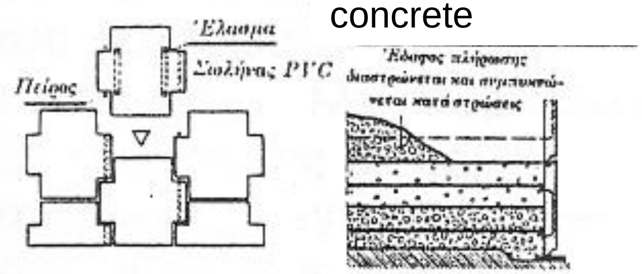
REINFORCED EARTH

- Reinforced earth _ Reinforced earthfill wall

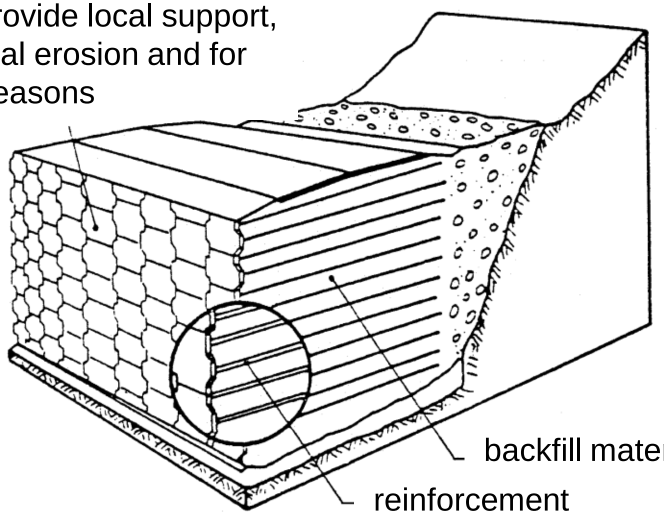
construction from base upwards



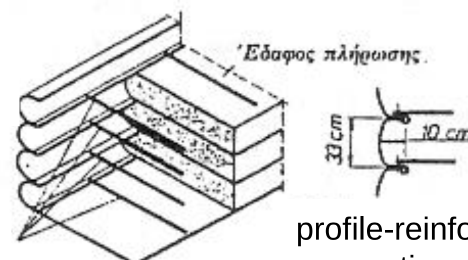
Face from prefabricated concrete



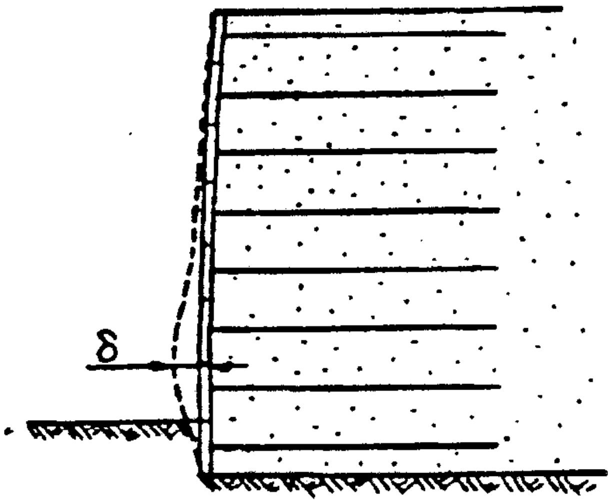
facing to provide local support, prevent local erosion and for aesthetic reasons



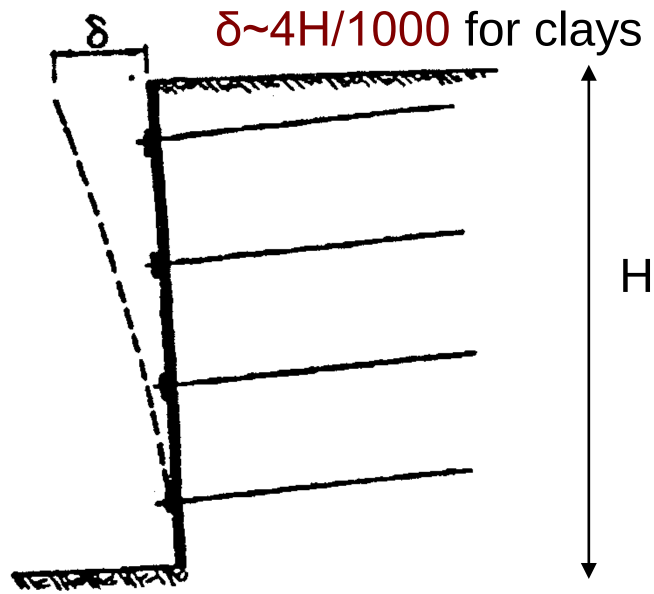
Face from metal profiles



MODES OF DEFORMATION FOR REINFOERCED EARTH AND SOIL NAILED WALL



Reinforced Earth Wall

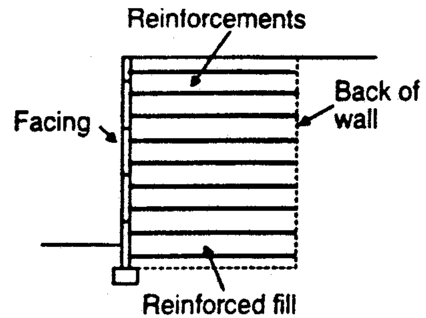


Soil nailed wall

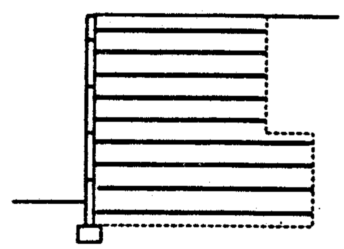
- Reinforcing layers increasingly stressed as successive layers are placed above them (the uppermost layers of reinforcement subjected to the smallest tensile forces). Consolidation settlement also increases with depth.

- As progressive layers of soil are excavated, the face of the excavation tends to move outwards from the resulting stress relief (active state). It is the upper nails that are loaded first during construction and carry the greatest tensile loads.

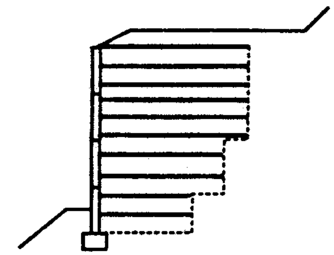
EXAMPLES OF REINFORCED EARTHFILL STRUCTURES



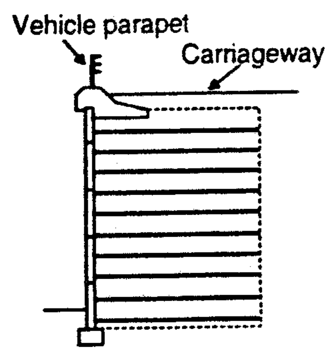
Definitions



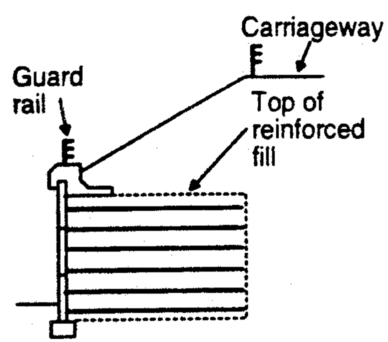
Stepped wall



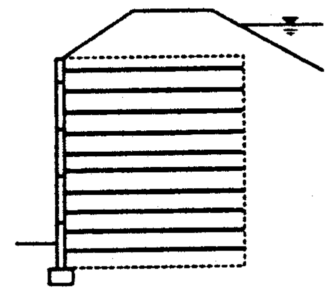
Trapezoidal wall



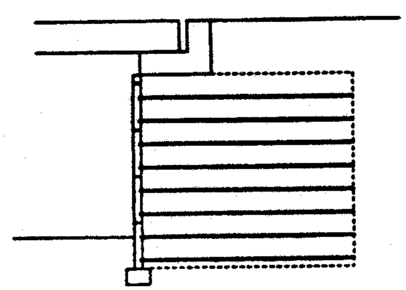
Full-height wall



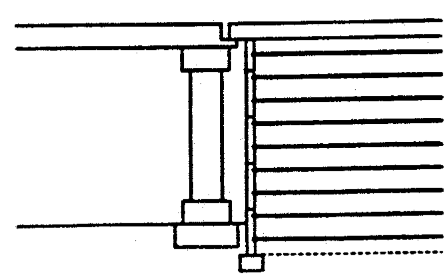
Part-height wall



Dam

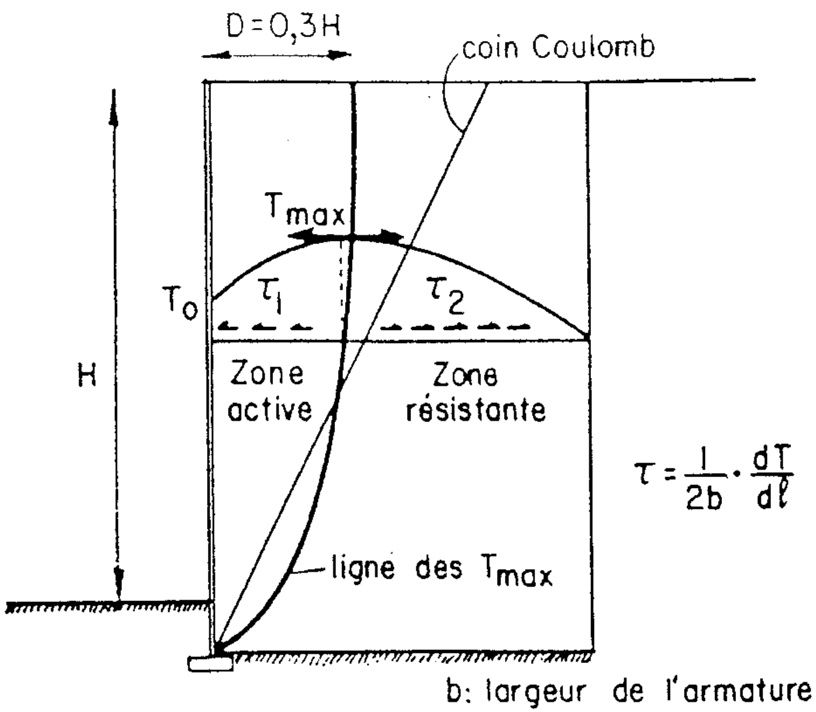


Reinforced soil abutment



Mixed abutment

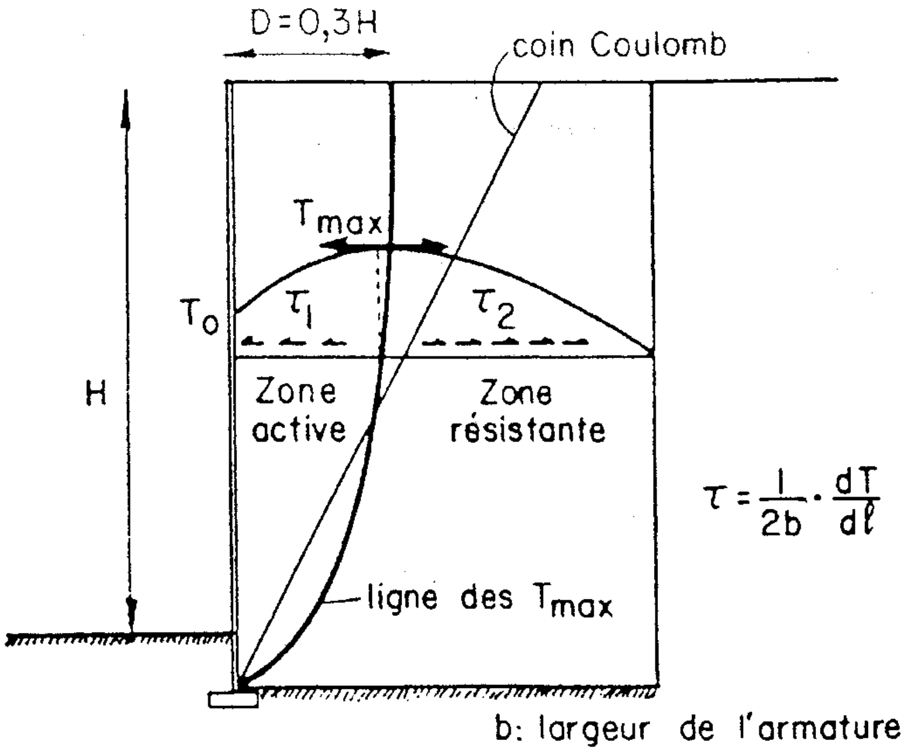
OPERATION OF A REINFORCED EARTHFILL WALL



