Athens

10.05.2011

INFRASTRUCUTRE PROJECTS IN LANDSLIDE-PRONE AREAS

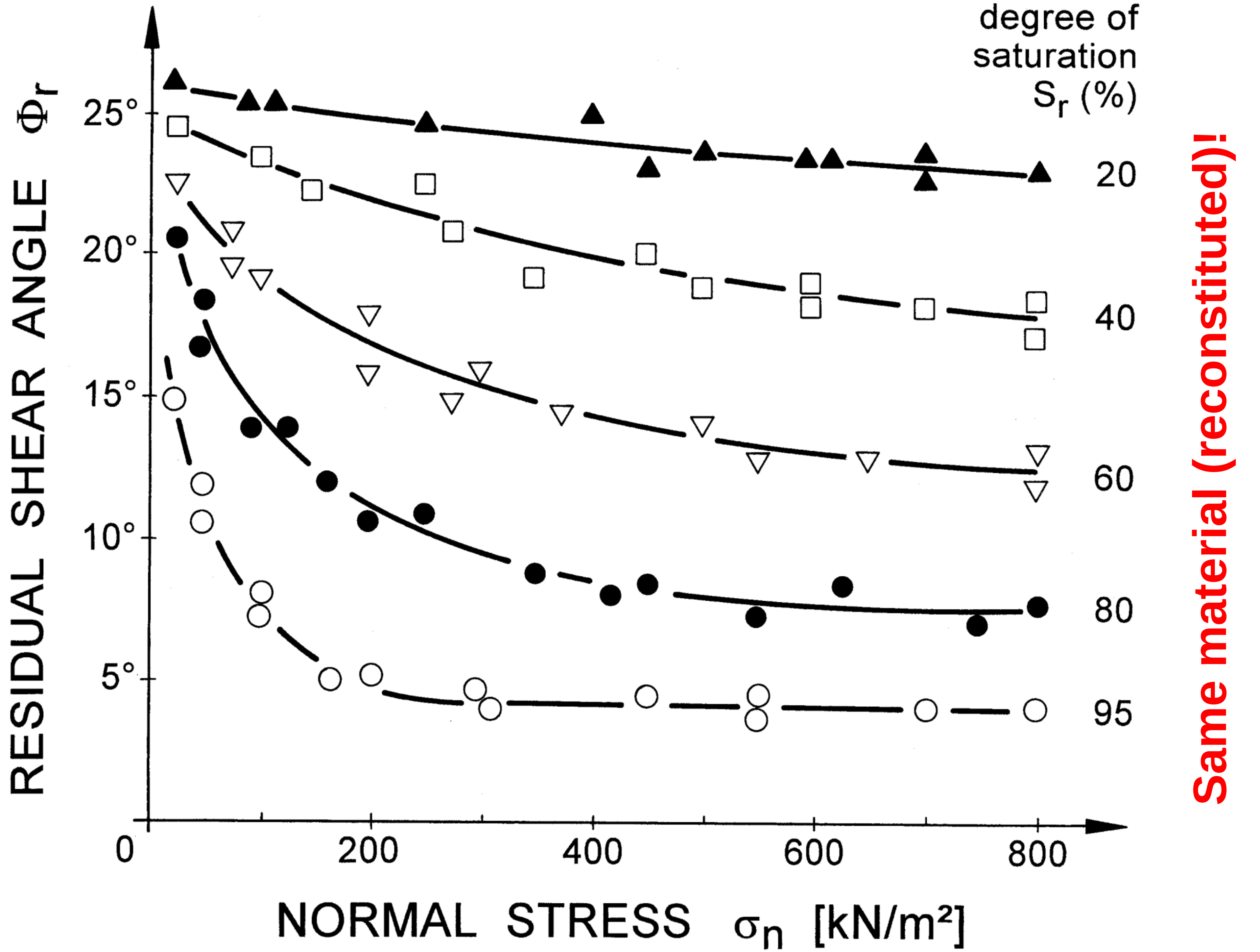
(Retaining measures, structures in unstable slopes)

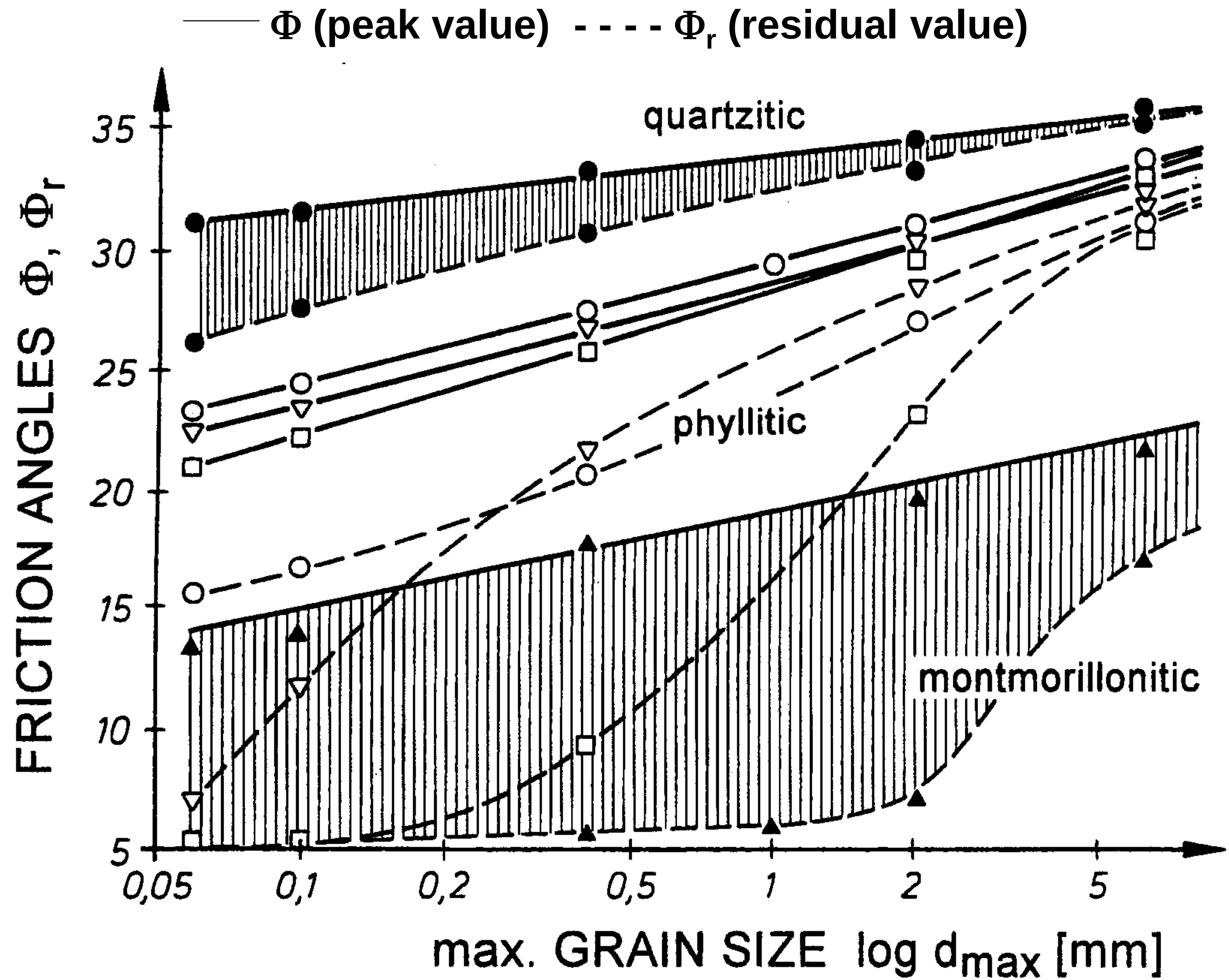
O.Univ.Prof. Dr. Heinz Brandl

Only 20 % of construction costs visible

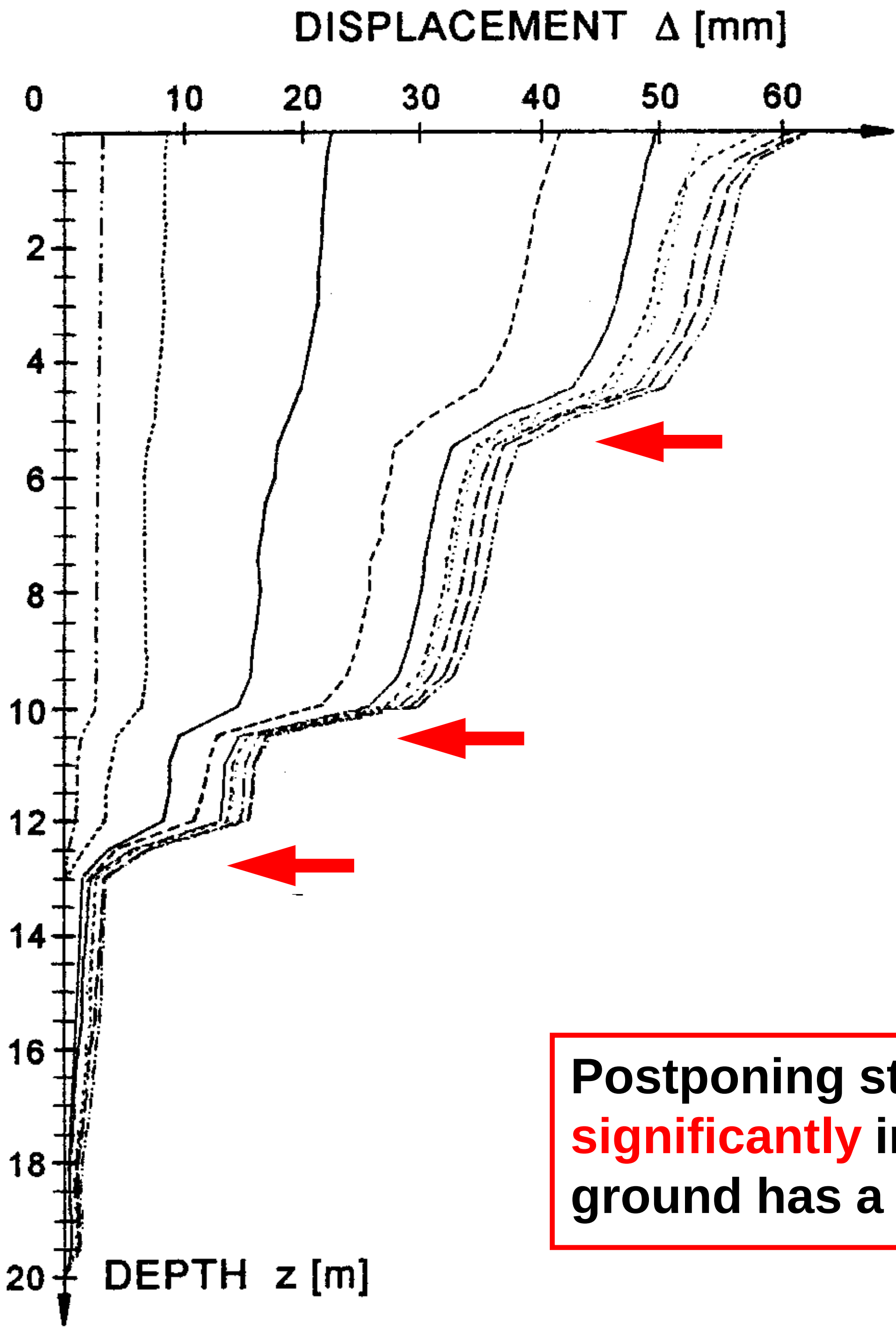
(Monitoring since 1979)


CABLE CRANE
(L=600m)


degree of saturation S_r (%)
20
40
60
80
95
RESIDUAL SHEAR ANGLE Φ_r
25°
20°
15°
10°
5°
0
200
400
600
800
NORMAL STRESS σ_n [kN/m²]
Same material (reconstituted)!



Φ (peak value) - - - - Φr (residual value)
quartzitic
phyllitic
montmorillonitic
FRICTION ANGLES Φ, Φr
35
30
25
20
15
10
5
0,05
0,1
0,2
0,5
1
2
5
max. GRAIN SIZE log dmax [mm]



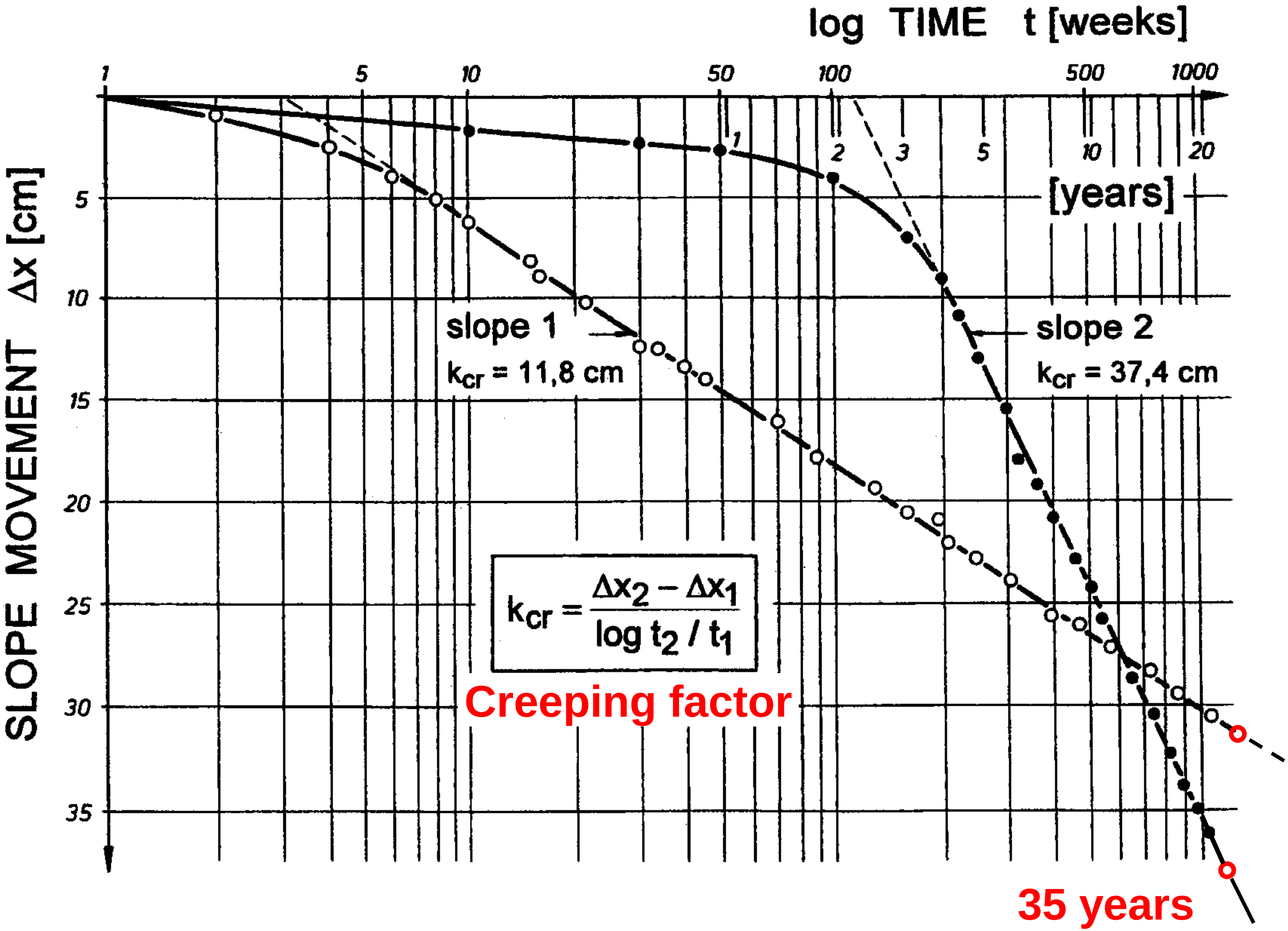
Multiple slope failure

slip surfaces progressively increasing

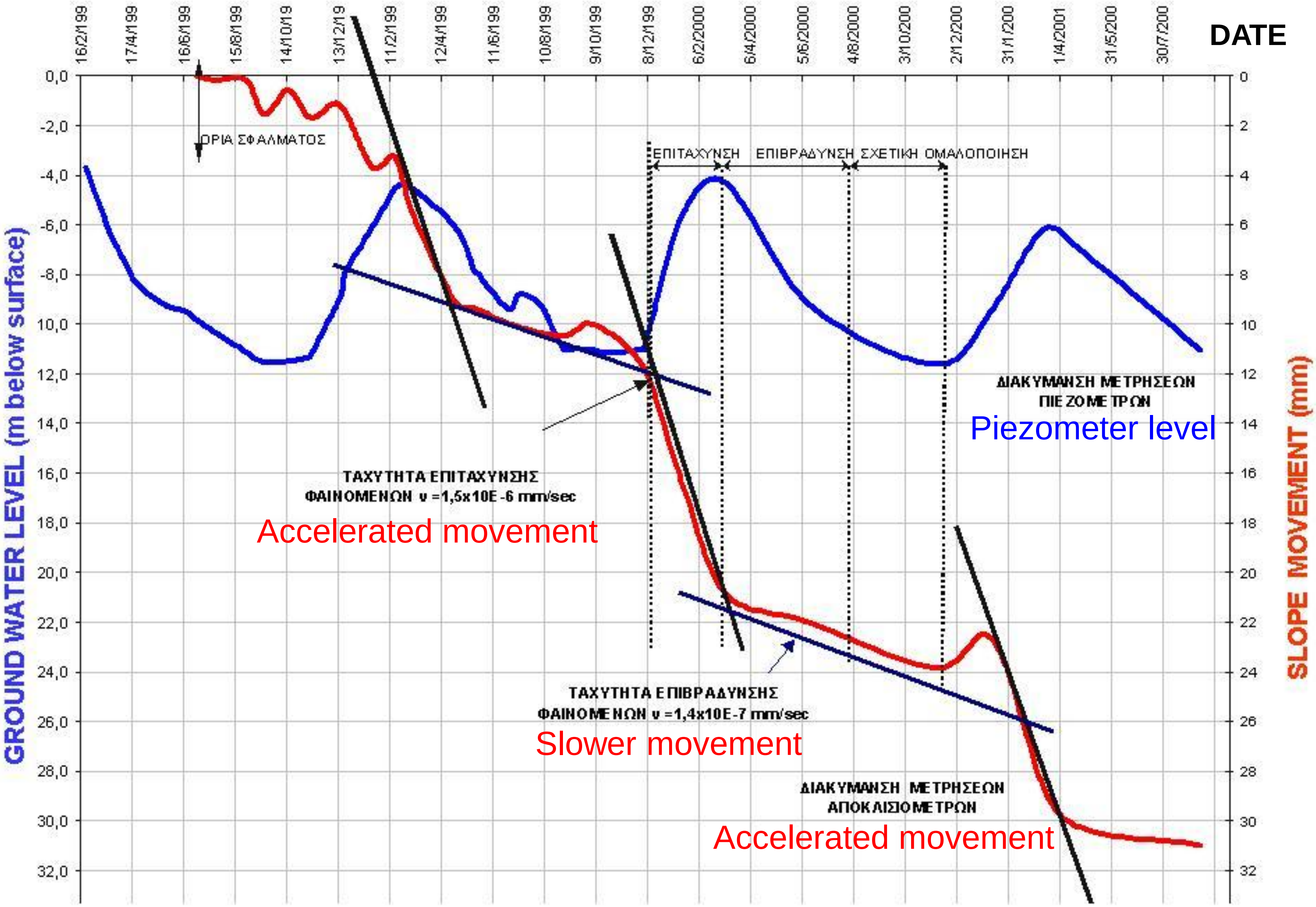
Δt = 5 years

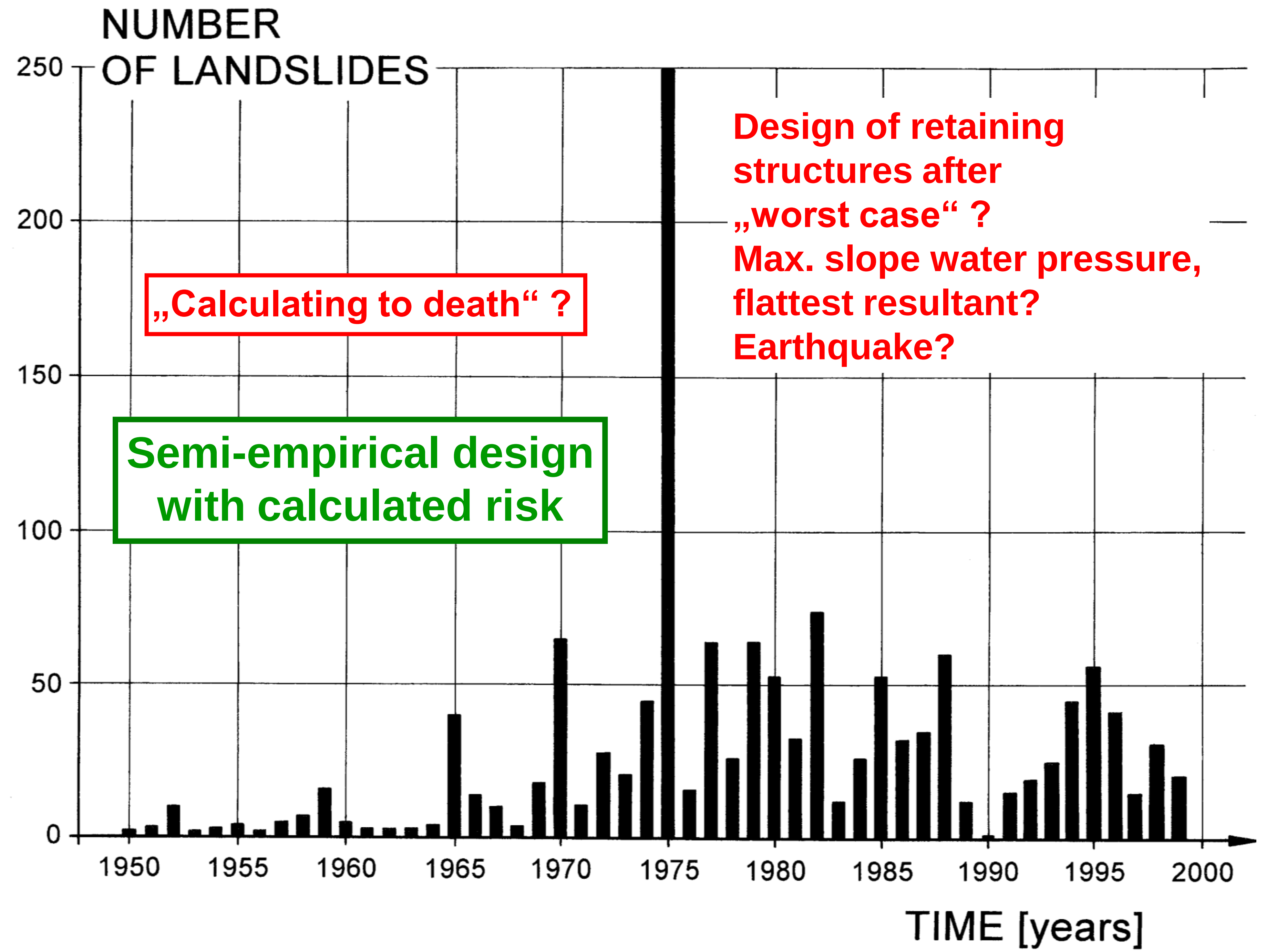
stabilised by 25m deep sockets

Postponing stabilizing measures may significantly increase the costs if the ground has a low residual shear strength



log TIME t [weeks]
1
5
10
50
100
500
1000
1
2
3
5
10
20
[years]
SLOPE MOVEMENT Δx [cm]
5
10
15
20
25
30
35
slope 1
kcr = 11,8 cm
slope 2
kcr = 37,4 cm
kcr = (Δx2 − Δx1) / (log t2 / t1)
Creeping factor
35 years


DATE
16/2/199
17/4/199
16/6/199
15/8/199
14/10/19
13/12/19
11/2/199
12/4/199
11/6/199
10/8/199
9/10/199
8/12/199
6/2/2000
6/4/2000
5/6/2000
4/8/2000
3/10/200
2/12/200
31/1/200
1/4/2001
31/5/200
30/7/200
GROUND WATER LEVEL (m below surface)
SLOPE MOVEMENT (mm)
ΟΡΙΑ ΣΦΑΛΜΑΤΟΣ
ΕΠΙΤΑΧΥΝΣΗ
ΕΠΙΒΡΑΔΥΝΣΗ
ΣΧΕΤΙΚΗ ΟΜΑΛΟΠΟΙΗΣΗ
ΔΙΑΚΥΜΑΝΣΗ ΜΕΤΡΗΣΕΩΝ ΠΙΕΖΟΜΕΤΡΩΝ
Piezometer level
ΤΑΧΥΤΗΤΑ ΕΠΙΤΑΧΥΝΣΗΣ ΦΑΙΝΟΜΕΝΩΝ v =1,5x10E-6 mm/sec
Accelerated movement
ΤΑΧΥΤΗΤΑ ΕΠΙΒΡΑΔΥΝΣΗΣ ΦΑΙΝΟΜΕΝΩΝ v =1,4x10E-7 mm/sec
Slower movement
ΔΙΑΚΥΜΑΝΣΗ ΜΕΤΡΗΣΕΩΝ ΑΠΟΚΛΙΣΙΟΜΕΤΡΩΝ
Accelerated movement



NUMBER
OF LANDSLIDES
250
200
150
100
50
0
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
TIME [years]
„Calculating to death“ ?
Semi-empirical design
with calculated risk
Design of retaining
structures after
„worst case“ ?
Max. slope water pressure,
flattest resultant?
Earthquake?

