Methods for slope stabilization

Course Slope Stability, Dr. Alessio Ferrari
EPFL / ENAC / GC section – Master semester 2 and 4 – 2024-2025

Causes identification

The causes and the failure mechanism should be understood before embarking on corrective actions.

Causes

- External loads
- Rise in the groundwater level
- Erosion at the toe
- Loss of soil strength (weathering)
- Seismic action
- …

Usually more than one simultaneously

Failure mechanism

- Involved soils
- Shape and position of the failure surface(s)
- Spatial and temporal evolution of displacements
- …

Slope stabilization

$$F = \frac{R}{D}$$

Slope stabilization methods are based on

Reduction of driving forces, *D*

Increase in resisting forces, *R*

or both,
aimed to increase slope safety factor

Bishop simplified method

Effects of the remedial measures on the factor of safety

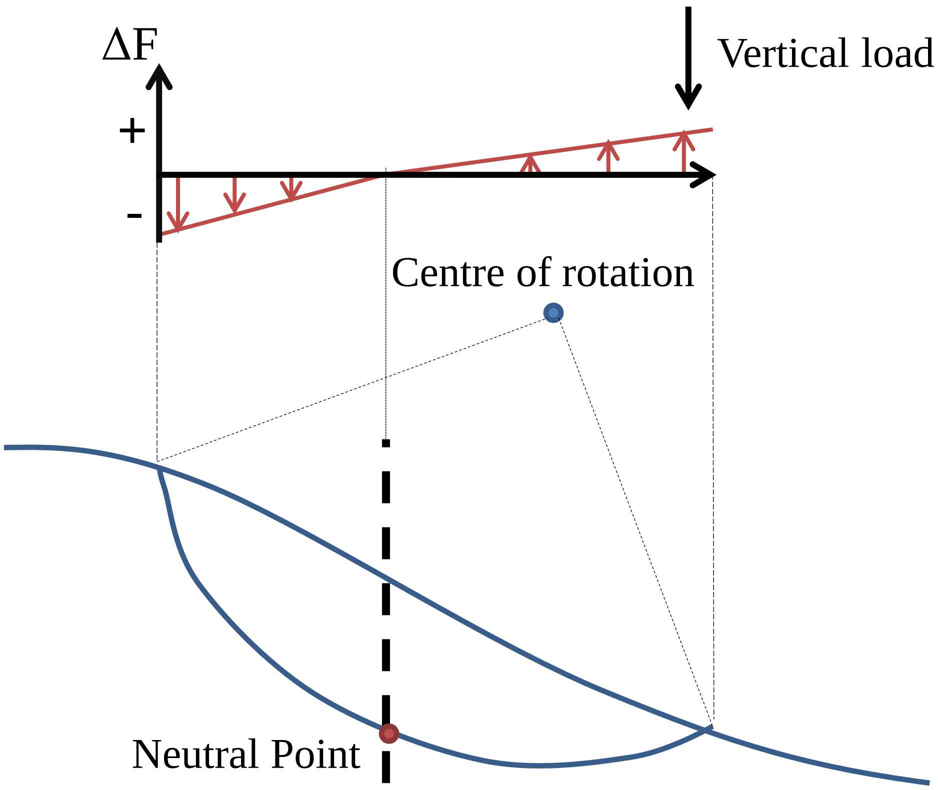
Cut and fill

Drainage

$$F_0 = \frac{\sum \left[c'_i \cdot b_i + \left(W_i - U_{b,i} \cdot cos\alpha_i \right) \cdot tan\varphi'_i \right] \cdot \frac{1}{cos\alpha_i + \frac{1}{F_0} \cdot tan\varphi'_i \cdot sin\alpha_i}}{\sum W_i \cdot sin\alpha_i - \sum H_i \cdot cos\alpha_{Hi}}$$

Retaining structure

Vertical load position influence on safety factor



Neutral line theory (1)

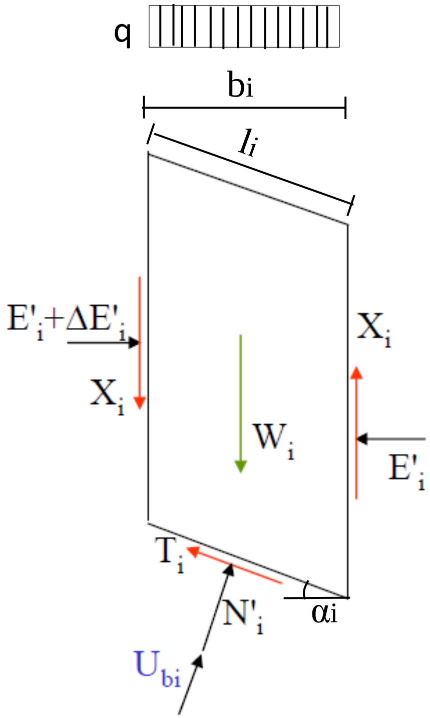
Bishop safety factor

$$F_0 = \frac{\sum \left[c'_i \cdot b_i + \left(W_i - U_{b,i} \cdot cos\alpha_i \right) \cdot tan\varphi'_i \right] \cdot \frac{1}{cos\alpha_i + \frac{1}{F_0} \cdot tan\varphi'_i \cdot sin\alpha_i}}{\sum W_i \cdot sin\alpha_i}$$

J_i = $c'_i \cdot b_i + \left(W_i - U_{b,i} \cdot cos\alpha_i \right) \cdot tan\varphi'_i$

$M_{0,i}$ = $\frac{1}{cos\alpha_i + \frac{1}{F_0} \cdot tan\varphi'_i \cdot sin\alpha_i}$

$$F_0 = \frac{\sum J_i \cdot M_{0,i}}{\sum W_i \cdot sin\alpha_i}$$



$\Delta W_i = q_i \cdot b_i$ Vertical load applied

$\Delta U_{b,i} = \Delta l_i \cdot \Delta u_{b,i}$ Change in resulting force of the pore water pressures distribution

$$\Delta u_{b,i} = \bar{B} \cdot \Delta\sigma_1 \approx \bar{B} \cdot \Delta\sigma_y = \bar{B} \cdot \frac{\Delta W}{b_i} = \bar{B} \cdot q_i$$

Hp: $\Delta\sigma_1 \approx \Delta\sigma_y$

$$\Delta U_{b,i} = \bar{B} \cdot q_i \cdot b_i \cdot sec\ \alpha_i = \bar{B} \cdot \Delta W_i \cdot sec\ \alpha_i$$

Neutral line theory (2)

After the application of the load, the factor of safety is:

$$F_1 = \frac{\sum J_i \cdot M_{1,i} + \left(\Delta W_i - \Delta U_{b,i} \cdot cos\alpha_i\right) \cdot tan\varphi'_i \cdot M_{1,i}}{\sum W_i \cdot \sin\alpha_i + \Delta W_i \cdot \sin\alpha_i} \qquad M_{1,i} = \frac{1}{cos\alpha_i + \frac{1}{F_1} \cdot tan\varphi'_i \cdot sin\alpha_i}$$

Searching for the α_i for which $F_1 = F_0$

$$\frac{\sum J_i \cdot M_{1,i} + (\Delta W_i - \bar{B} \cdot \Delta W_i \cdot sec\alpha_i \cdot cos\alpha_i) \cdot tan\varphi'_i \cdot M_{1,i}}{\sum W_i \cdot sin\alpha_i + \Delta W_i \cdot sin\alpha_i} = F_0$$

$$\Sigma J_i \cdot M_{1,i} + \Delta W_i(1 - \bar{B}) \cdot tan\varphi'_i \cdot M_{1,i} = F_0 \cdot \Sigma W_i \cdot sin\alpha_i + F_0 \cdot \Delta W_i \cdot sin\alpha_i$$

$If \quad F_1 = F_0 \longrightarrow M_1 = M_0$

$$\Sigma J_i \cdot M_{1,i} = F_0 \, \Sigma W_i \cdot sin\alpha_i$$

$$\Delta W_i(1 - \bar{B}) \cdot tan\varphi'_i \cdot \frac{1}{cos\alpha_i + \frac{1}{F_0} \cdot tan\varphi'_i \cdot sin\alpha_i} = F_0 \cdot \Delta W_i \cdot sin\alpha_i$$

Neutral line theory (3)

$$(1-\bar{B})\cdot tan\varphi'_i = F_0\cdot sin\alpha_i\cdot\left(cos\alpha_i+\frac{1}{F_0}\cdot tan\varphi'_i\cdot sin\alpha_i\right)$$

$$(1-\bar{B}-sin^2\alpha_i)\cdot tan\varphi'_i = F_0\cdot sin\alpha_i\cdot cos\alpha_i$$

$$(cos^2\alpha_i-\bar{B})\cdot tan\varphi'_i = F_0\cdot sin\alpha_i\cdot cos\alpha_i$$

$$cos^2\alpha_i(1-\bar{B}\cdot\sec^2\alpha_i)\cdot tan\varphi'_i = F_0\cdot sin\alpha_i\cdot cos\alpha_i$$

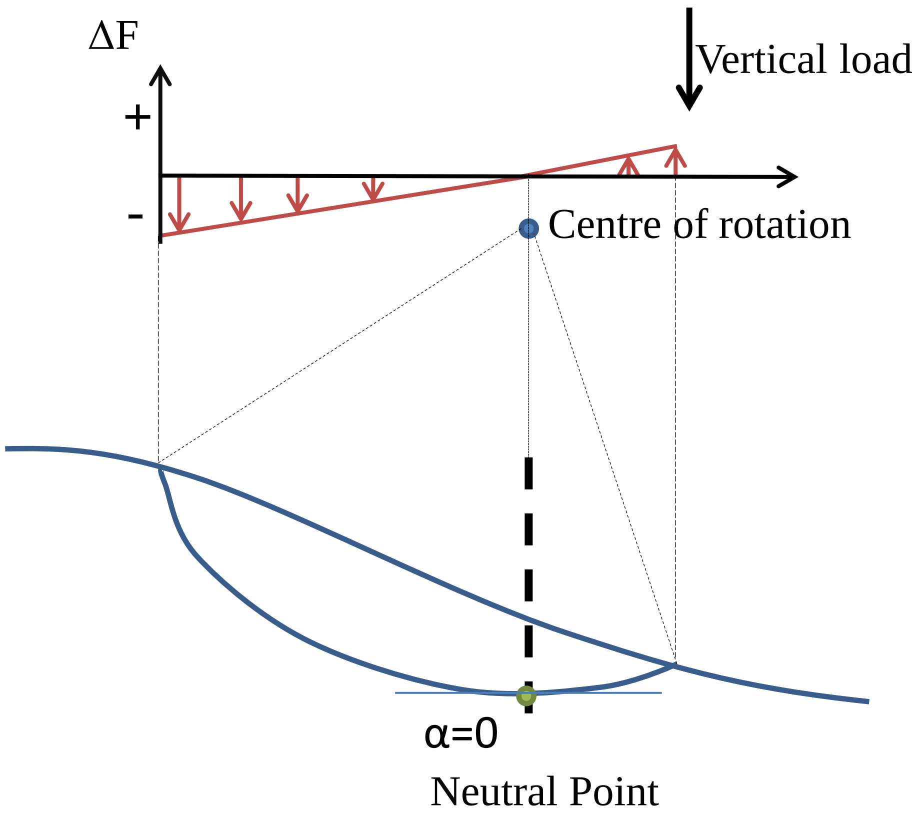
$$\tan\alpha_i = (1-\bar{B}\cdot\sec^2\alpha_i)\cdot\frac{tan\varphi'_i}{F_0}$$

if $\bar{B}=1$ $\quad \tan\alpha_i = (1-\sec^2\alpha_i)\cdot\frac{tan\varphi'_i}{F_0} \rightarrow \alpha_i = 0$ Undrained condition

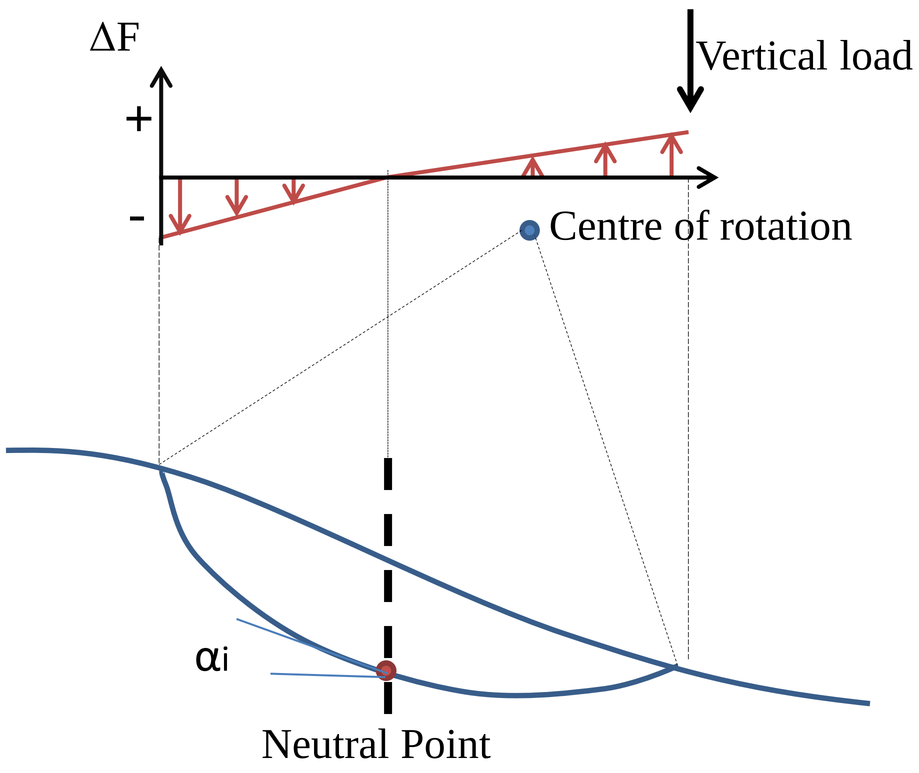
if $\bar{B}=0$ $\quad \tan\alpha_i = \frac{tan\varphi'_i}{F_0} \rightarrow \alpha_i = \arctan(\frac{tan\varphi'_i}{F_0}) = \varphi'_{mob}$ Drained condition

Neutral line theory (4)