- As the height of the wall increases, vertical stress increases and shear stresses build up inside the soil mass. Then a tendency for the face to displace outwards is resisted by the reinforcing elements as frictional forces develop along them and they go into tension.
- The maximum tensile forces in the reinforcement occur within the soil mass rather than at the facing. ***This applies to both reinforced and nailed soil structures.***

- If the points of maximum tensile force along each row of reinforcement are joined a line is formed which separates the reinforced soil mass in two regions: the ***active zone*** and the ***passive or resistant zone.***

OPERATION OF A REINFORCED EARTHFILL WALL

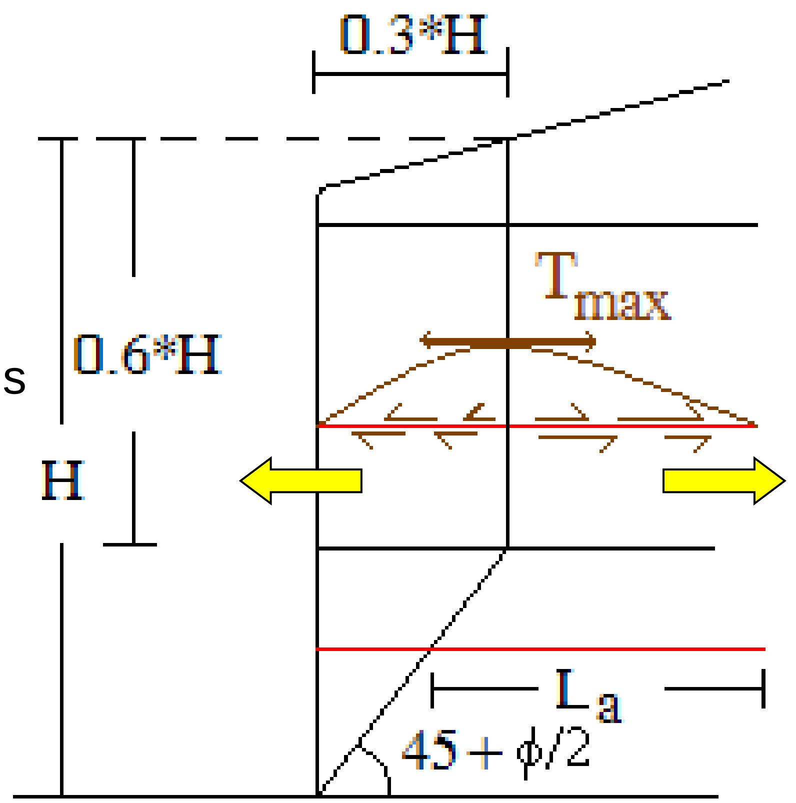


- **ACTIVE ZONE** develops immediately behind the facing where the soil tends to move outwards exerting shear stresses along the reinforcement towards the facing
- **PASSIVE ZONE** where the shear stresses exerted along the reinforcement act inwards as the soil in this zone resists movement

- The stresses generated in the passive zone oppose those resulting from the outward movement in the active zone and define the position of ***the line of maximum tension***

LINE OF MAXIMUM TENSION

Forces towards facing

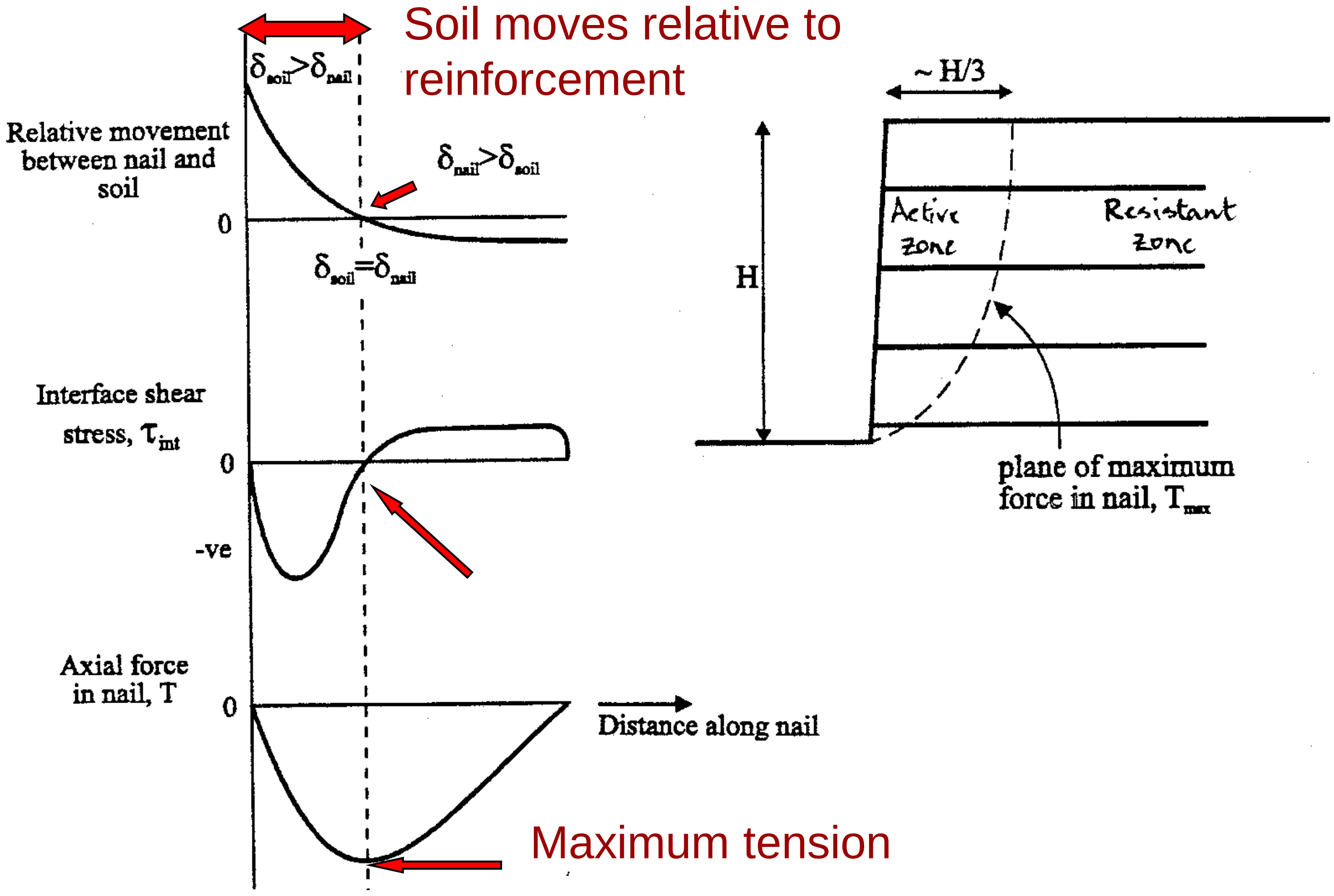


Inwards forces due to soil resistance to outward movement

- **Simplified line of maximum tension**

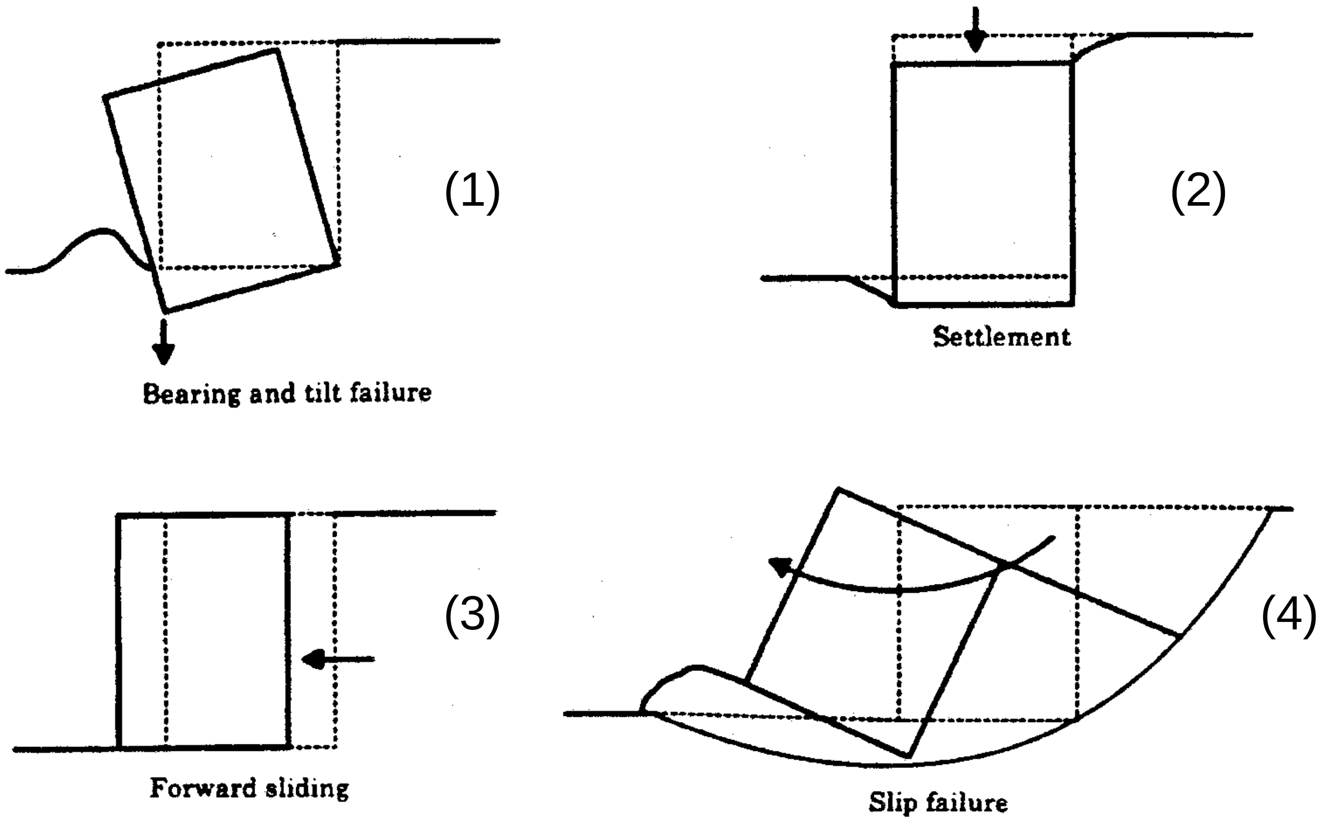
assuming Coulomb's failure plane at an angle 45+φ/2 to the horizontal