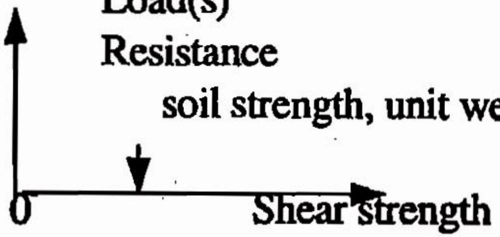
SCHEME OF GEOTECHNICAL CALCULATIONS OF SAFETY FACTORS

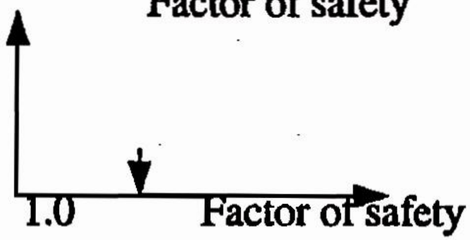
CONVENTIONAL ANALYSIS

Input parameters → $\Sigma F_x = 0$ → **Output of analysis**

Input parameters
- Load(s)
- Resistance
  - soil strength, unit weight, ……

Output of analysis
- Factor of safety





ANALYSIS ACCOUNTING FOR UNCERTAINTIES

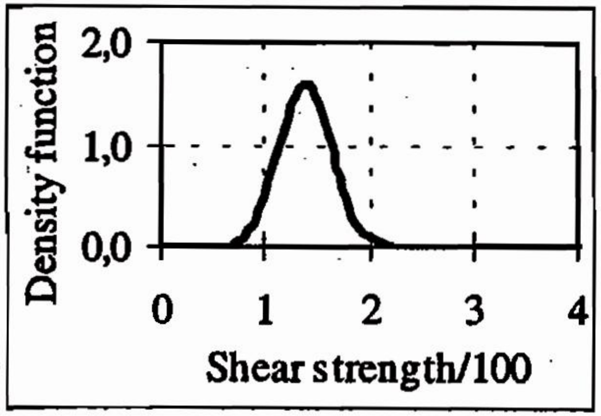
Input parameters →

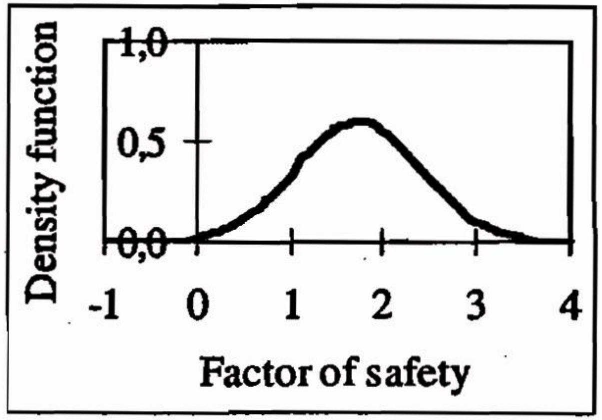
$$G_x = \Sigma F_x = 0$$
$$P_f = P[G_x \leq 0]$$
$$(P_f = P\,[\text{Load} > \text{Resistance}])$$

→ **Output of analysis**

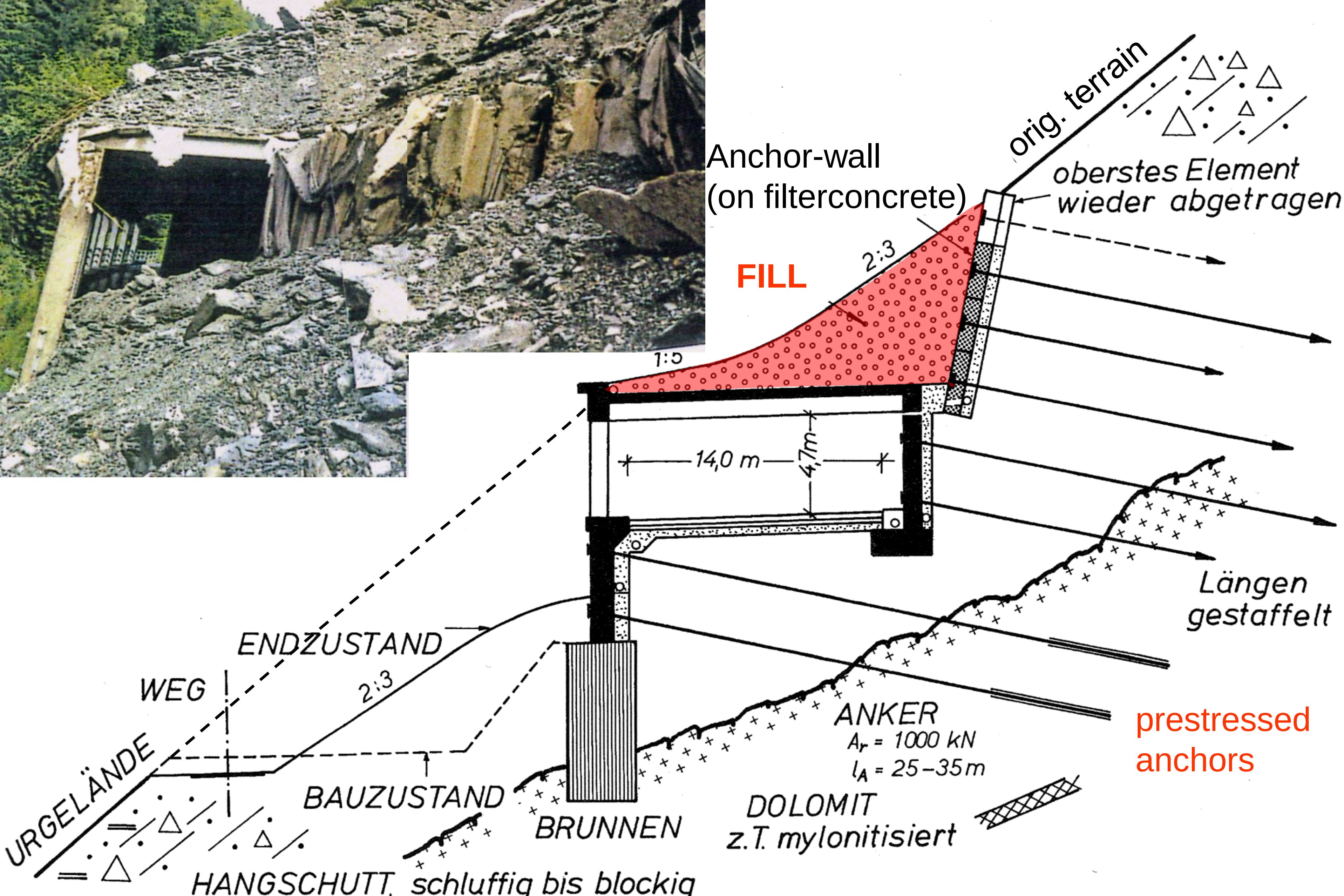
Input parameters
- Load(s)
- Resistance
  - soil strength, unit weight, ……
- Model uncertainty

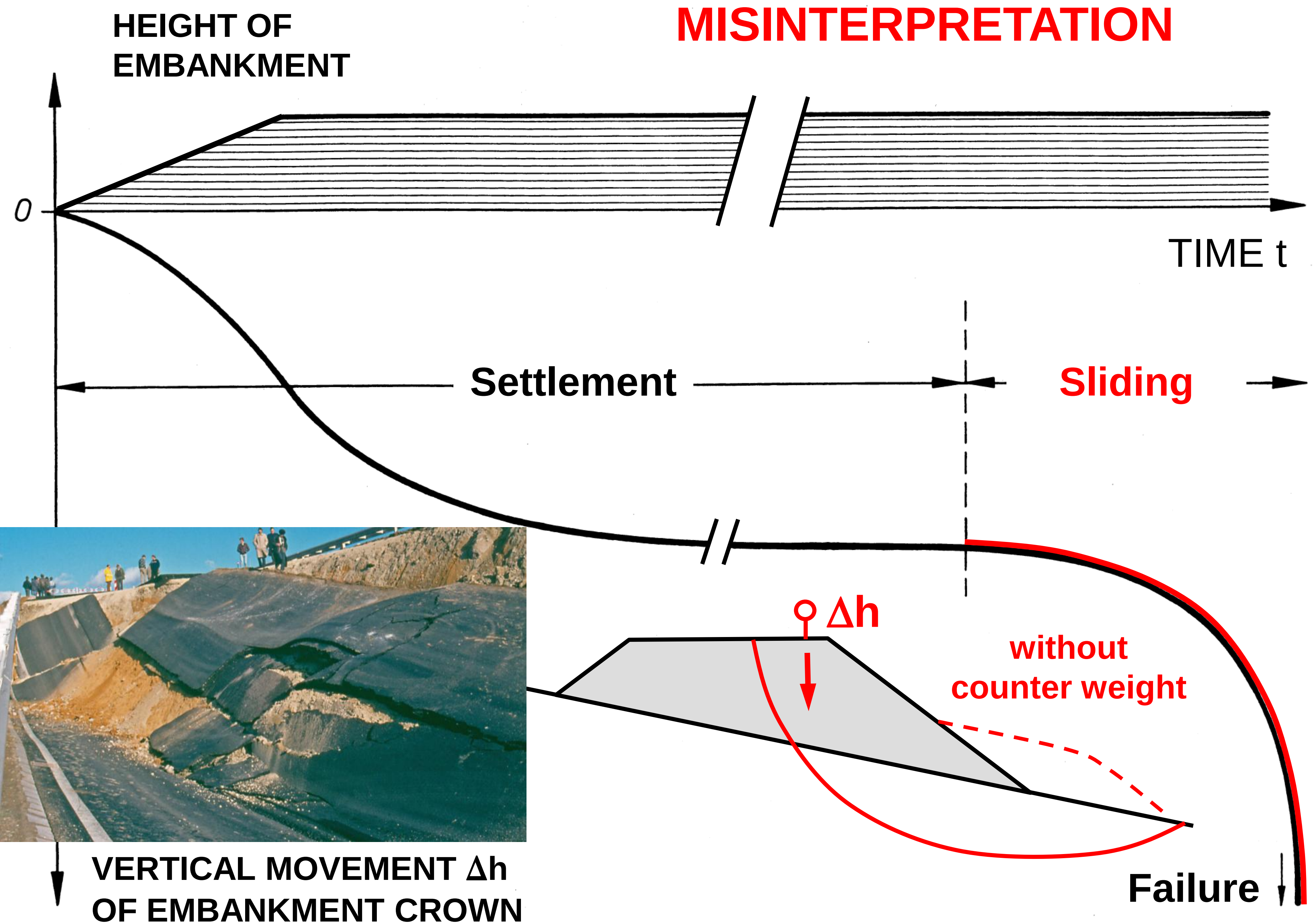
Output of analysis
- Probability of failure
- Reliability index
- Parameter(s) which cause failure





ROCKFALL GALLERIES WITH BACKFILL

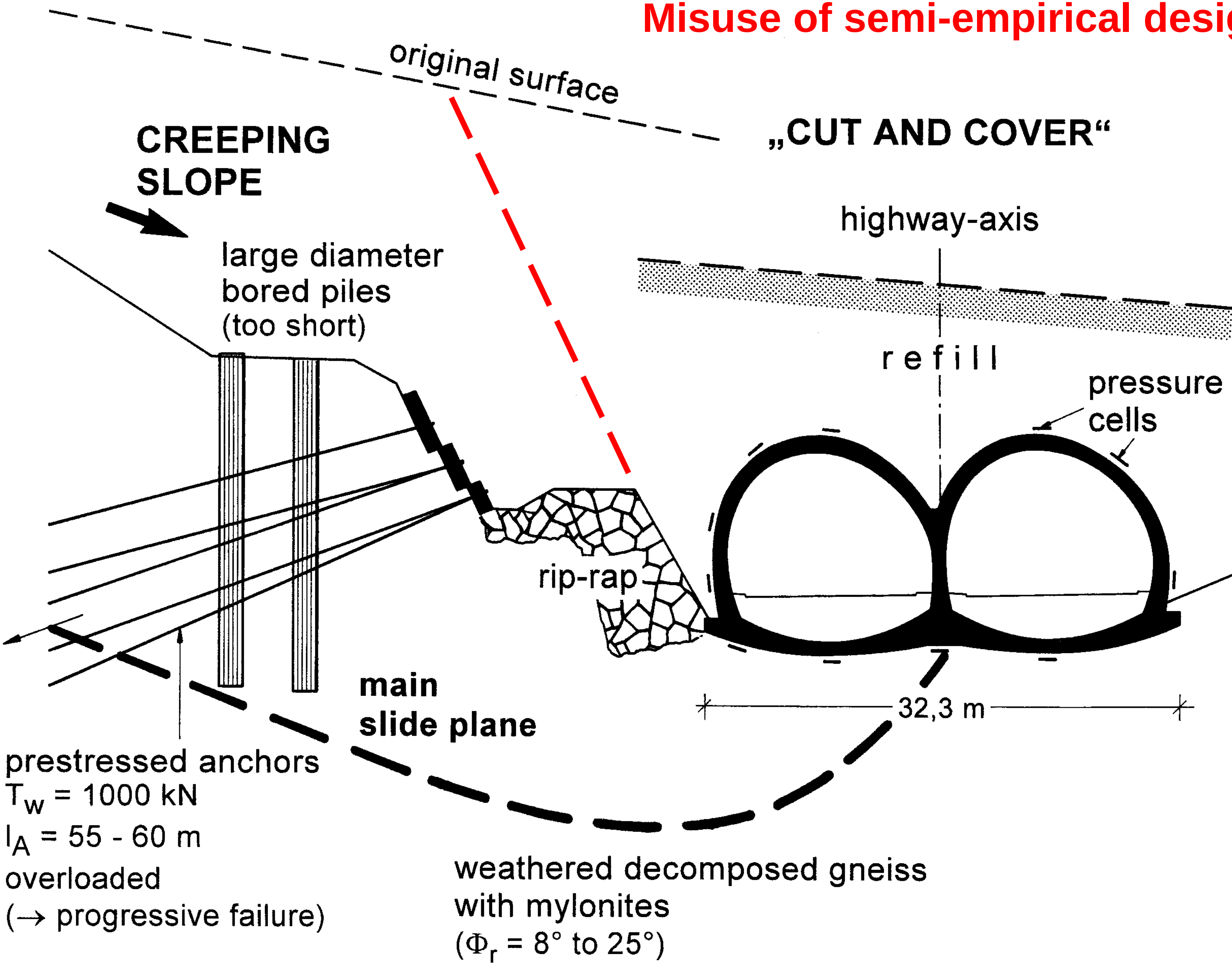



MISINTERPRETATION
HEIGHT OF
EMBANKMENT
0
TIME t
Settlement
Sliding
Δh
without
counter weight
Failure
VERTICAL MOVEMENT Δh
OF EMBANKMENT CROWN

HIGHLAND TOWER (Kuala Lumpur)

Collapse due to sliding slope

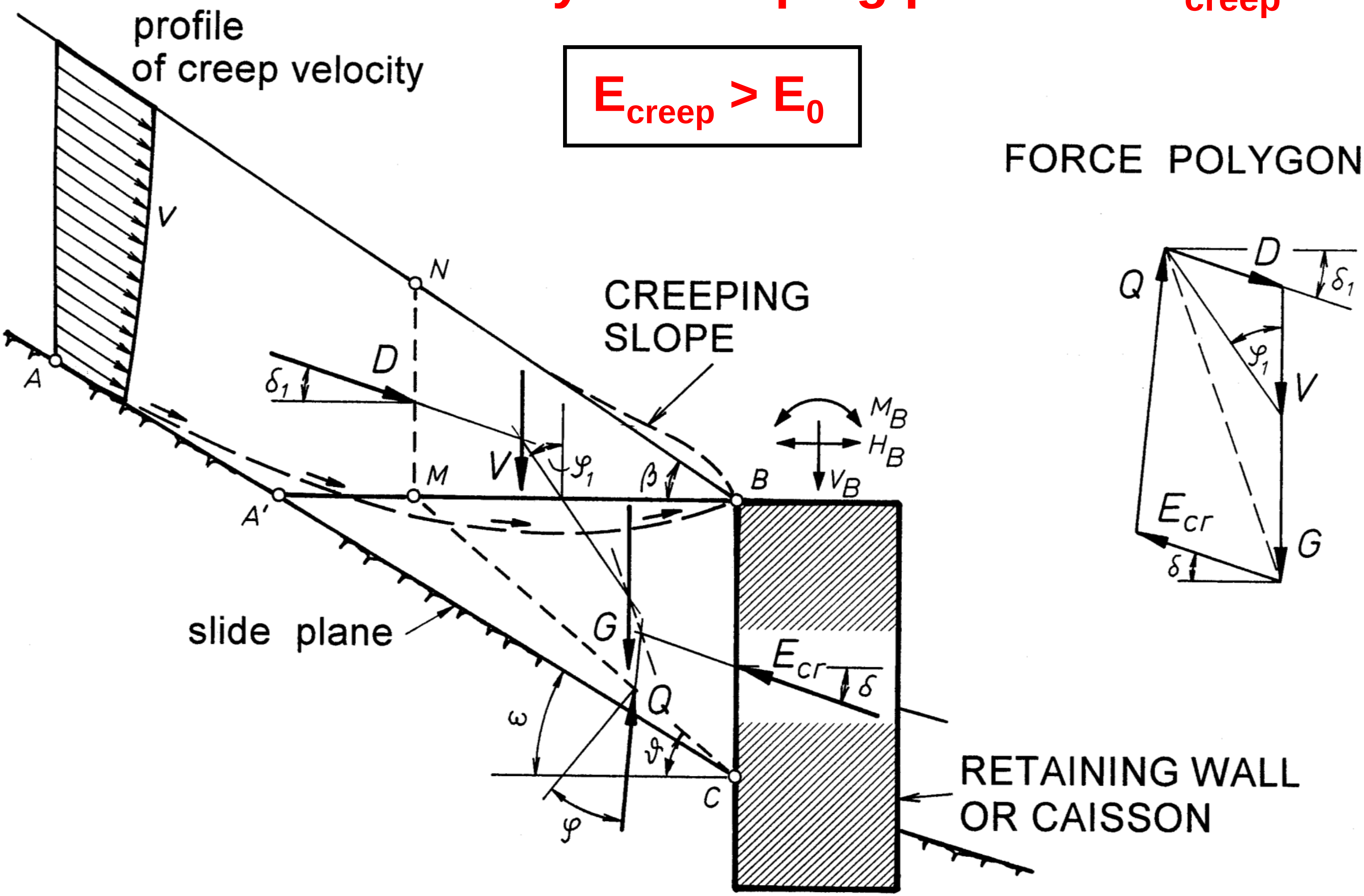
Misuse of semi-empirical design



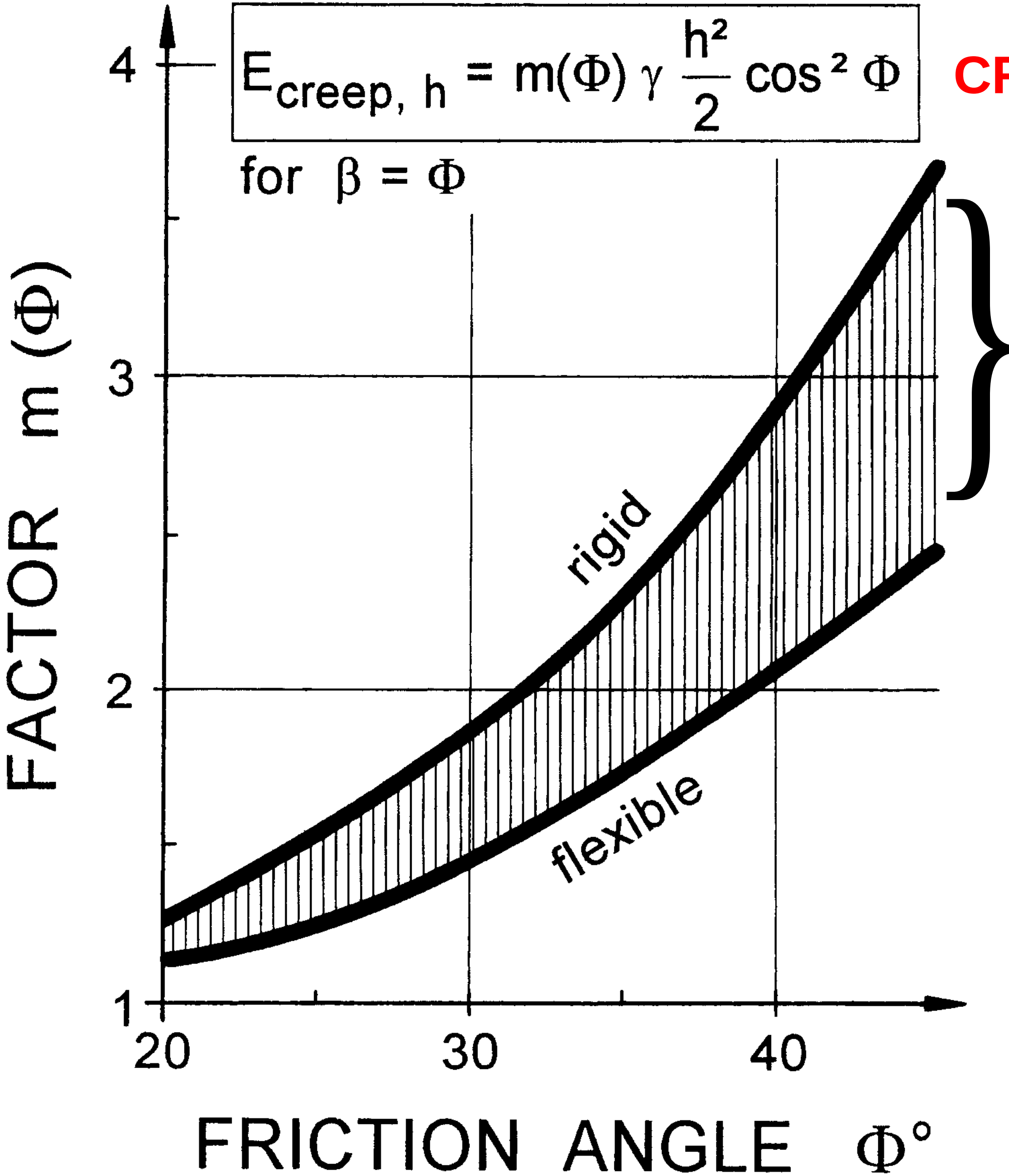
Cut and cover system for highway tunnel in steep/unstable slope

Theory of creeping pressure E_{creep}

$$E_{creep} > E_0$$



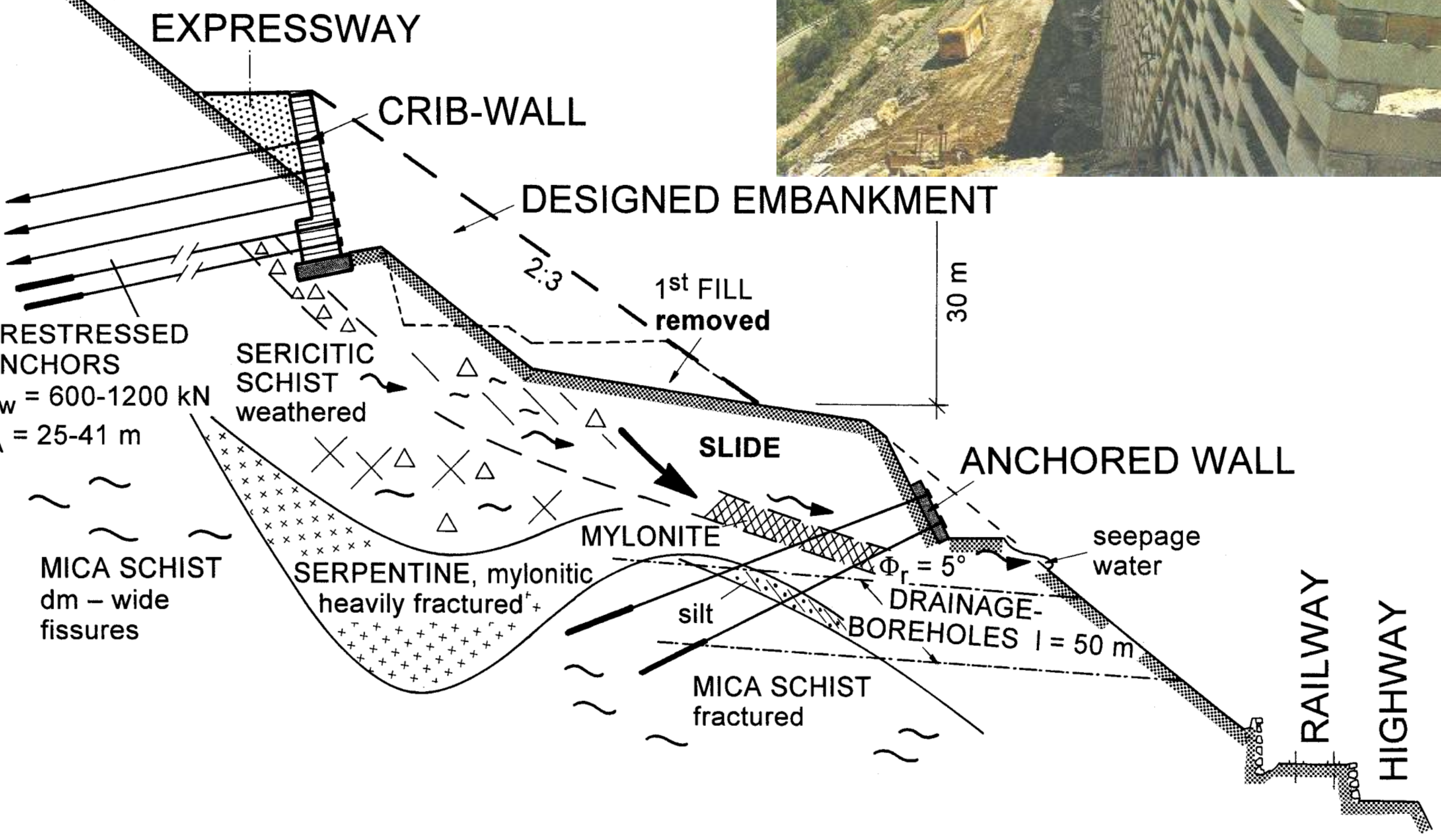
CREEPING PRESSURE



Influence of stiffness of the structure

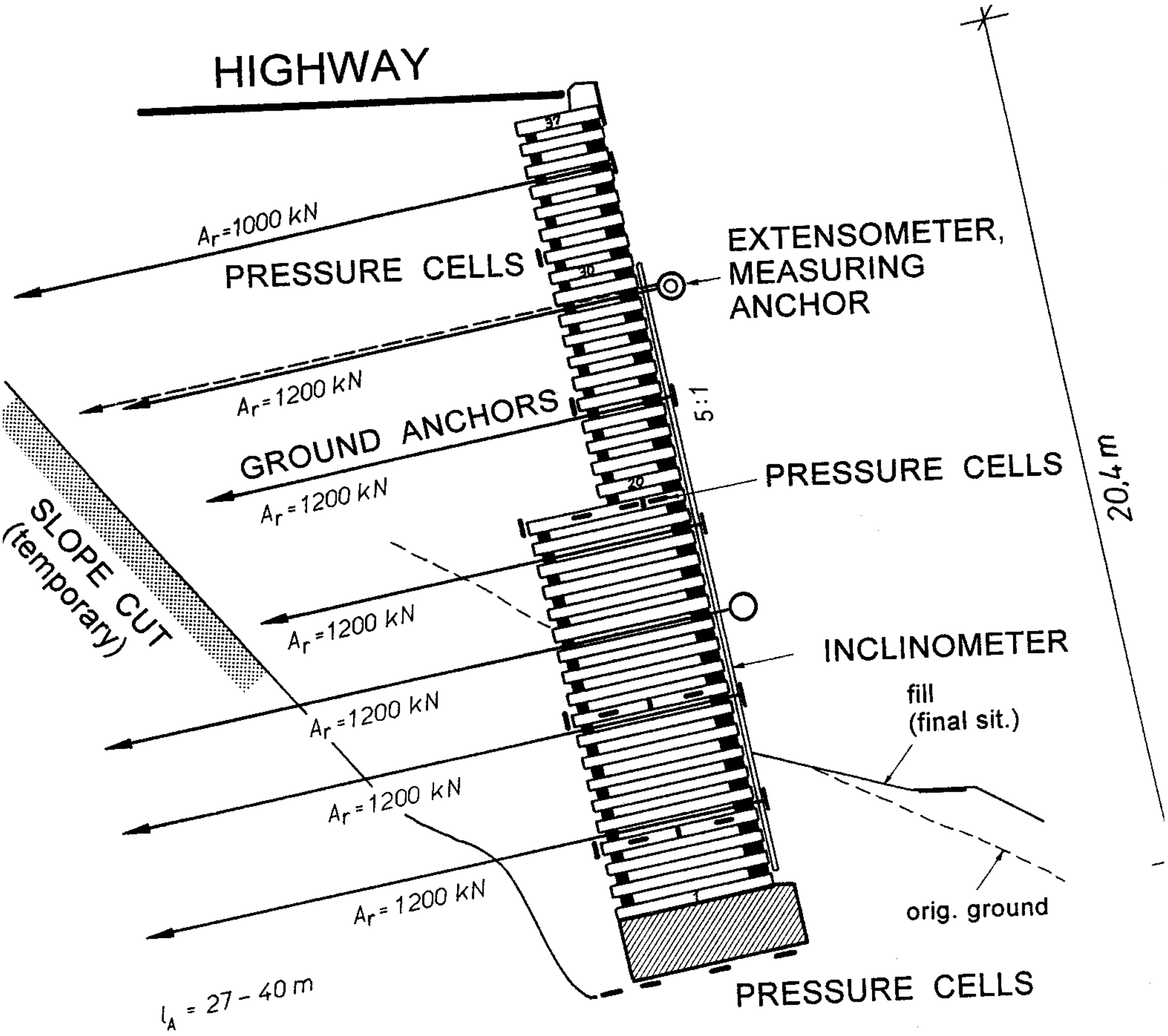
m(Φ) is multiplication factor for creeping pressure E_{creep}