Undrained condition

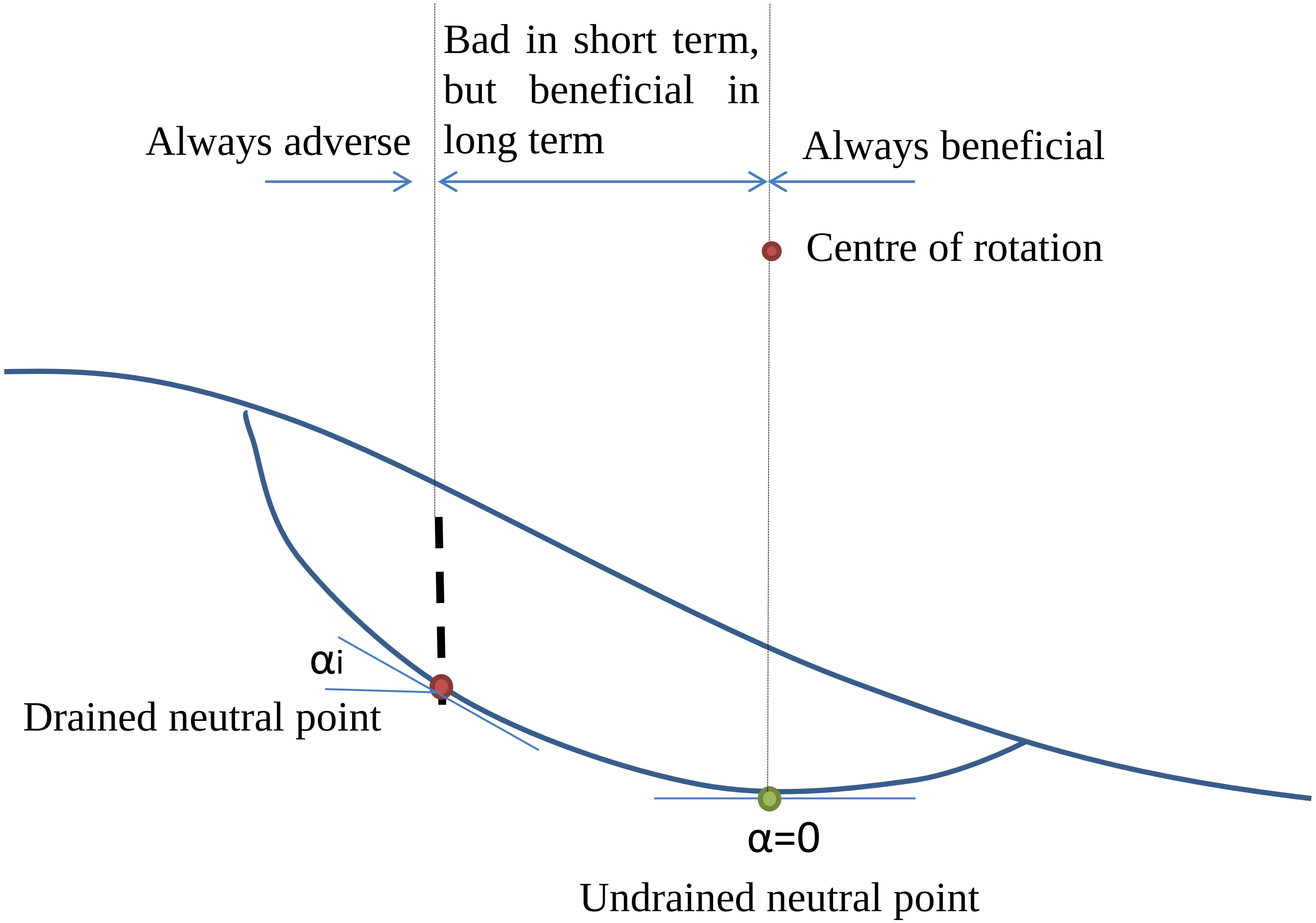


Drained condition



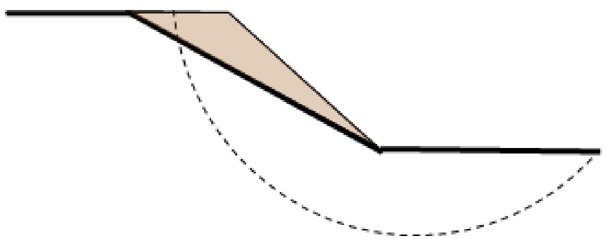
Neutral line theory (5)

The application of the vertical load is:

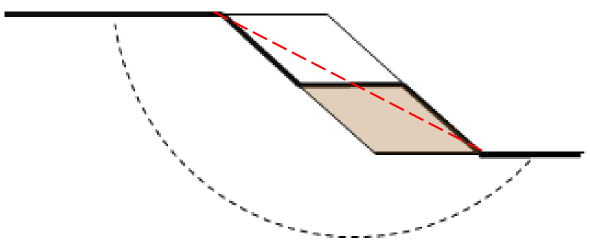


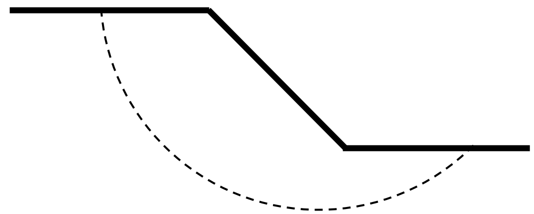
Cut and fill operation

(a) Flattering overall slope

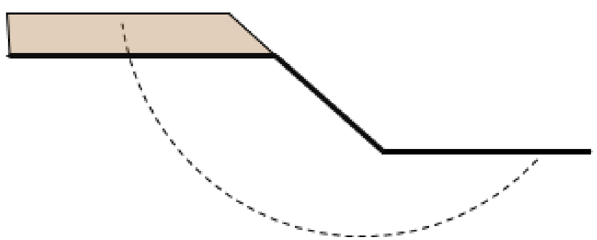


(b) Creating one or more berms

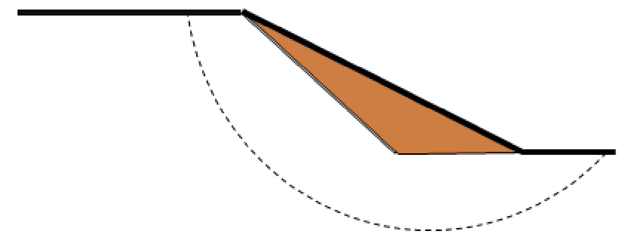




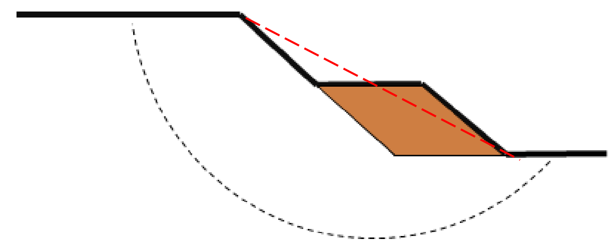
(c) Reducing slope height



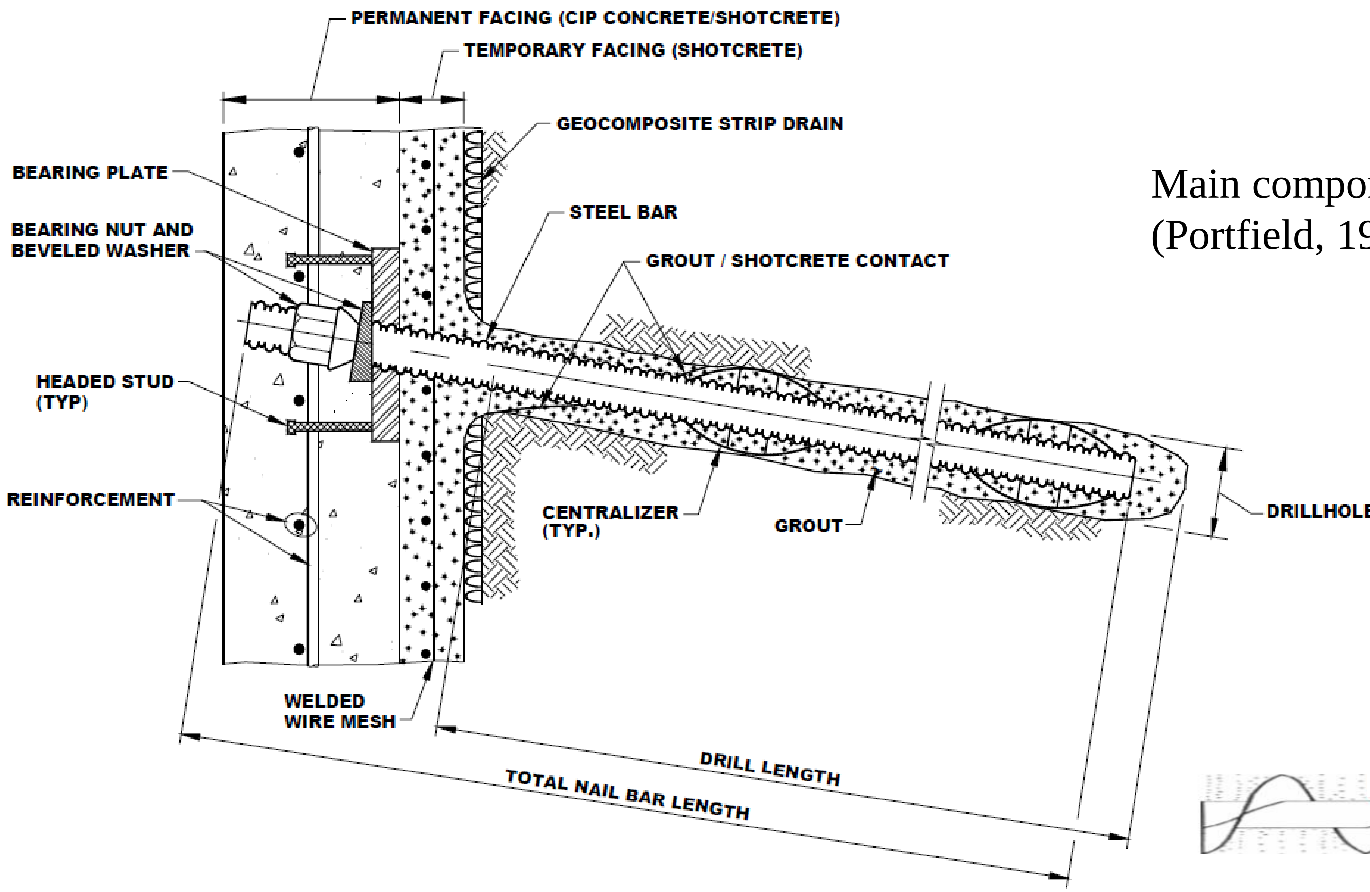
(d) flattering overall slope



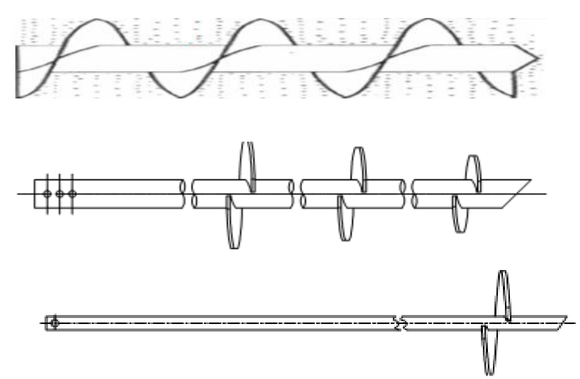
(e) Creating one or more berms



Soil Nailing reinforcement



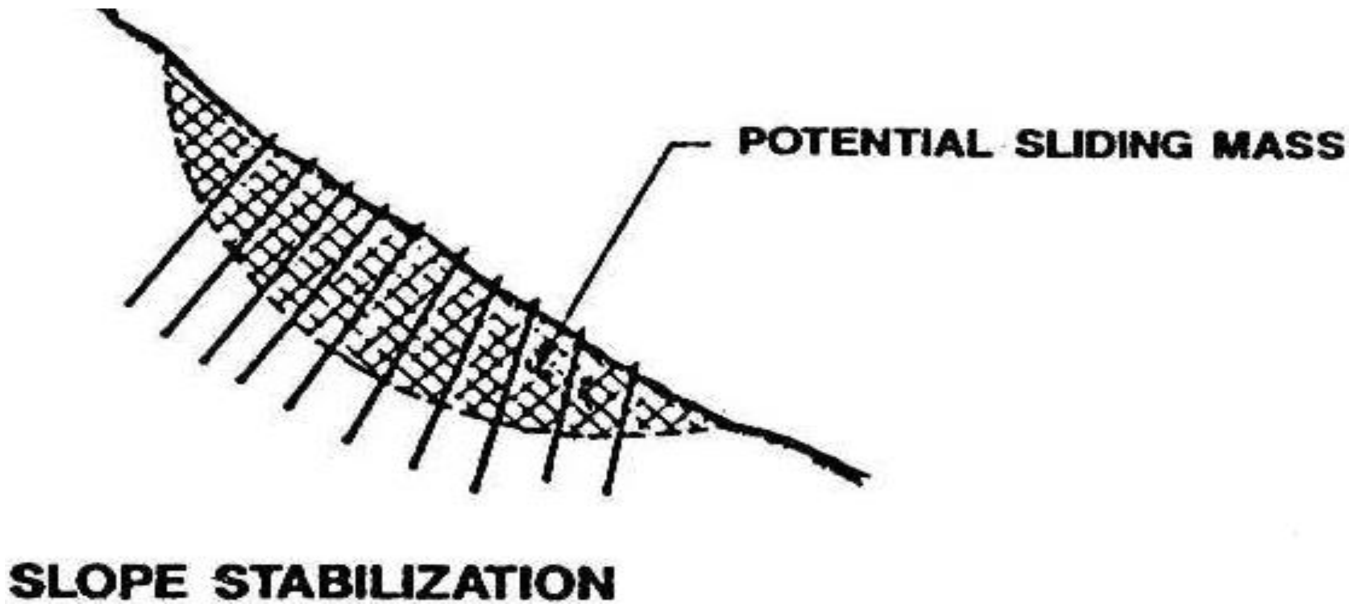
Main components of a typical soil nail, (Portfield, 1994)



Nail shapes, increasing pull-out resistance

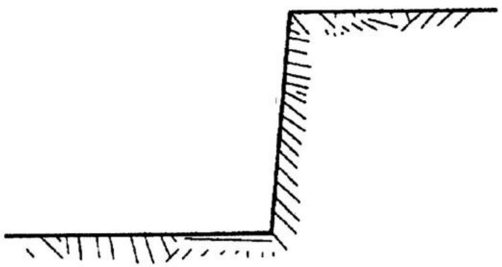
Soil Nailing reinforcement

Passive steel bar mobilized if movement occurs

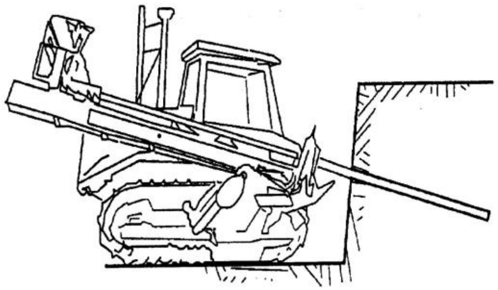


Ambrason, et al., 2002

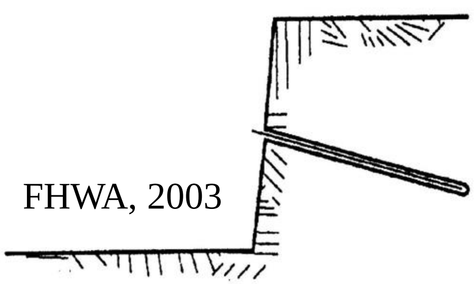
Soil Nailing reinforcement



Step 1 Excavate a small cut



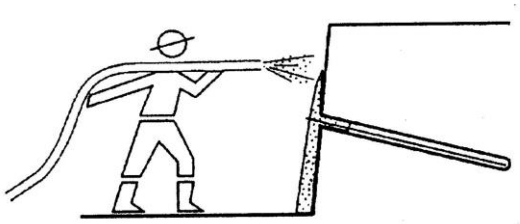
Step 2 Drill nail hole



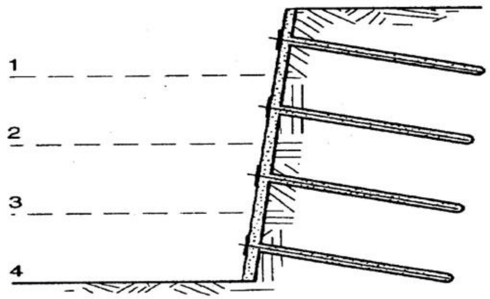
FHWA, 2003

Step 3 Install and grout nail

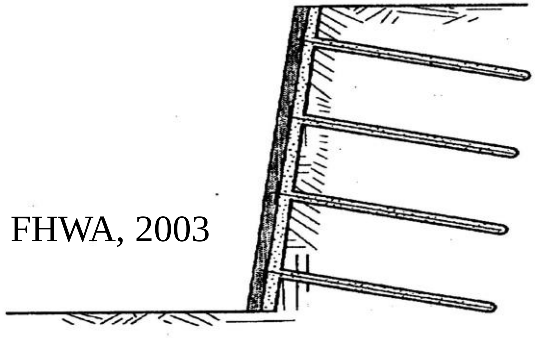
Soil Nailing reinforcement



Step 4. Place temporary facing
(shotcrete, reinforcement, bearing plate)