STRESS AND STRAIN DISTRIBUTION ALONG REINFORCING ELEMENTS



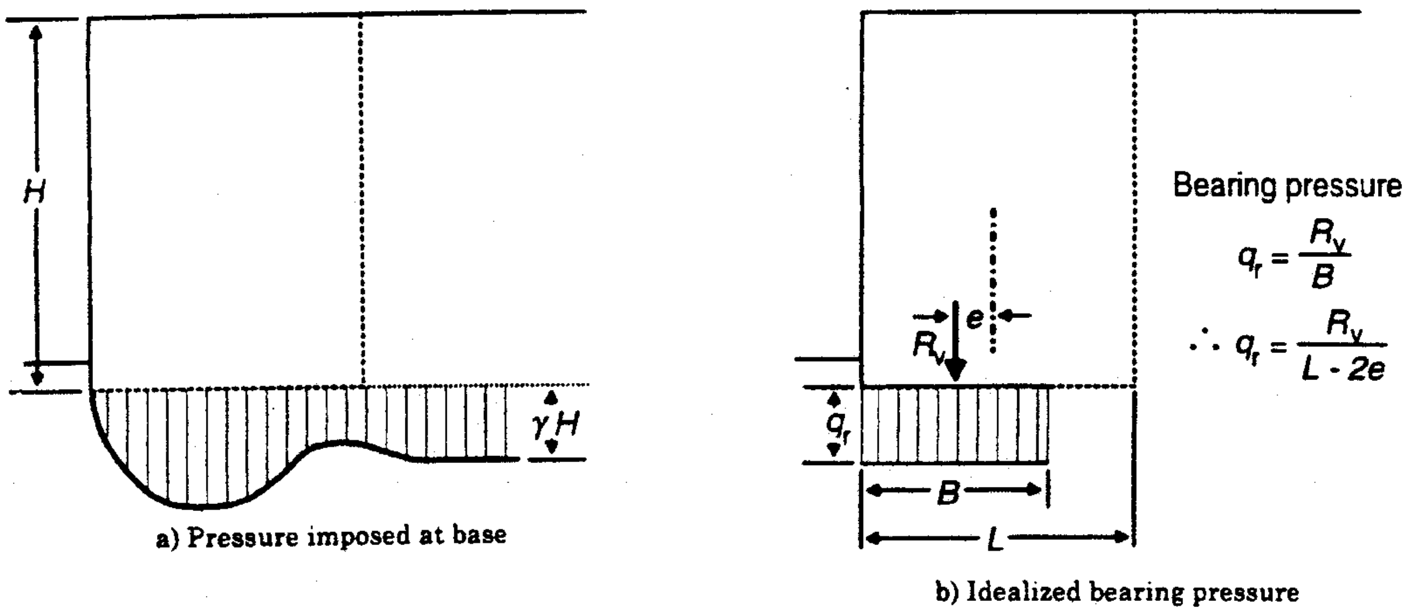
In the active zone the soil exerts shear stresses to the reinforcement towards the wall face while in the passive zone shear stresses at the reinforcement-soil interface act towards the soil mass. This applies to both earth reinforced and nailed soil structures.

OVERALL STABILITY CHECKS



- **Cases 1,2 & 3 & 4 should be considered for reinforced earthfill structures while only case 4 applies to nailed soil structures**

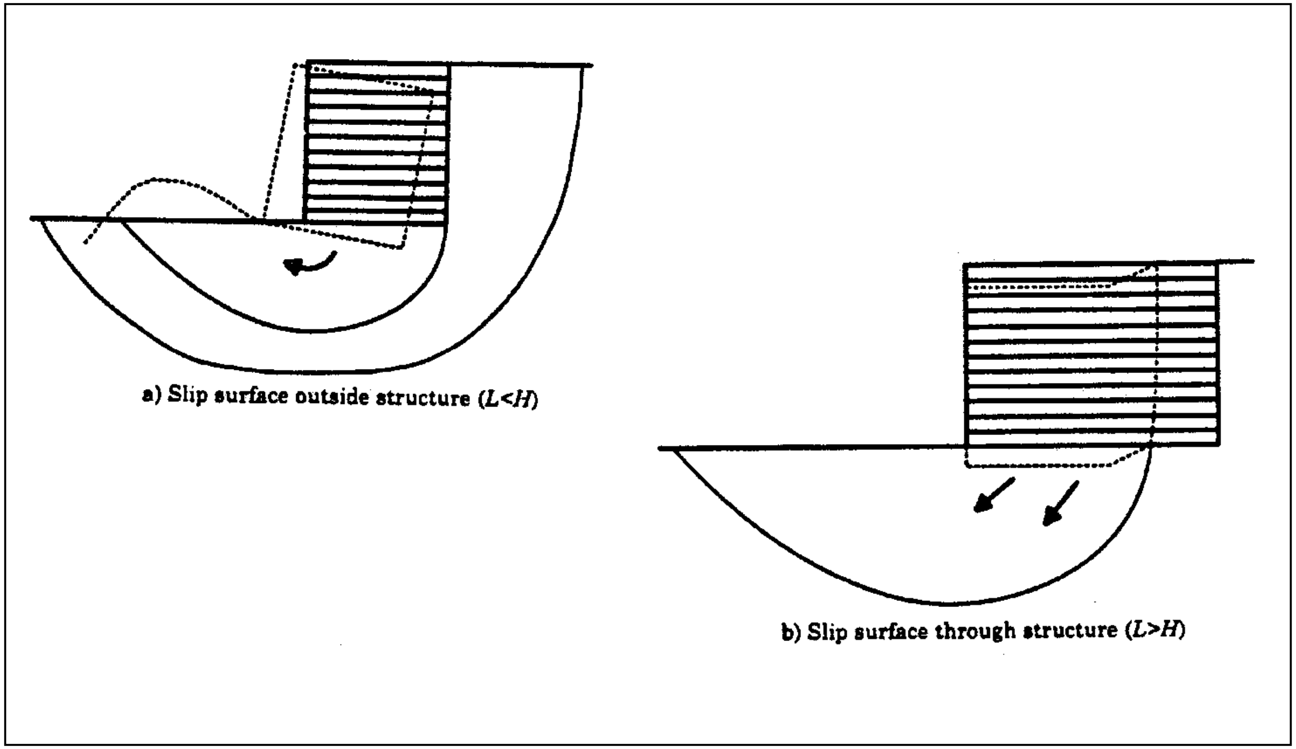
BEARING FAILURE



- pressure distribution along base of wall, according to Meyerhof a linear load is assumed across part of the base:

$$q_r = \frac{R_v}{B} \therefore q_r = \frac{R_v}{L - 2 \times e} < q_{ult}$$

SLIP FAILURE



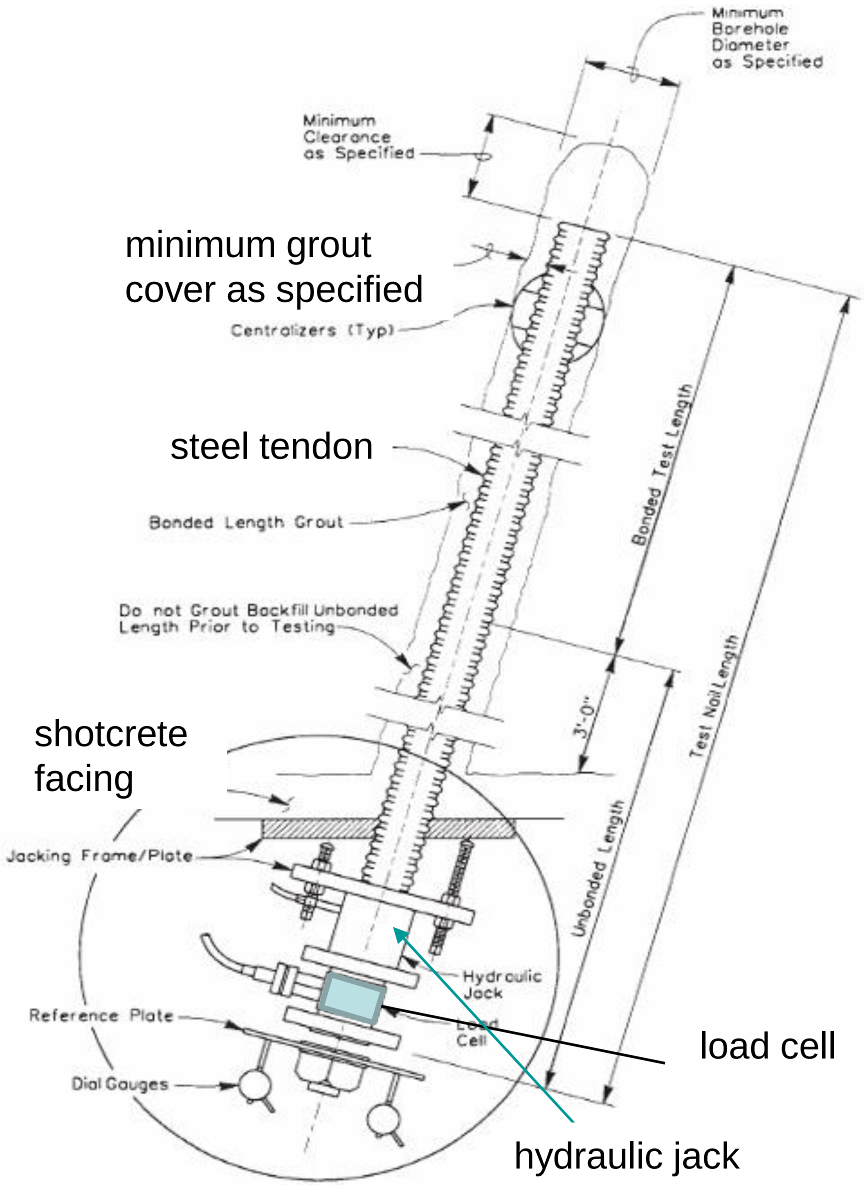
(a) Potential slip surfaces outside reinforced mass

(b) Potential slip surfaces through reinforced mass

INTERNAL STABILITY CONSIDERATIONS

- Checking the stability within the reinforced mass. The stability of all block masses enclosed by the wall boundary and possible failure surfaces of all shapes should be checked at all stages of construction.
- Checking the stability of the blocks involves the additional forces provided by the reinforcing elements apart from forces on the block such as weight, pore water pressure, surcharge, forces due to soil friction and cohesion.
- Check for failure of the reinforcing elements
  - Rupture of the element (tensile capacity)
  - Soil failure due to maximum shear stress mobilised at the interface with the element (bond strength)

PULL-OUT TESTS



- Pull-out test on nail
- Pull-out tests on strip elements avoided due to the effect of surrounding strips
  - *Bond strength at the interface between soil and reinforcing element* <u>*estimated*</u> *by the soil shear strength parameters and the normal stress acting at the interface*
  - *The angle of interface friction can be obtained from shear box tests with shearing carried out on the reinforcing material*

ESTIMATE OF BOND STRENGTH

- assumptions:
  - Constant length of reinforcement L_a
  - Tensile resistance $T_\eta = q_s * \pi * D * L_a$
    - q_s=bond shear strength
    - L_a=length of reinforcement extending into the resistant zone (passive)
    - D=borehole diameter