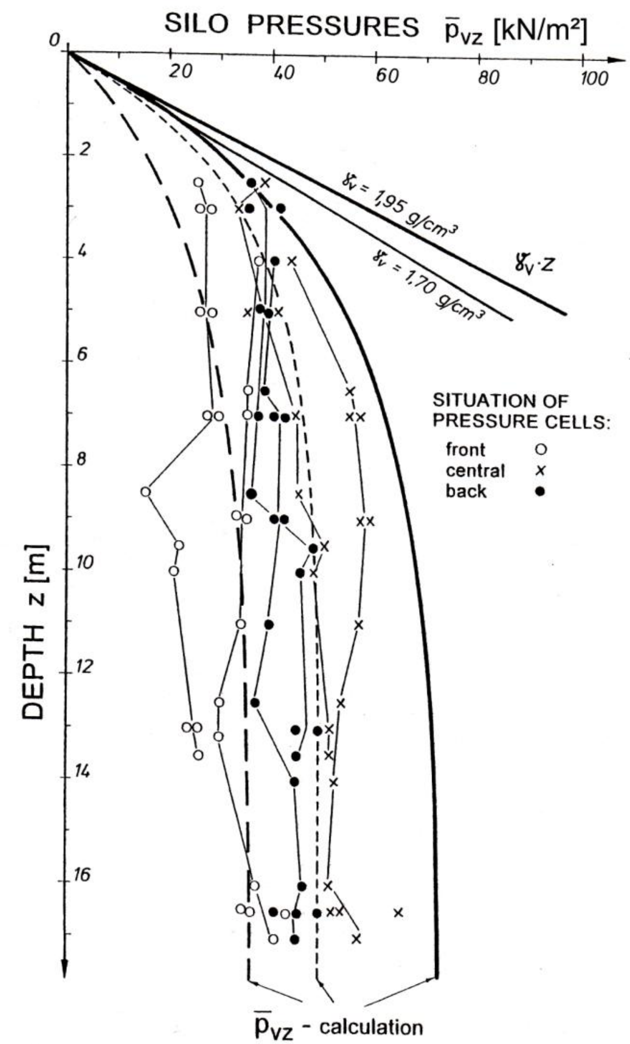
Tied back crib walls instead of embankment in unstable slope



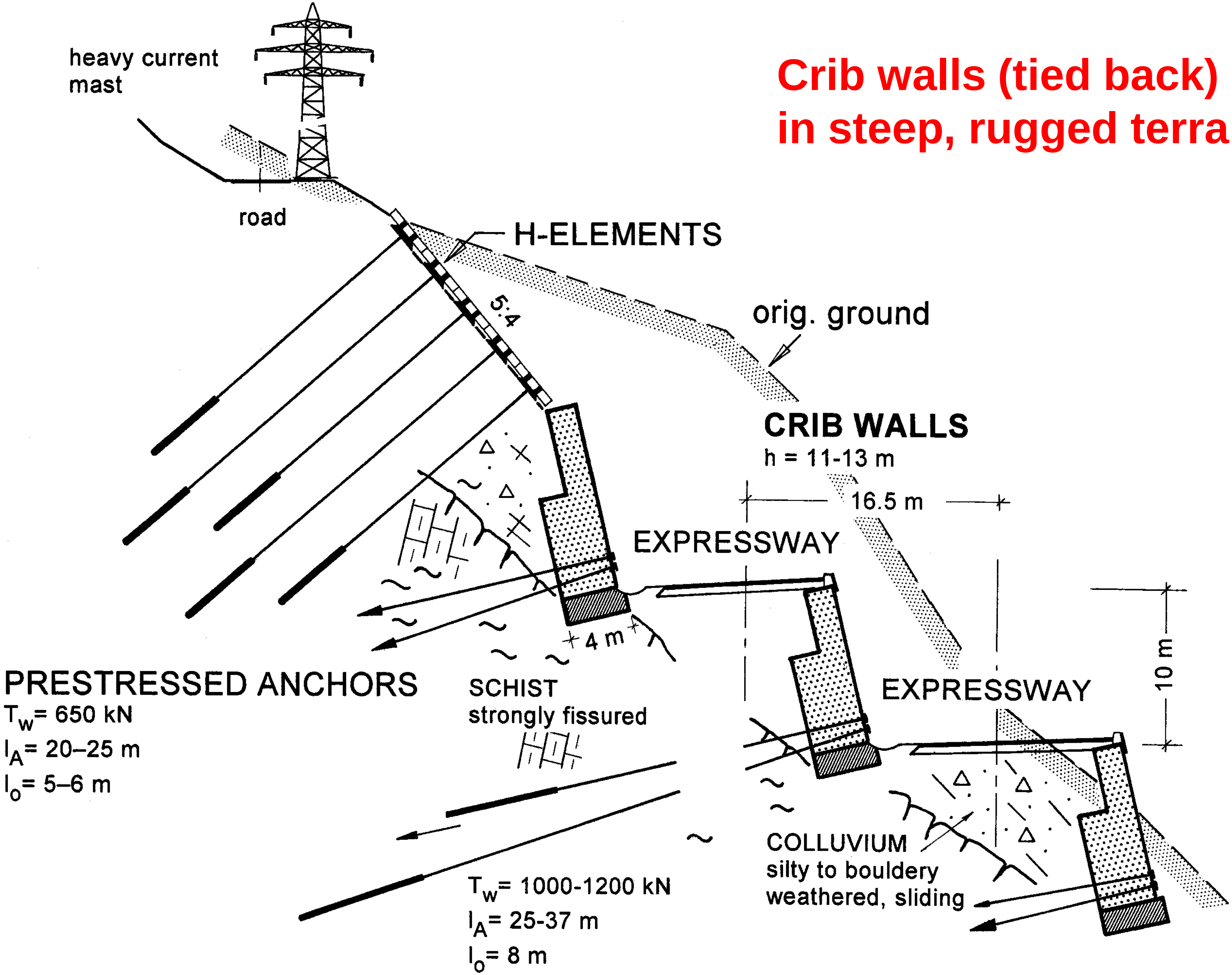
CRIB WALLS (inclined)

Asymetric silo pressure within the soil fill



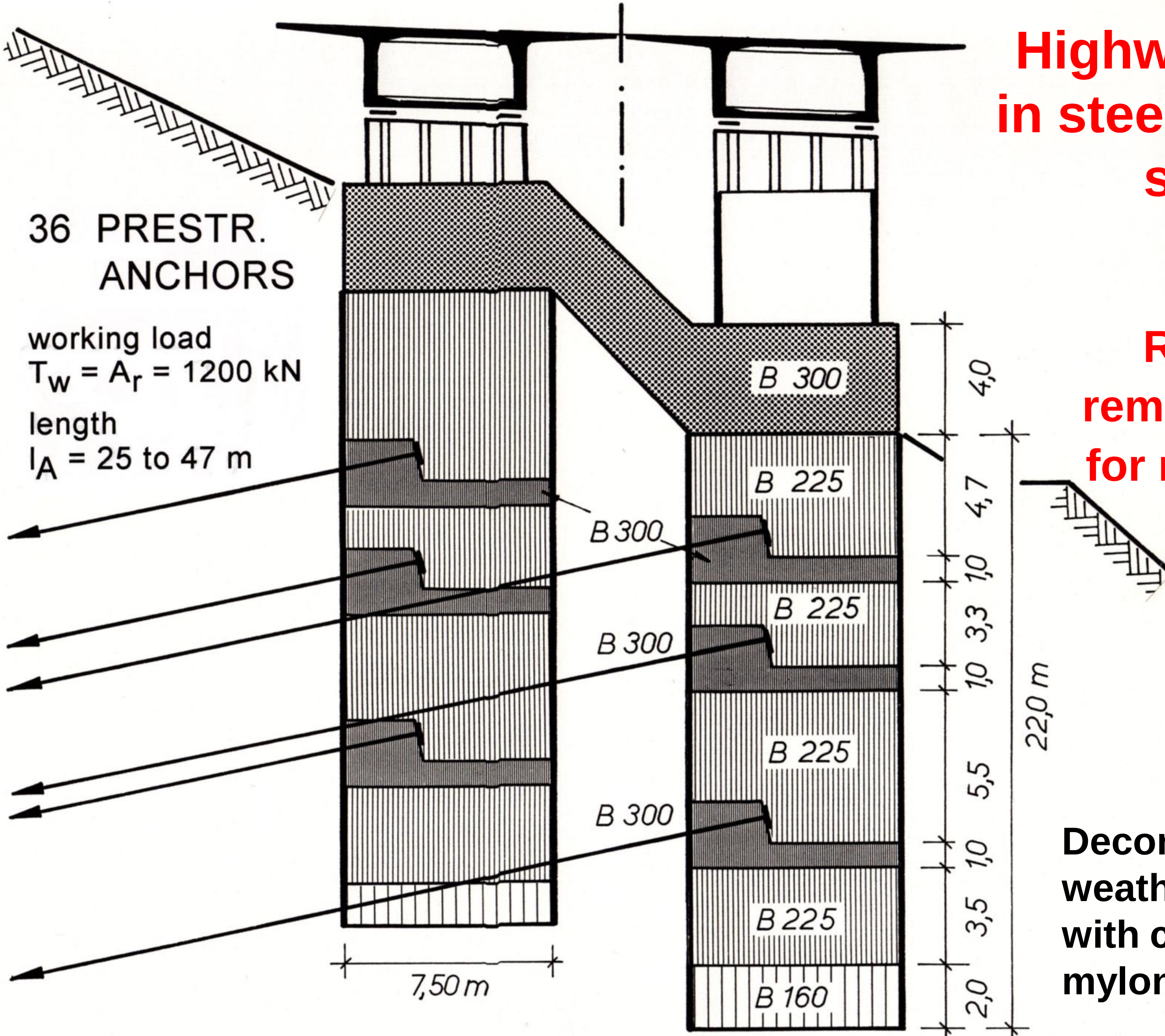


Crib walls (tied back) in steep, rugged terrain



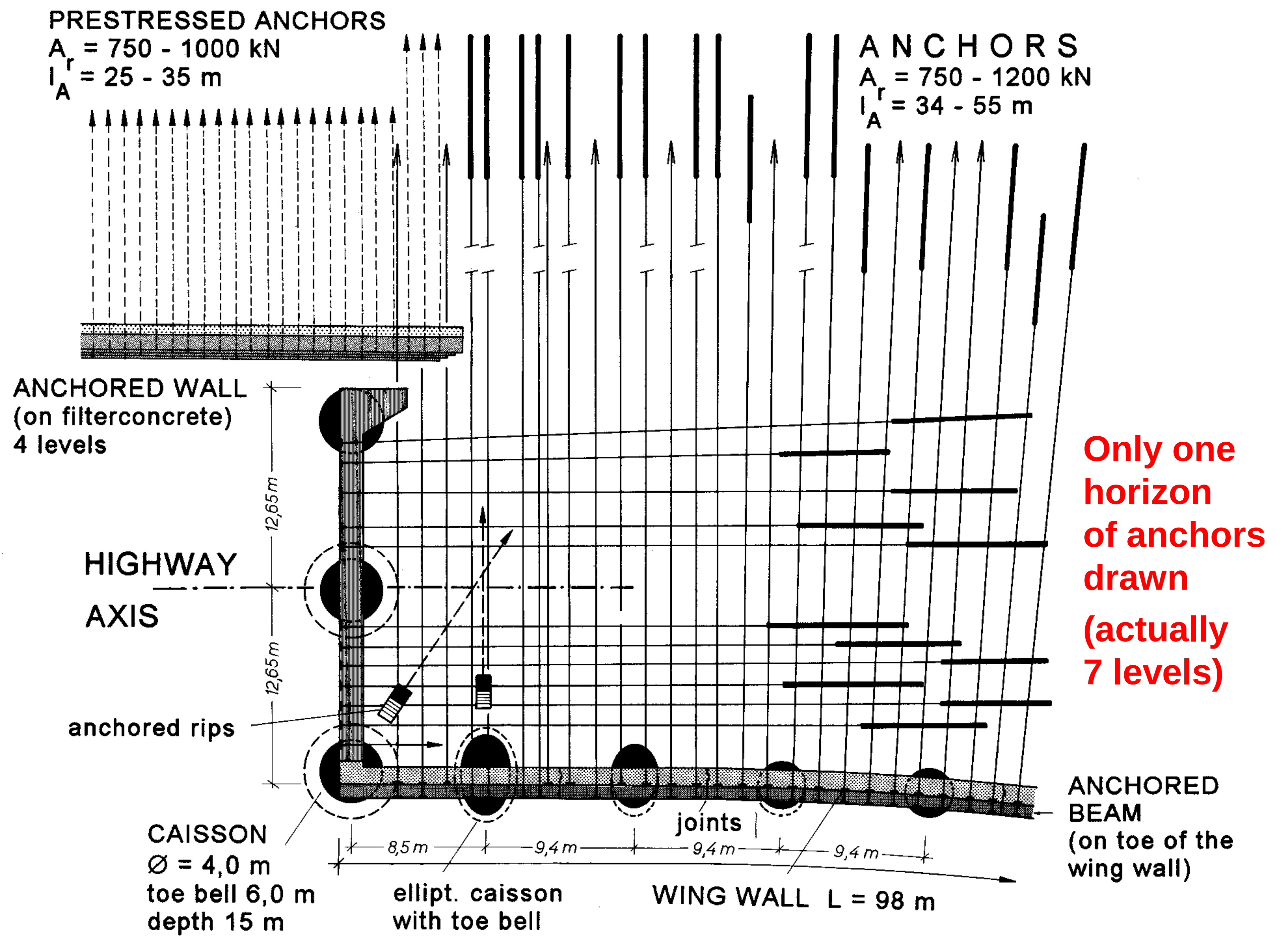
Crib walls of max. 43m height (locally tied back)

Highway bridge in steep unstable slope

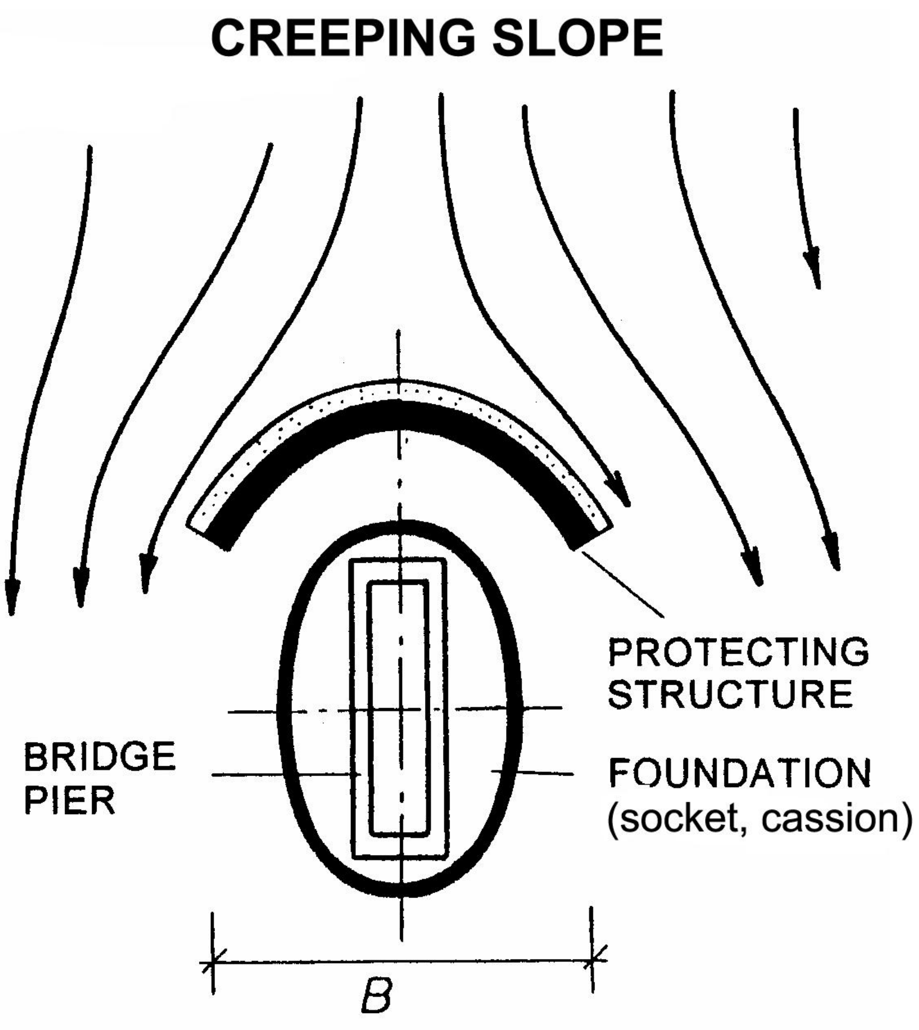


Requires remote control for monitoring

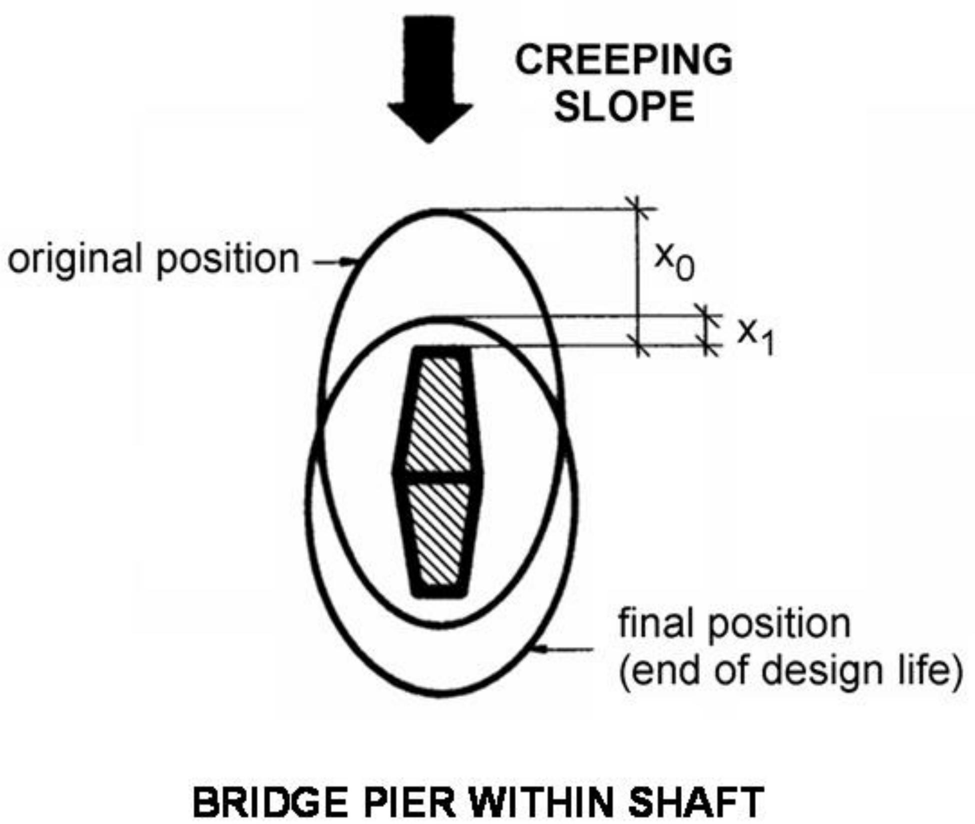
Decomposed, weathered schist with clayey mylonites


PRESTRESSED ANCHORS
A_r = 750 - 1000 kN
l_A = 25 - 35 m
ANCHORS
A_r = 750 - 1200 kN
l_A = 34 - 55 m
ANCHORED WALL
(on filterconcrete)
4 levels
12,65 m
12,65 m
HIGHWAY
AXIS
anchored rips
Only one horizon of anchors drawn
(actually 7 levels)
ANCHORED BEAM
(on toe of the wing wall)
joints
8,5 m
9,4 m
9,4 m
9,4 m
CAISSON
Ø = 4,0 m
toe bell 6,0 m
depth 15 m
ellipt. caisson
with toe bell
WING WALL L = 98 m