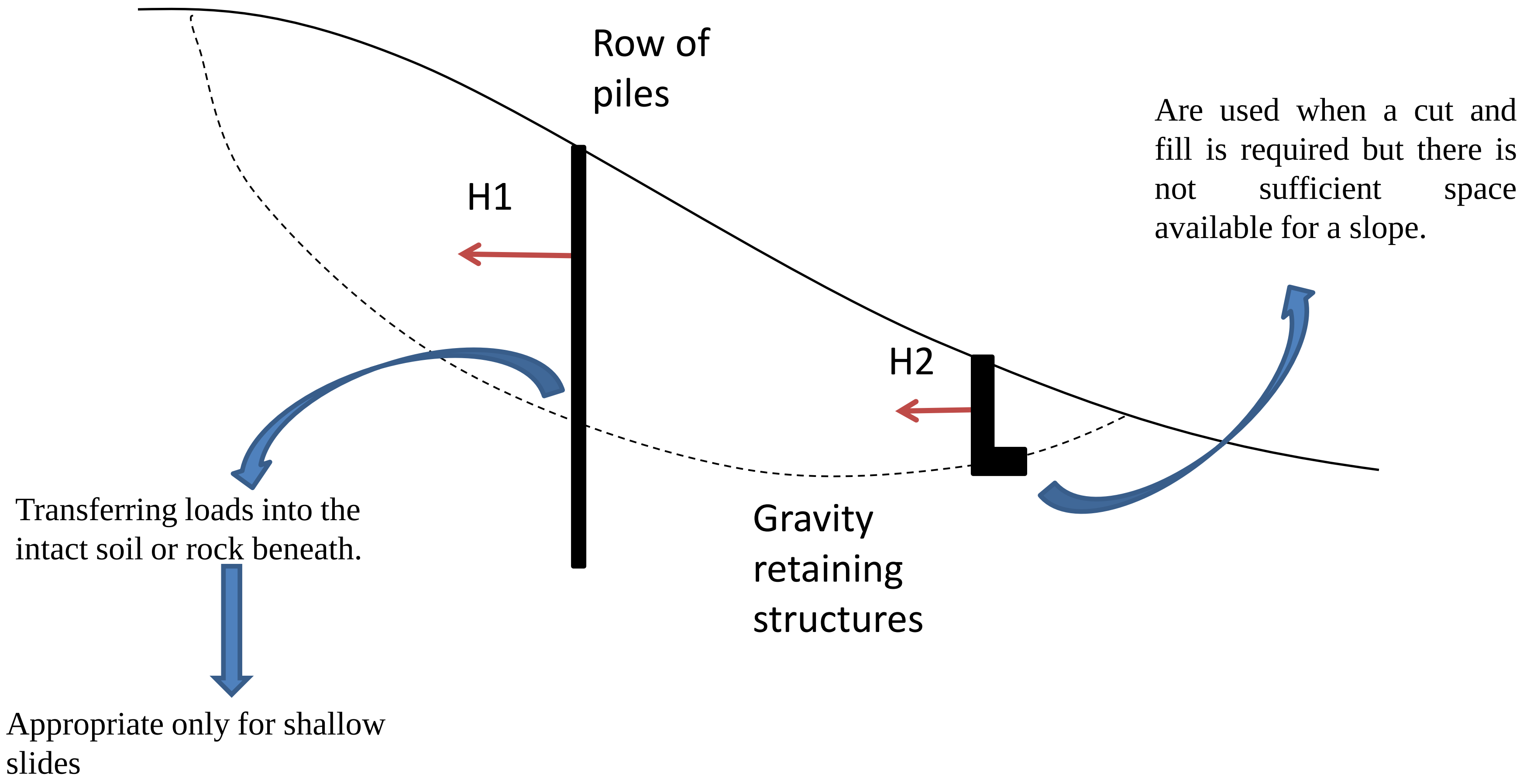
Step 5. Construction of subsequent levels



Step 6. Place final facing on permanent walls

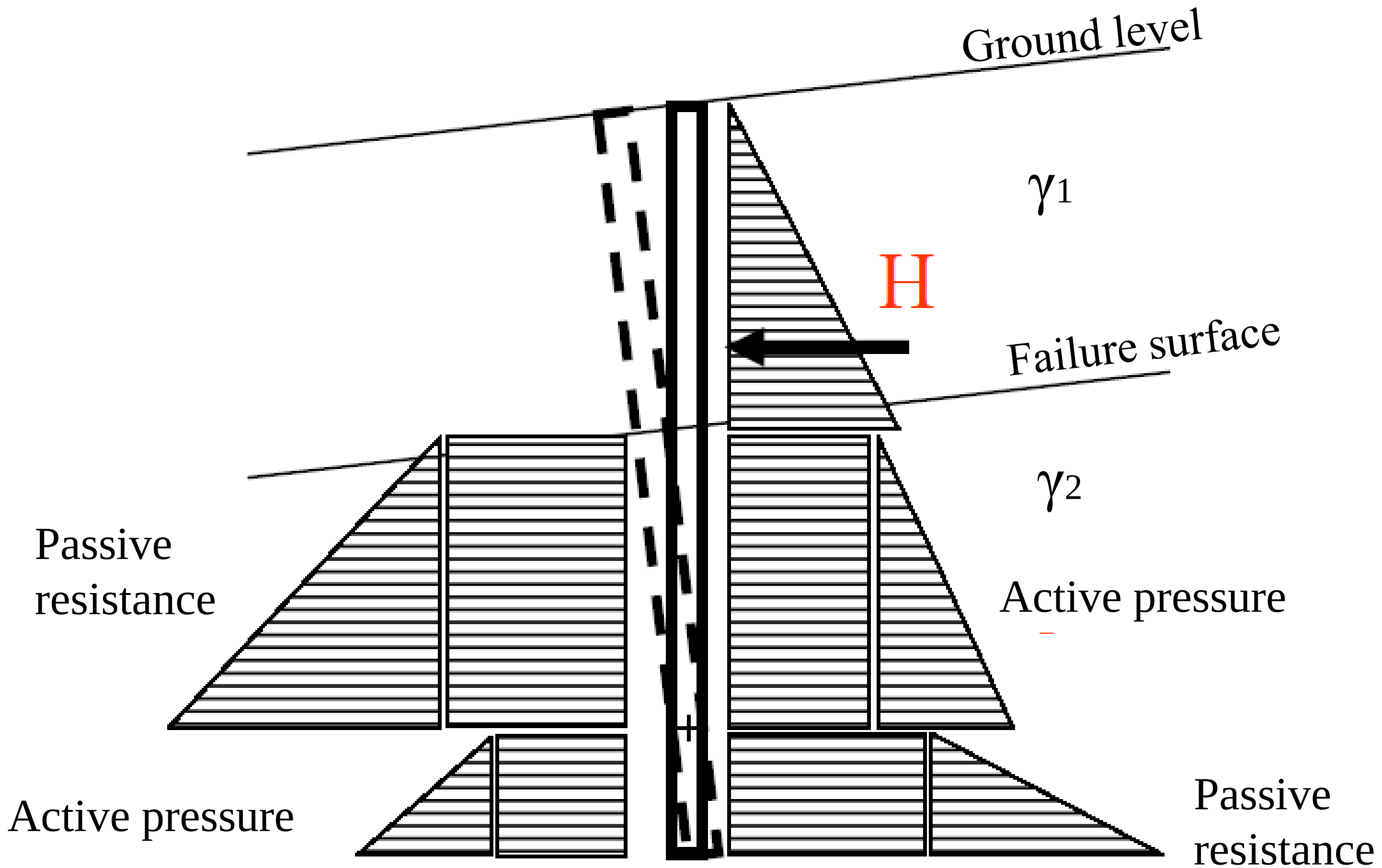
FHWA, 2003

Retaining structure



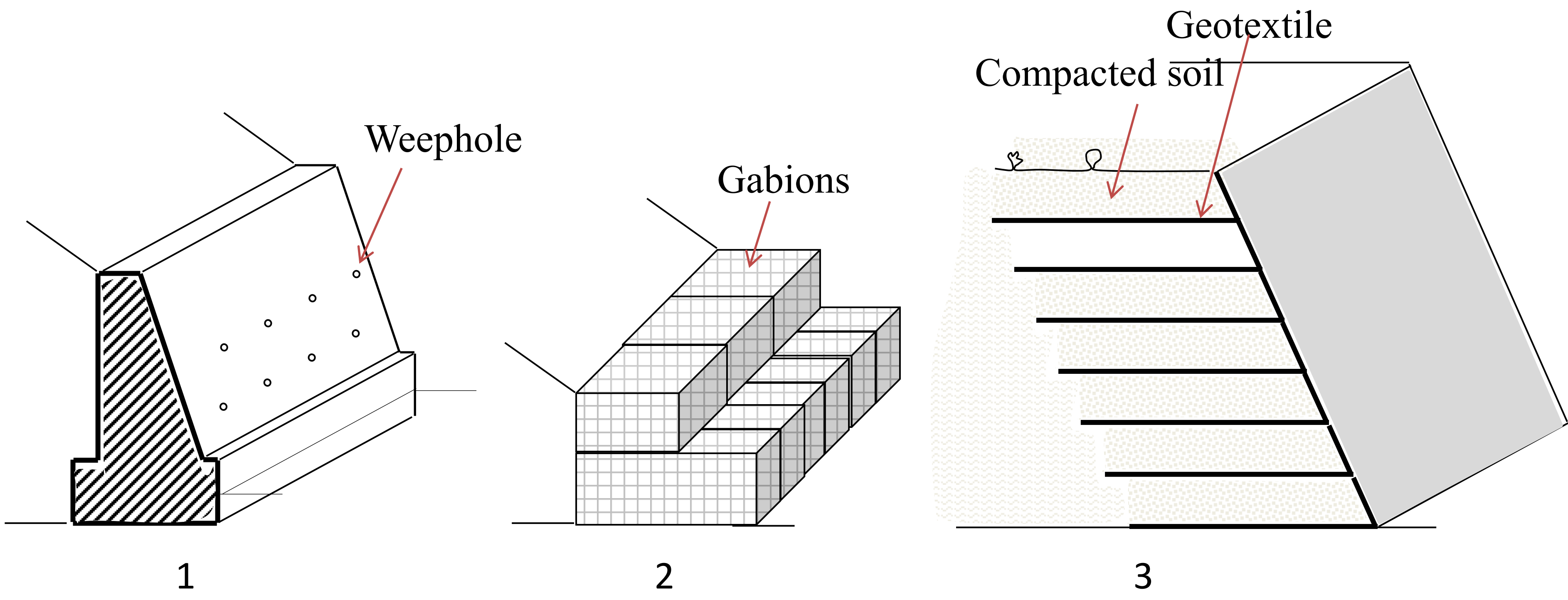
Rows of piles

Forces acting on a pile

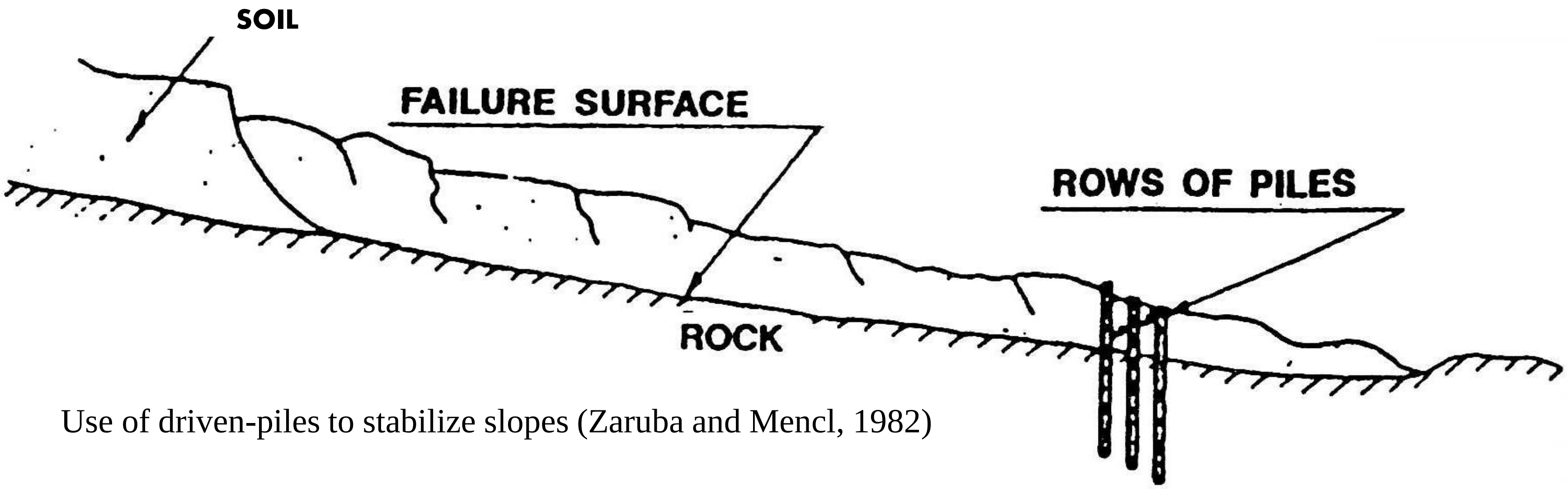


Gravity retaining structure

1. Retaining walls,
2. Gabion walls
3. Geosynthetically reinforced slopes



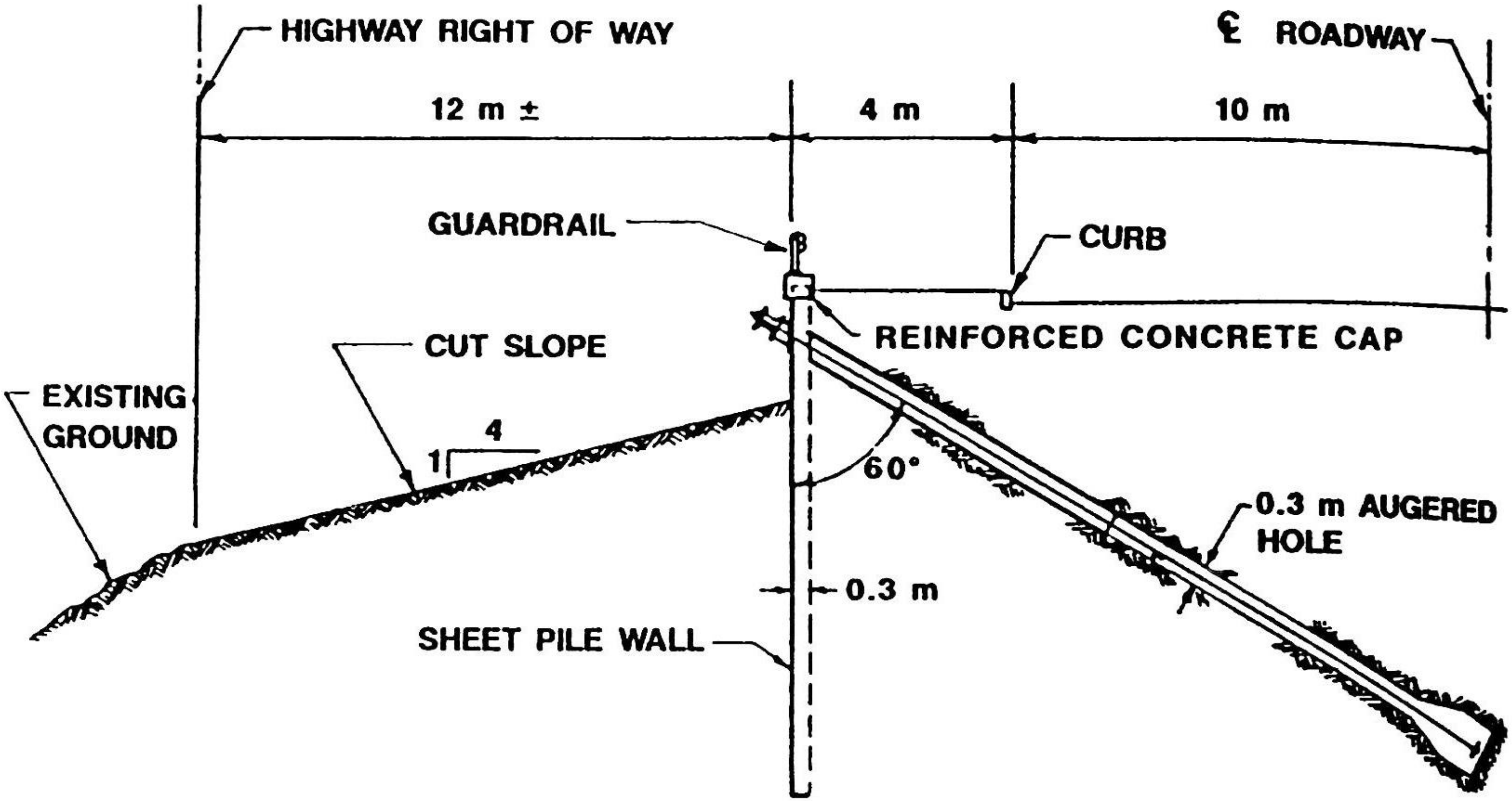
Rows of piles



Use of driven-piles to stabilize slopes (Zaruba and Mencl, 1982)