Mohr-Coulomb failure criterion: **$q_s = c' + \sigma_\eta' * \tan\varphi'$**

$$\sigma_\eta' = \sigma_v' = \gamma * h - u, u = r_u * \gamma * h \Rightarrow$$

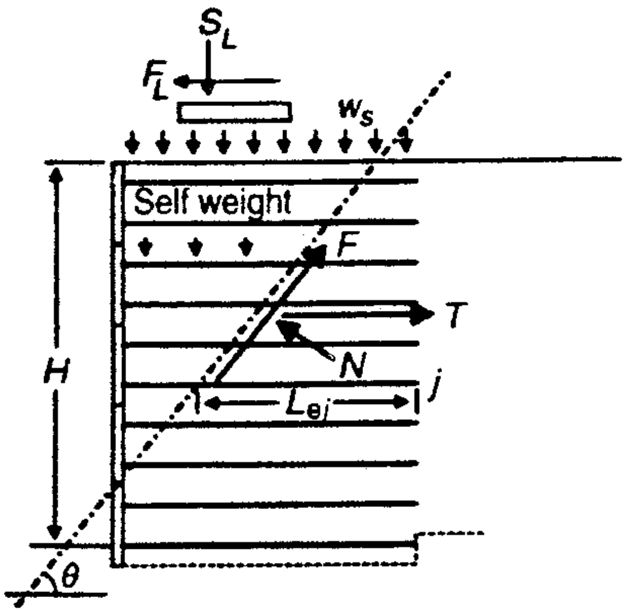
$$\tau = \gamma * h * (1 - r_u) \tan\varphi'$$

$$q_s = (k_a * (\gamma * h * (1 - r_u)) \tan\varphi'$$

$$q_s = (\sigma_v' + \sigma_h') / 2 * \tan\varphi'$$

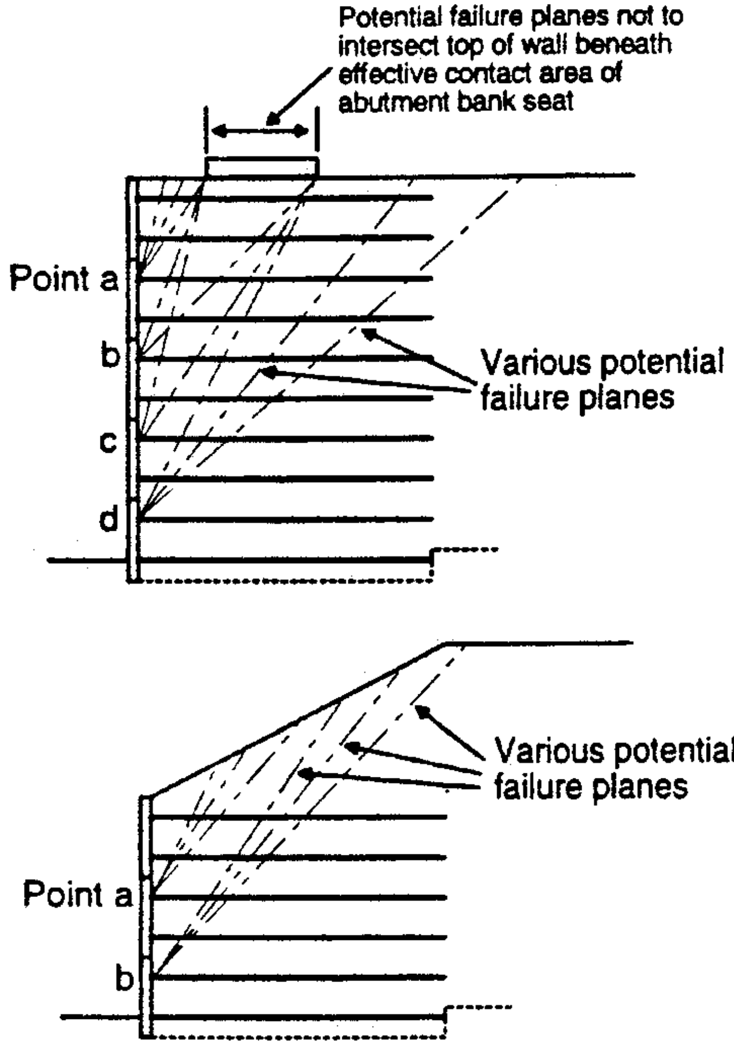
for nails installed in boreholes where stress relief takes place around the hole → active stress conditions apply

INTERNAL WEDGE STABILITY CHECKS



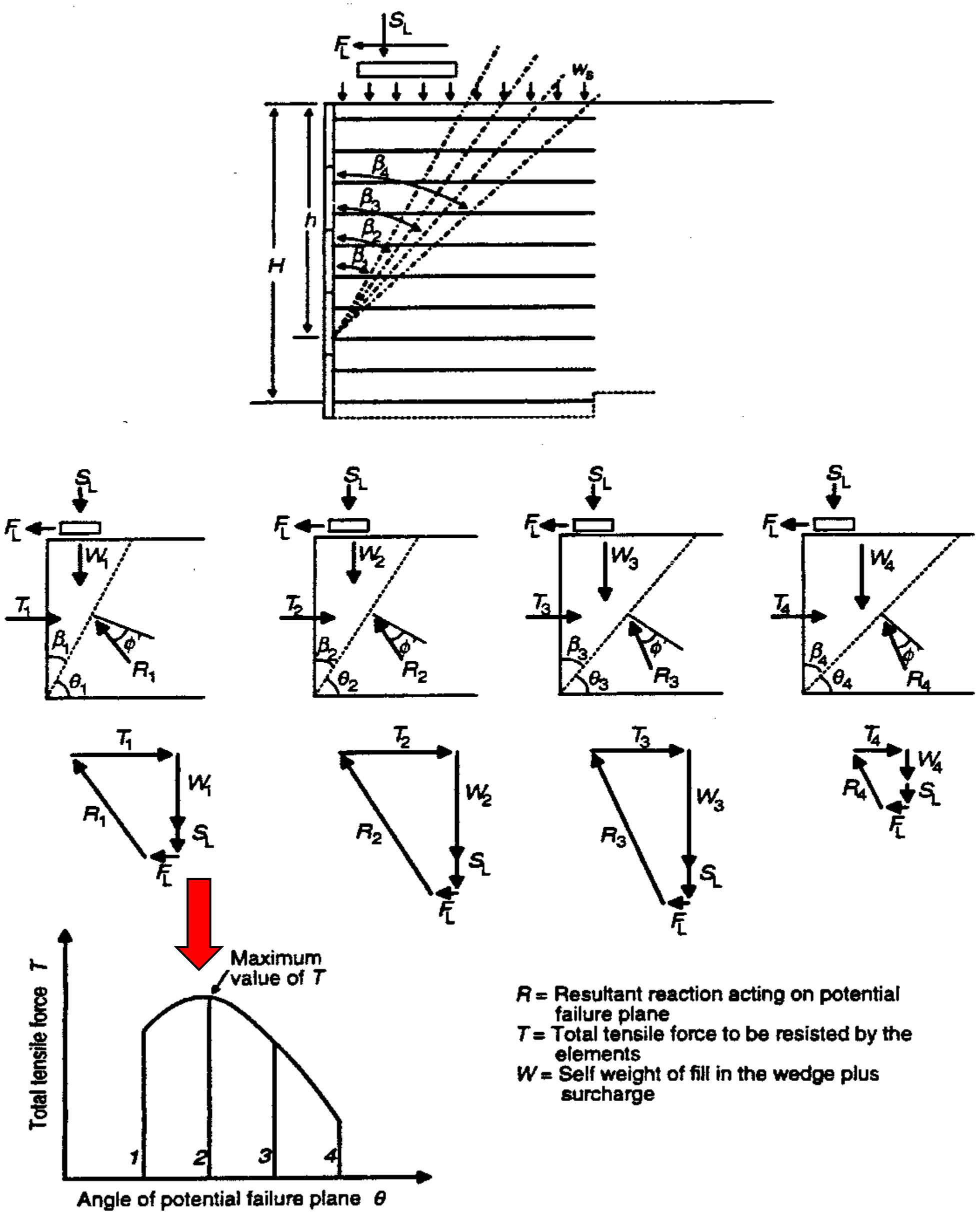
F = Frictional and cohesive forces
T = Total tensile force resisted by reinforcement elements
N = Normal reaction

a) Forces to be considered



b) Various potential failure planes

INTERNAL WEDGE STABILITY CHECKS



- Simplified analysis

Calculation of the resultant tensile force required for the stability of the reinforced soil mass

- Tj= tensile force resisted by layer (j) of reinforcement

CHECKS: 1. $T_j < T_D$ (tensile force<design strength=rupture strength/factor of safety)

2. $$\sum_{j=1}^{m} P_i \times L_{ej} \times (c' + \sigma_{vj} \tan\varphi) \geq T_{max}$$

where P_i=perimeter of jth layer of reinforcement
L_{ej}=length of reinforcement layer (j) in resistant zone outside failure wedge
σ_{vj}=normal stress acting on the reinforcement layer (j) due to overburden pressure and any surcharge
Tmax=total tensile force to be resisted by reinforcement (previous slide)

CALCULATIONS: $$T_j = T_{pj} + T_{sj} + T_{fj} - T_{cj}$$

where T_{pj}=force due to self weight of fill plus any surcharge and bending moment from external loading on the wall
T_{sj}=force induced by a vertical strip loading
T_{fj}=force induced by horizontal shear force applied to a strip contact area
T_{cj}=resisting force due to cohesion (negative sign in the expression)

TENSILE FORCES AT EACH LAYER OF REINFORCEMENT

- Tensile force at reinforcement layer (j)

$$T_j = T_{pj} + T_{sj} + T_{fj} - T_{cj}$$

$$T_{pj} = Ka \times \sigma_{vj} \times S_{vj}$$

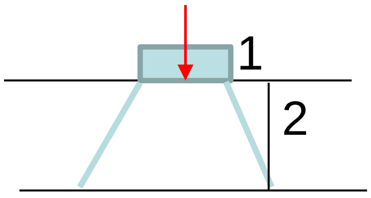
$$T_{sj} = Ka \times S_{vj} \times S_L / D_j,$$

$$D_j = (h_j + b) \rightarrow h_j \leq (2d - b)$$

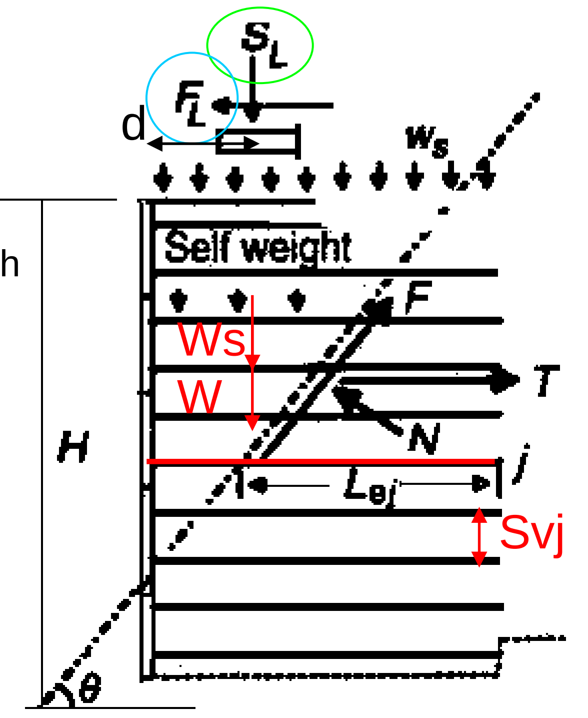
$$D_j = (h_j + b)/2 + d \rightarrow h_j \geq (2d - b)$$

$$T_{fj} = 2 \times S_{vj} \times F_L \times Q \times (1 - h_j \times Q)$$

$$Q = \{\tan(45^0 - \varphi_p'/2)\}/(d + b/2)$$



Strip contact area increases with depth slope 2 to 1



T_{pj}: σ_{vj} vertical stress acting on j^{th} level of reinforcement due to W (Meyerhof distribution) and Ws, and s_{vj} the vertical spacing of the reinforcements at j level

T_{sj}: vertical strip loading S_L of width b (D_j factor to account for stress dispersion with depth)

T_{fj}: horizontal shear force strip loading of width b (Q factor to account for distance from face)