FOUNDATION OF BRIDGE PIERS, MASTS, etc. IN UNSTABLE SLOPES

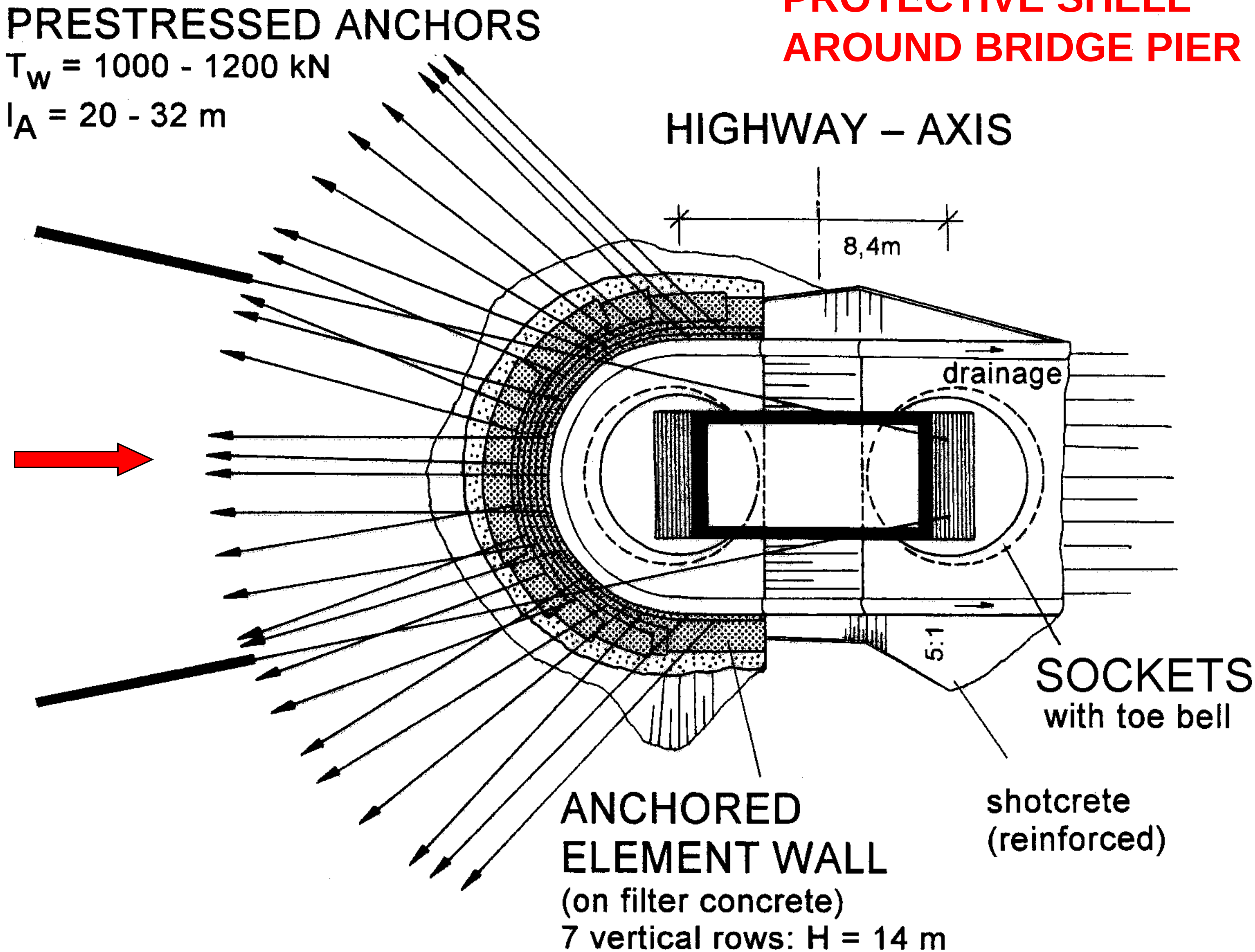


Protective shell

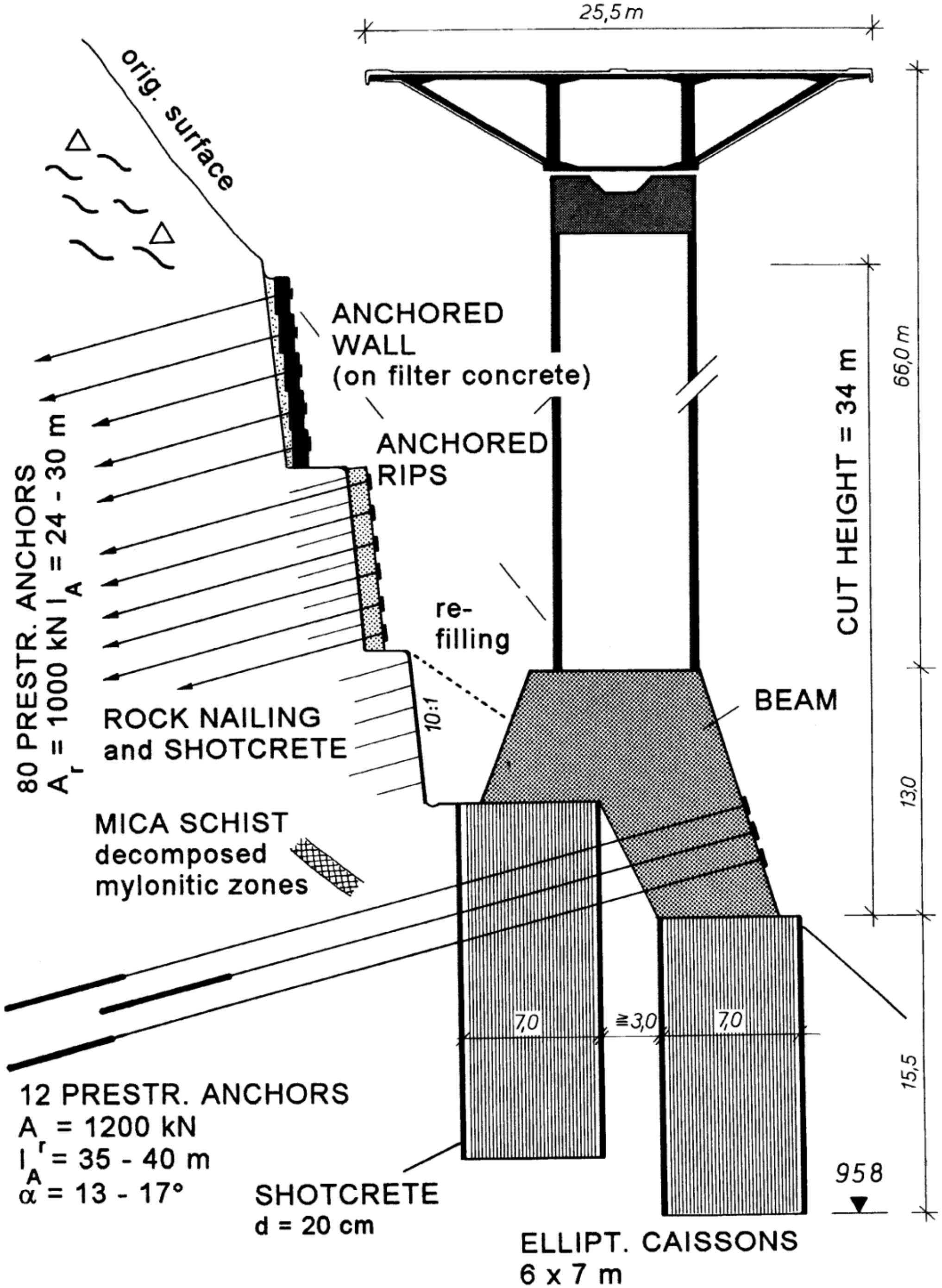


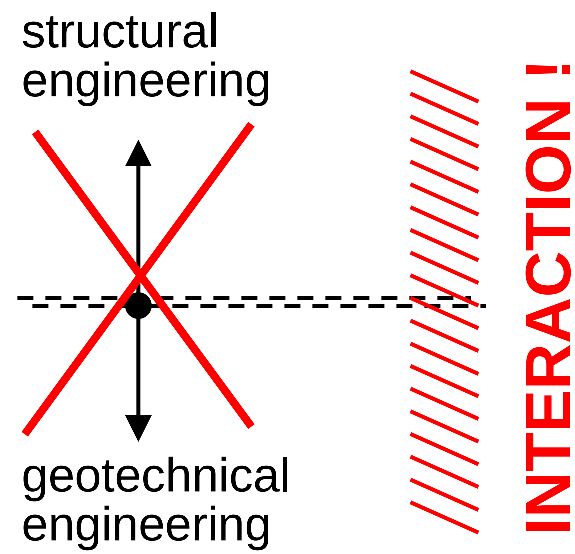
“Buttonhole solution“

PROTECTIVE SHELL AROUND BRIDGE PIER

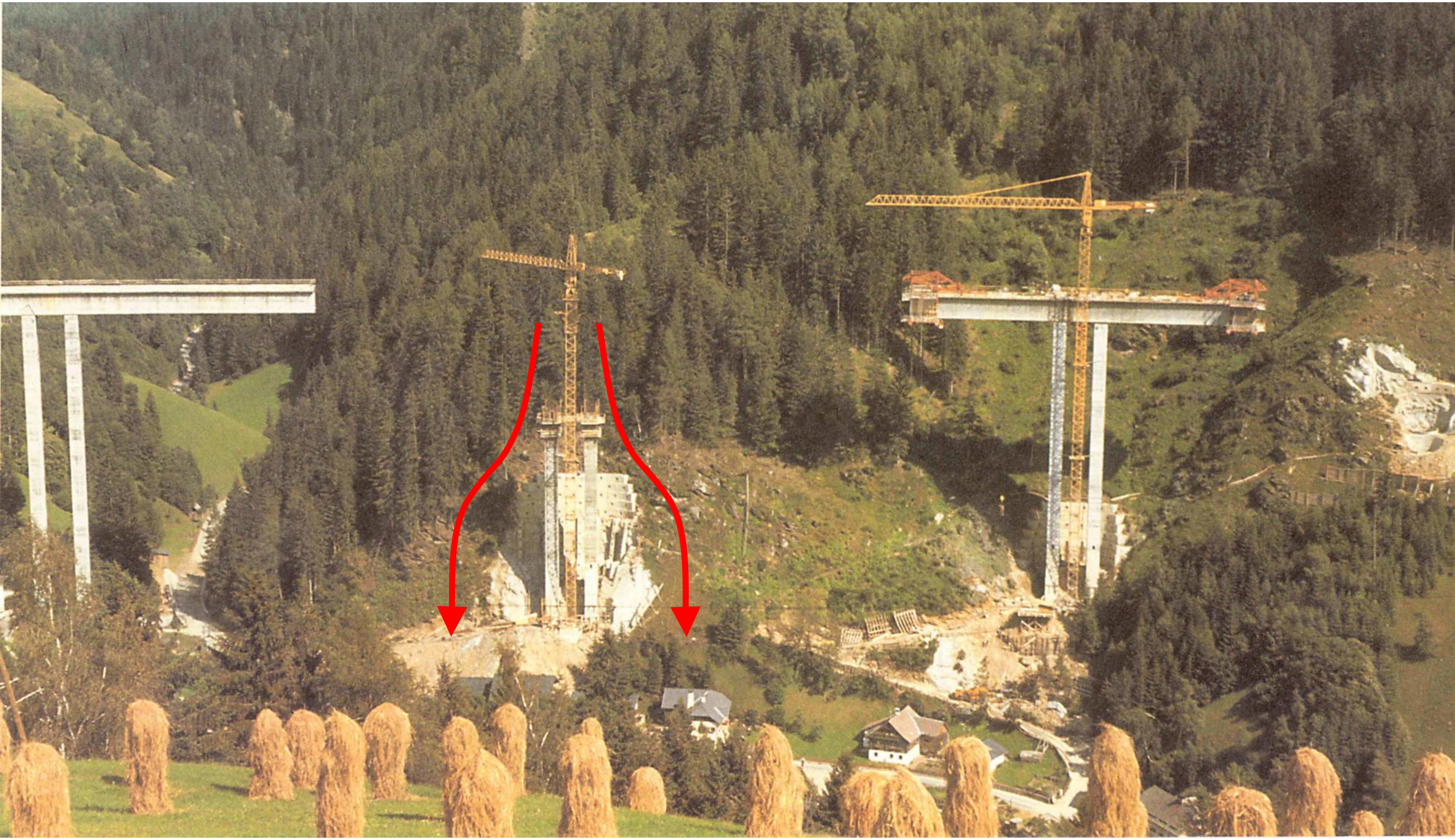


Optimised design only possible if considering interaction

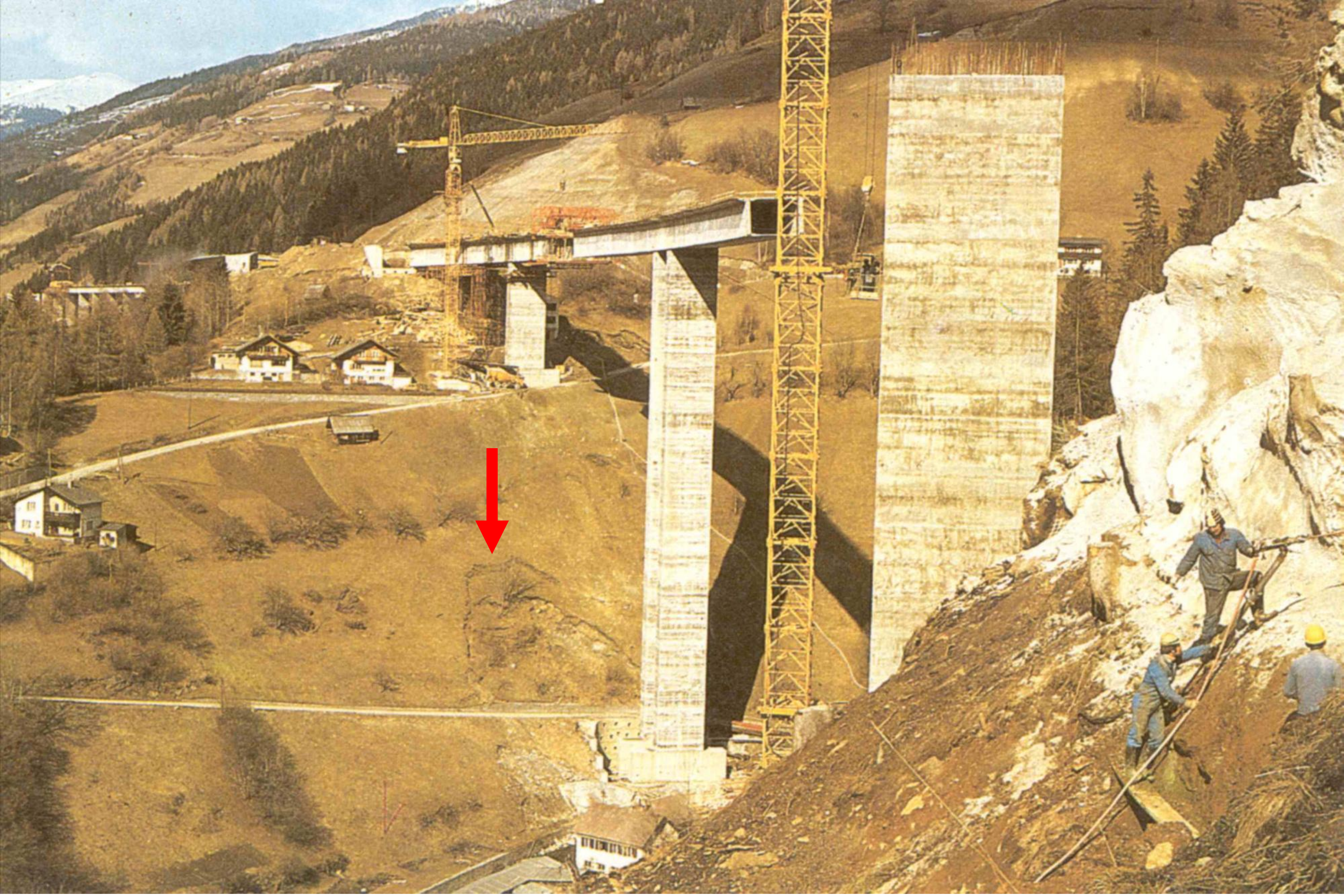




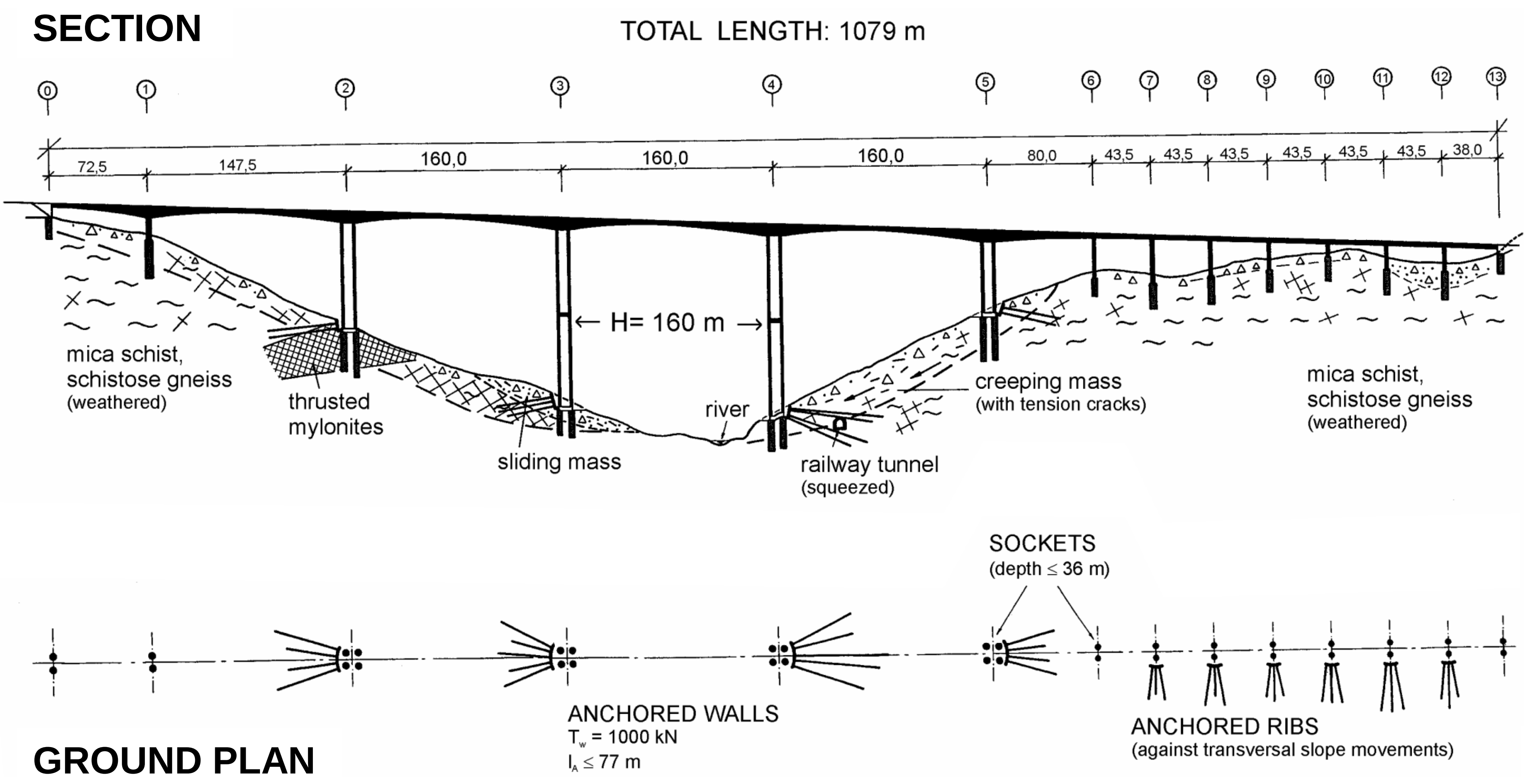
CREEPING SLOPE (800 m high)



36m high protective shells uphill the bridge piers



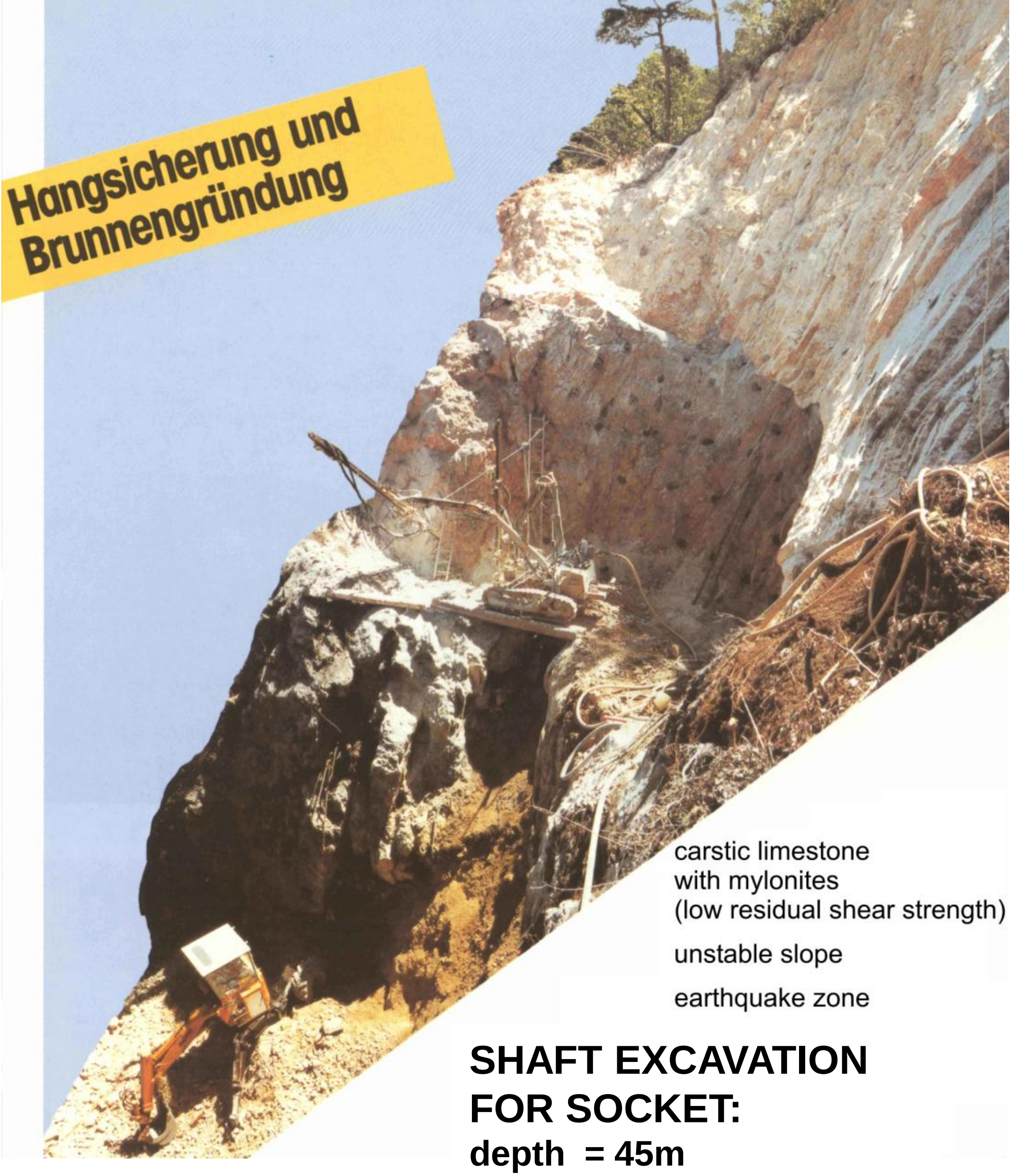
Sliding mass creeps aside the protective shell



"SECOND EUROPE-BRIDGE„

In unstable terrain; monitored since 1982


Max. height of bridge pier: 160 m

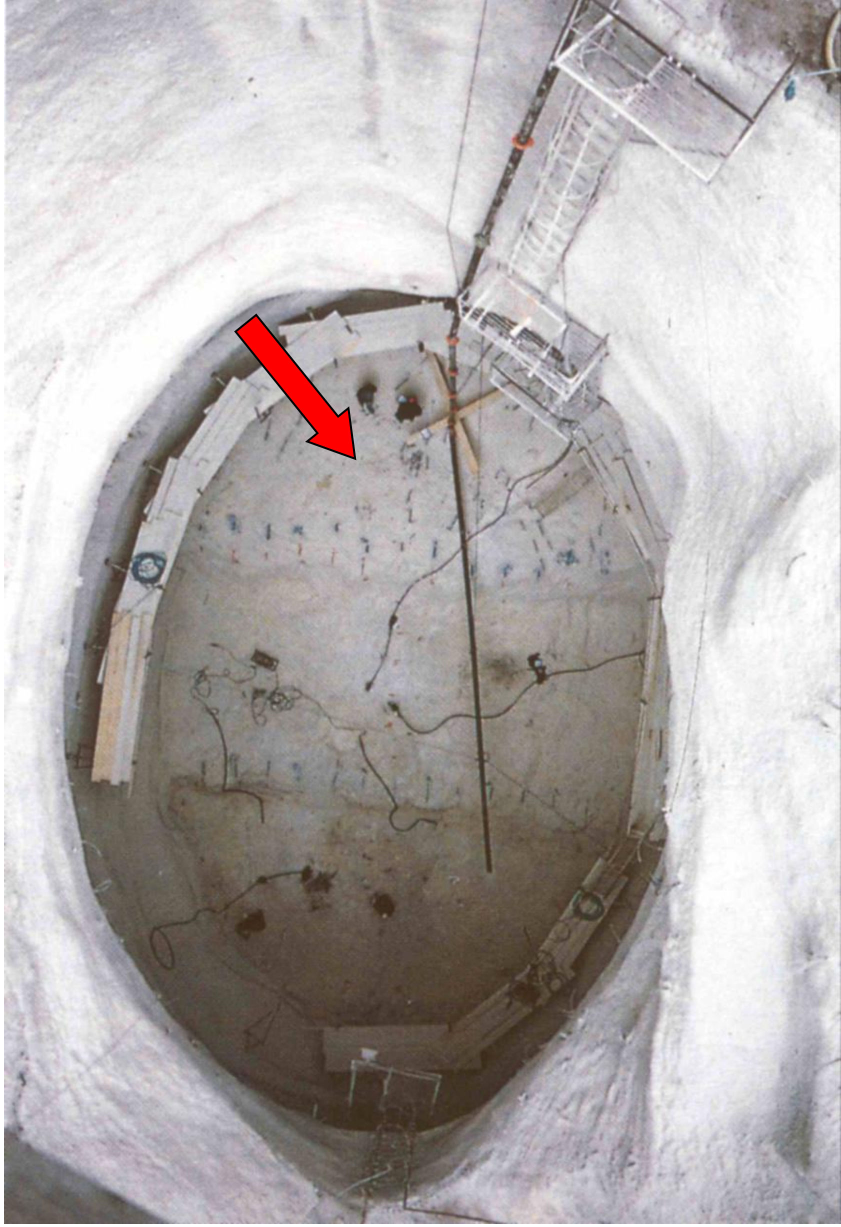


carstic limestone
with mylonites
(low residual shear strength)

unstable slope

earthquake zone

SHAFT EXCAVATION
FOR SOCKET:
depth = 45m
diameter 23x18m



Sockets (caissons) in carstic and seismic zone

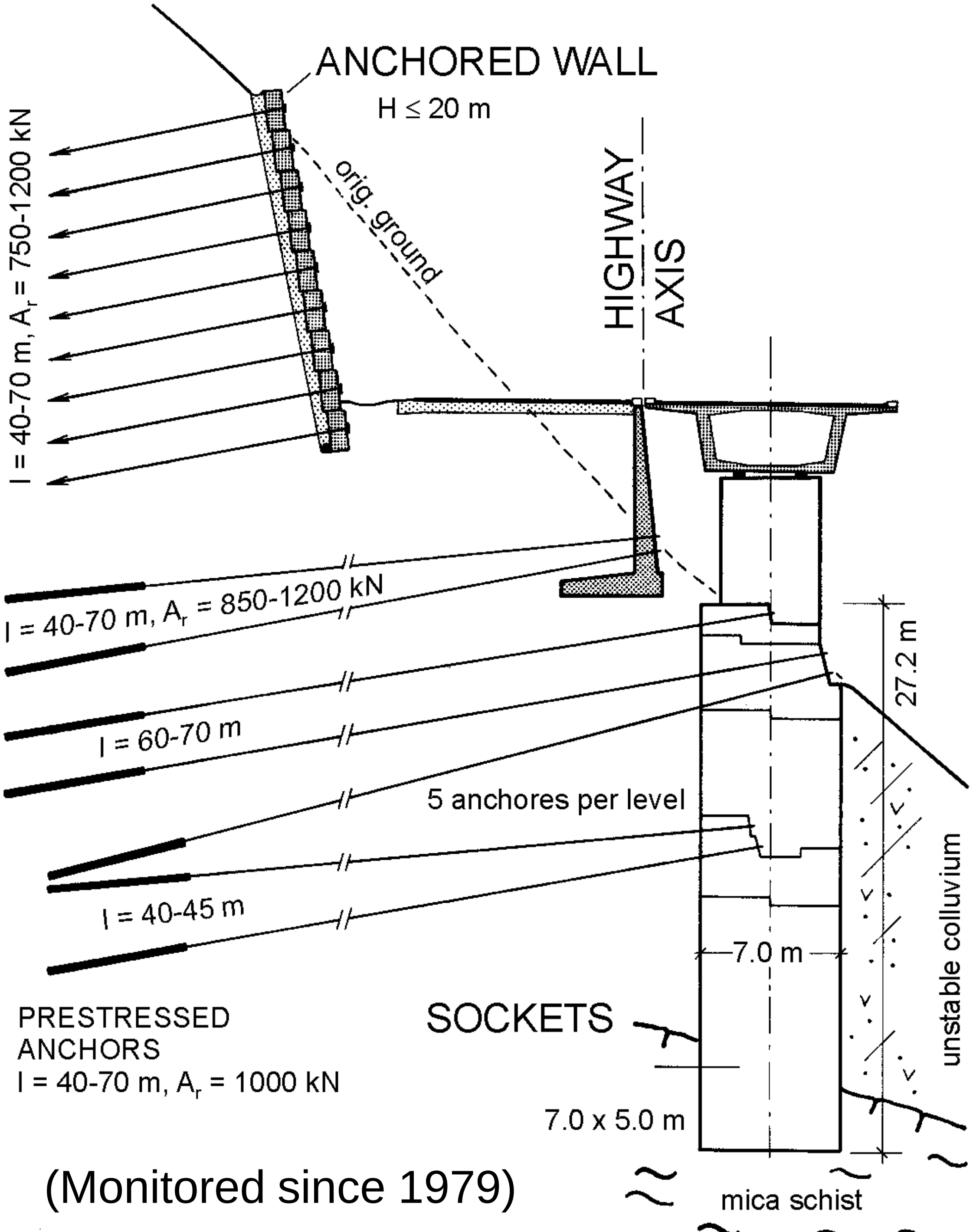
HIGHWAY ALONG UNSTABLE/CREEPING SLOPES

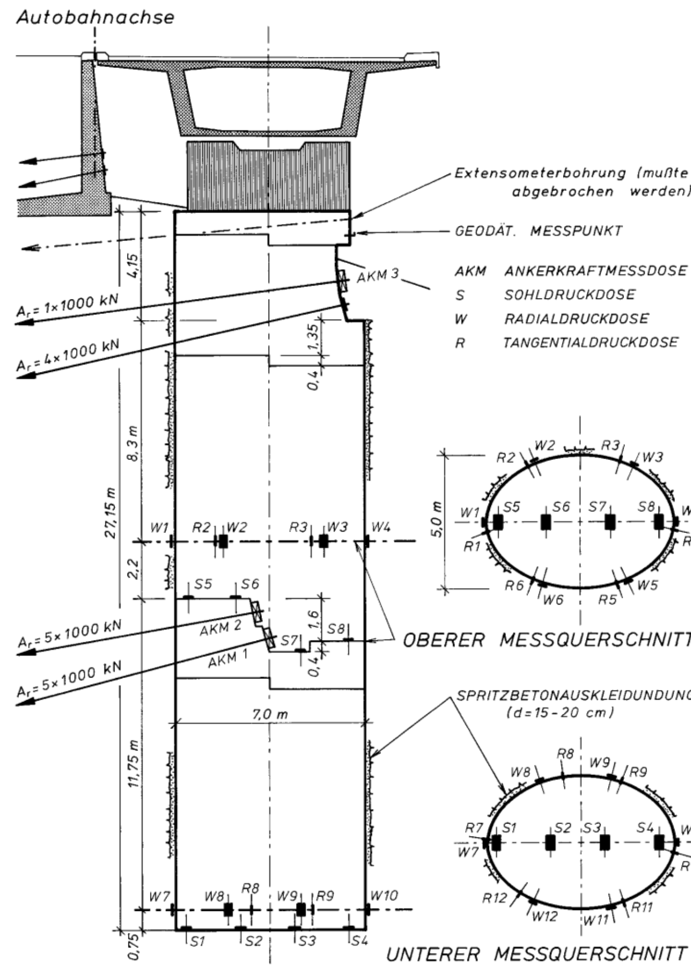
More than 75% of the highway run on bridges