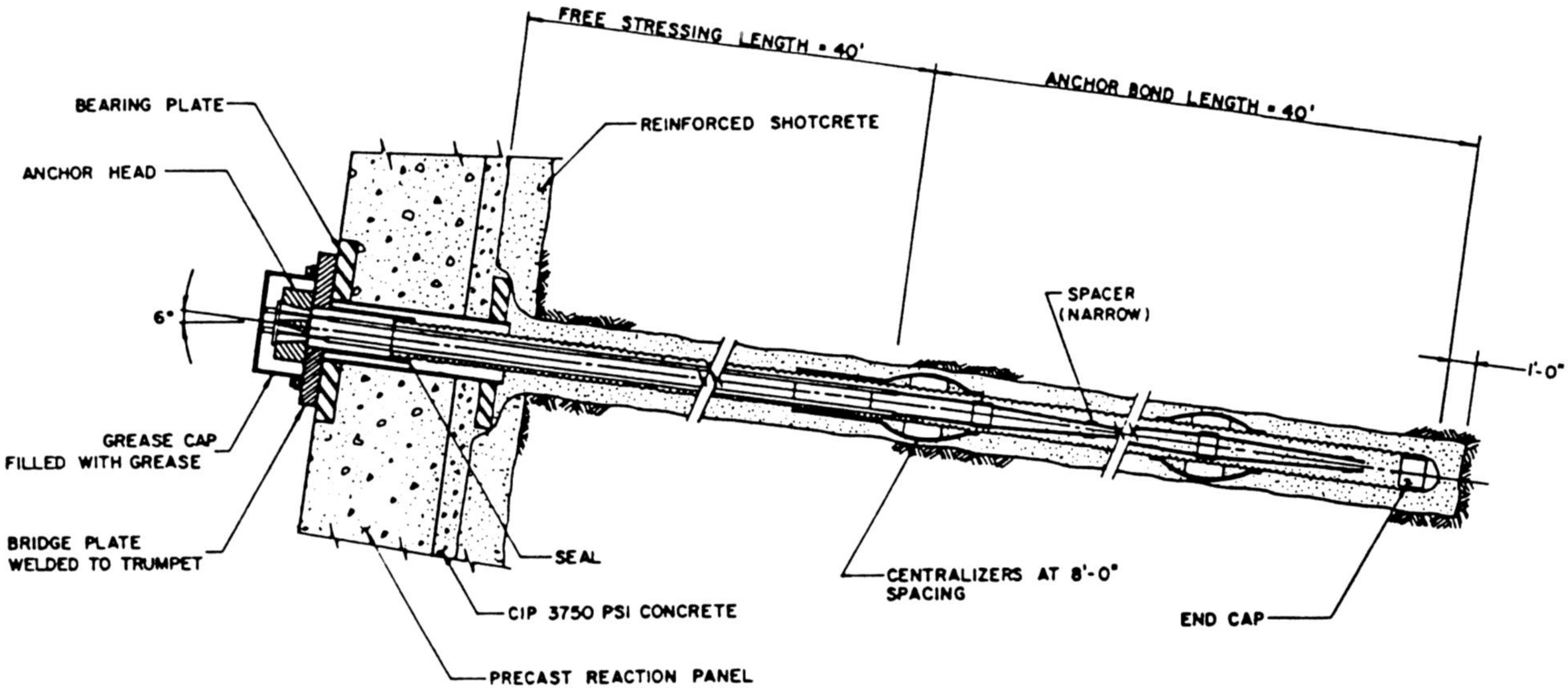
Drilled piles must be embedded deeply into a firm ground stratum to provide resistance against the lateral forces transmitted from the unstable soil mass. The depth of the piles should pass through the potential critical slip surface

Anchors



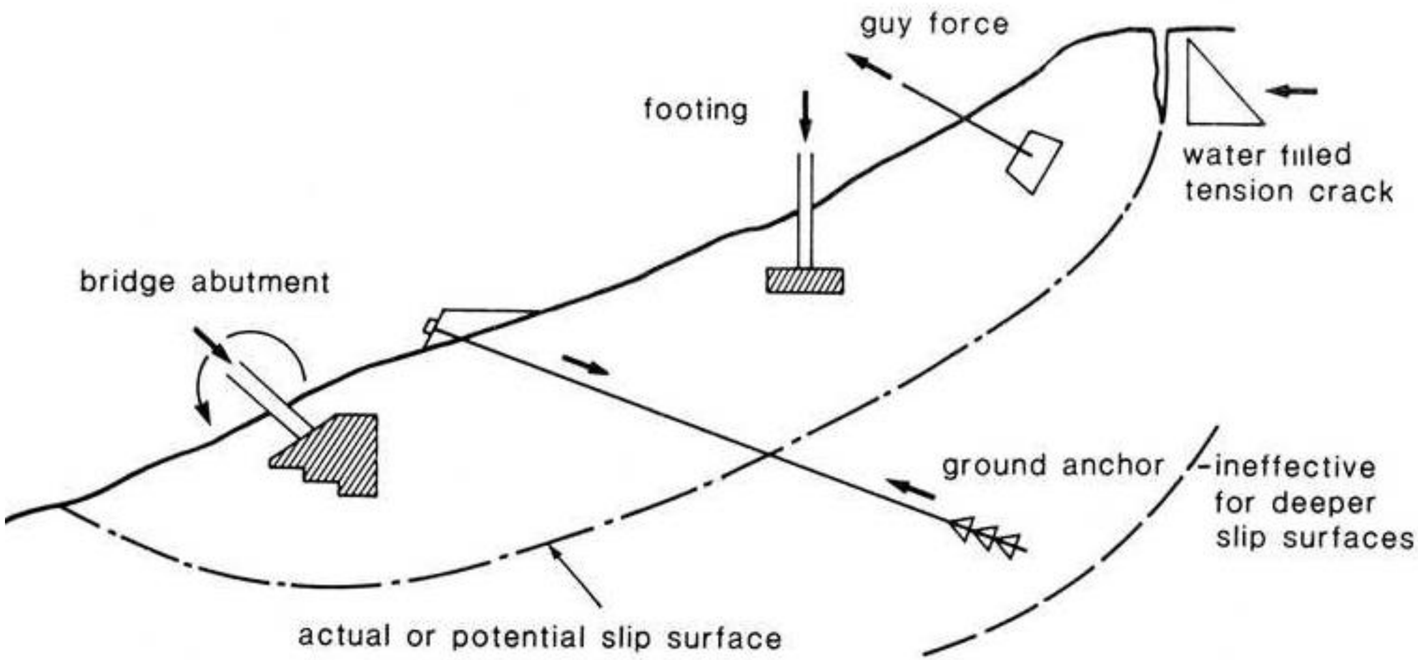
Section of tieback to correct slide condition on New York Avenue in Washington DC (Ambrason et al. 2002).

Anchors



Tieback detail, (Ambrason et al., 2002)

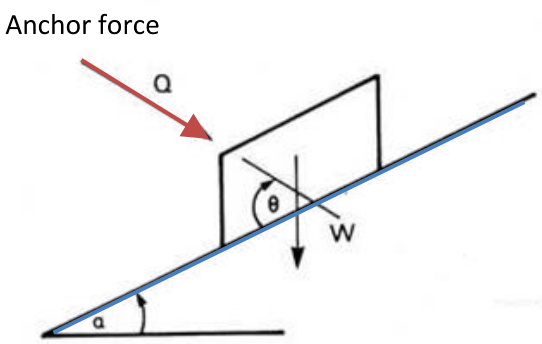
Anchors

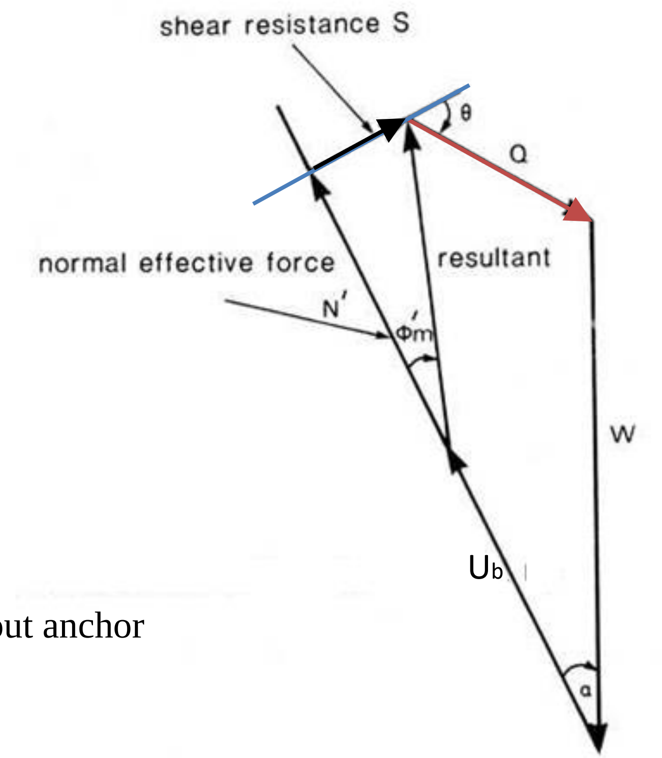


(Bromhead, 1986)

Anchors

Action on a sliding block





$$F_0 = \frac{(W\cos\alpha - U_b)\cdot\tan\varphi'}{W\sin\alpha}$$

Safety factor without anchor

$$F_1 = \frac{(W\cos\alpha + Q\sin\theta\ - U_b)\cdot\tan\varphi'}{W\sin\alpha - Q\cos\theta}$$

Safety factor with anchor

Optimum anchor inclination

$$\theta_c = arctan\,(\mathrm{tg}\,{}^{\varphi'}/_{F_1})$$

Bishop simplified method

Cut and fill

Drainage

$$F_0 = \frac{\sum\left[c'_i \cdot b_i + \left(W_i - U_{b,i} \cdot cos\alpha_i\right) \cdot tan\varphi'_i\right] \cdot \frac{1}{cos\alpha_i + \frac{1}{F_0} \cdot tan\varphi'_i \cdot sin\alpha_i}}{\sum W_i \cdot sin\alpha_i - \sum H_i \cdot cos\alpha_{Hi}}$$

Retaining structure

Increase in resisting forces

$$F = \frac{R}{D}$$

Drainage effect

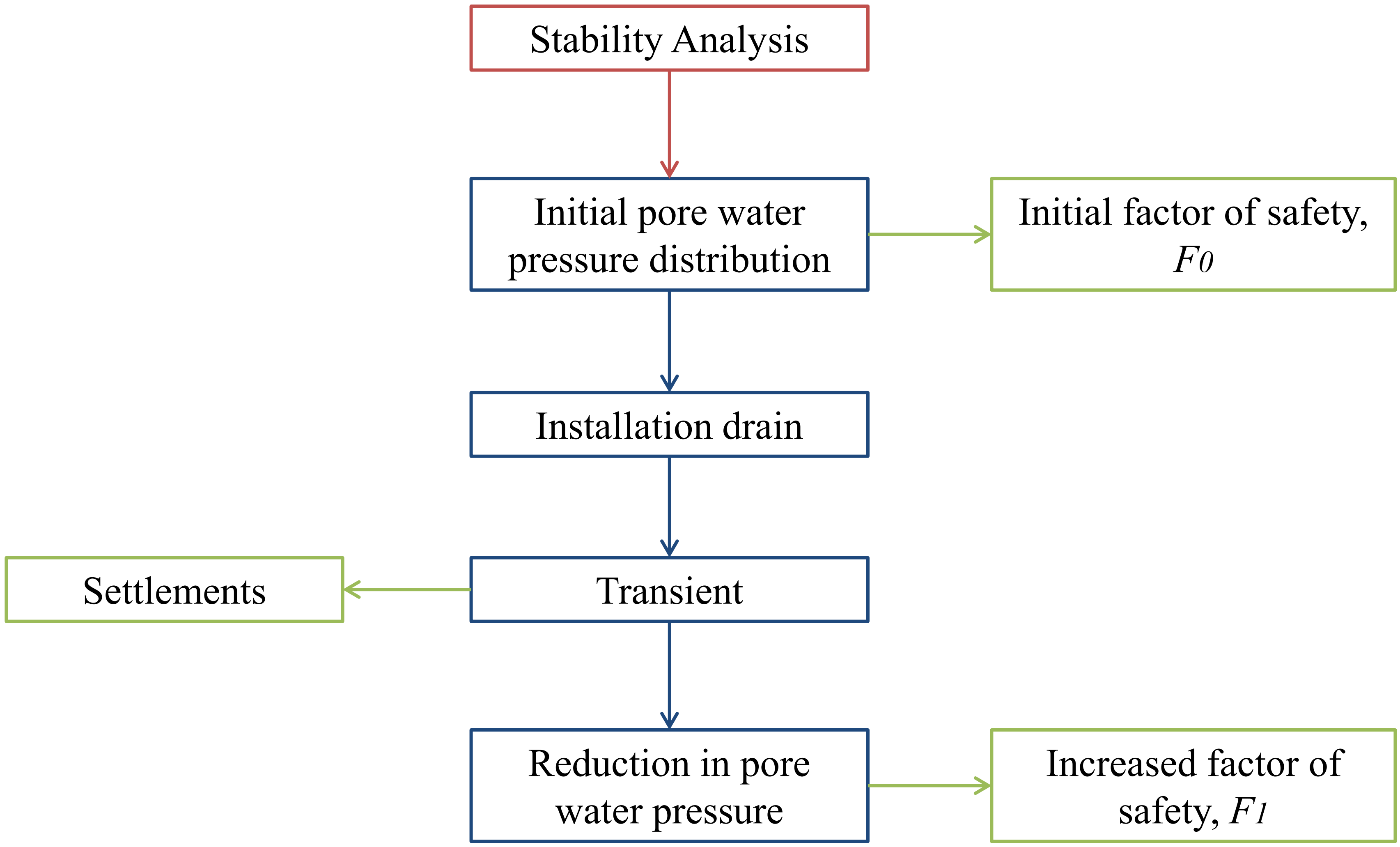
Drainages fixe pore water pressures in some zones of the slope (typically pwp = 0 by putting the water in contact with the atmosphere).