T_{cj}: resisting force due to cohesion =2 * S_{vj} * c' * √Ka

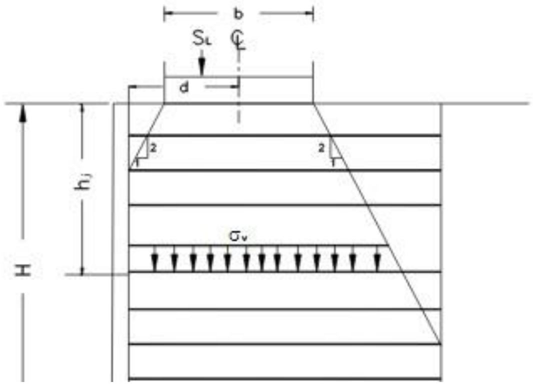
7.1.4.3 Vertical strip loading S_L applied to a strip contact area of width b on top of the wall, as shown in Fig 25 . For the purpose of deriving the magnitude only of the tensile force T_{sj} dispersal of the vertical load S_L from the contact area on top of the wall, may be taken at a slope of 2 vertically to 1 horizontally as shown in Fig 25 (As per BS 8006:1995 page 52):

$$T_{sj} = K_{aw} S_{vj} (f_f S_L) / D_j$$

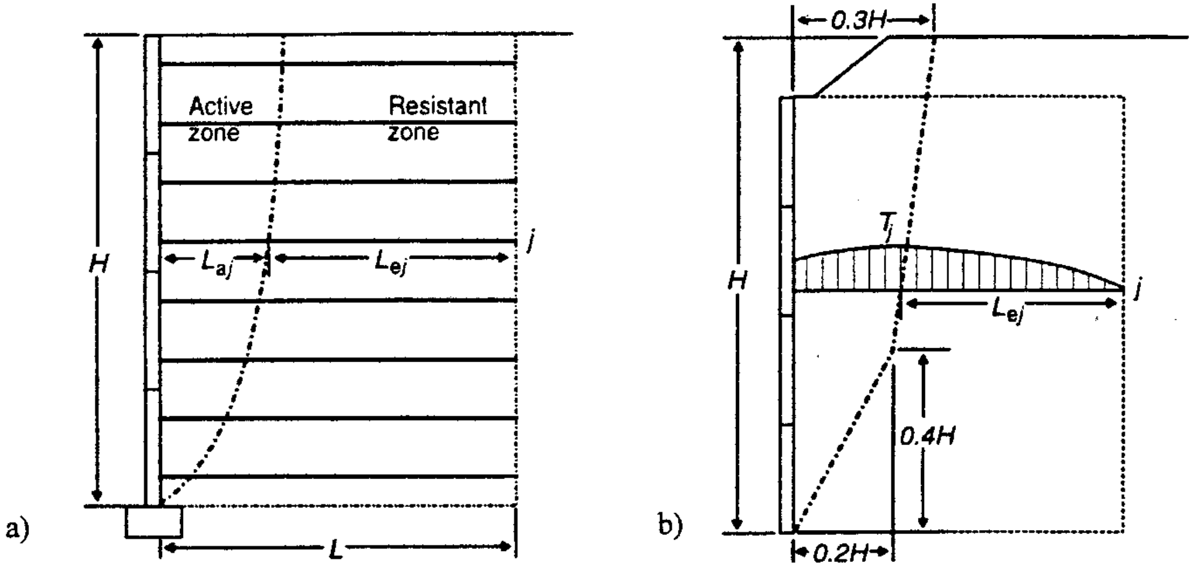
Where $D_j = (h_j + b)$ if $h_j \leq (2d - b)$

$= (h_j + b)/2 + d$ if $h_j > (2d - b)$

The tensile force obtained from the equation above should be taken as not less than that derived from the bending moment caused by the vertical loading S_L alone acting on the wall treated as a rigid body.

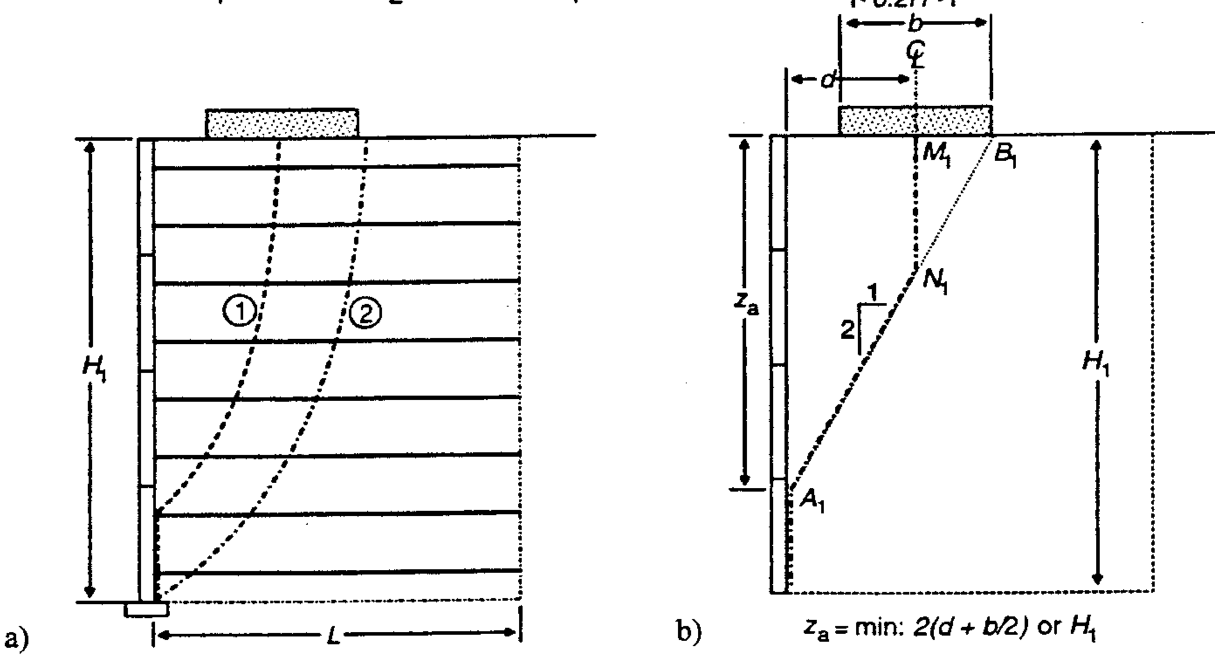


LINE OF MAXIMUM TENSION (Tj represents max load in reinforcement)



(α) log-spiral line of maximum tension

(β) its approximation for calculation purposes

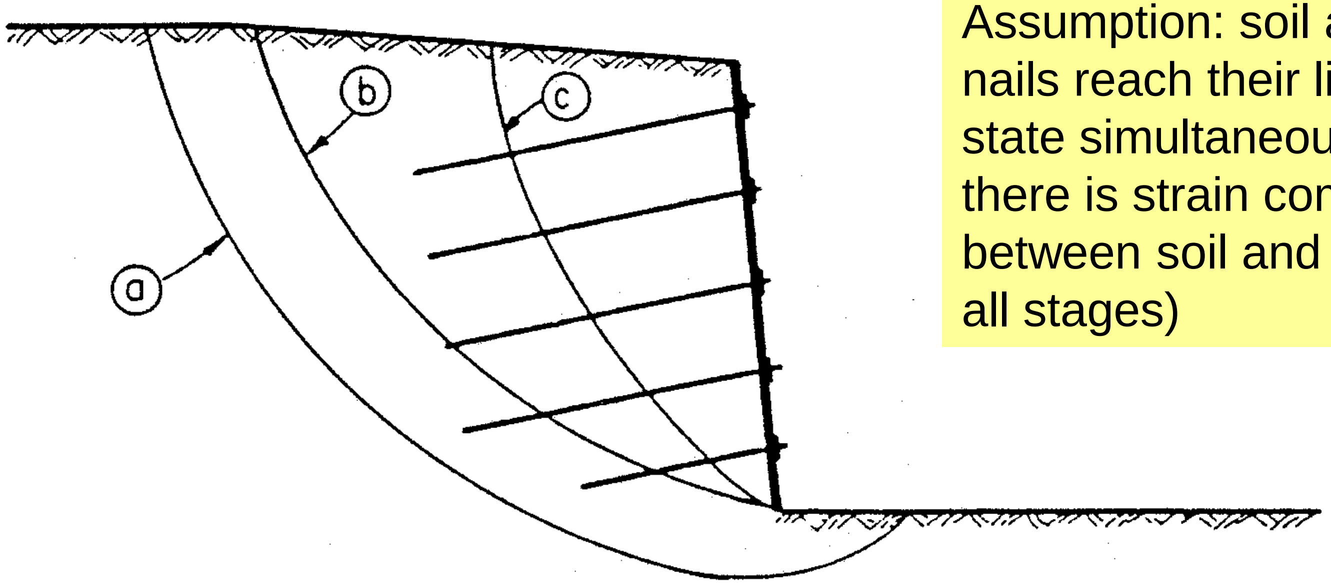


Application of strip load

- (α) assumed

  (β) approximated

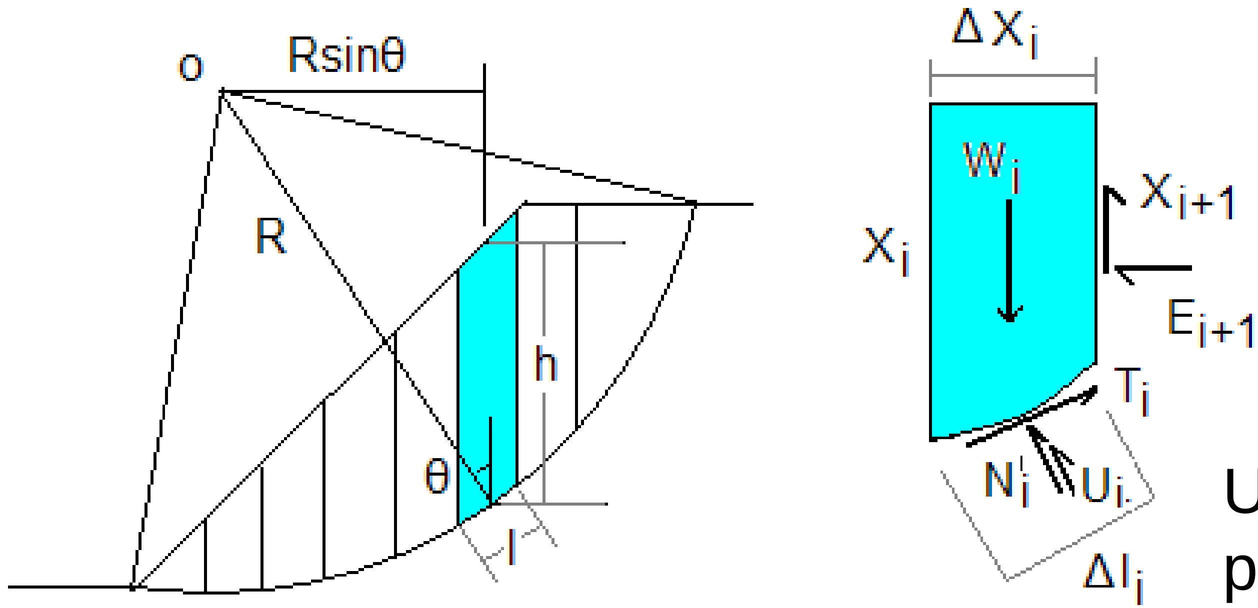
STABILITY CHECKS



Assumption: soil and all nails reach their limiting state simultaneously (i.e. there is strain compatibility between soil and nails at all stages)

- ❑ possible mechanisms of failure inside (c) and outside the reinforced mass
- ❑ limit equilibrium of forces (weight, pore pressure, external loads, normal and shear forces along the slip surface and forces in the reinforcement)