SEMI-BRIDGE

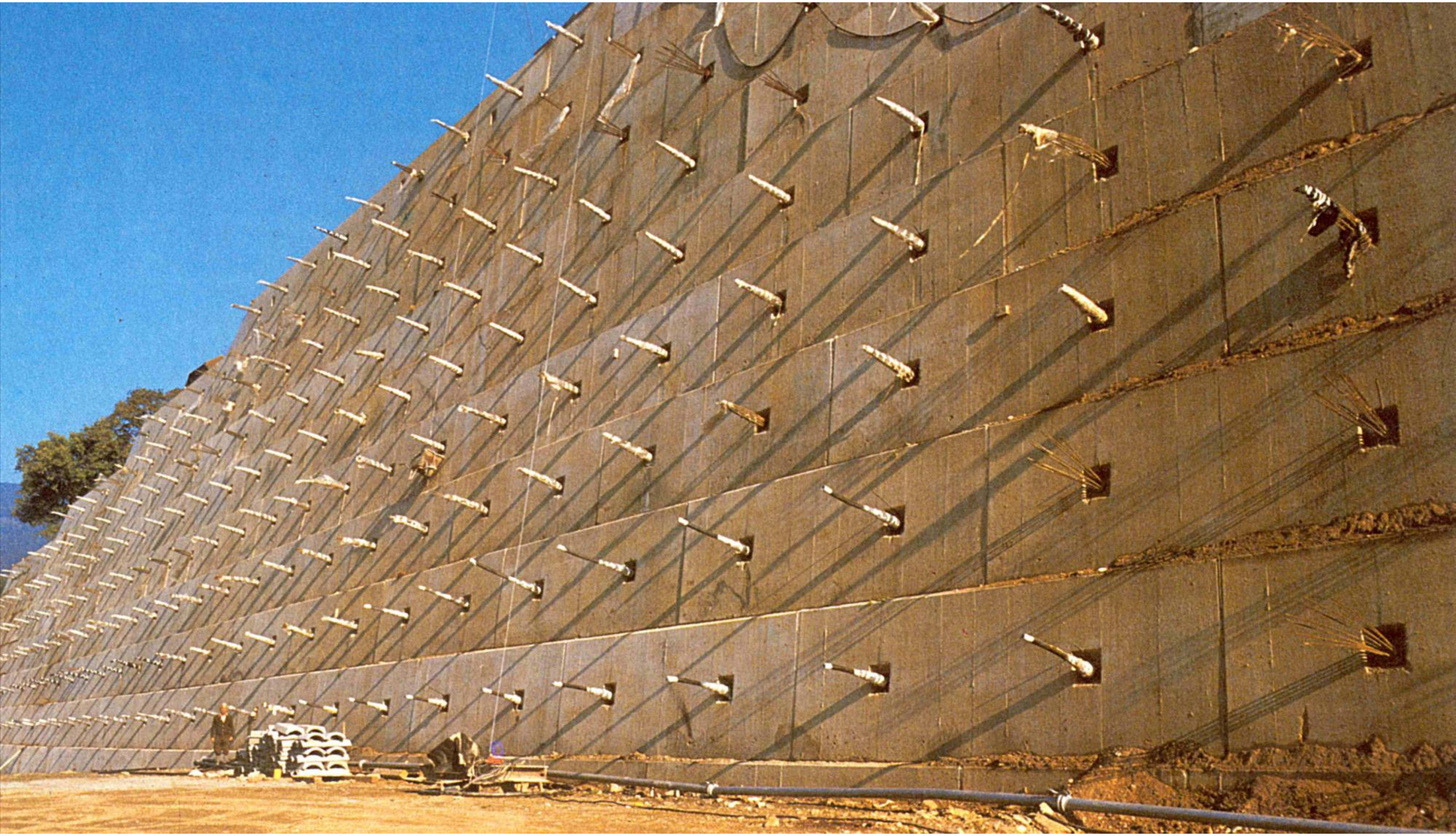
separated lanes

Reduction of cuts and embankments



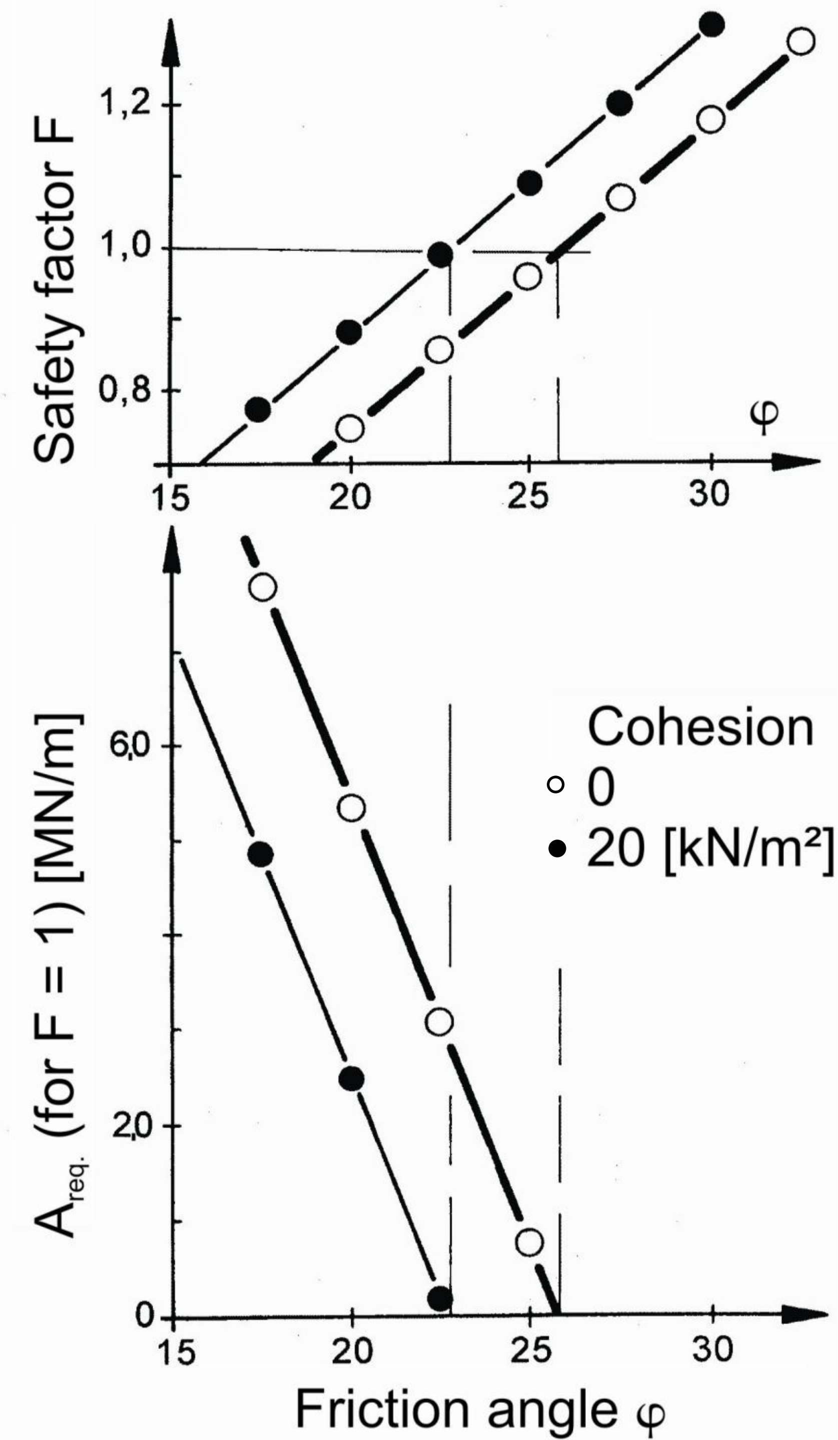


Steep slope in limit equilibrium (F~1,0)



22m high anchored wall (monitored since 1978)

Required anchor force T
to gain a safety factor of F = 1



Extreme influence of friction angle Φ on required anchor forces.

ΔΦ = 1°
→ ΔT = 1000 kN/m
(for F = 1)

actually ΔΦ = 15°

→Requires “interactive design” (semi-empirical design, observational method)

RESERVE FOR ANCHORS

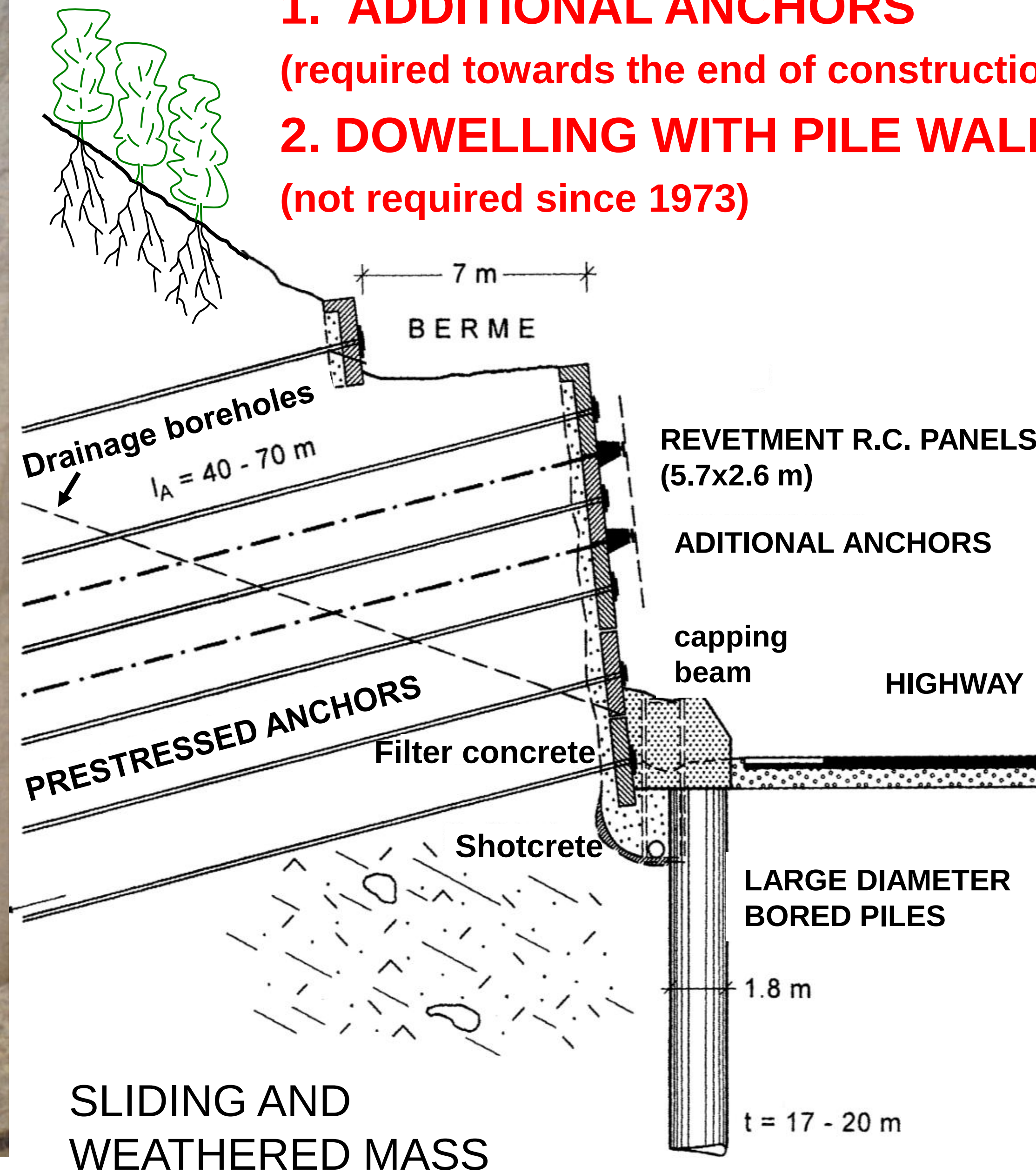
CONTINGENCY PLANS:

1. ADDITIONAL ANCHORS

(required towards the end of construction)

2. DOWELLING WITH PILE WALL

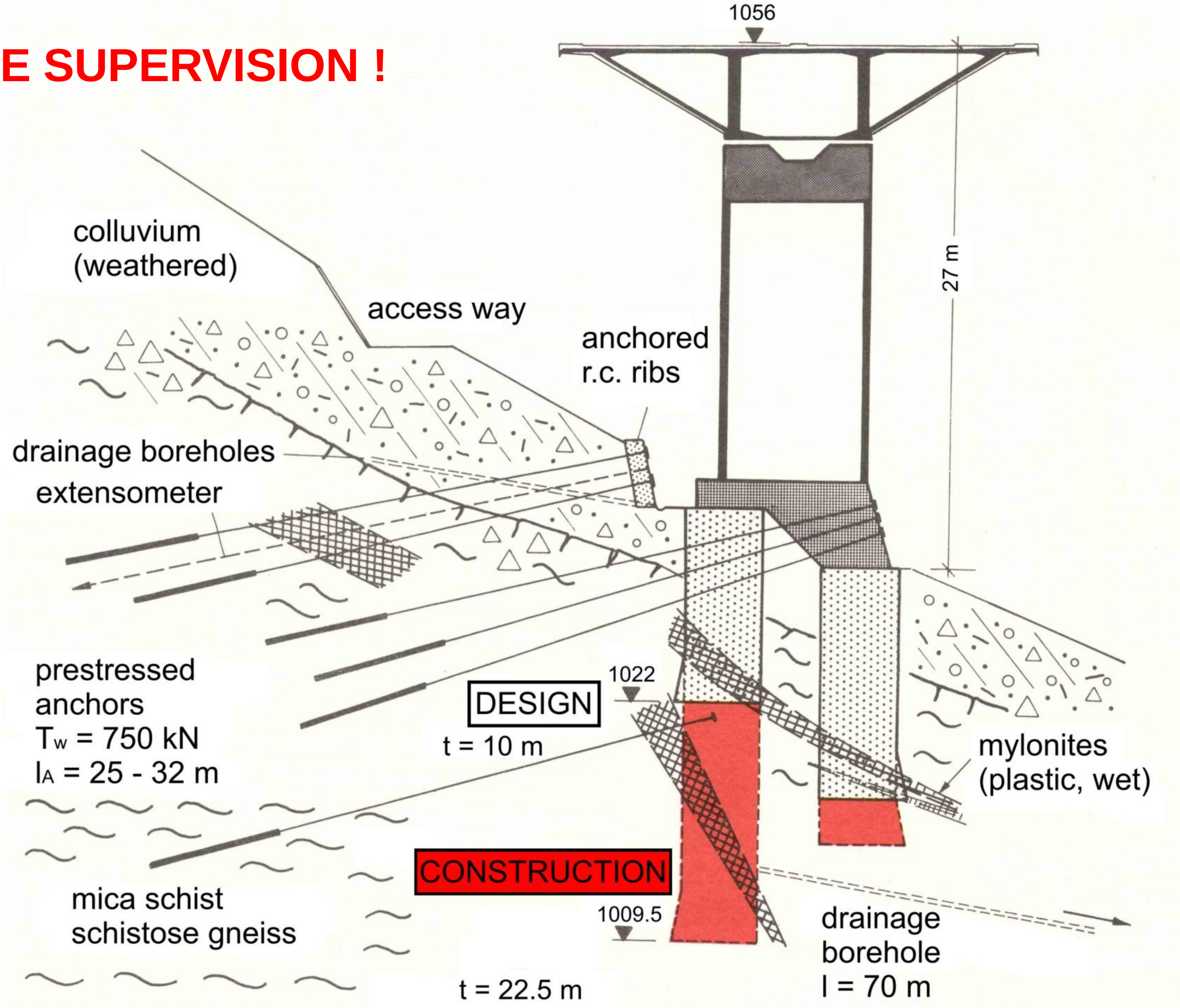
(not required since 1973)

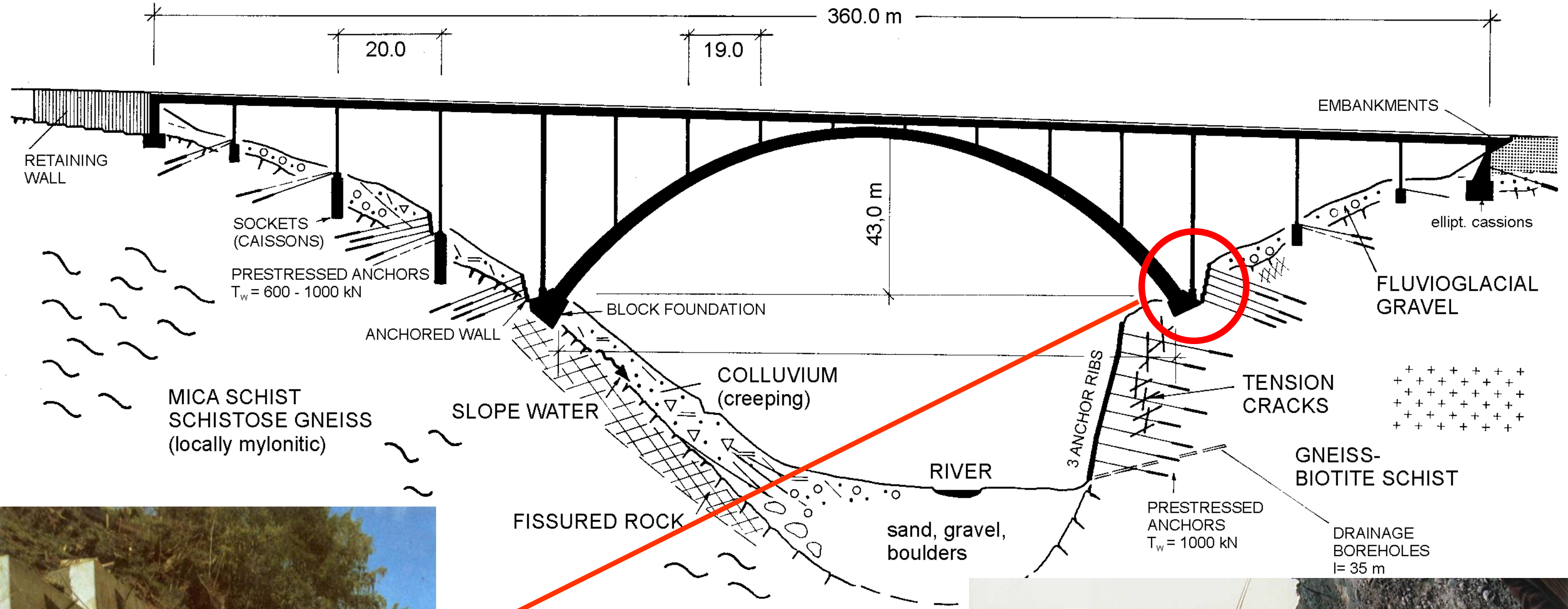


H_{max}=65m

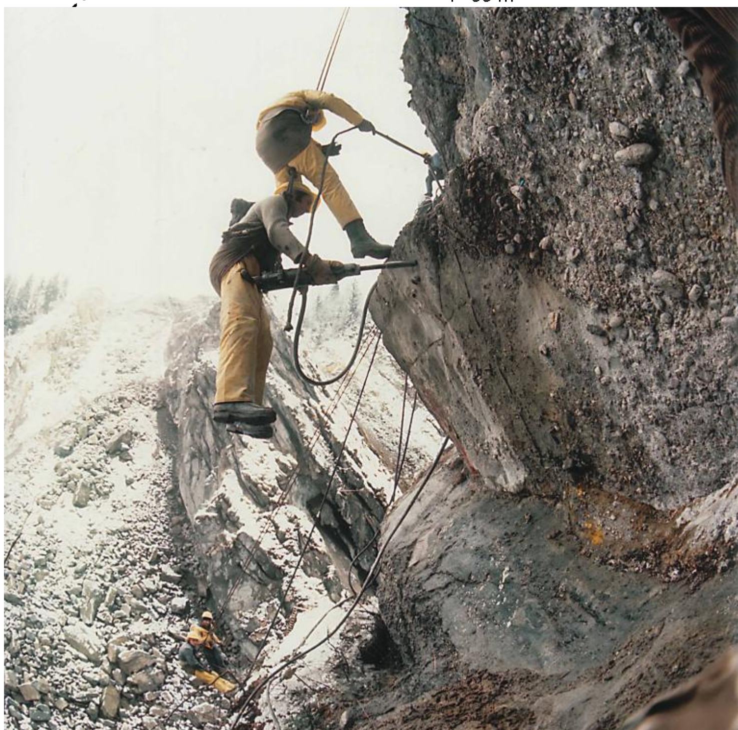
Local adaption of design inevitable

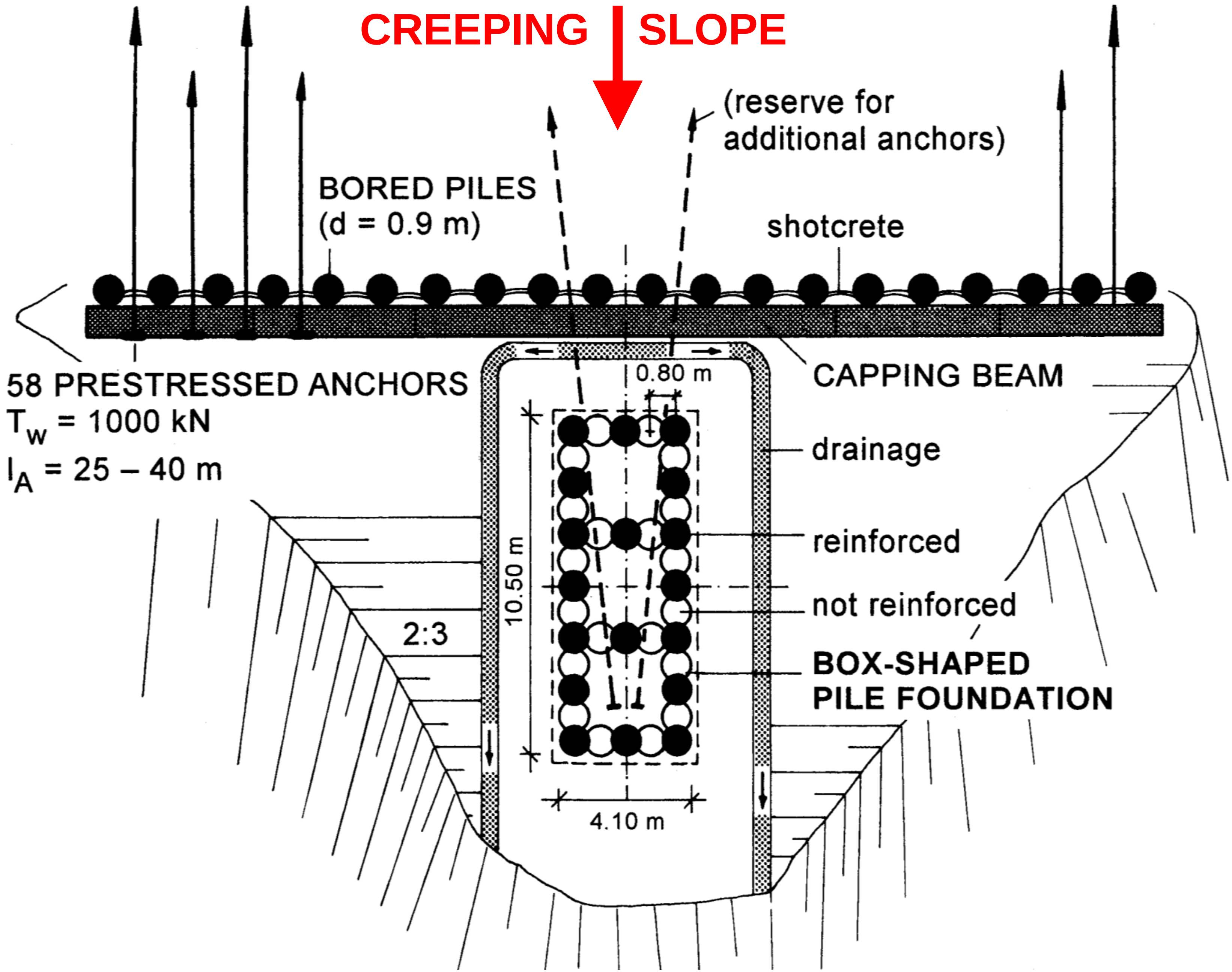
SITE SUPERVISION !





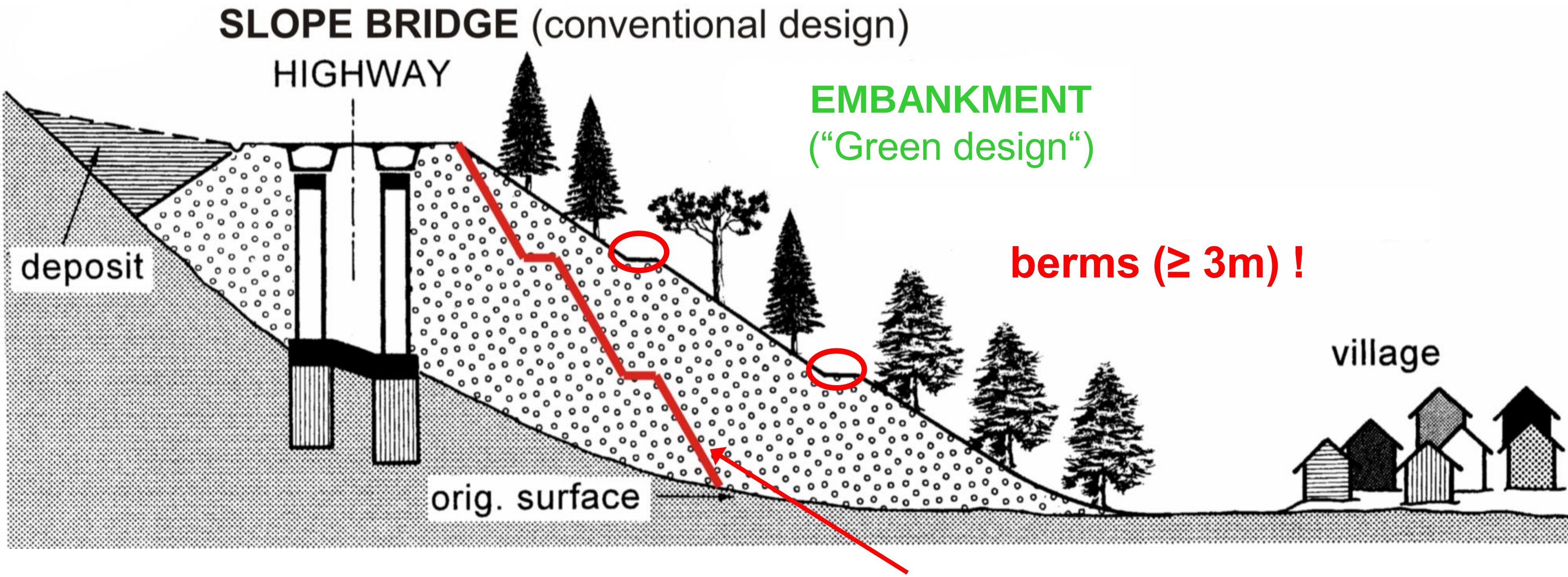
Large-scale in-situ determination of rock moduli during construction