These fixed pwp correspond to a change in the boundary conditions that will affect the overall pwp distribution.

The changes in pwp do not necessarily correspond to changes in the degree of saturation (e.g. soil can remain saturated when pwp are < 0).

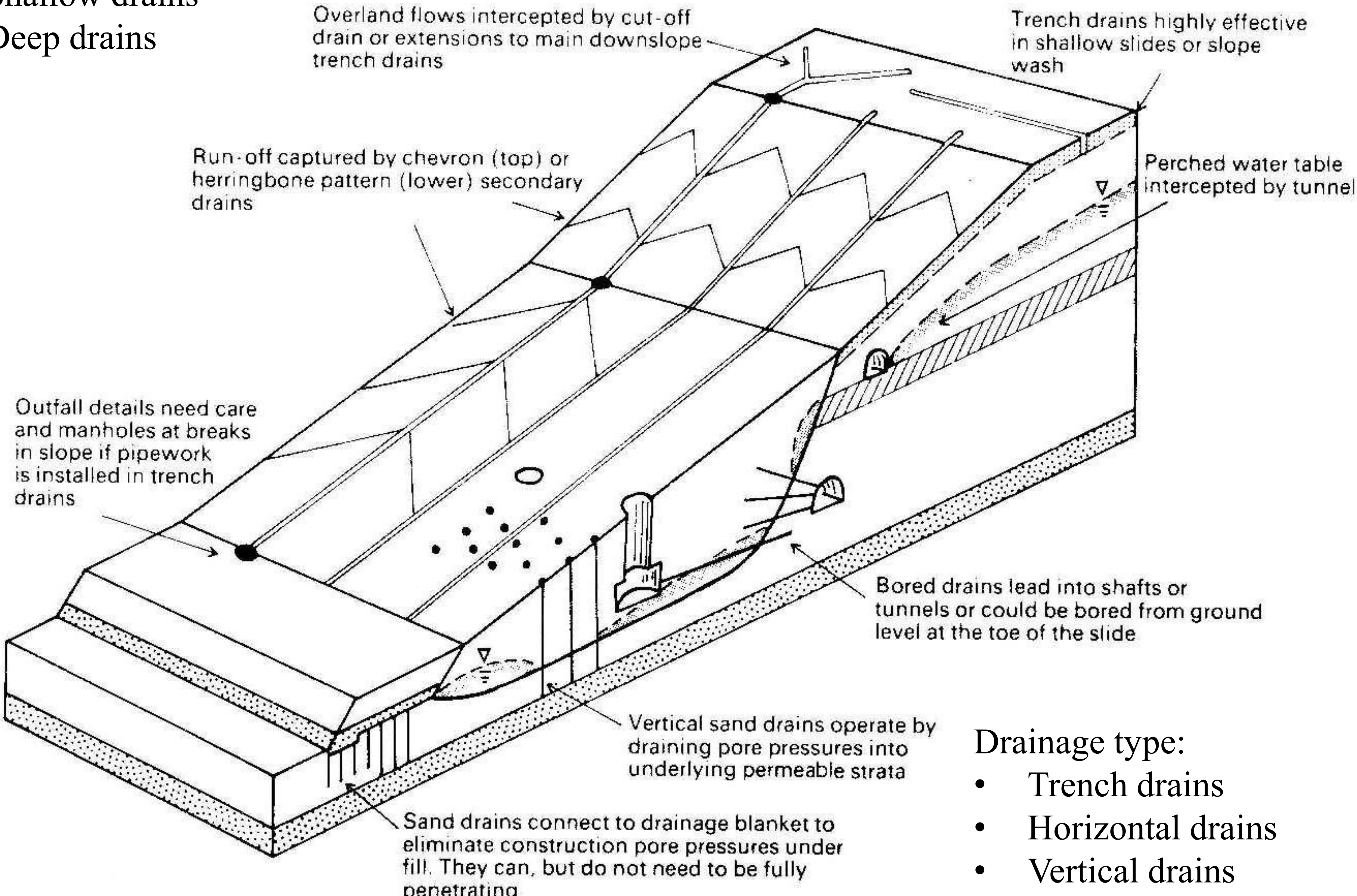
The efficiency of a drainage system must always been assessed in term of pore water pressure changes (not flow!)

Project process



Drainage classification:

- Shallow drains
- Deep drains

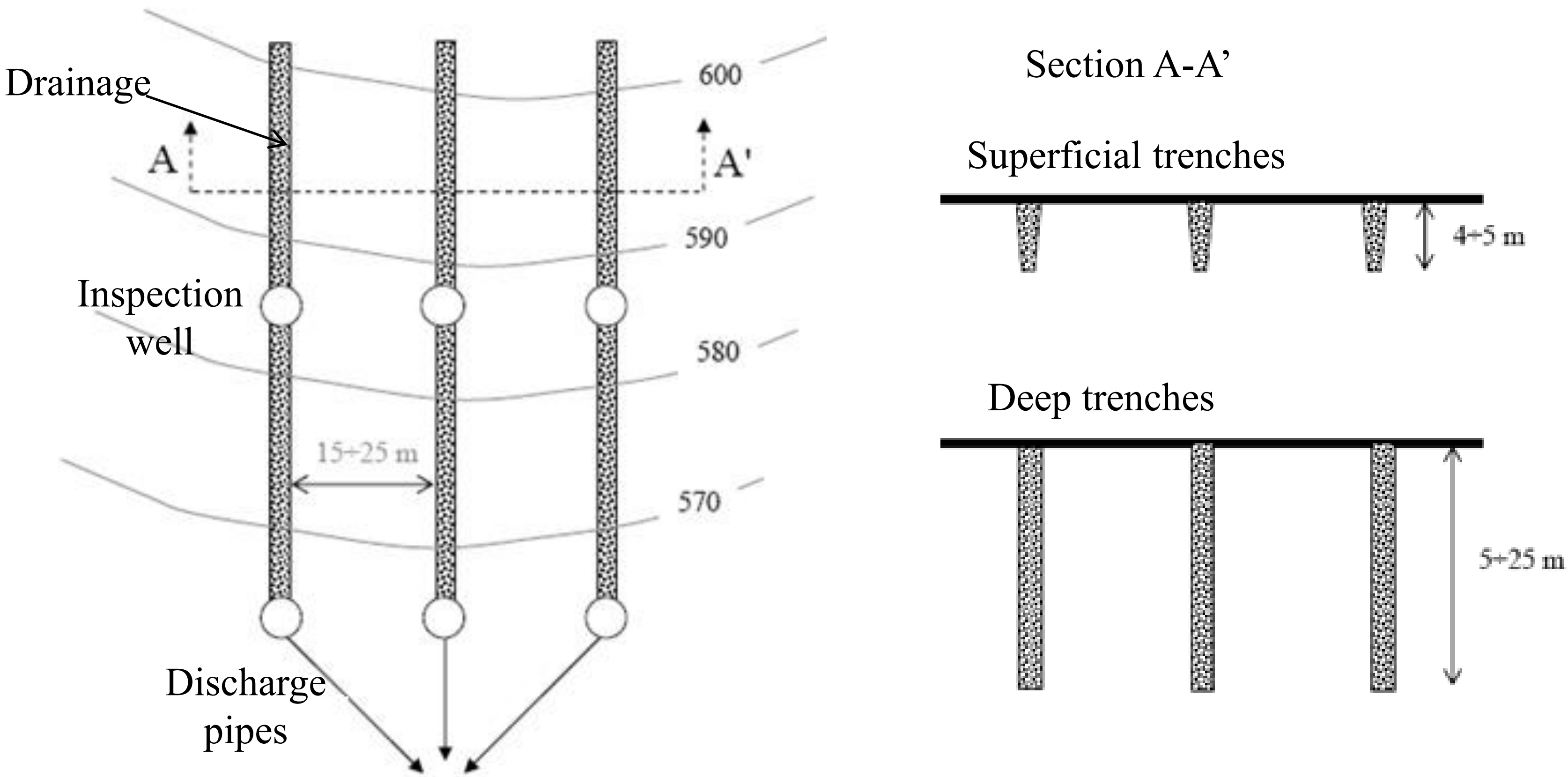


Different drainages (Bromhead, 1986)

Drainage type:

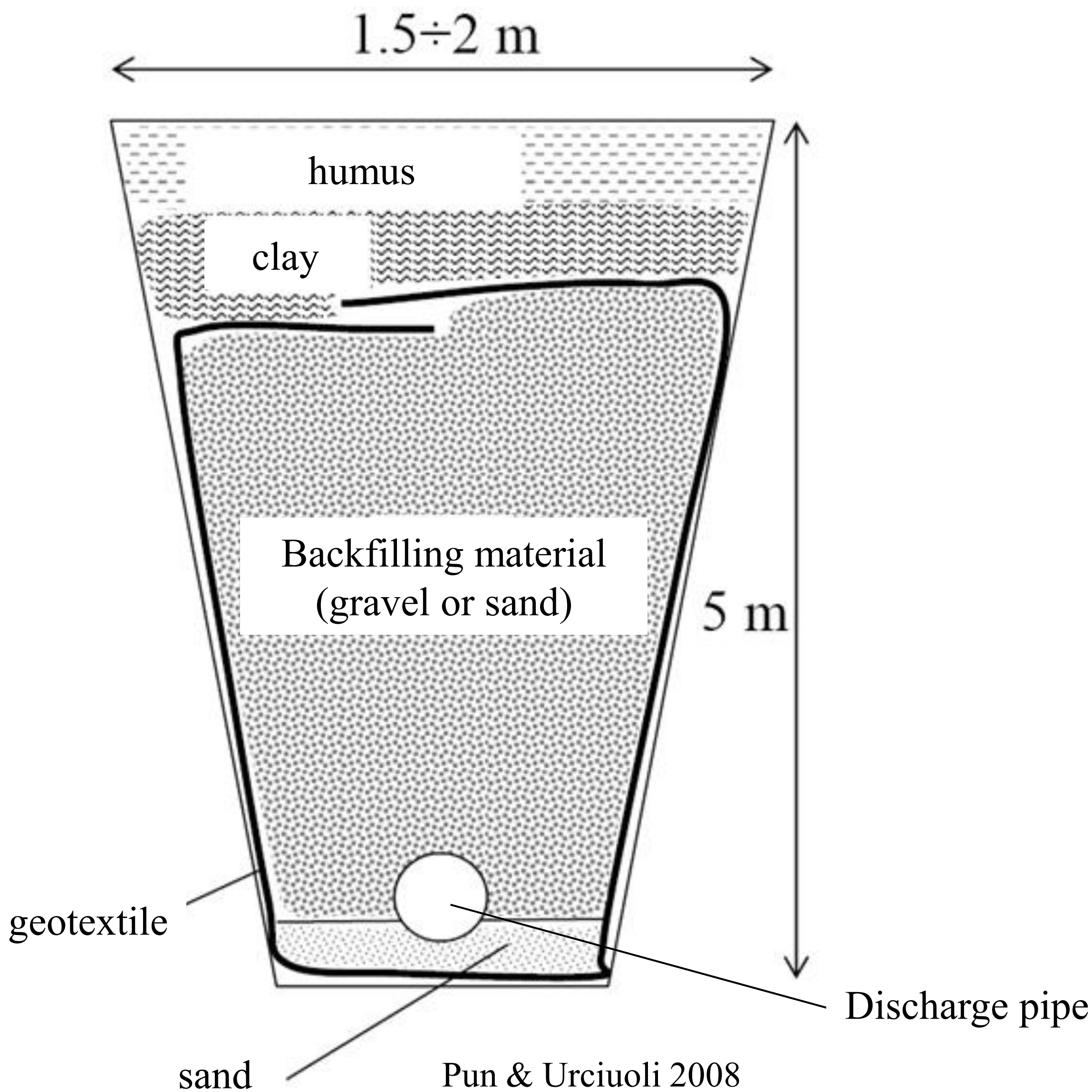
- Trench drains
- Horizontal drains
- Vertical drains
- Drainage gallery

Trench drains

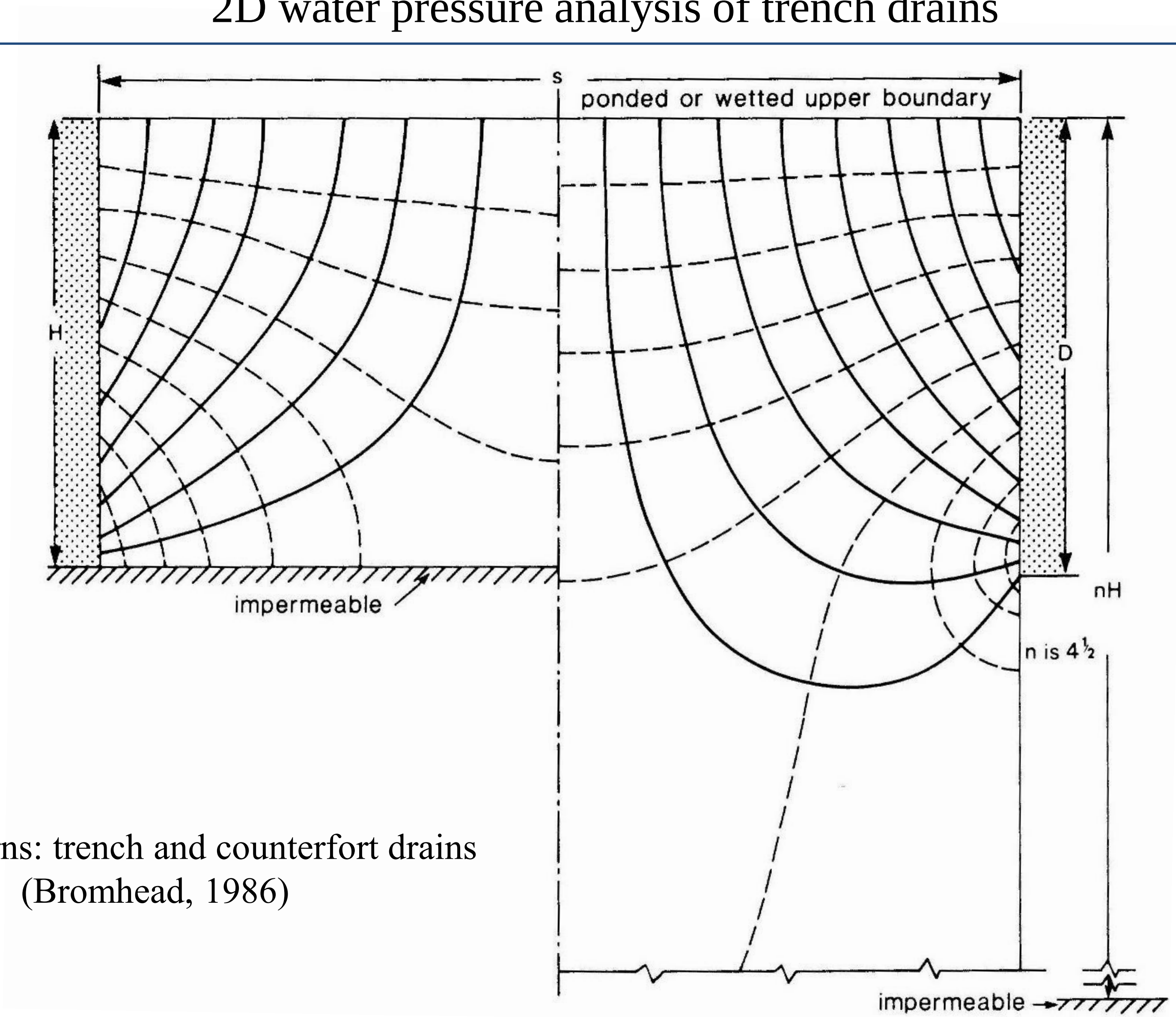


Superficial and deep trenches with only main branches (Pun & Urciuoli, 2008)