BISHOP'S METHOD



shear

normal

$U_i=u_i*\Delta l_i$ pore pressure force

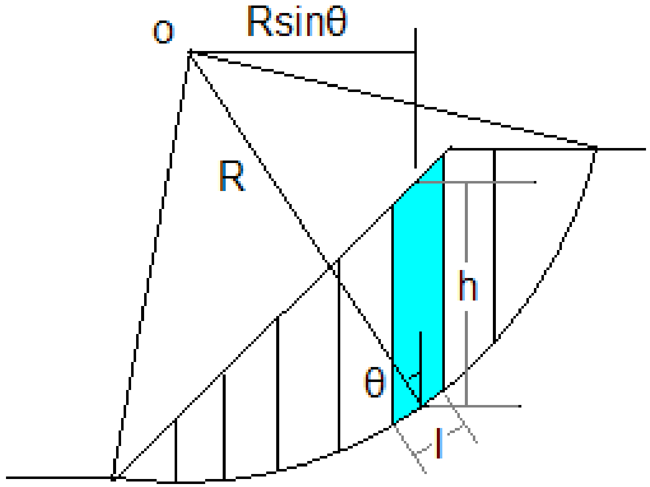
Method of slices

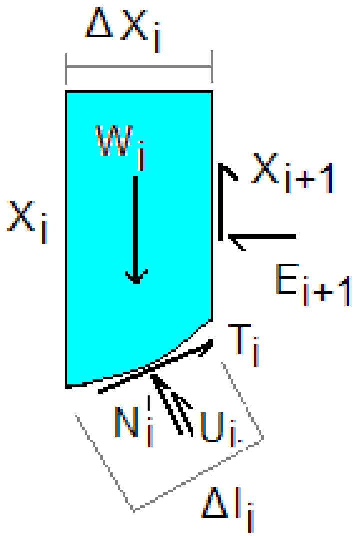
1. No friction at the (v-1) interfaces between slices
2. Constant factor of safety for all slices

$$T_i = \frac{1}{F}(c_i + \sigma_i' \tan\varphi_i),\ c_i \ \&\ \varphi_i$$

Soil strength parameters at the base of slice i

BISHOP'S METHOD





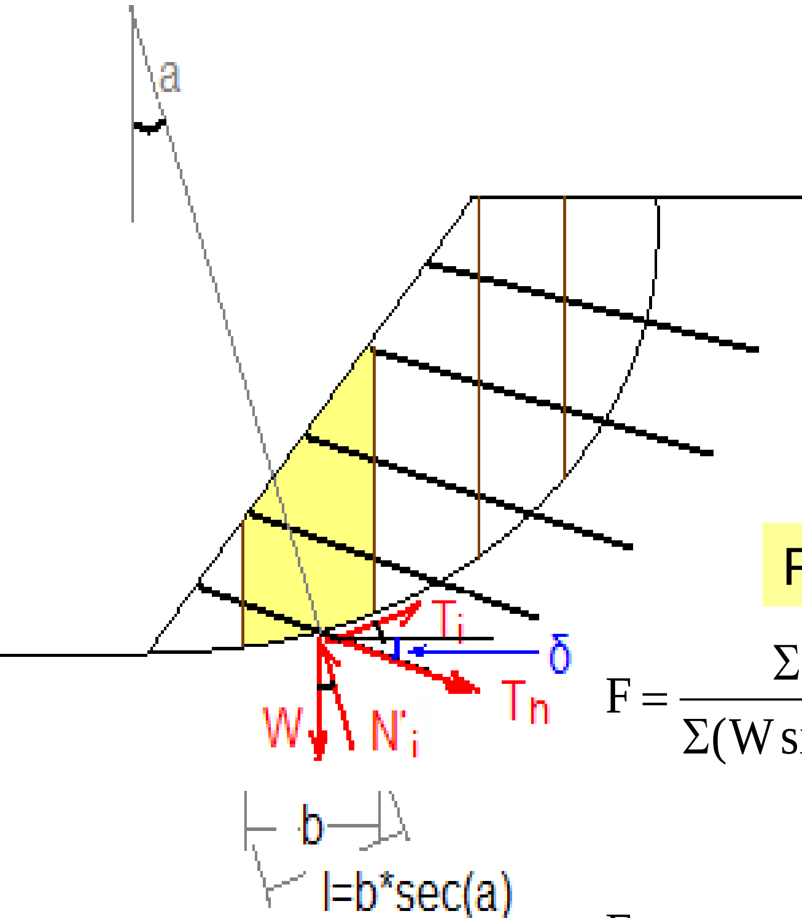
$$N_i^{'} = \frac{W_i - u_i \Delta x_i - \frac{1}{F} c_i \Delta x_i \sin\theta_i}{\cos\theta_i (1 + \frac{1}{F}\tan\theta_i \tan\varphi_i)}$$

Vertical equilibrium for slice i

$$F = \frac{\Sigma(c_i \Delta l_i + N_i^{'} \tan\varphi_i)}{\Sigma W_i \sin\theta_i}$$

Moment equilibrium around the centre of circular slip surface for slice i

NAILED SLOPE



Force equilibrium

$$N' = \frac{\dfrac{W}{\cos a} - ul - \dfrac{c'l\tan a}{F_m} + T_\eta \dfrac{\sin\delta}{\cos a}}{1 - \dfrac{\tan a}{F_m}\tan\varphi}$$

F = (resisting moments/overturning moments)

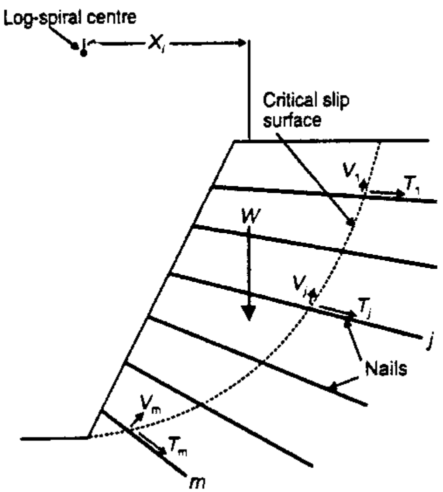
$$F = \frac{\Sigma(c'l + N'\tan\varphi)}{\Sigma(W\sin a - T_\eta\cos(a+\delta))} \Rightarrow$$

$$F = \frac{1}{\Sigma\{W\sin a - T_\eta\cos(a+\delta)\}}\Sigma\left\{\frac{[c'b + (W - ub + T_\eta\sin\delta)\tan\varphi]\sec a}{1 + \dfrac{\tan a}{F_m}\tan\varphi}\right\}$$

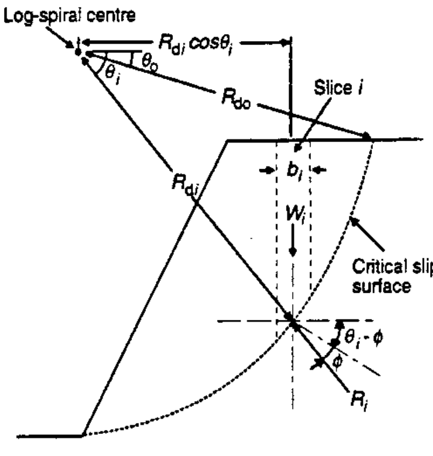
Rocscience Inc, SLIDE v5.0

LOG-SPIRAL SLIP SURFACE, METHOD OF SLICES

Internal stability of nailed reinforced slope assessed with method of slices



a) Force components in log-spiral analysis



b) Determination of out-of balance-moment

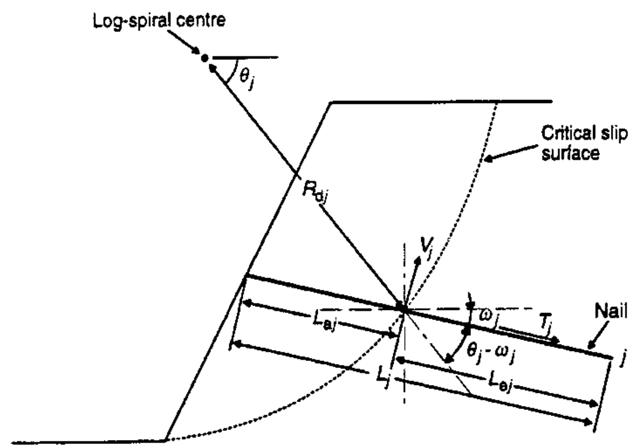
Nail action

$$T_j R_{dj} \sin(\theta_j - \omega_j)$$

Restoring moment due to nail tension

$$V_j R_{dj} \cos(\theta_j - \omega_j)$$

Restoring moment due to shear in nail



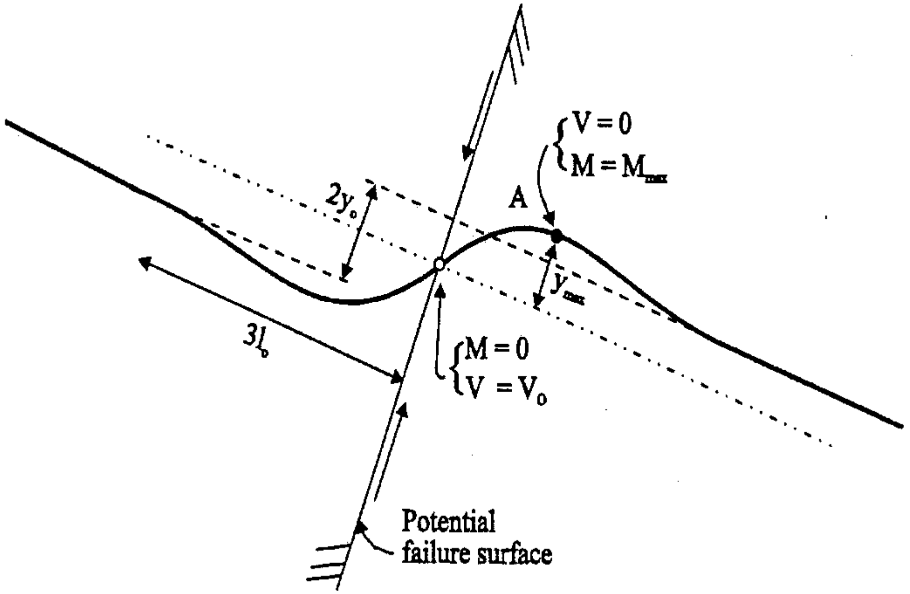
Restoring moment due to tension in nail j:
$T_j R_{dj} \sin(\theta_j - \omega_j)$

Restoring moment due to shear in nail j:
$V_j R_{dj} \cos(\theta_j - \omega_j)$

c) Restoring moments due to tension and shear in nail j

NAIL DEFORMED ALONG FAILURE SURFACE

- nails can withstand shear forces and bending moments when deformed perpendicular to their axis. Due to their thin nature reinforcing strips can only provide tensile resistance



- prerequisite: development of considerable deformations along slip surface (delineating deflection y in the schematic diagram)
- Jewell & Pedley (1990). "Soil nailing design-the role of bending stiffness", Ground Engineering, 30-36. *Shear forces and bending moments increase stability by 10%.*