Bridge foundation and protection in creeping slope

TWO OPTIONS FOR HIGHWAYS IN SLOPED TERRAIN

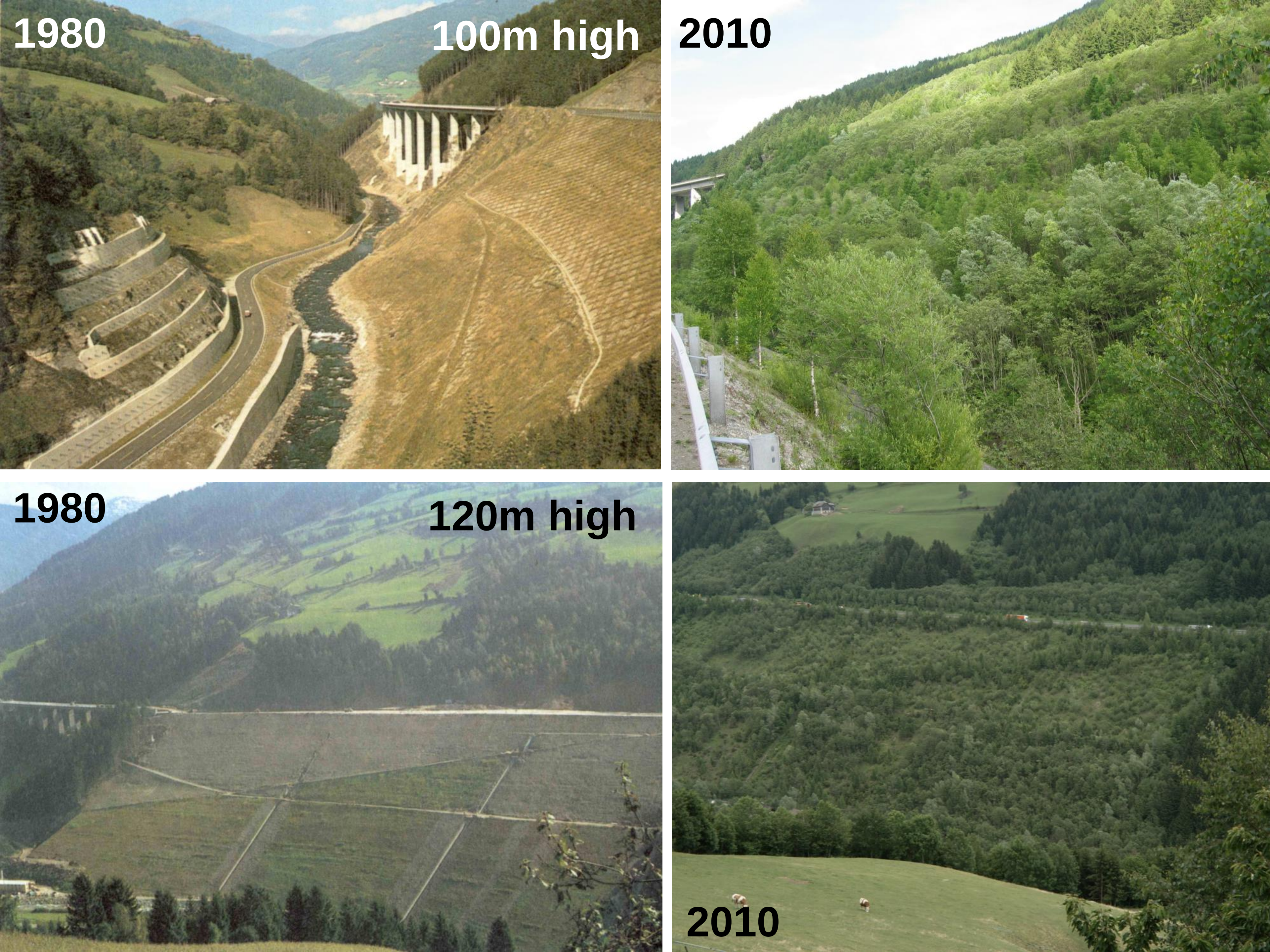


Steeper embankment slope if geosynthetic reinforced fills

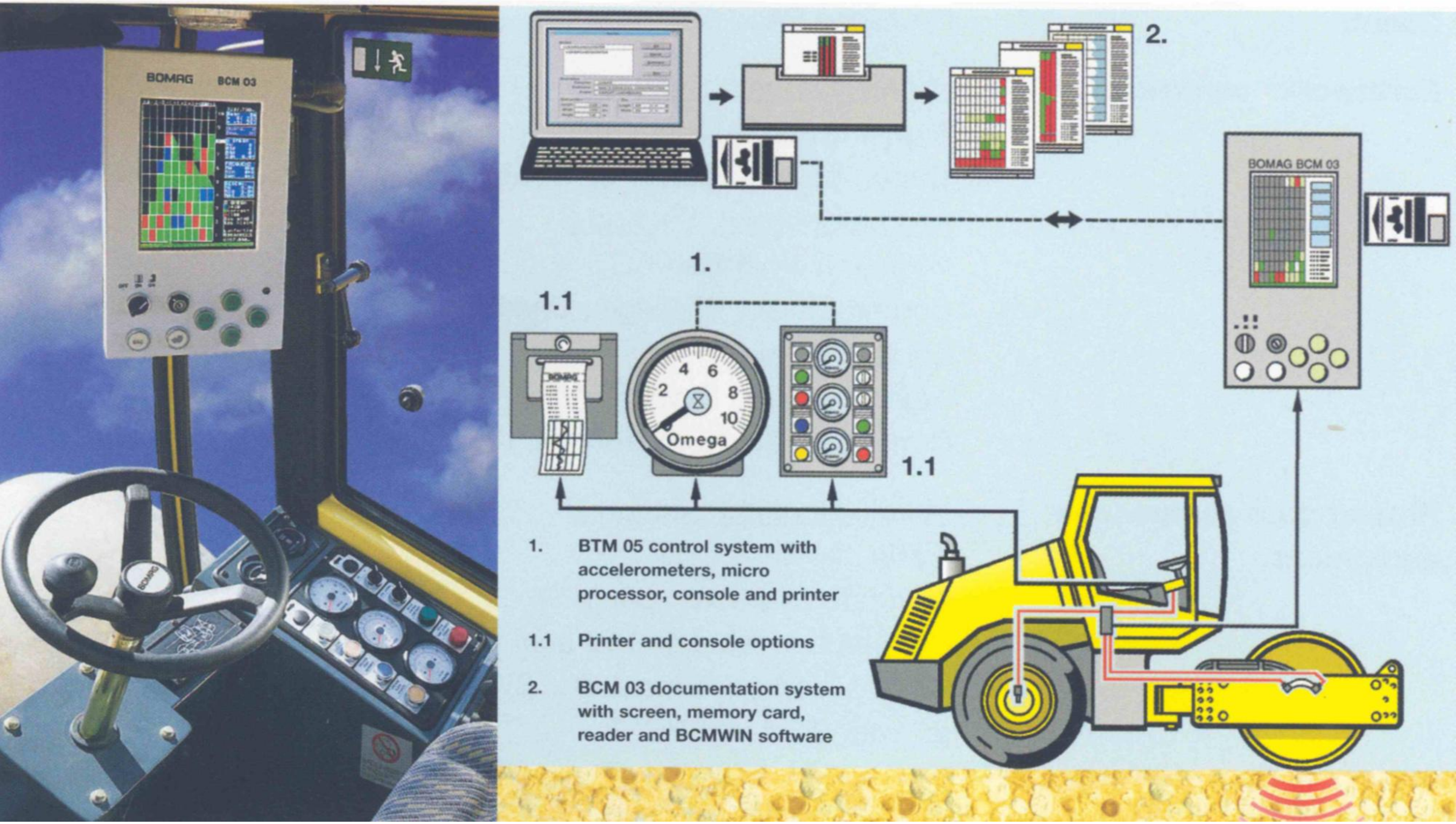
Self settlements of high embankments:

s = 1 – 3 ‰ for good material and high compaction

s = 1 – 3 % for medium material and poor compaction


1980
100m high
2010
1980
120m high
2010

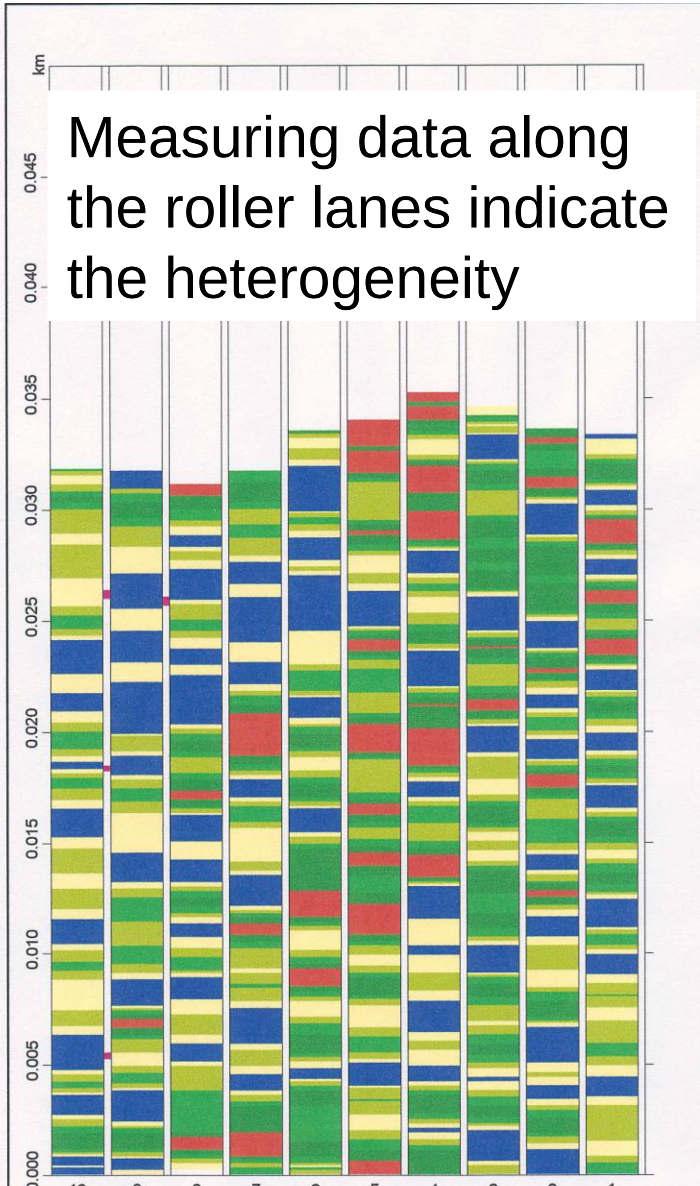
CONTINUOUS COMPACTION CONTROL (CCC)



CCC increases significantly the composite effect of geosynthetic reinforced earth structures

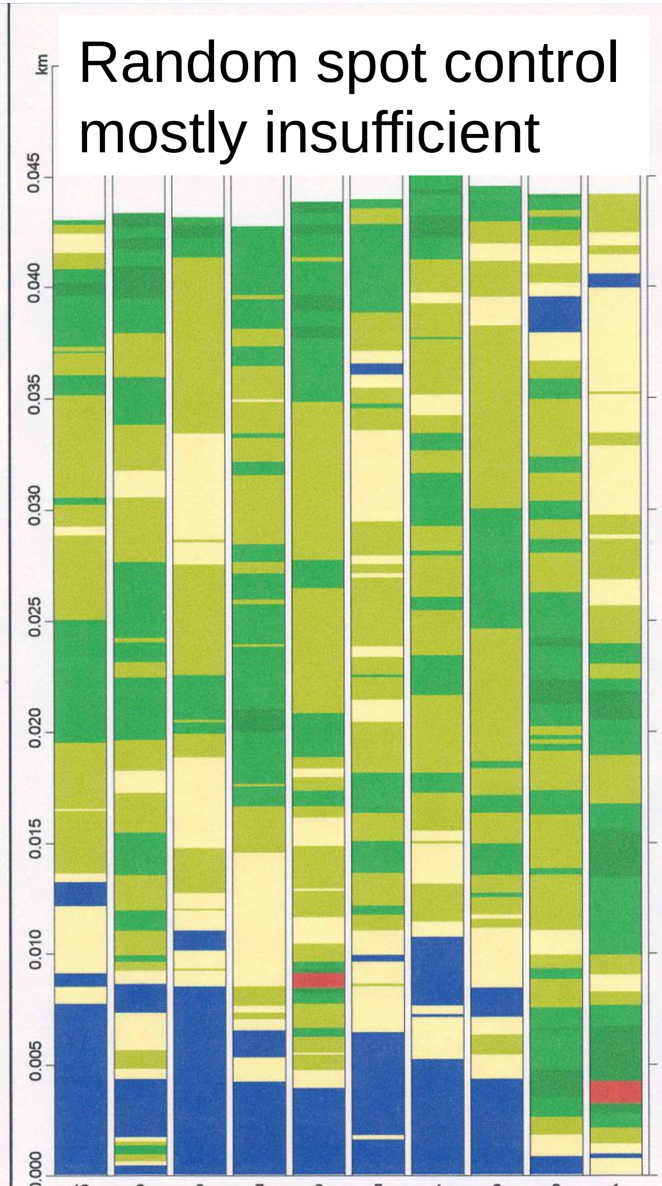
CONTINUOUS COMPACTION CONTROL (CCC)

Measuring data along the roller lanes indicate the heterogeneity



Omega Mittelwerte	10	9	8	7	6	5	4	3	2	1	Überfahrt
	559	566	545	531	532	481	505	520	528	526	n
	548	564	538	520	508	468	500	510	515	518	n-1
	518	519	506	500	465	440	473	488	494	510	n-2
	481	0	0	480	398	399	439	461	467	494	n-3
Bahndatum	03.02.100	02.02.100	02.02.100	02.02.100	03.02.100	03.02.100	03.02.100	03.02.100	03.02.100	03.02.100	

Random spot control mostly insufficient



Omega Mittelwerte	10	9	8	7	6	5	4	3	2	1	Überfahrt
	458	419	466	428	416	448	446	435	409	413	n
	452	413	461	418	418	441	441	429	402	407	n-1
	444	401	443	403	398	429	422	410	389	396	n-2
	422	366	429	390	385	420	402	396	382	392	n-3
Bahndatum	07.02.100	07.02.100	07.02.100	07.02.100	07.02.100	07.02.100	07.02.100	07.02.100	07.02.100	07.02.100	

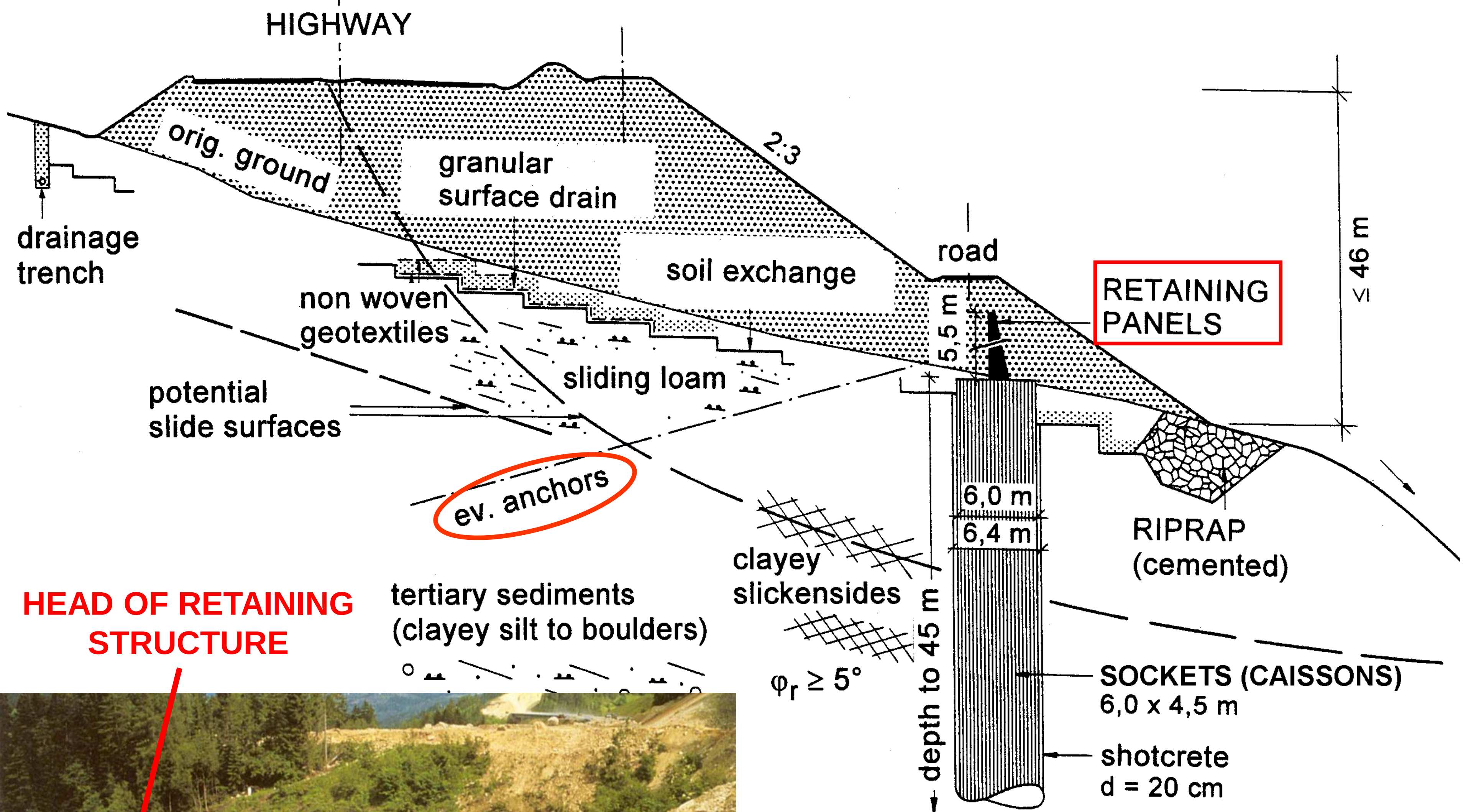
Dynamic load plate test under confined site conditions

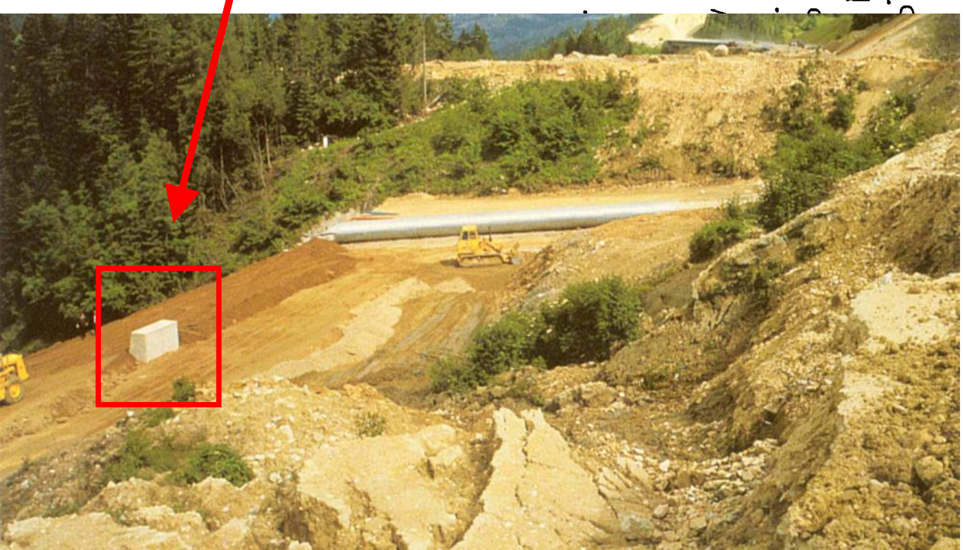
Omega Skala

1000 – 0

- Omega 500 ...1000
- Omega 450 ... 499
- Omega 400 ... 449
- Omega 350 ... 399
- Omega 300 ... 349
- Omega 0 ... 299
- Bahn gesperrt
- Bahn unbearbeitet
- Sprungbetrieb

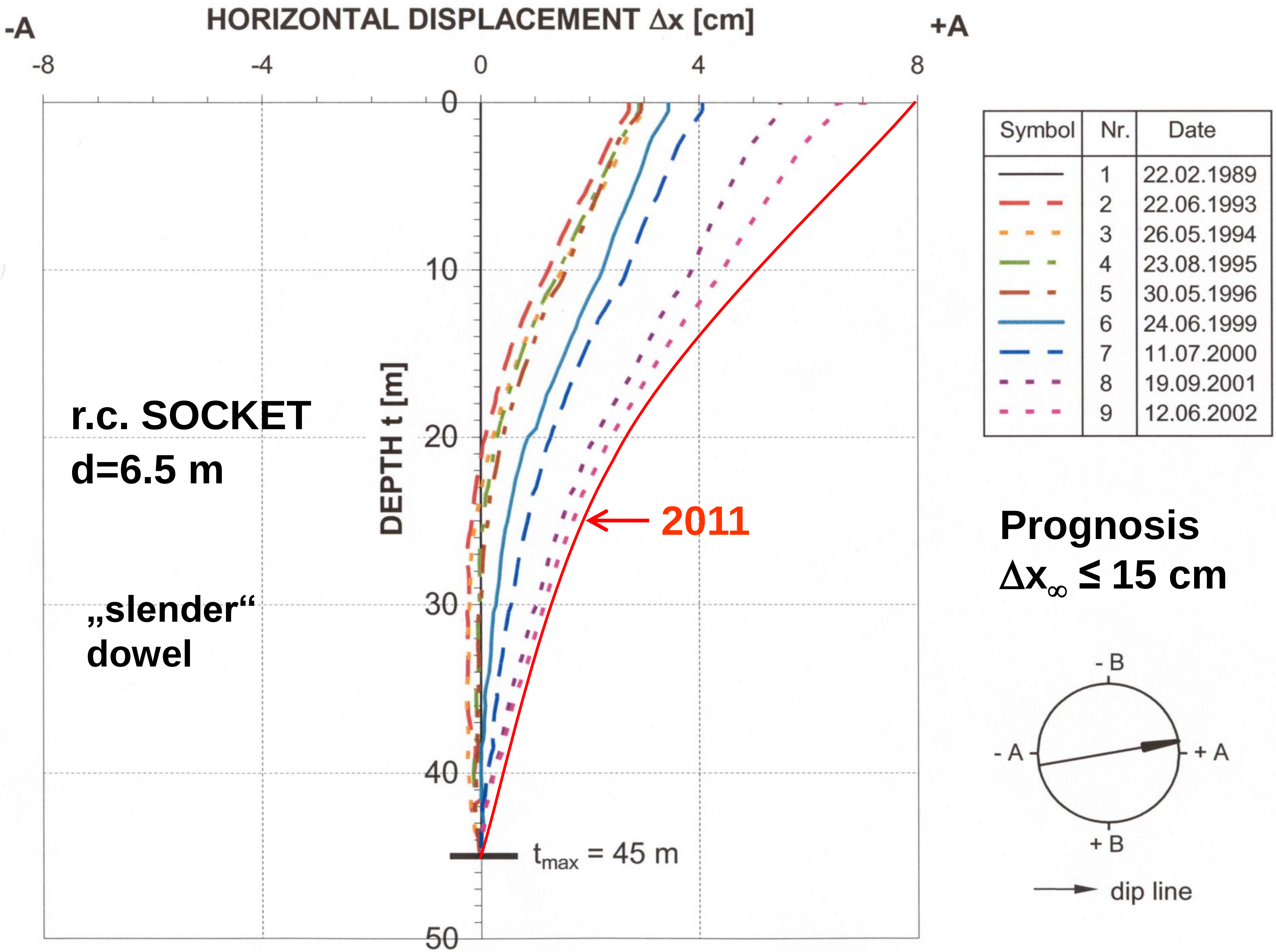
PORR ERDBAU GMBH
Erd- u. Abbrucharbeiten
Bauleitung





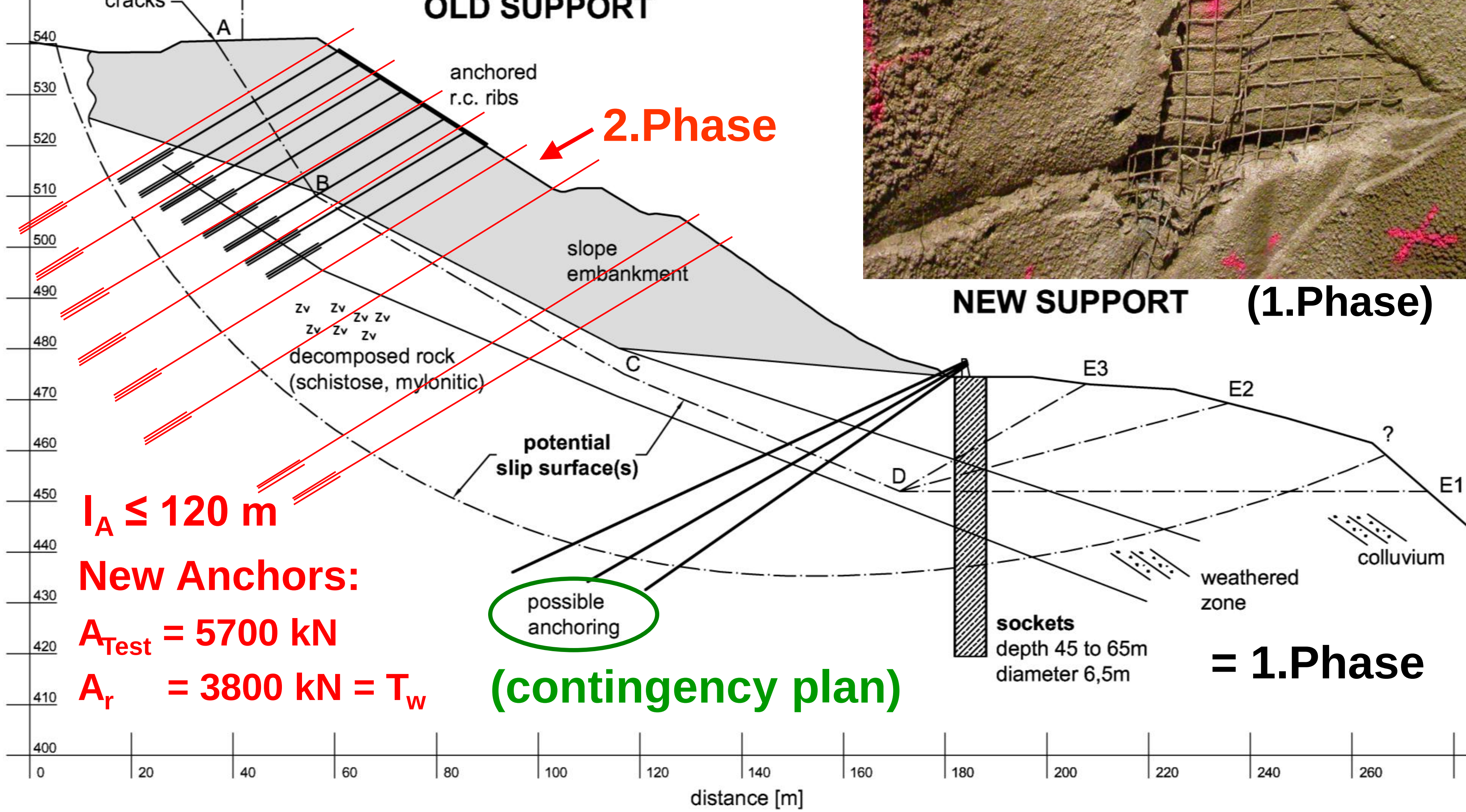
SLOPE DOWELLING

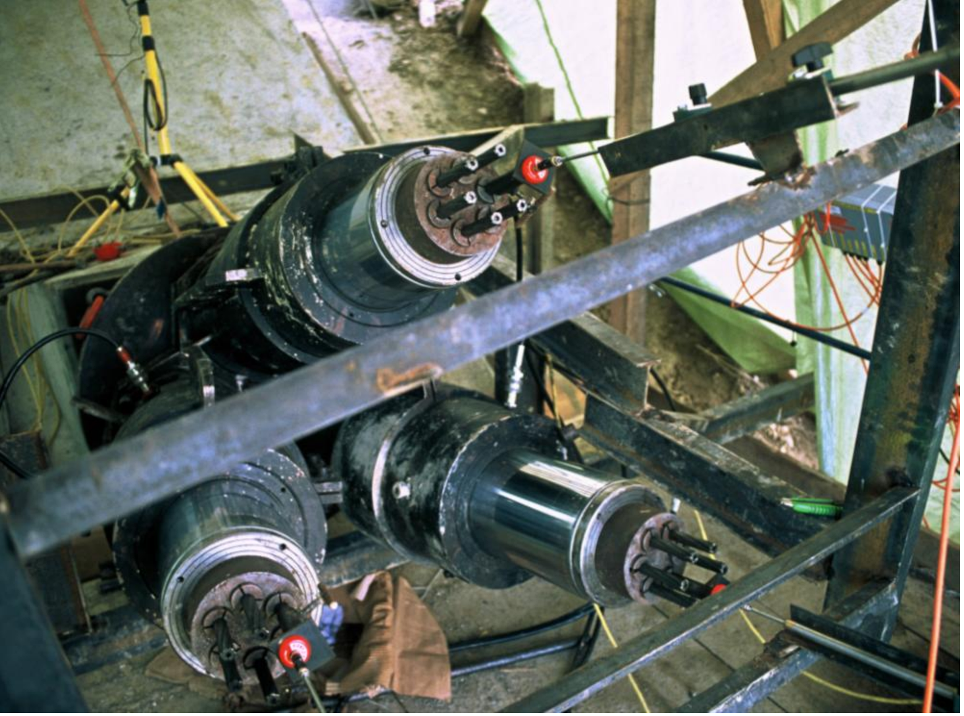
Rather flexible and not stiff culvert in unstable slope



-A
HORIZONTAL DISPLACEMENT Δx [cm]
+A
-8
-4
0
4
8
DEPTH t [m]
0
10
20
30
40
50
r.c. SOCKET
d=6.5 m
„slender“
dowel
2011
t_max = 45 m
Symbol
Nr.
Date
1 22.02.1989
2 22.06.1993
3 26.05.1994
4 23.08.1995
5 30.05.1996
6 24.06.1999
7 11.07.2000
8 19.09.2001
9 12.06.2002
Prognosis
Δx∞ ≤ 15 cm
- B
- A
+ A
+ B
dip line