Trench drains

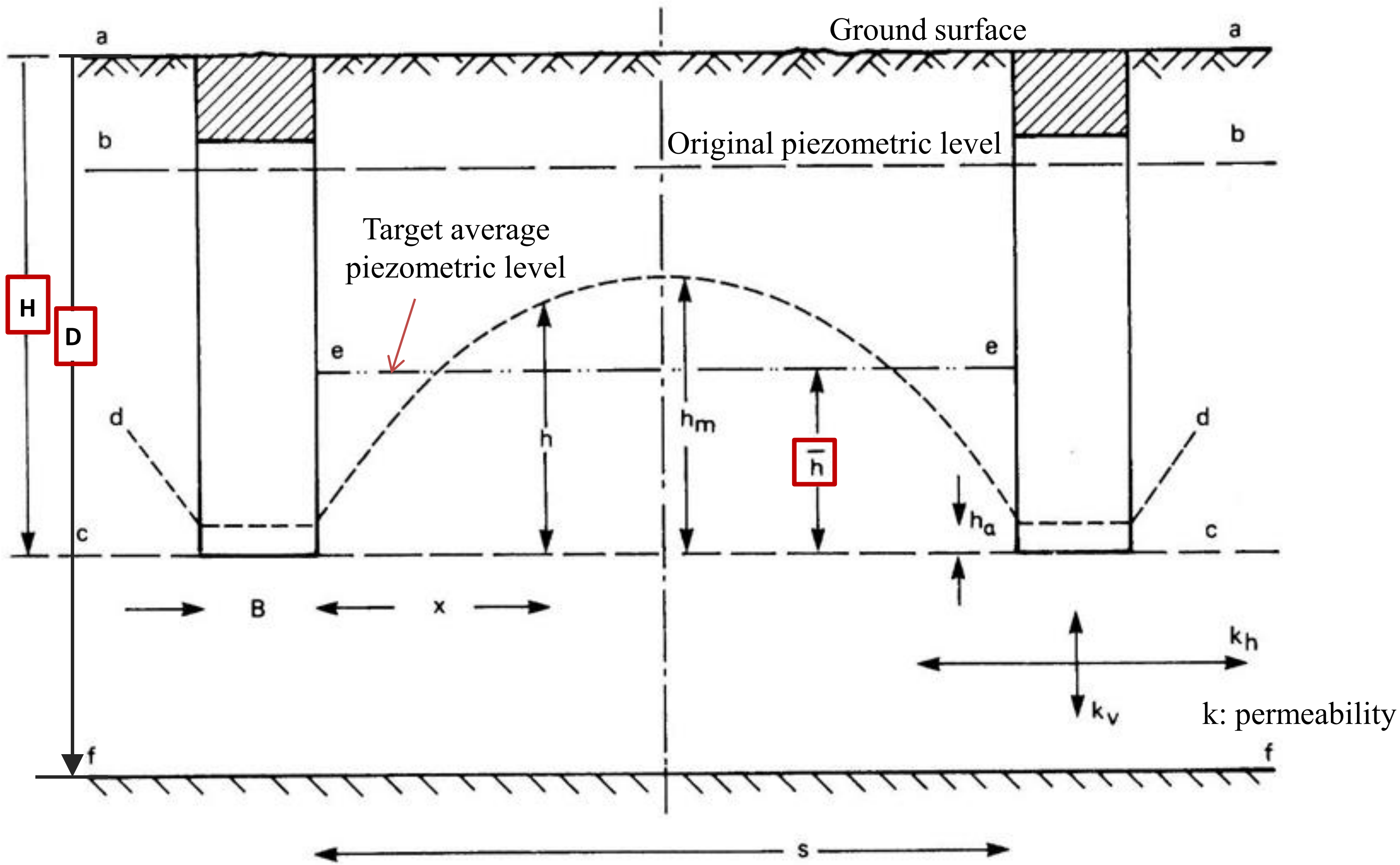


2D water pressure analysis of trench drains



Flow patterns: trench and counterfort drains
(Bromhead, 1986)

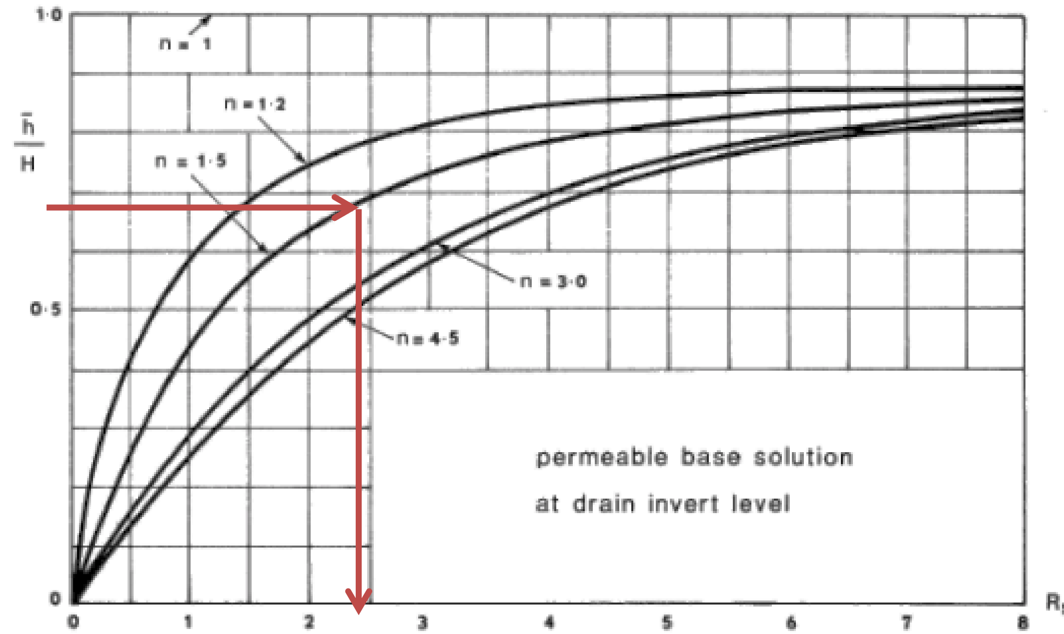
2D water pressure analysis of trench drains



Trench and counterfort drains (after Bromhead, 1986)

Trench drains simplified design

1. From stability analysis, define the $\bar{h}$ value that provides the desired safety factor
2. Define the drain depth *H* (based on slip surface depth)
3. Compute $n = (D/H)$
4. Enter in the diagram with the $\bar{h}/H$ value
5. Intersect the curve with the evaluated *n*
6. Obtain R_s value on the x-axis
7. Calculate the spacing between drains (s) for the specific permeability conditions

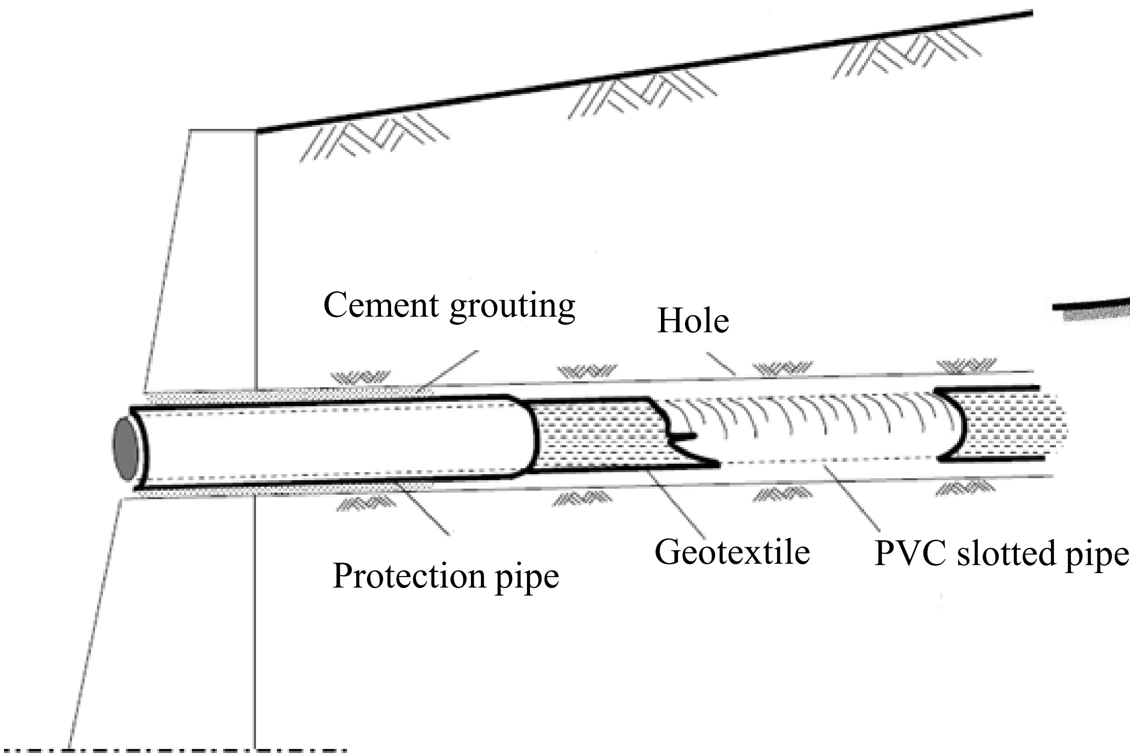


Design charts, set of solutions obtained from finite-element methods (Bromhead, 1986)

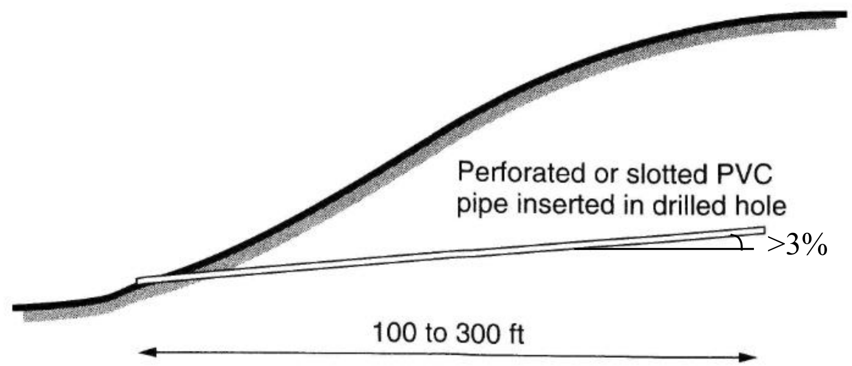
n = effective stratum depth / effective drain depth = D/H

$$R_s = \sqrt{(k_v / k_h) s / H}$$

Horizontal Drains



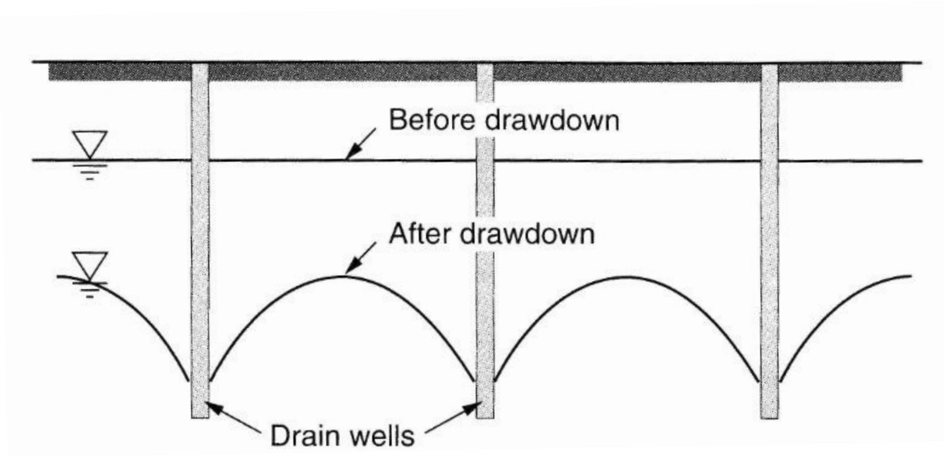
Scheme of a horizontal drain (Pun & Urciuoli, 2008)



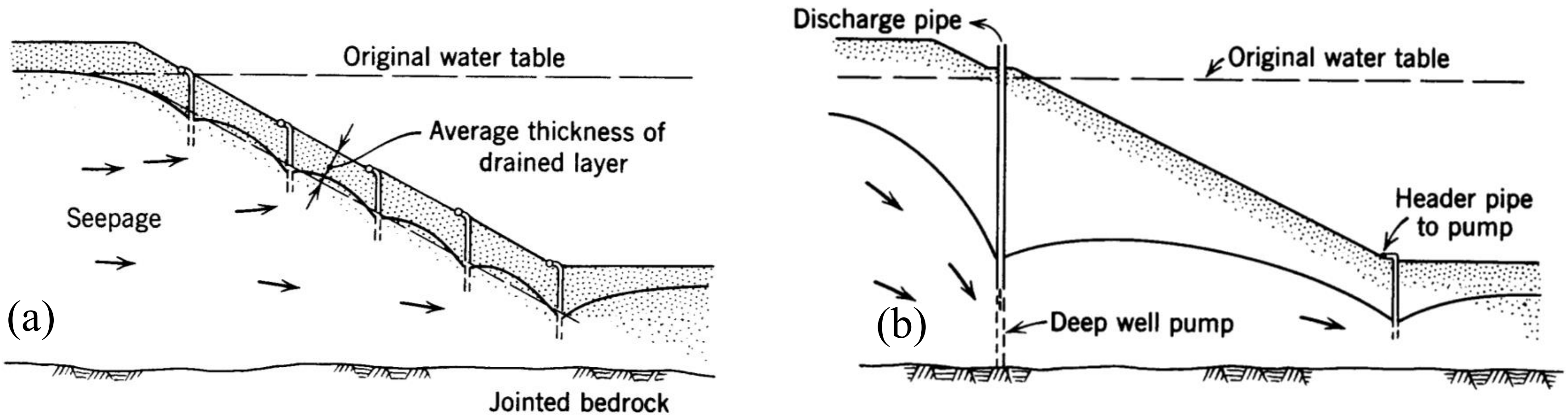
Duncan et al., 2014

Horizontal drains can be drilled directly into a hillslide (when slope is steep) or into a reteining structure.