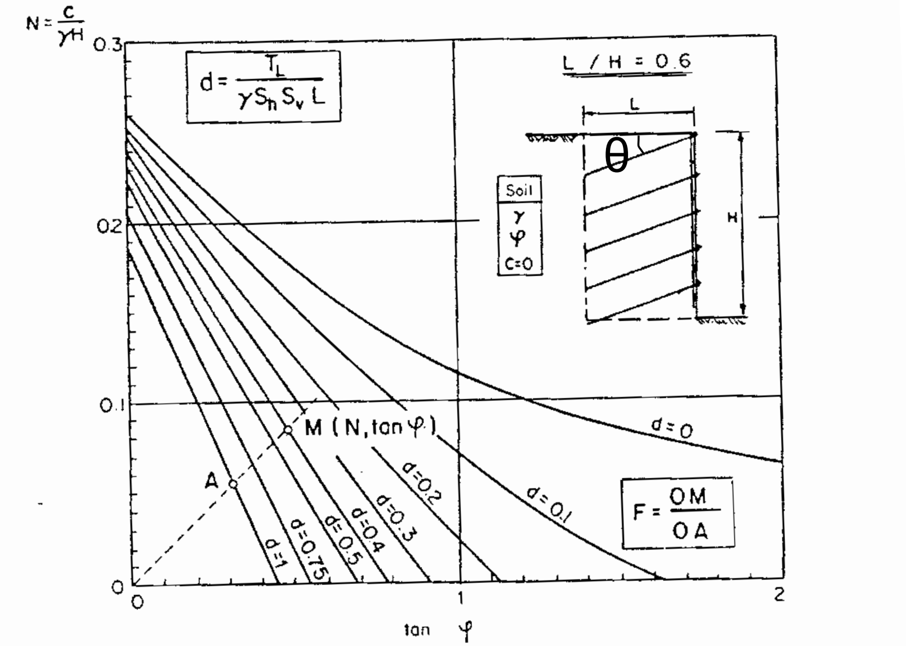
PRELIMINARY DESIGN

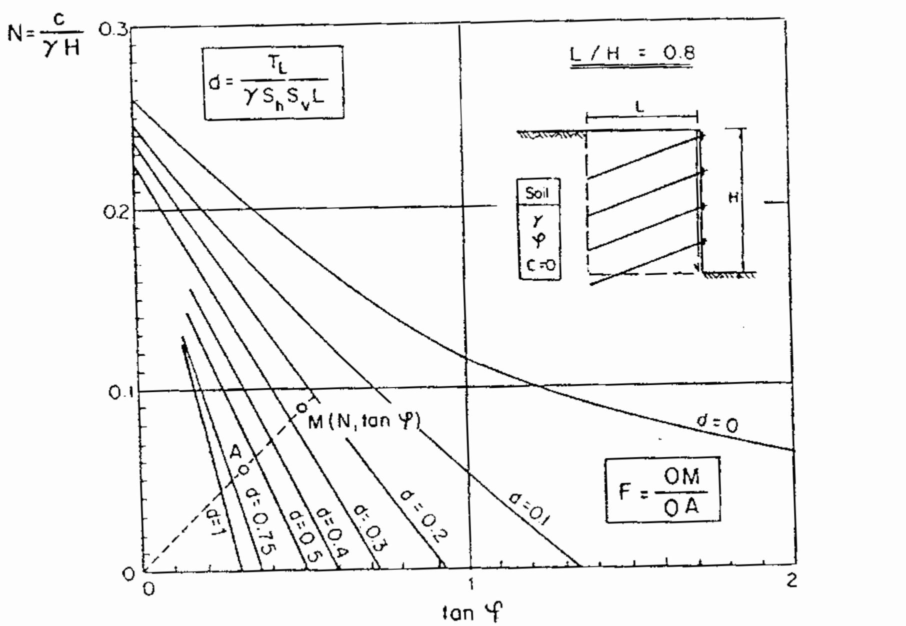
Design charts of nailed soil wall for H/L=0.6 and 0.8, θ=20^0 (after Recommandations Clouterre, 1991)

- for N=c/γH & tanφ define $d=T_L/\gamma S_h S_v L$ where:

  T_L=nail pull-out strength
  S_h=horizontal spacing of nails
  S_v=vertical spacing of nails

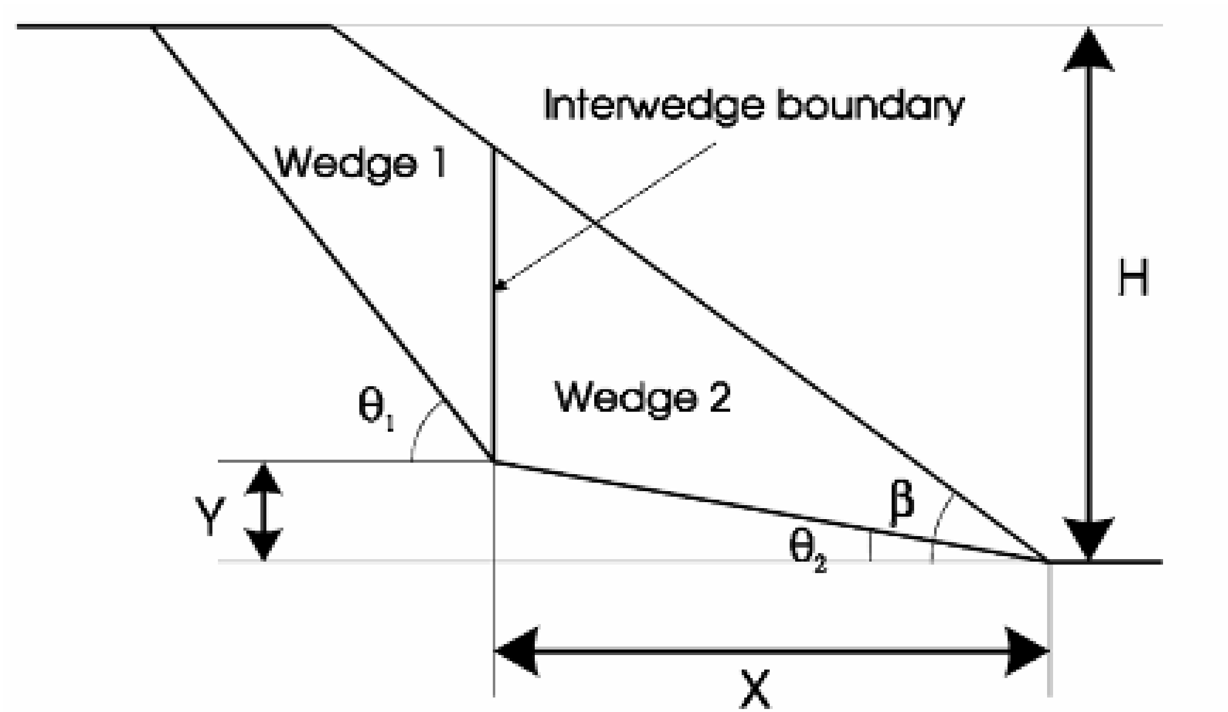
- for factor of safety F on soil parameters (c & tanφ) redefine the dimensionless density index referred to as the nailing density $d=T_L/\gamma S_h S_v L$





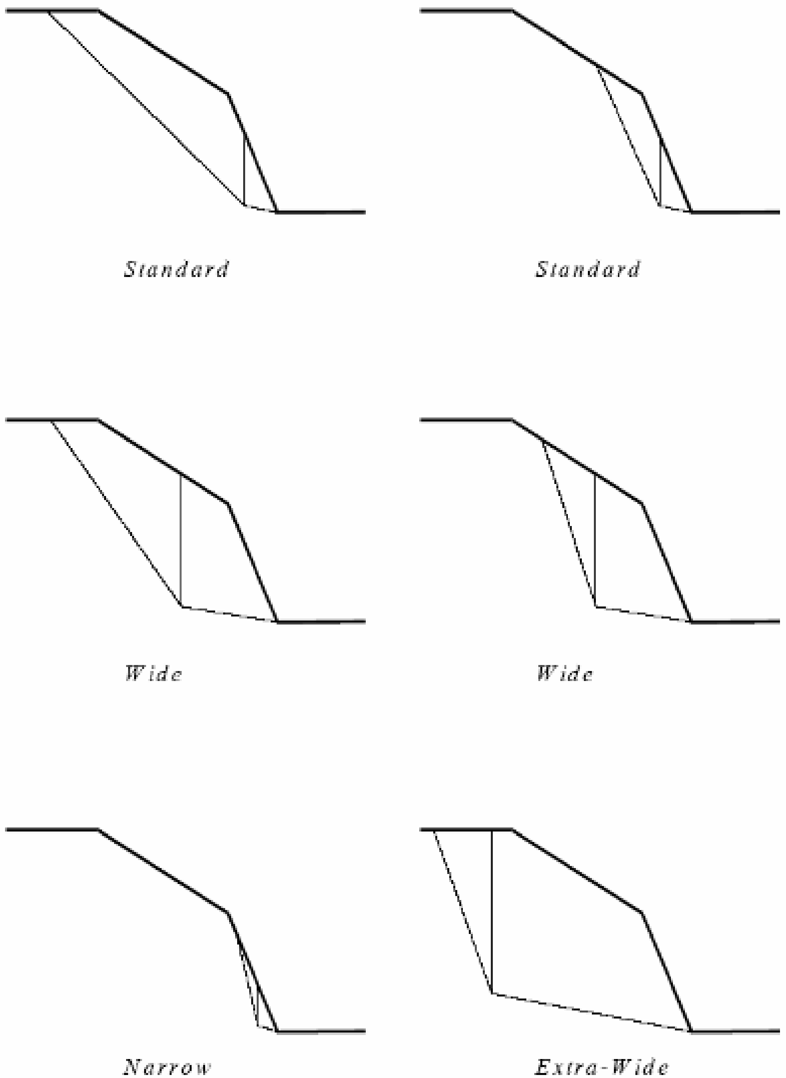
DESIGN OF REINFORCED SLOPES USING ReActiv

HA68/94, UK Highways Agency (HA): Design methods for the reinforcement of highway slopes by reinforced soil and soil nailing techniques



A bilinear two part wedge mechanism is analysed using limit equilibrium

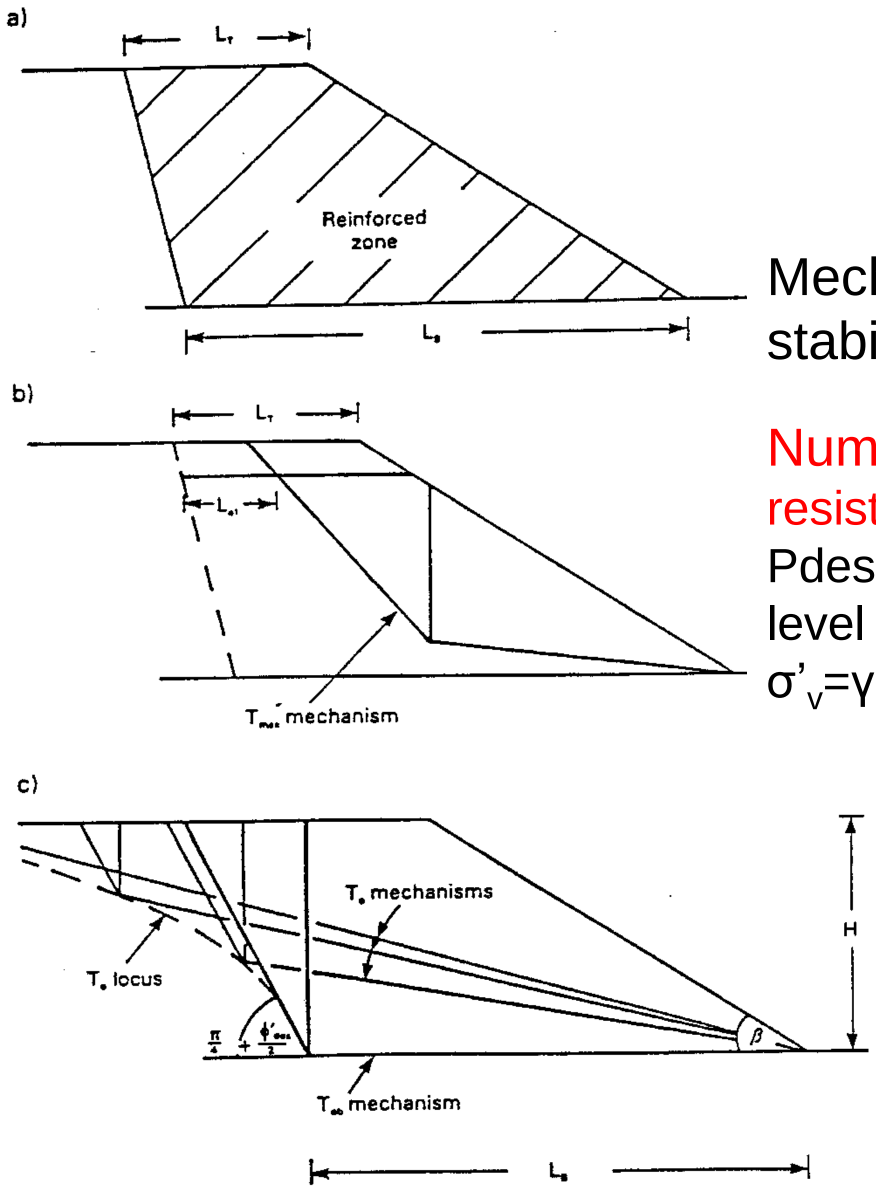
DESIGN OF REINFORCED SLOPES USING ReActiv