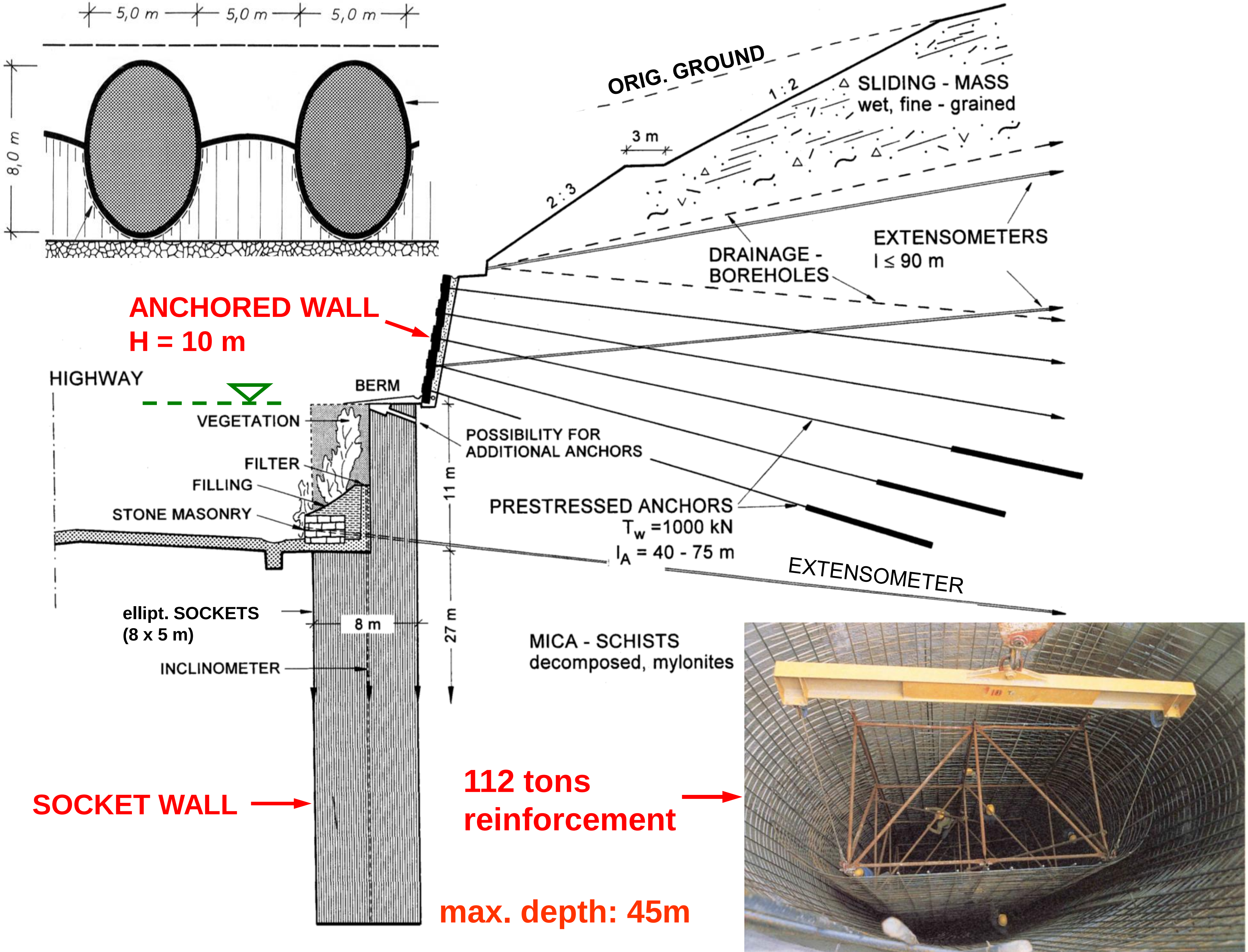
Progressive decrease of (residual) shear strength over the years





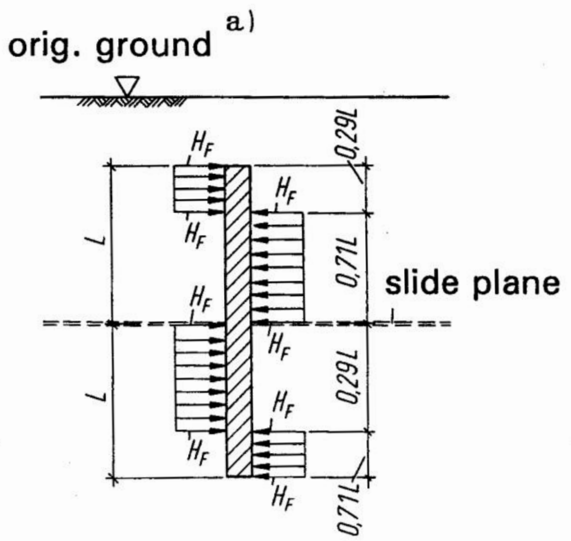
Pier wall (5 x 8 m „dowels“, 45m deep) before planting
ΣH ~ 4400 E-Locs á 100t

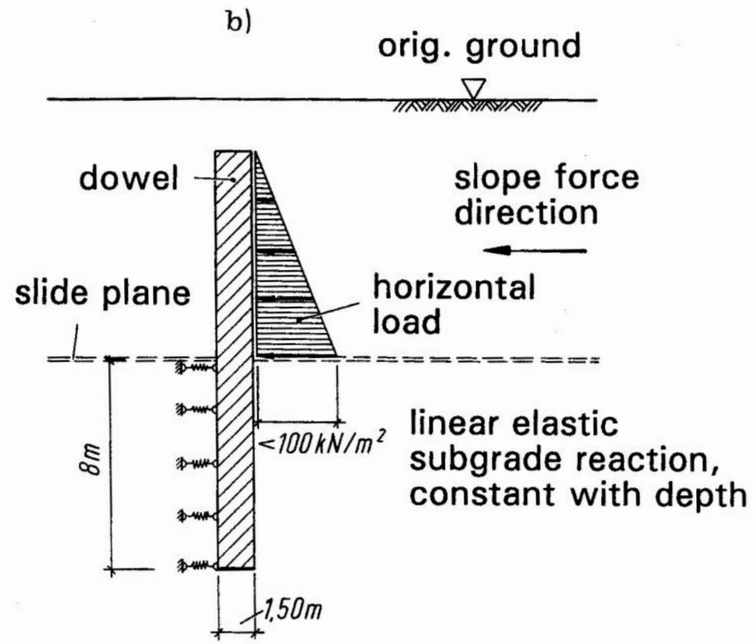
High absorption of traffic noise and air pollution

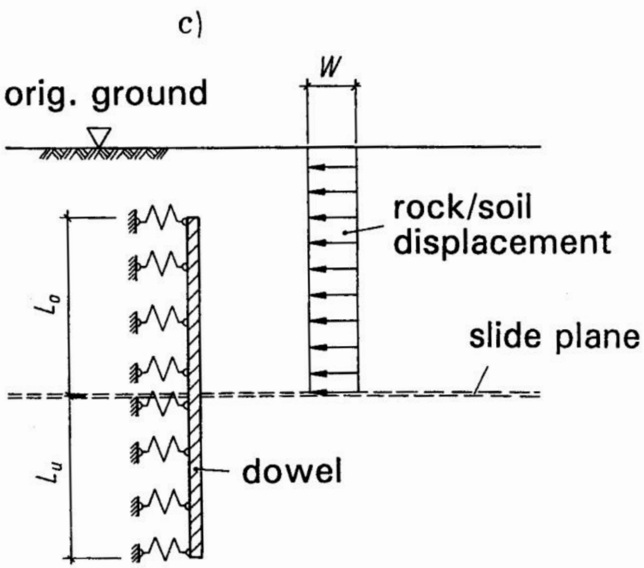

5,0 m
5,0 m
5,0 m
8,0 m
ORIG. GROUND
1 : 2
SLIDING - MASS
wet, fine - grained
3 m
2 : 3
DRAINAGE -
BOREHOLES
EXTENSOMETERS
l ≤ 90 m
ANCHORED WALL
H = 10 m
HIGHWAY
BERM
VEGETATION
POSSIBILITY FOR
ADDITIONAL ANCHORS
FILTER
FILLING
11 m
STONE MASONRY
PRESTRESSED ANCHORS
T_w =1000 kN
l_A = 40 - 75 m
EXTENSOMETER
ellipt. SOCKETS
(8 x 5 m)
8 m
27 m
INCLINOMETER
MICA - SCHISTS
decomposed, mylonites
SOCKET WALL
112 tons
reinforcement
max. depth: 45m

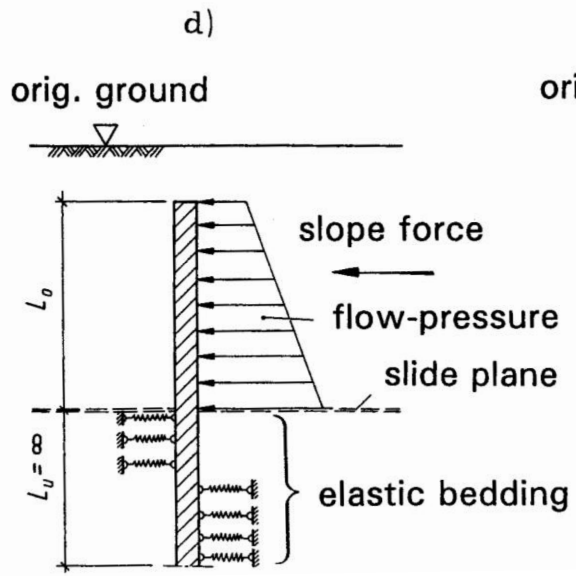
Combined socket-anchor-wall: greenery after 3 years

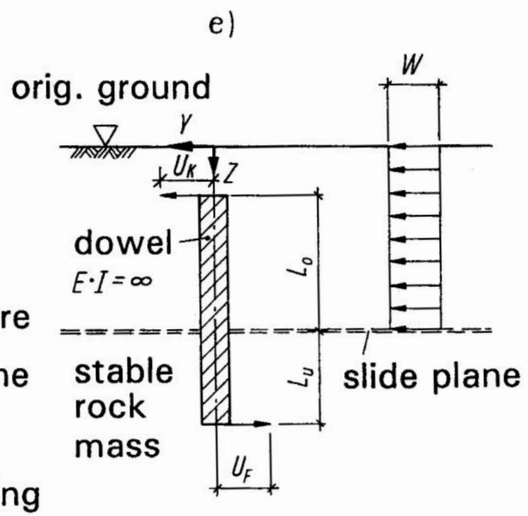
SLOPE DOWELLING:
SCHEMES OF CALCULATION

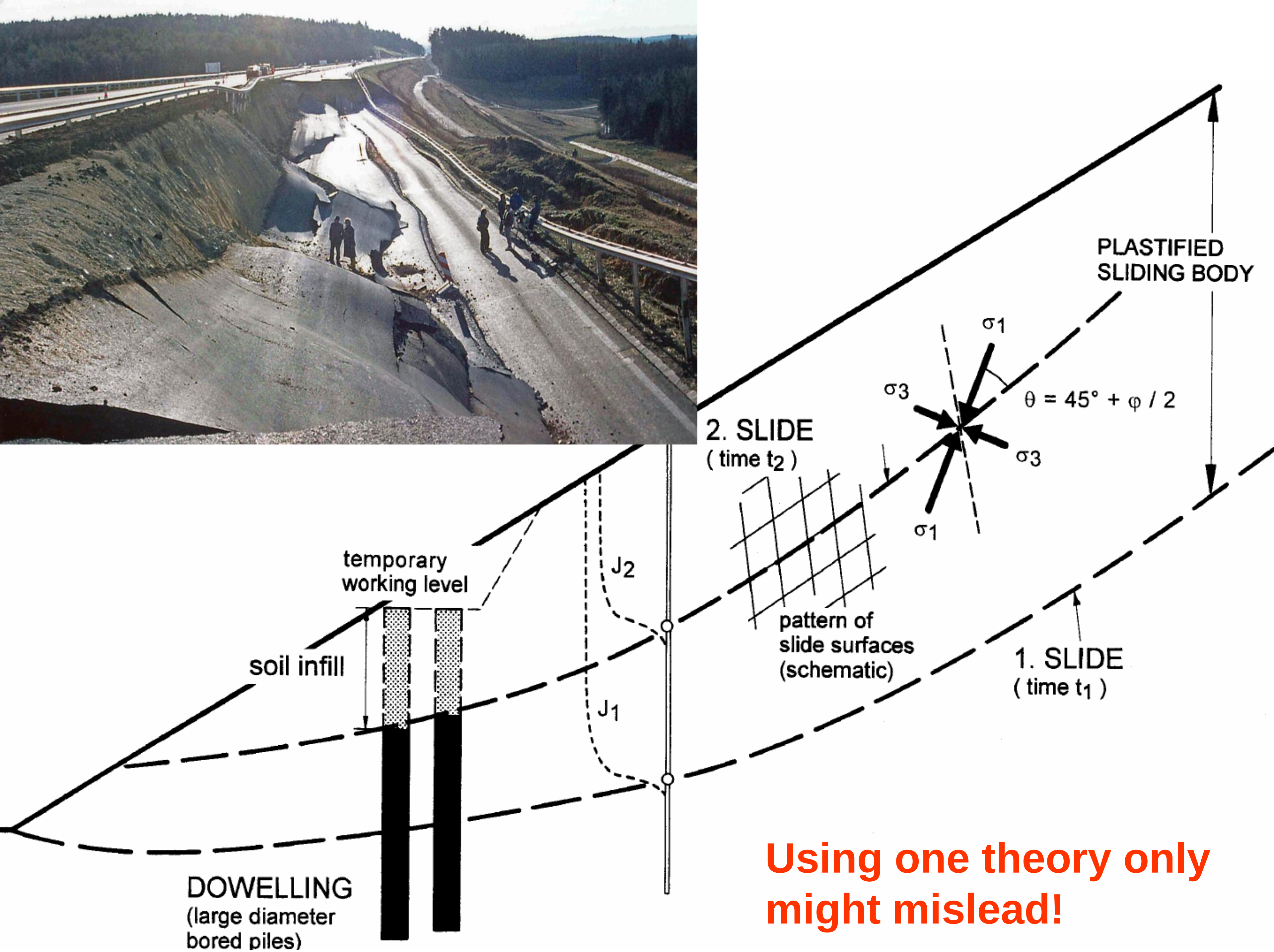








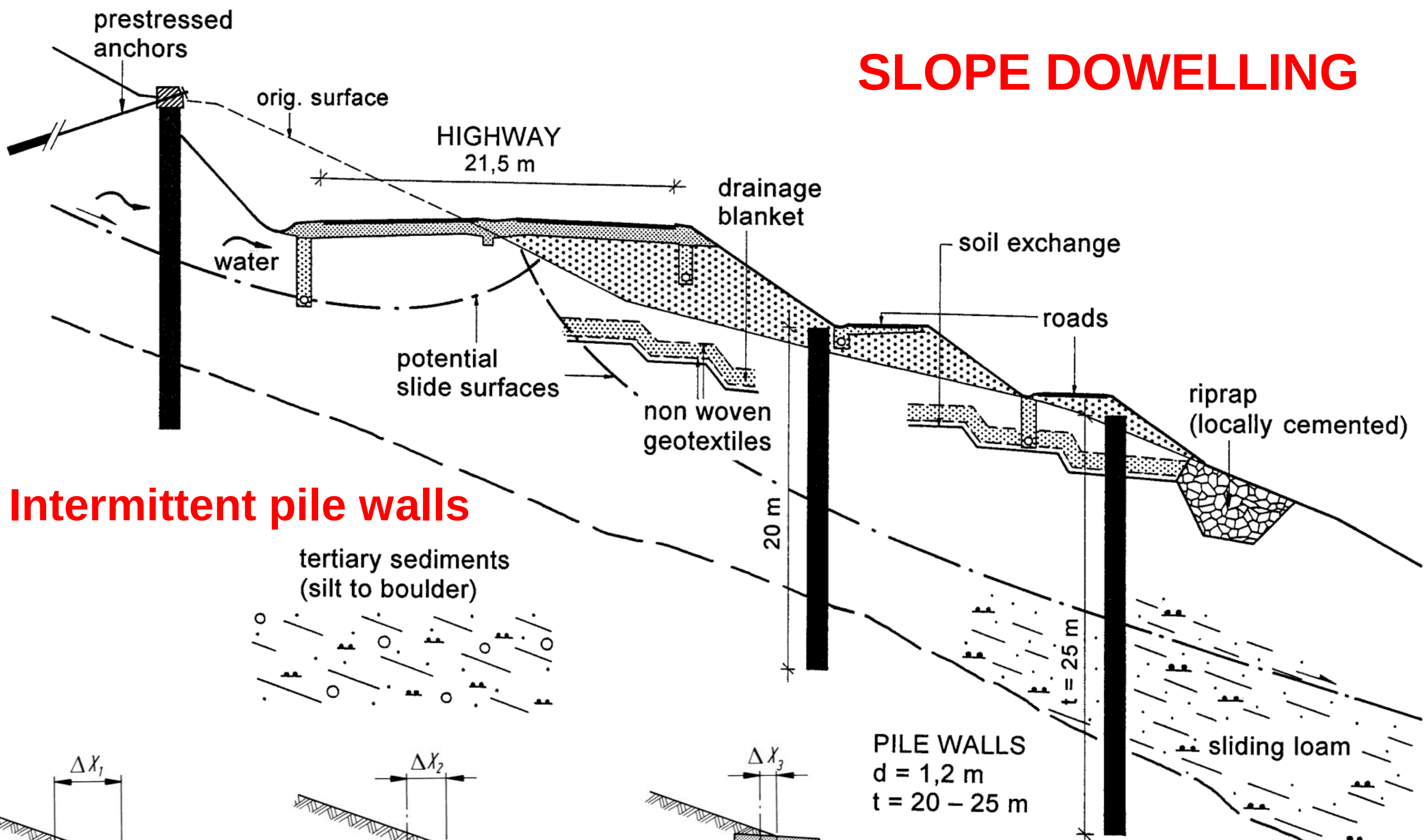


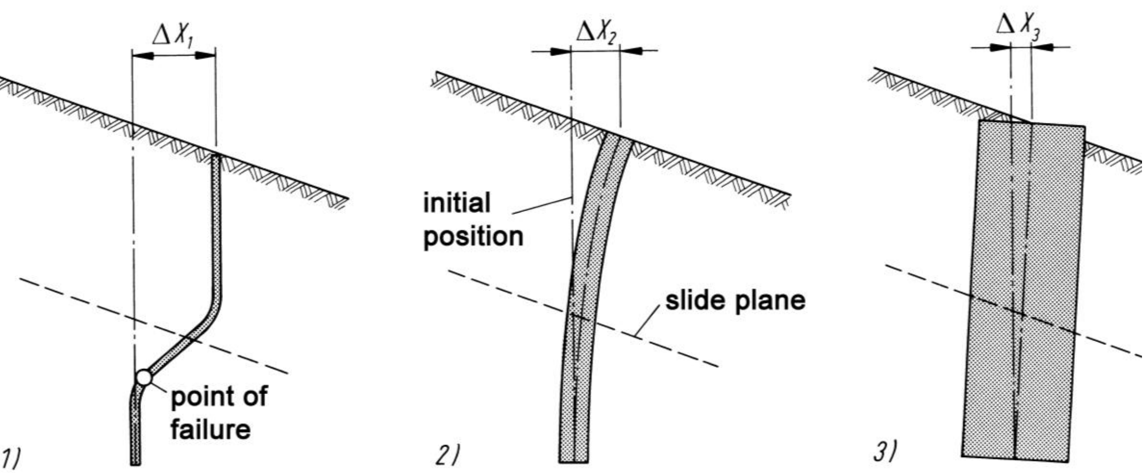


Using one theory only might mislead!

SLOPE DOWELLING

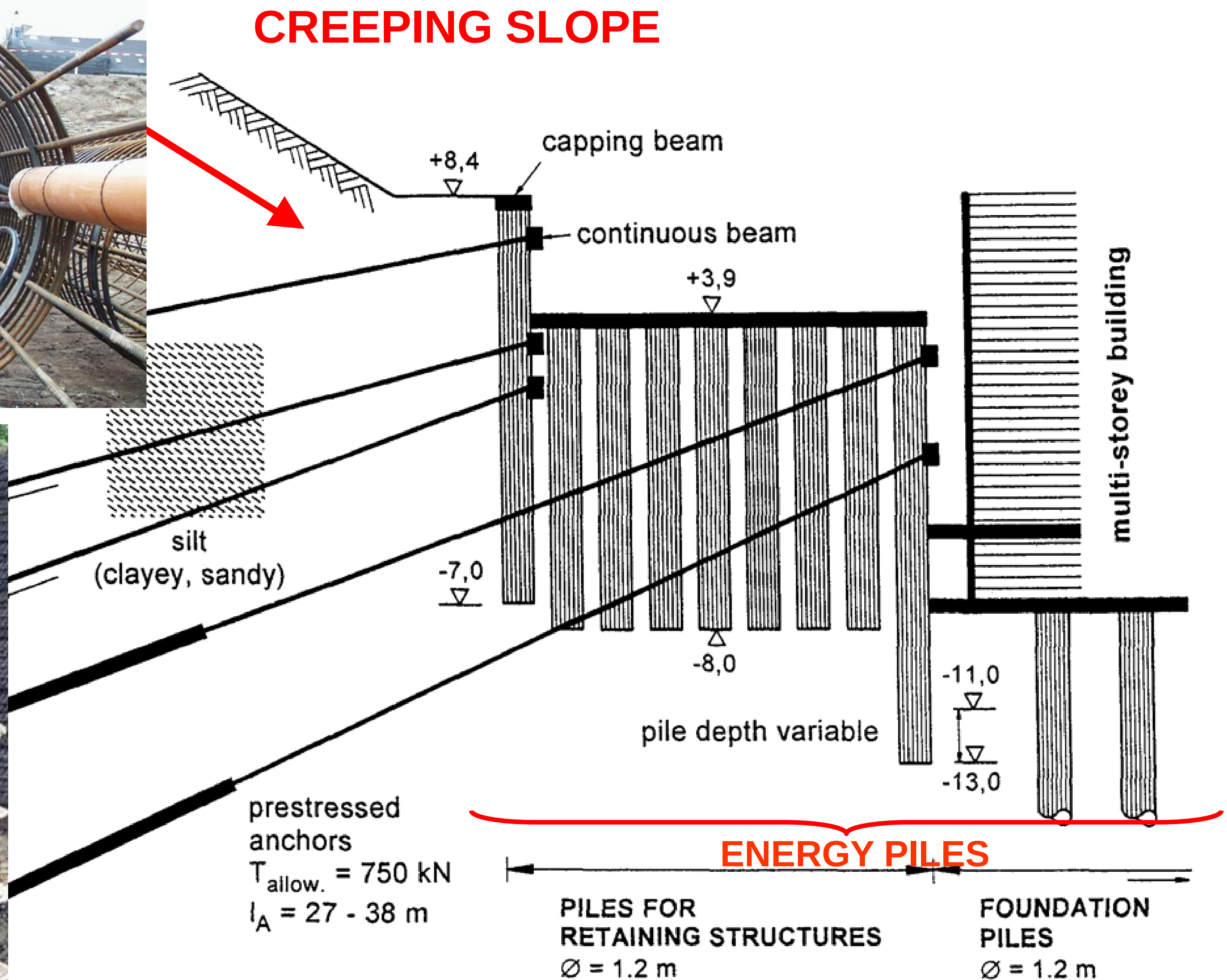
Intermittent pile walls





$$\Delta X_1 > \Delta X_2 > \Delta X_3$$

INFLUENCE OF DOWEL STIFFNESS!

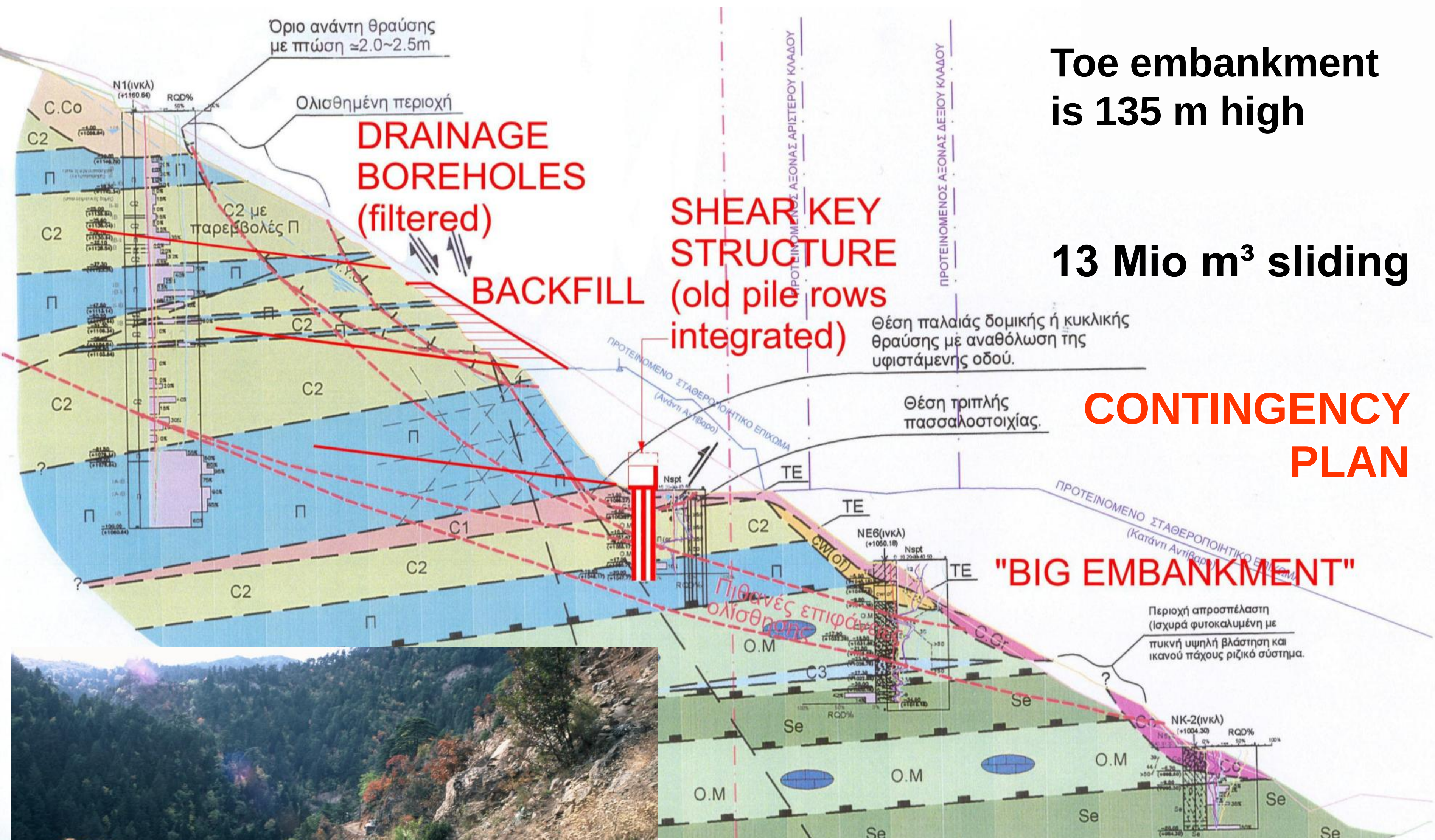


Partial view of the anchored energy pile wall on the uphill side of the building being part of the heating/cooling system