Wells

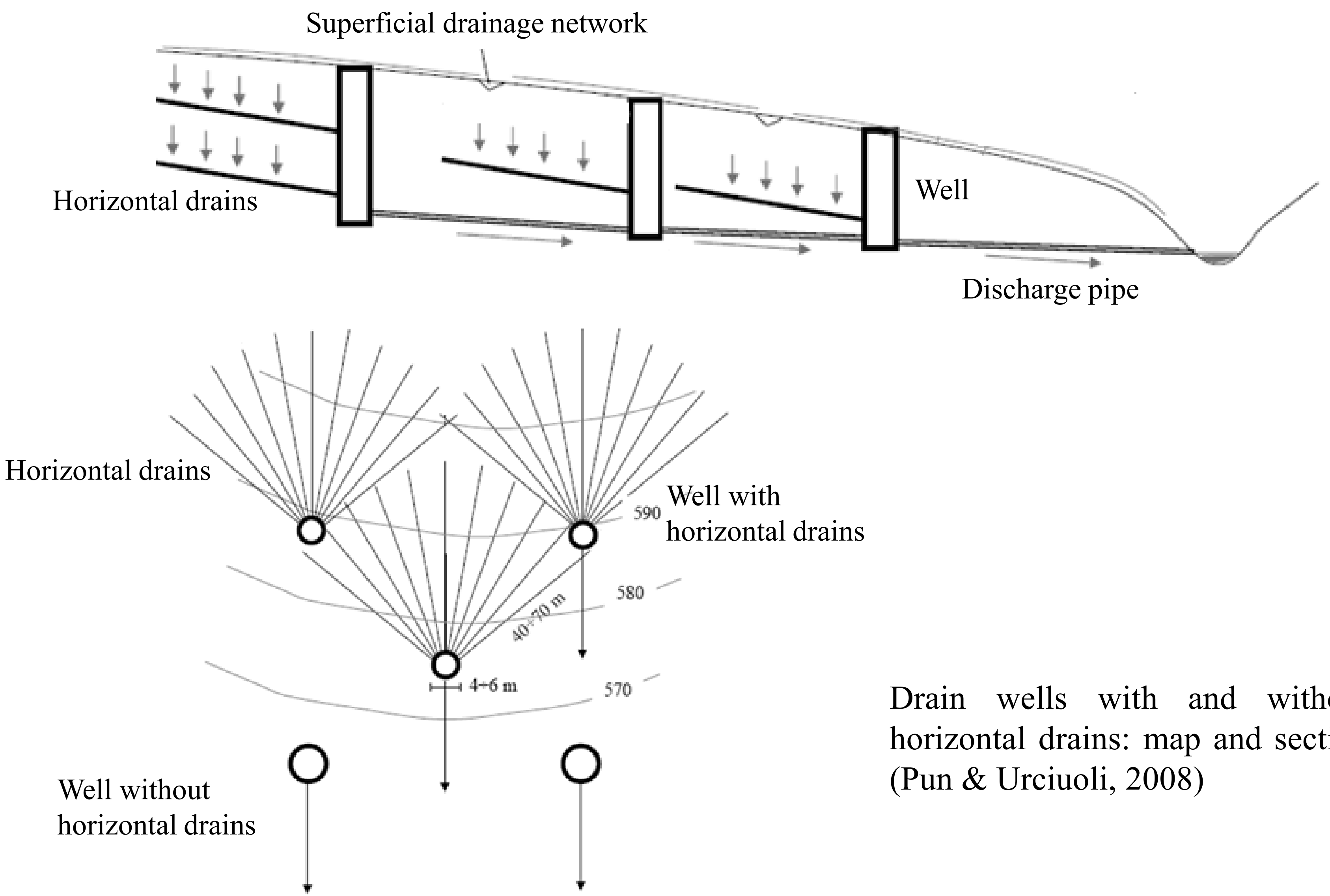


Water level between drain wells (Bromhead,1986)



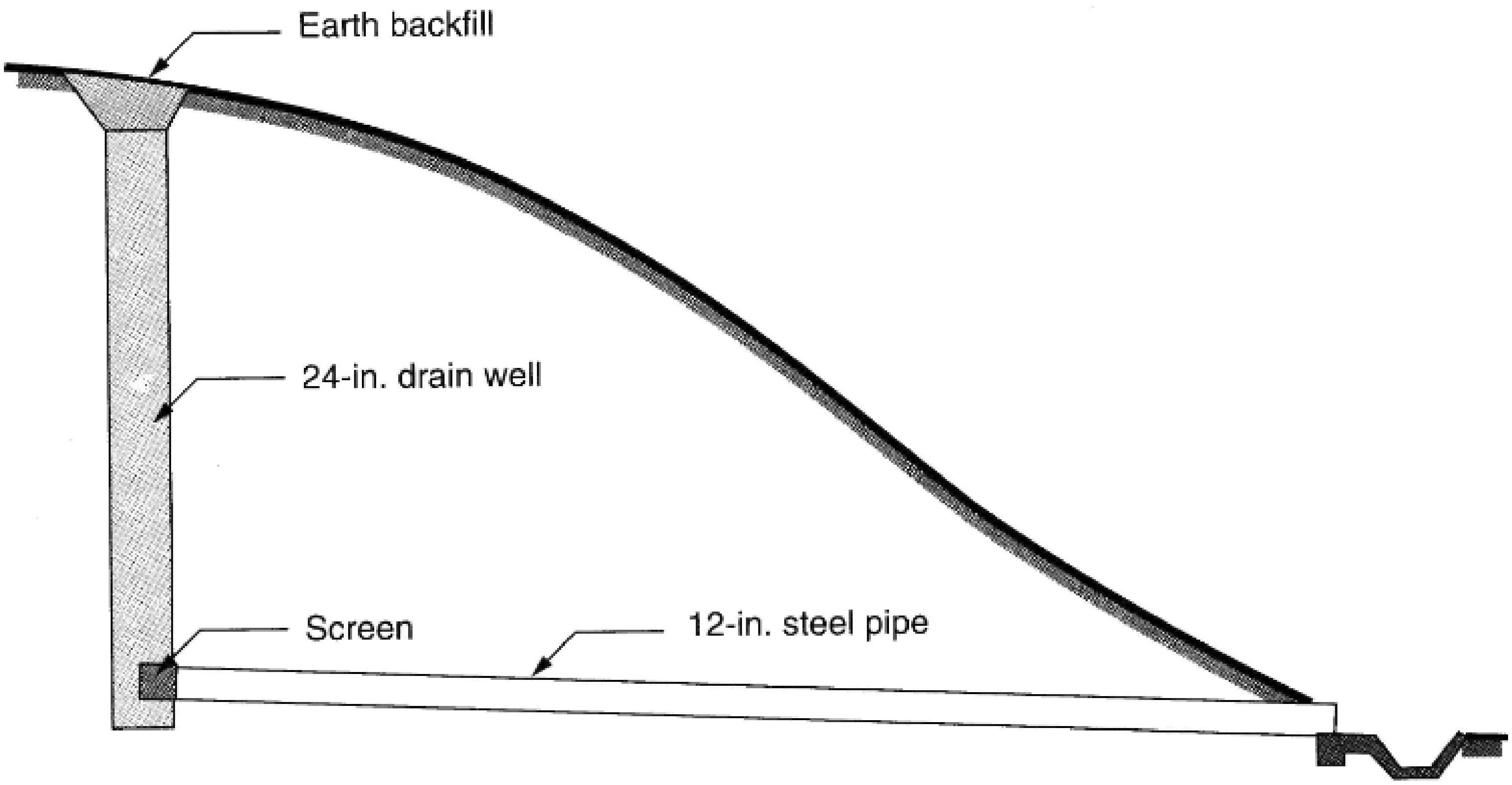
a) Excavation stabilized with five-stage well point system;
b) excavation stabilized with deep wells and well points. (Bromhead,1986)

Vertical drains



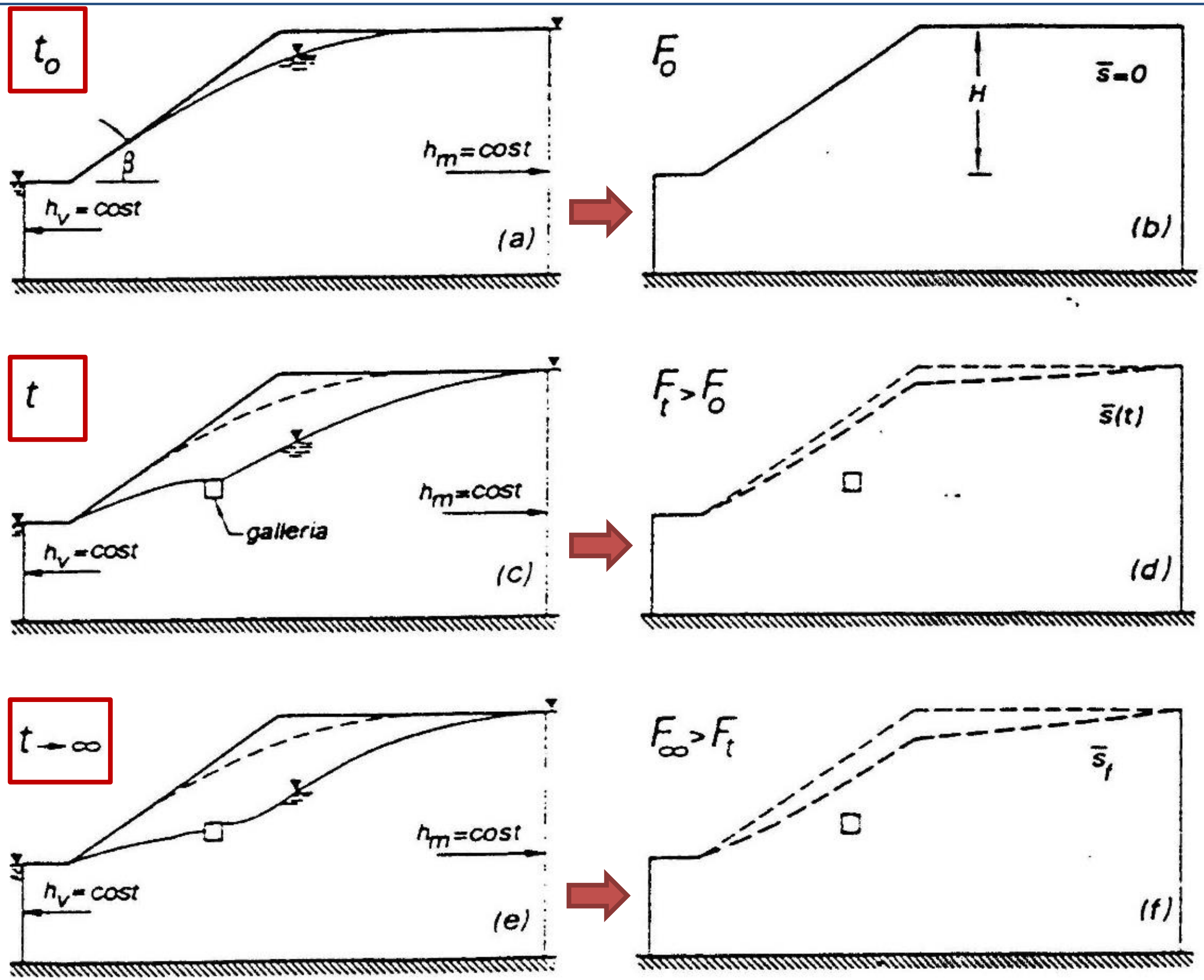
Drain wells with and without horizontal drains: map and section (Pun & Urciuoli, 2008)

Vertical drains



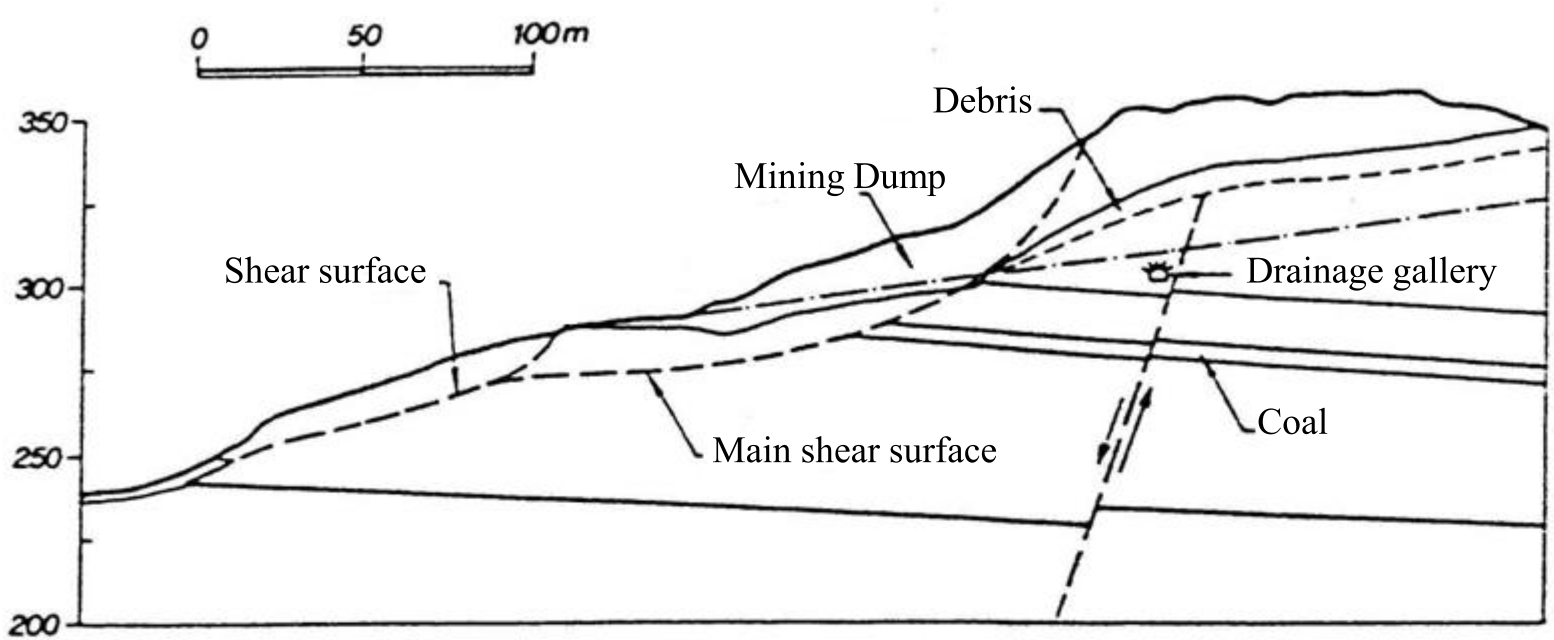
Drain wells used to stabilize four landslides near Seattle
(Bromhead,1986)

Drainage gallery



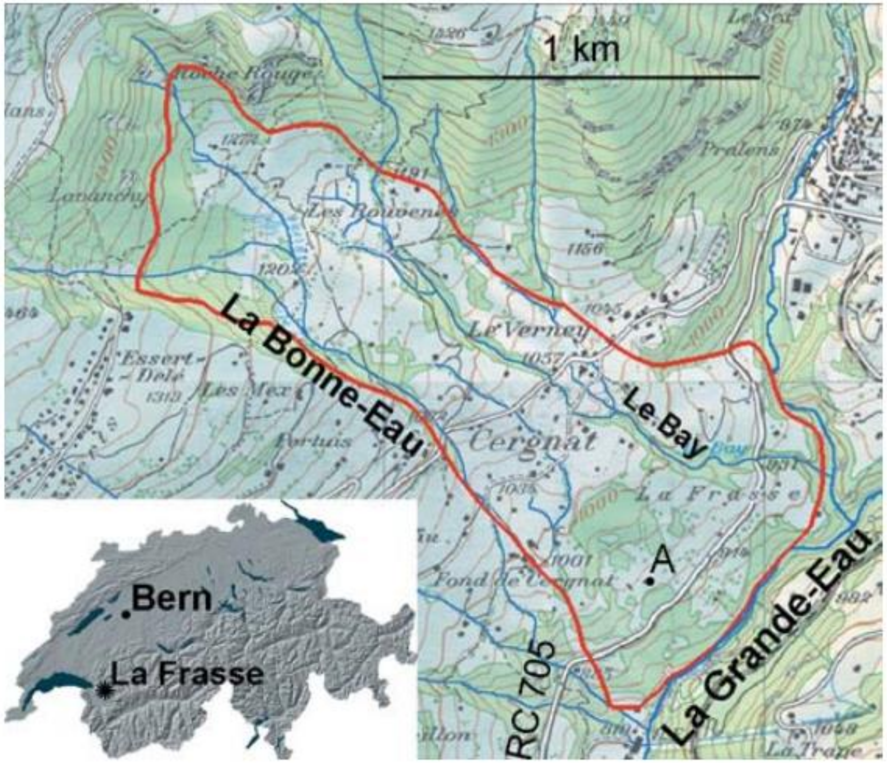
(a) Initial piezometric level, (c) at time t, (e) at $t = \infty$ and corresponding settlments, Airò Farulla & Valore, 1994