Assess overall stability for different wedge geometries and orientations looking for the most unstable condition by establishing the mechanism requiring the maximum stabilising force Tmax

Mechanism type	Wedge 1 outcrops at...	Interwedge boundary outcrops at...
Standard	Crest or upper slope	Lower slope
Narrow	Lower slope	Lower slope
Wide	Crest or upper slope	Upper slope
Extra-wide	Crest	Crest

DESIGN OF REINFORCED SLOPES USING ReActiv



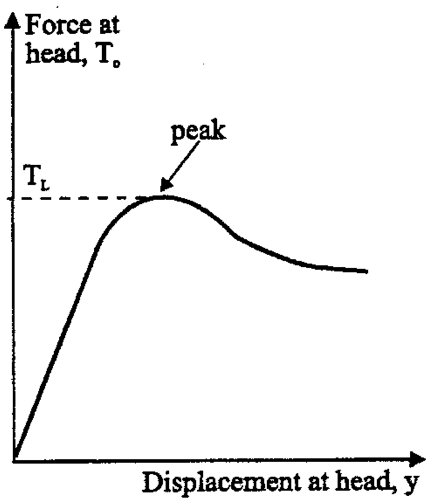
Mechanism requiring the maximum stabilising force **T_{max}**

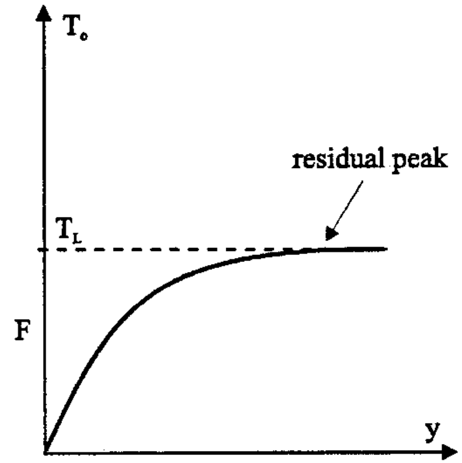
Number of nail layers = T_{max} / P_{des} (pull-out resistance)

Pdes also fixes the length of the uppermost level of nails: $Le_i = P_{des} / (2a\sigma_v' \tan\varphi_{des})$, $\sigma'_v = \gamma z_1(1-r_u)$, $z_1 = 0.5H_{des}/N$^1/2

Define limiting mechanisms requiring no reinforcement referred to as **T_0**. There is an infinite number of these mechanisms bounded by the To locus. The **T_{0b}** mechanism **where the locus intersects the baseline** fixes the length of the lowest nails.

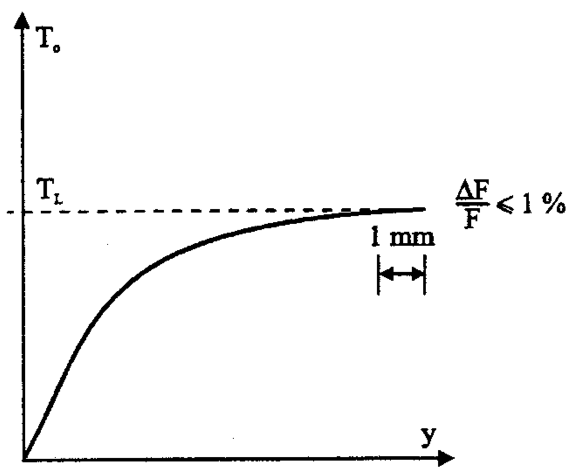
FAILURE CRITERIA IN PULL-OUT TESTS





- $T_L = q_s * \pi * D * L_a$ →
- q_s

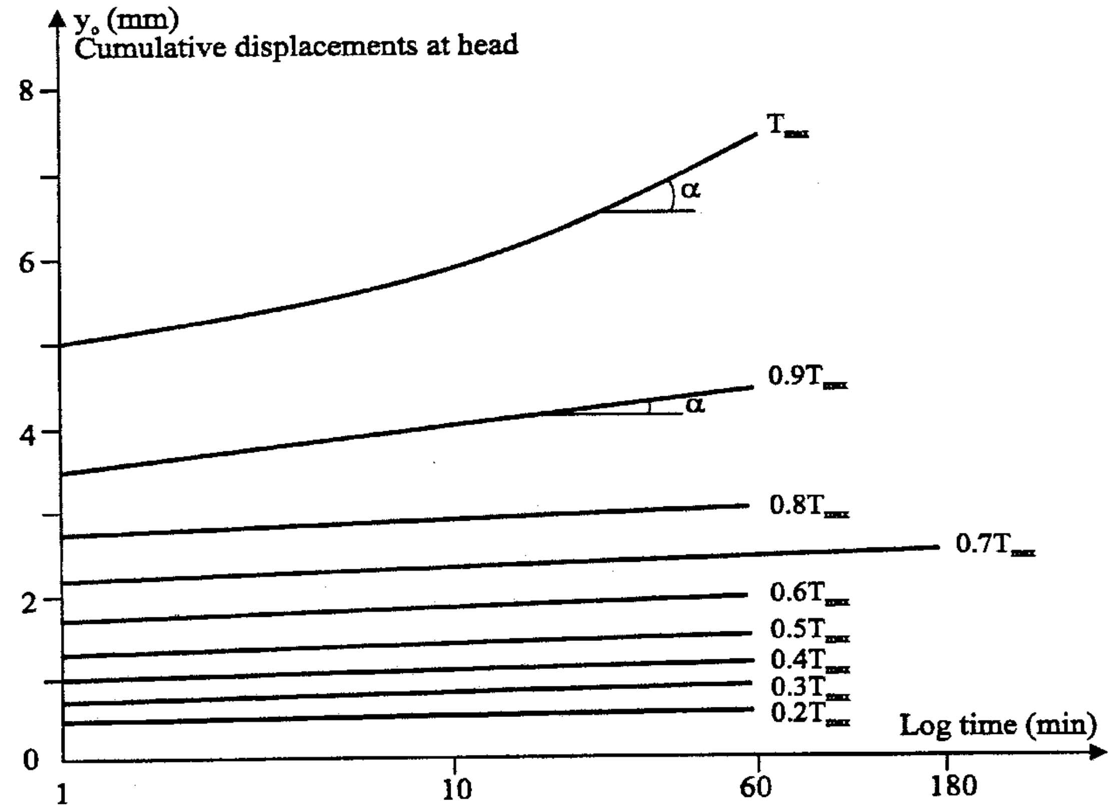
Controlled displacement (1mm/min), minimum 50mm



Controled force i.e. creep
s
L
e
displacement test)

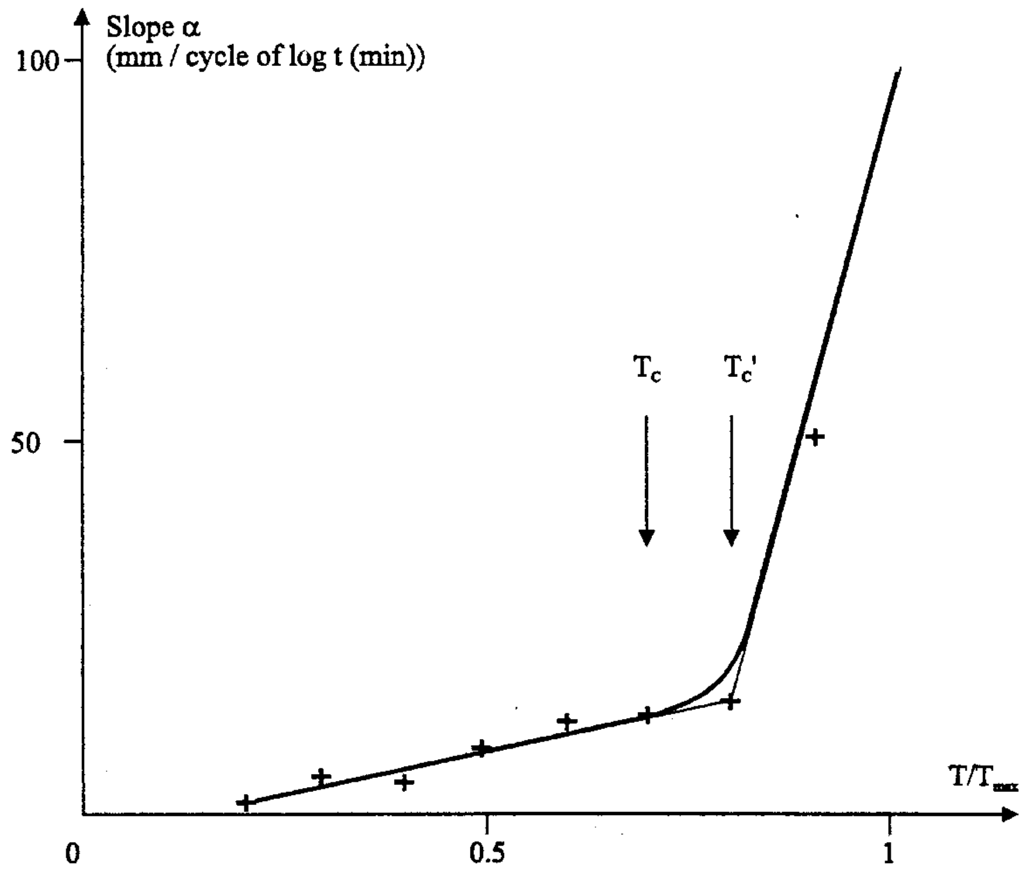
The test continues until the force changes by less 1% for 1mm displacement

CREEP CURVES FROM CONTROLLED FORCE PULL-OUT TESTS



- creep curves – linear at lower loads
- angle (α) is defined as the slope of the tangent to each curve at t=1h

RESULTS OF CREEP TESTS



• plot angle (α) versus T/T_{max}
• and determine the critical creep tension T_c as the load applied before the curve changes slope.

RESULTS OF PULL-OUT TESTS

- Characteristic limit pull-out force
  - Minimum 6 test (displacement or force controlled pull-out tests) to define T_L
- Characteristic unit skin friction value qs
  - $q_s = T_L/p*Ls$
  - Where p: nail perimeter
  - Ls: length of nail in contact with soil

RESULTS OF PULL-OUT TESTS

- When controlled force pull-out tests do not allow determination of pull-out limit force T_L, this value can be estimated from the critical creep tension T_c

		$K=T_L/T_c$
Gravity	Sands	1.2
Injection	Clays	1.3
	Marls & Chalks	1.3
Driving	Sands	1.4