Toe embankment is 135 m high

13 Mio m³ sliding

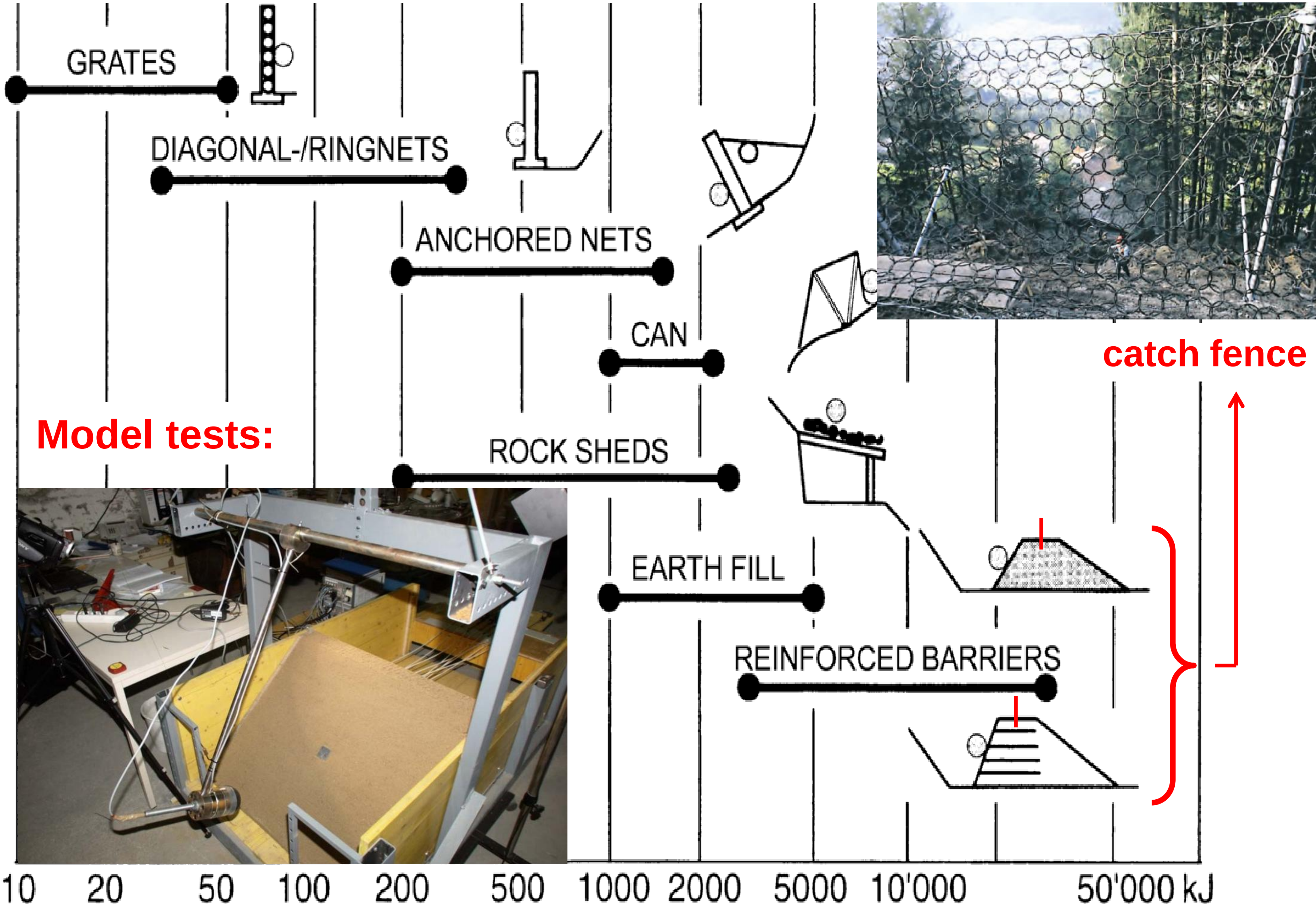
CONTINGENCY PLAN



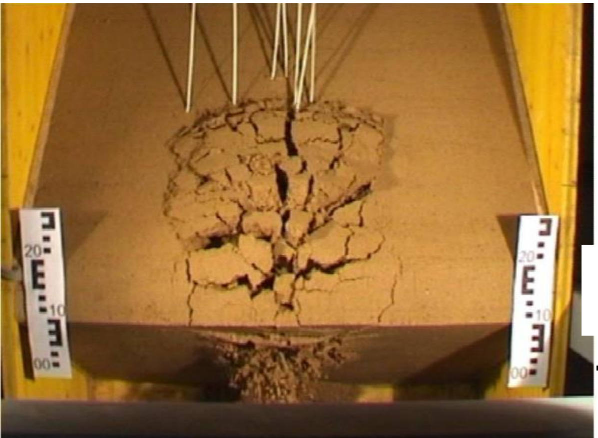
STABILIZING MEASURES:

“Dowels“, anchors, drainage, backfill and toe embankment; Limited re-alignment

STRUCTURES AGAINST ROCKFALL

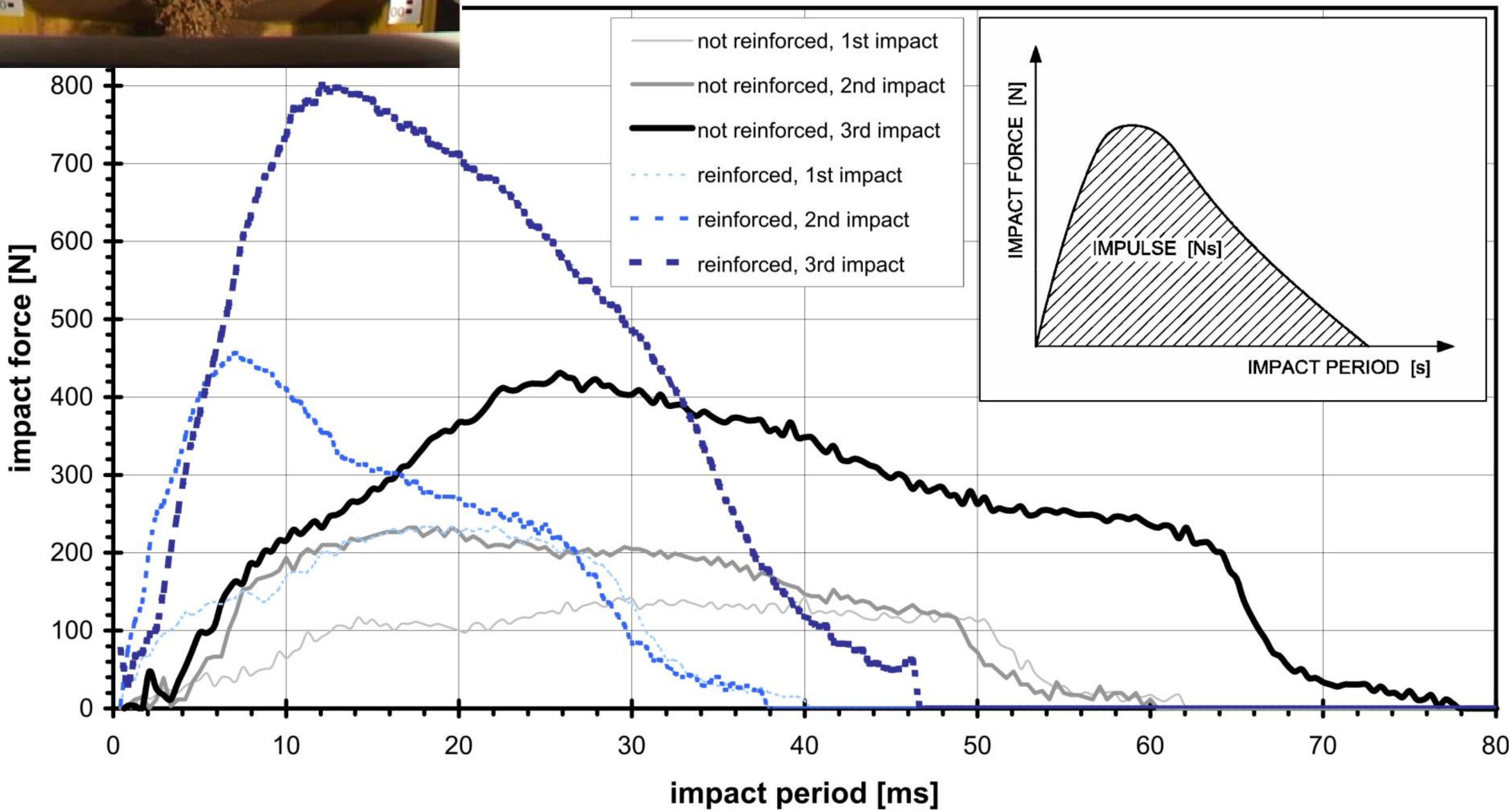


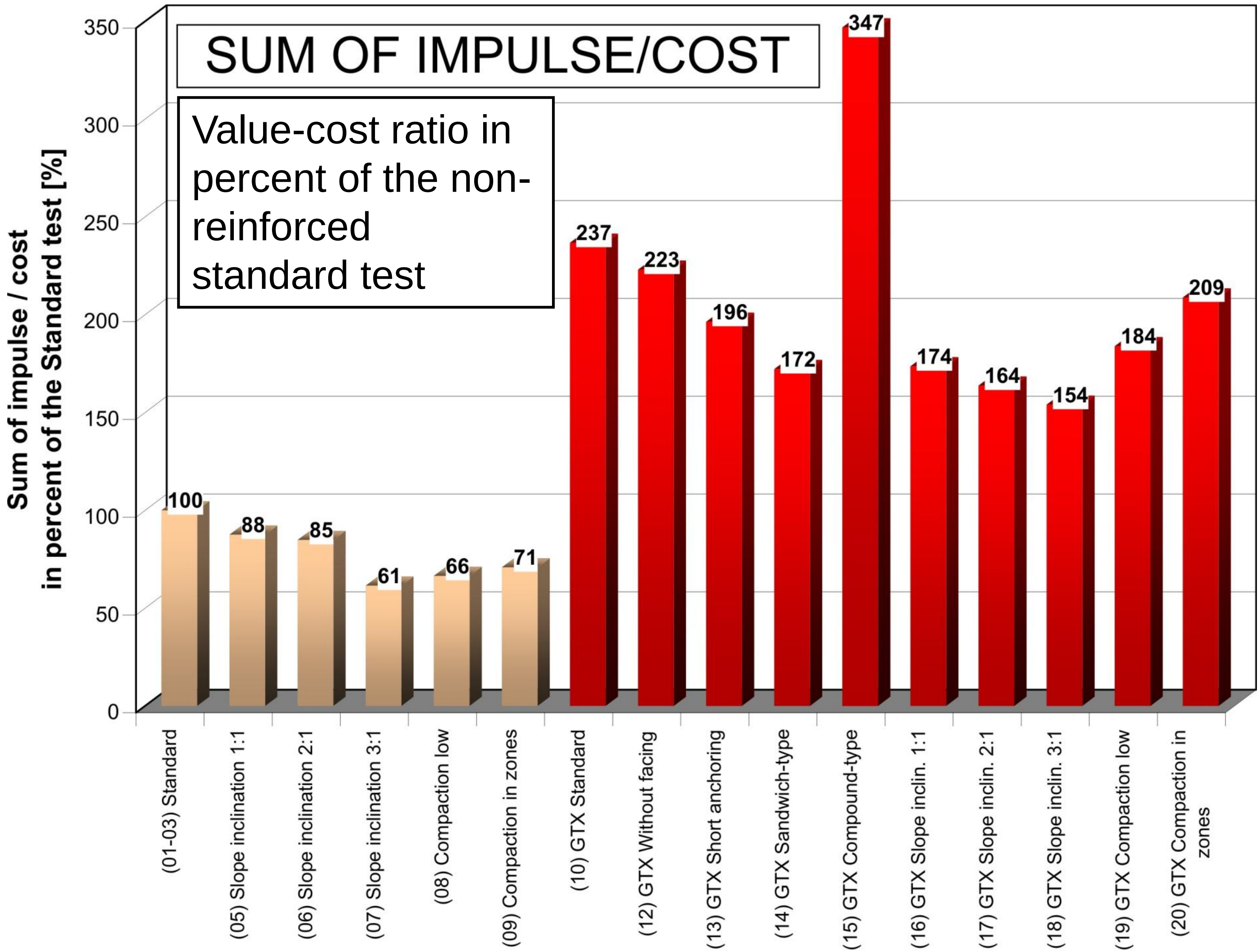
FORCE-TIME RELATION FOR THE FIRST THREE IMPACTS



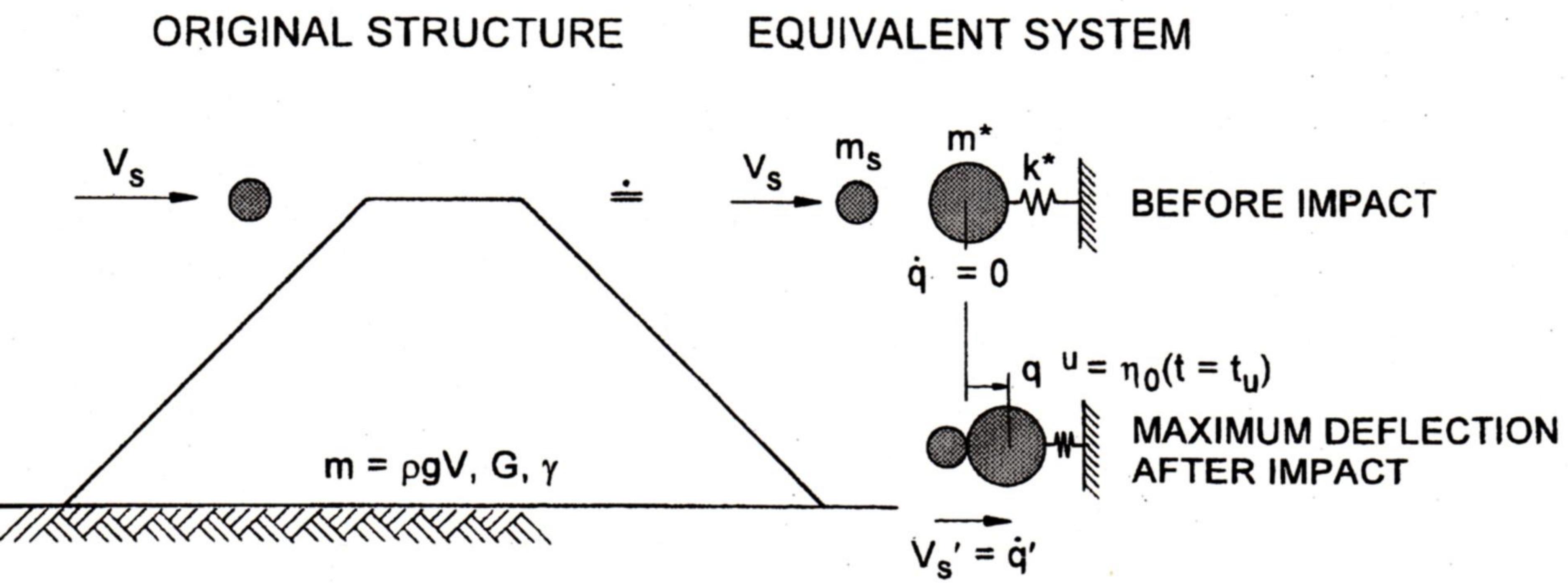
GEOMETRY: slope inclination (mountain facing) 4:5

FORCE

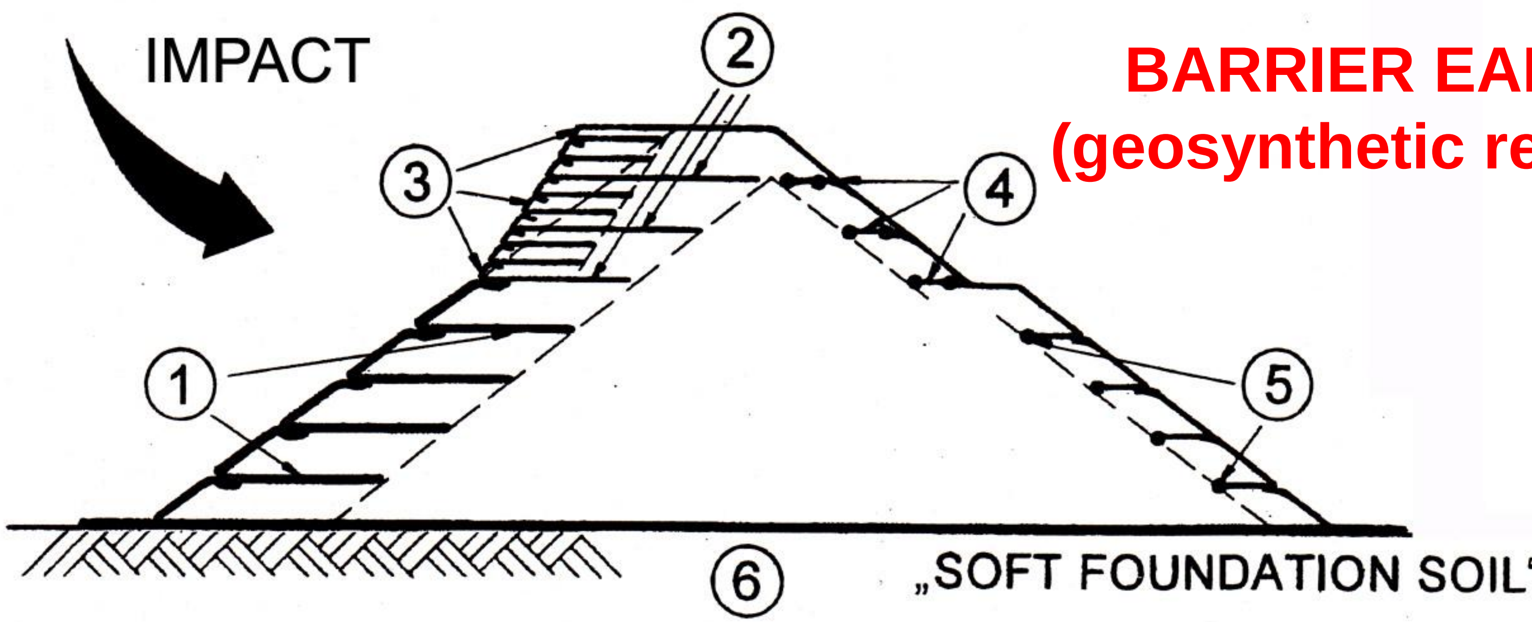


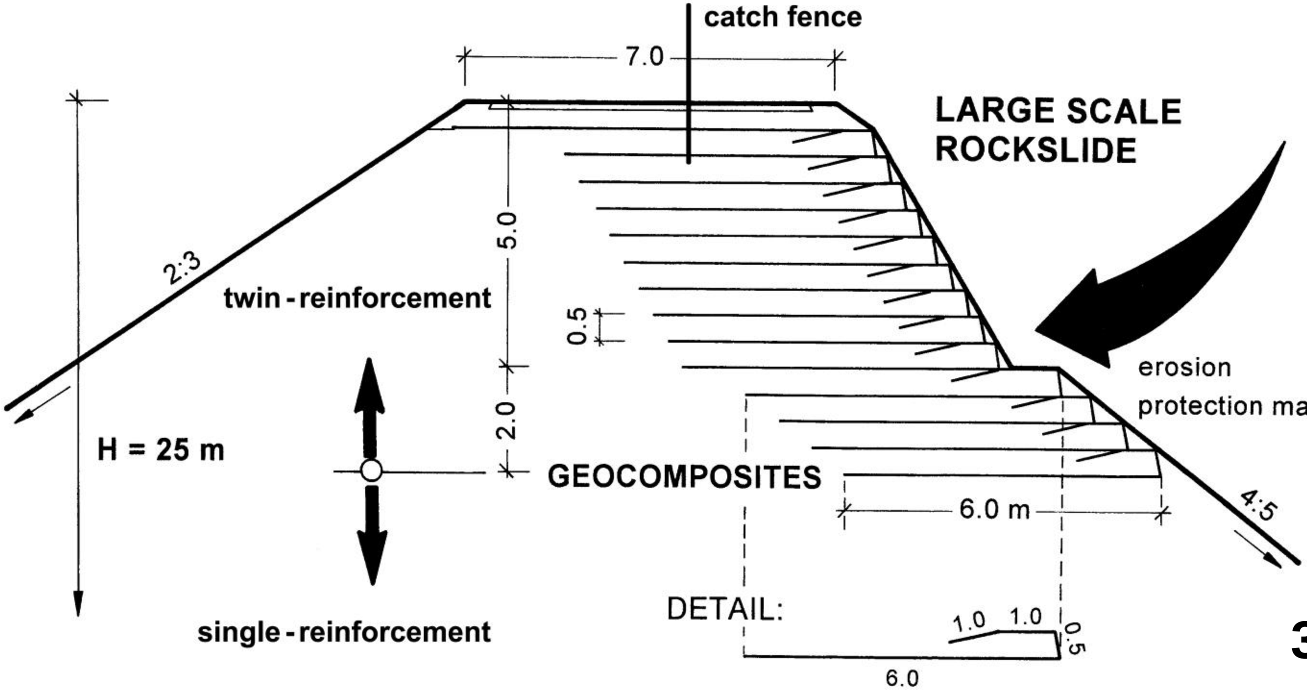


SUM OF IMPULSE/COST
Value-cost ratio in percent of the non-reinforced standard test
Sum of impulse / cost in percent of the Standard test [%]
0
50
100
150
200
250
300
350
100
88
85
61
66
71
237
223
196
172
347
174
164
154
184
209
(01-03) Standard
(05) Slope inclination 1:1
(06) Slope inclination 2:1
(07) Slope inclination 3:1
(08) Compaction low
(09) Compaction in zones
(10) GTX Standard
(12) GTX Without facing
(13) GTX Short anchoring
(14) GTX Sandwich-type
(15) GTX Compound-type
(16) GTX Slope inclin. 1:1
(17) GTX Slope inclin. 2:1
(18) GTX Slope inclin. 3:1
(19) GTX Compaction low
(20) GTX Compaction in zones



BARRIER EARTH DAM (geosynthetic reinforced)

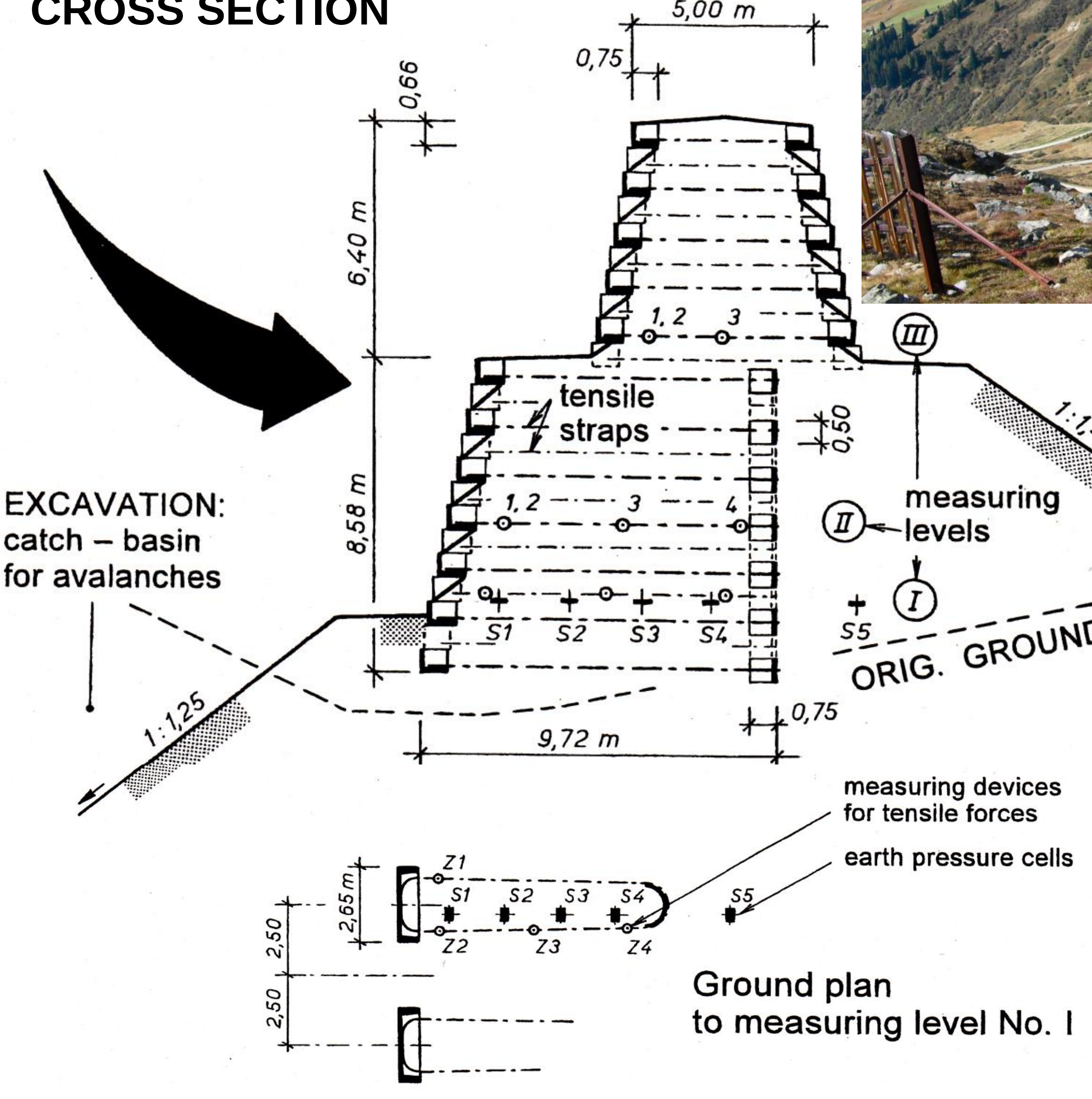




300 persons evacuated

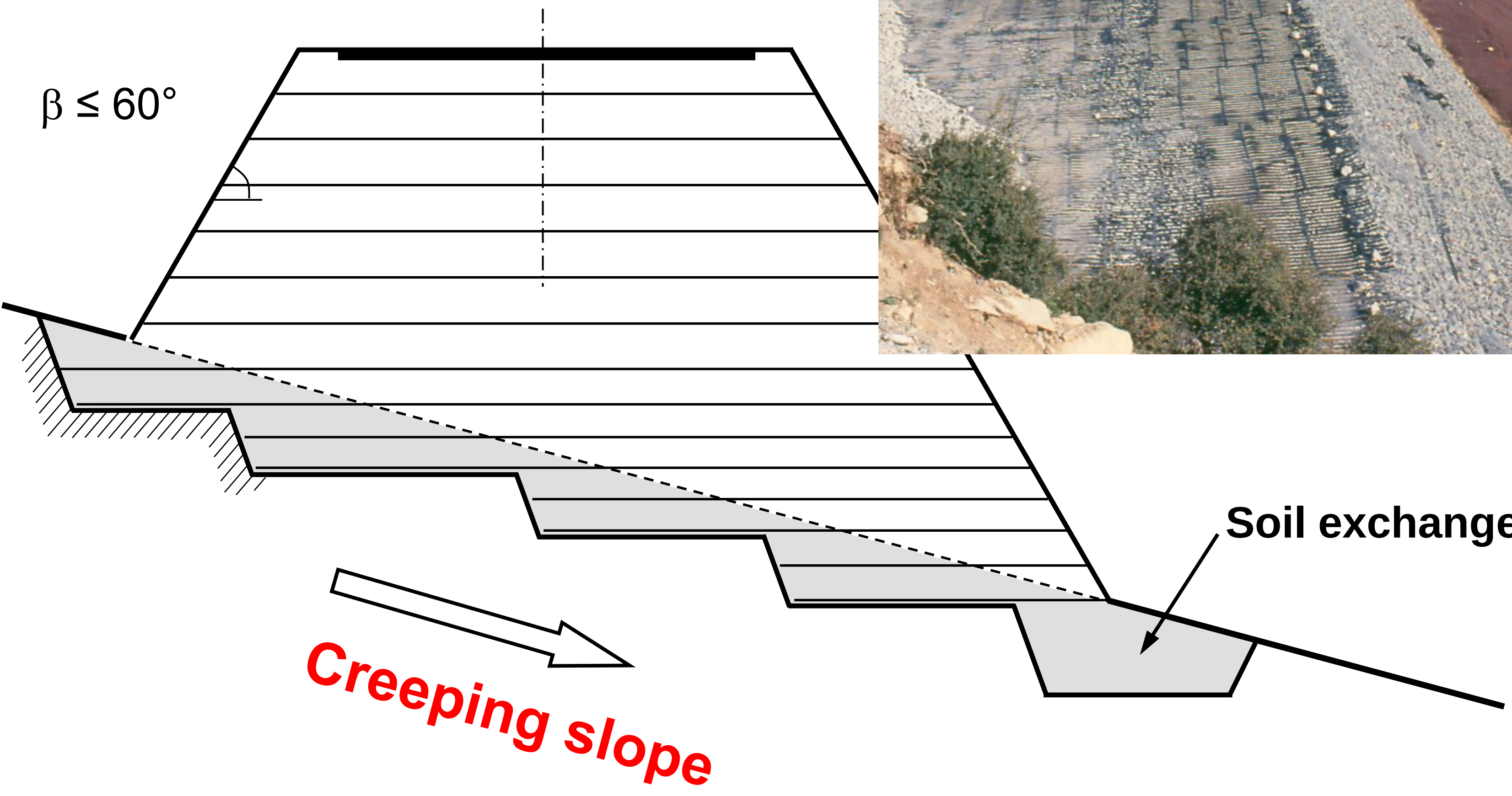
BARRIER FILLS AGAINST AVALANCHES AND MUDFLOWS

CROSS SECTION



L = 600m; H = 27m

"FLOATING" EMBANKMENT



Geosynthetic reinforced steep embankment
(steep fill slopes to minimize the embankment mass)

House on r.c. box foundation and stiffened cellar moved 30 m without cracks (and still moving)

New owner ?

∇ = original ground

„OBSERVATIONAL METHOD“