Drainage gallery

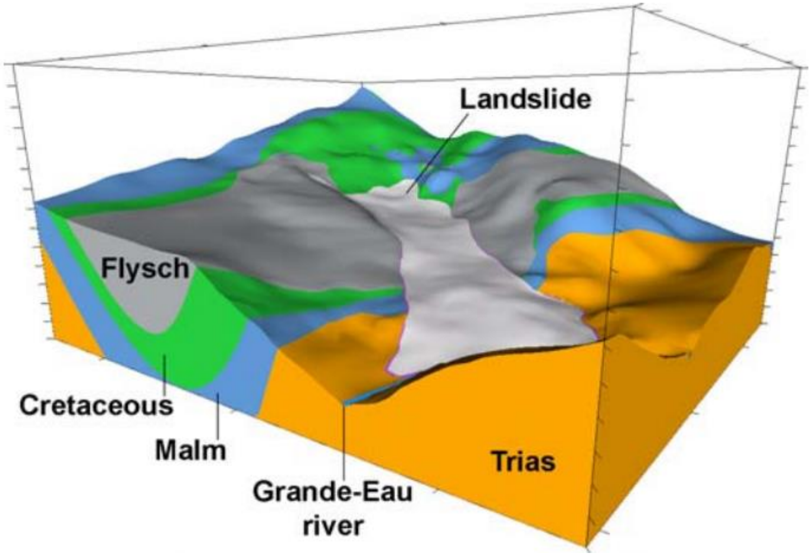


Drainage Gallery for the stabilization of a mining dump. After Airò Farulla & Valore, 1994

La Frasse landslide



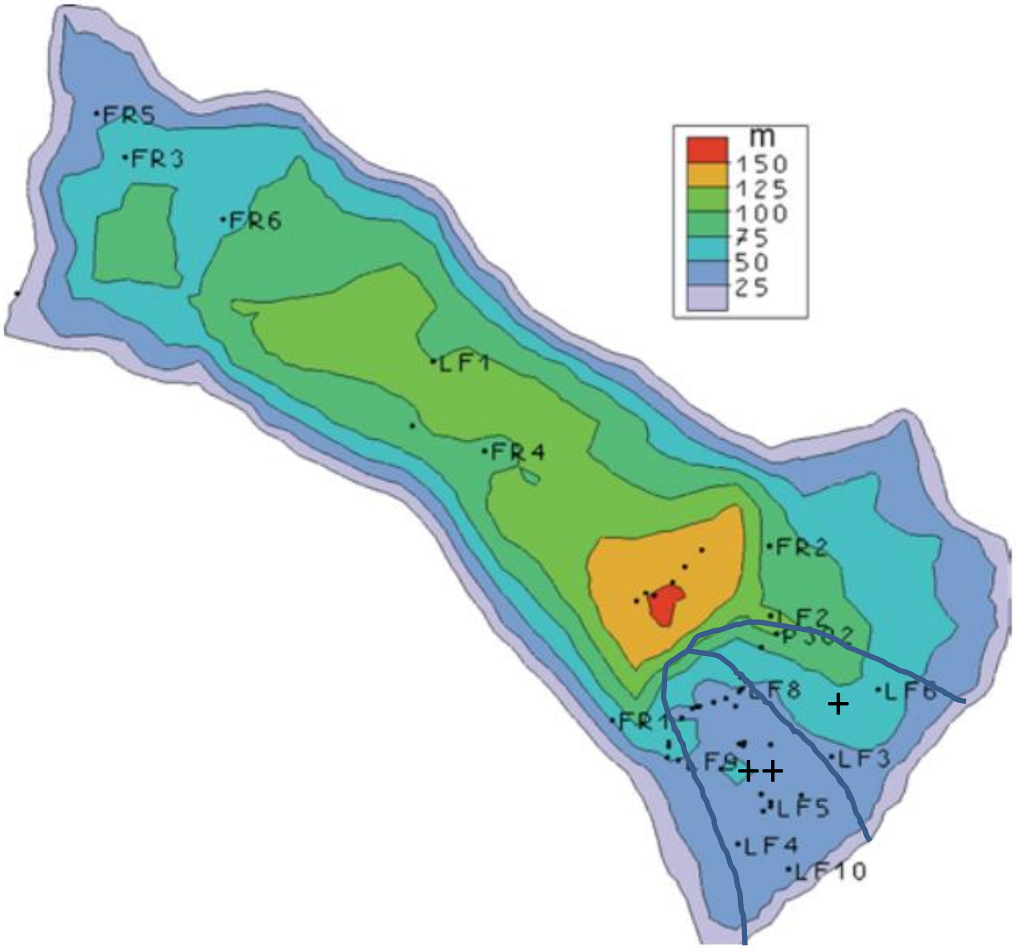
Location of the La Frasse Landslide. Tacher et al., 2005



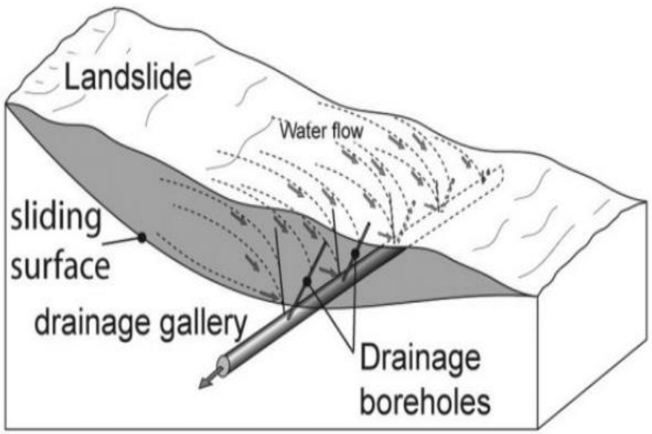
La Frasse 3D geological model. View from S-E. Commend et al. 2006

La Frasse landslide

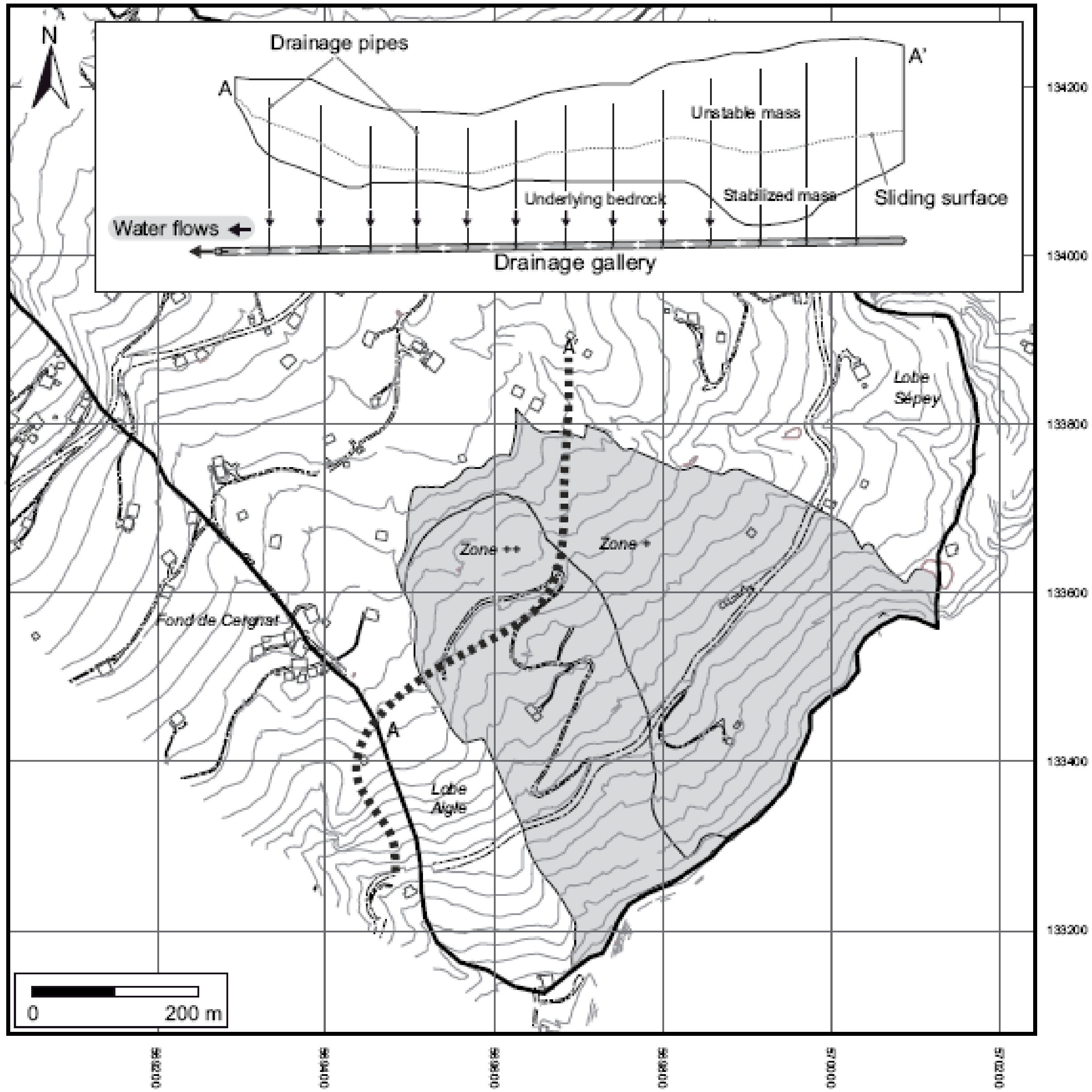
Length:	2000 m
Wide:	500 – 1000 m
Thickness:	50 – 110 m
Surface :	plus de 1 km^2
Volume :	
active :	42 mio m^3
total :	73 mio m^3
Slope :	
upper part:	11°
upper part:	20°
Average speed:	
upper part :	10-15 cm/year
lower part : zone «+» :	15-30 cm/year
zone «++» :	40-60 cm/year



Location of some representative boreholes and total thickness of the landslide mass (active plus stabilised). Tacher et al., 2005

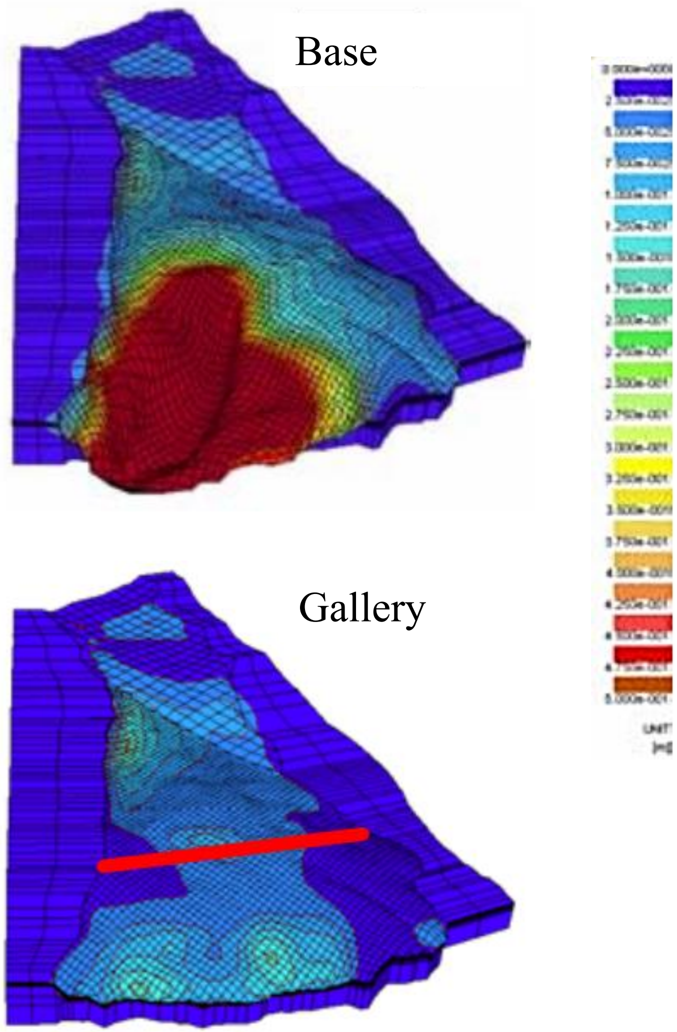


Drainage gallery concept

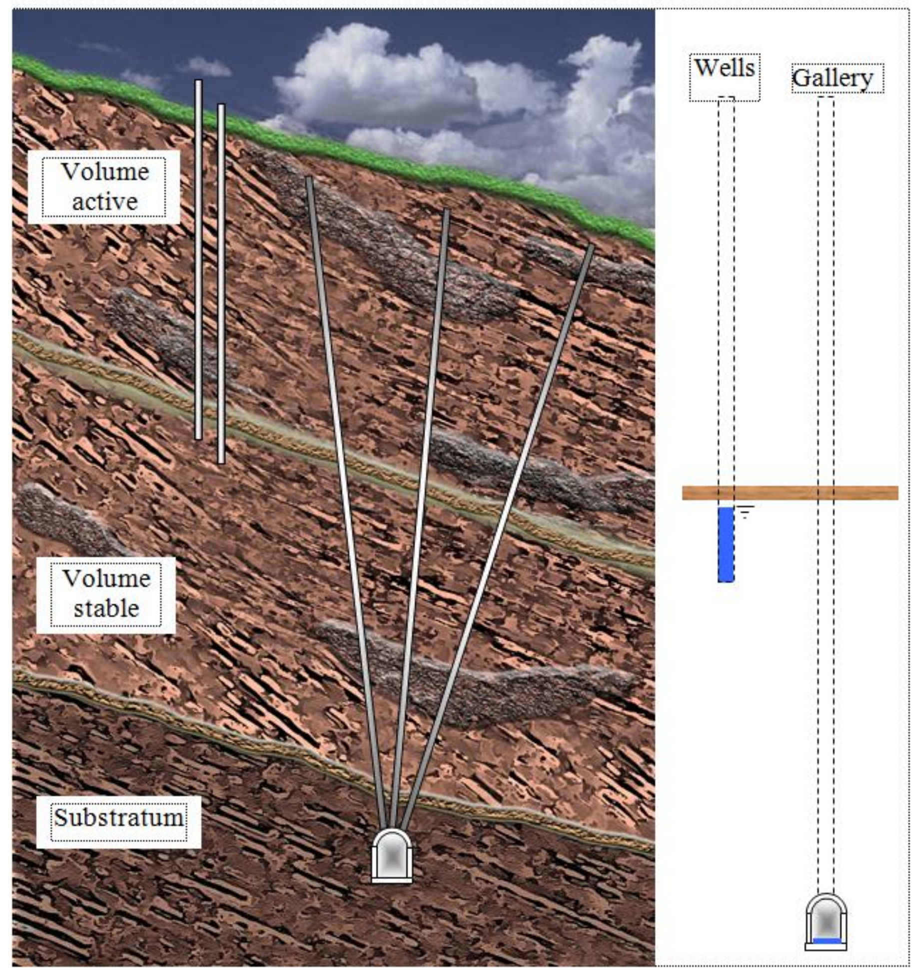


Location of the projected drainage gallery
Matti, 2008

La Frasse landslide



Displacement field with and without the gallery Tacher et al., 2005



Gallery and pipes schematic rappresentation

Inside of the la frasse drainage gallery
http://www.vd.ch/

Measures of surface movement of the landslide during the period 2006-2014