Geotechnical aspects of bridge design (EN 1997)

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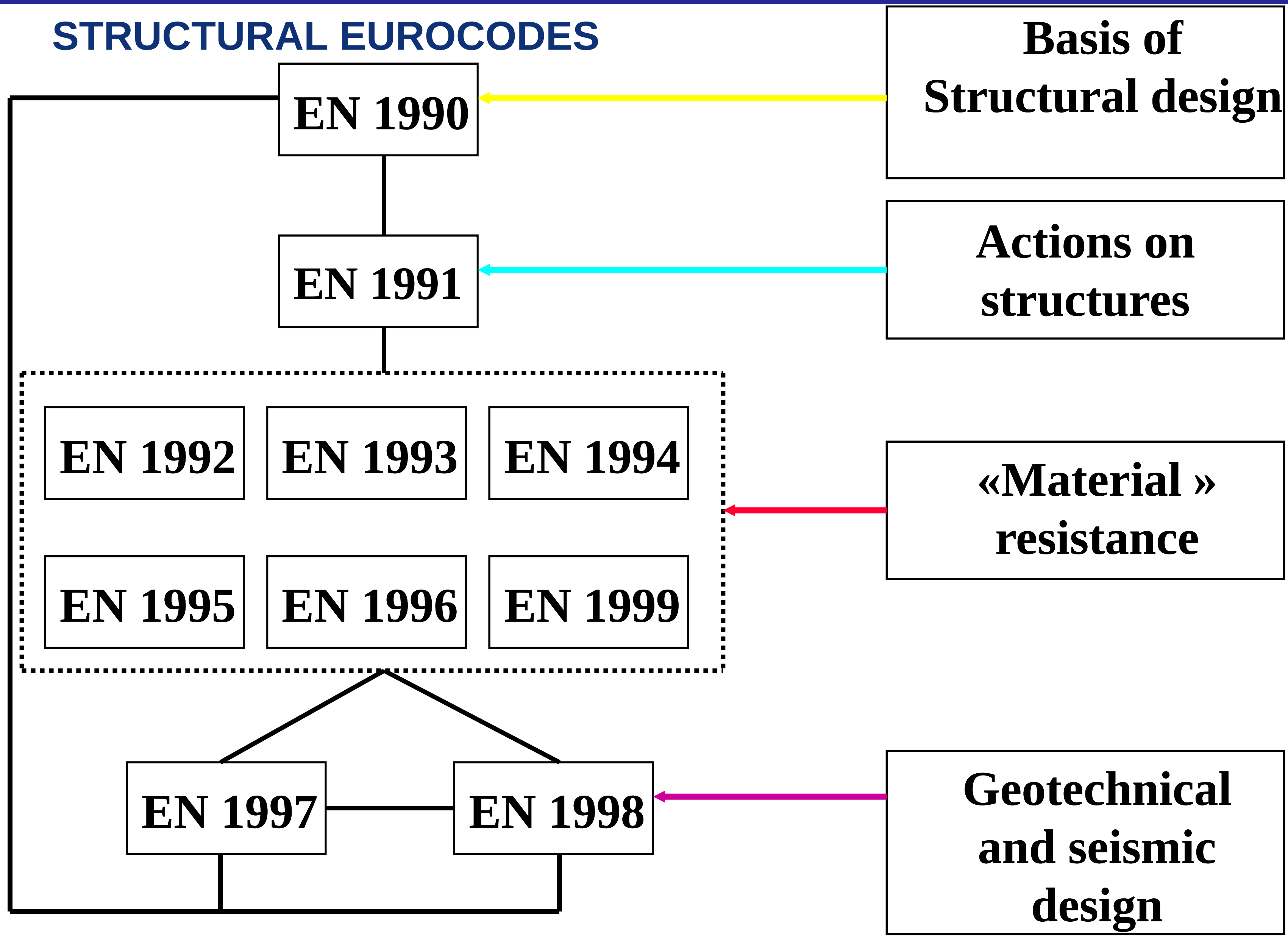
Outline

1. General presentation of Eurocode 7
    - Contents of Part 1 and 2
    - 3 ULS-Design Approaches (DAs)
    - Allowable movements of foundations
    - Spread foundations
    - Retaining structures (mainly gravity walls)
2. Application to bridge design
    - Geotechnical context
    - Abutment C0
        - ULS-bearing capacity
        - ULS-sliding
    - Squat pier P1
        - ULS-bearing capacity
        - SLS-settlement
3. Seismic design situations

General presentation of Eurocode 7

STRUCTURAL EUROCODES



Eurocode 7 – Geotechnical design

EN 1997-1 (2004) : Part 1 - General rules

EN 1997-2 (2007) : Part 2 - Ground investigation and testing

Contents of Part 1 (EN 1997-1)

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1997-1

November 2004

ICS 91.120.20 Supersedes ENV 1997-1:1994

English version

Eurocode 7: Geotechnical design - Part 1: General rules

Eurocode 7: Calcul géotechnique - Partie 1: Règles générales

Eurocode 7: Entwurf, Berechnung und Bemessung in der Geotechnik - Teil 1: Allgemeine Regeln

This European Standard was approved by CEN on 23 April 2004.

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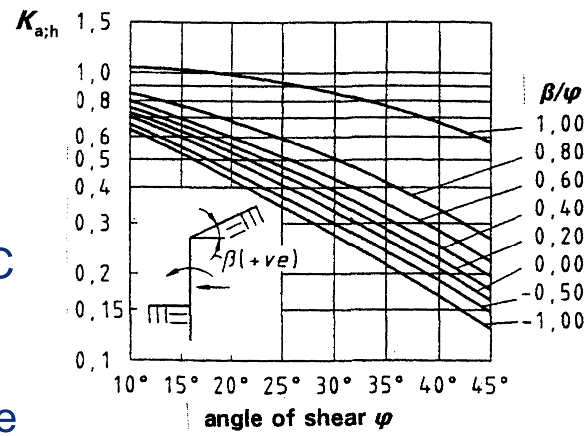
Ref. No. EN 1997-1:2004: E

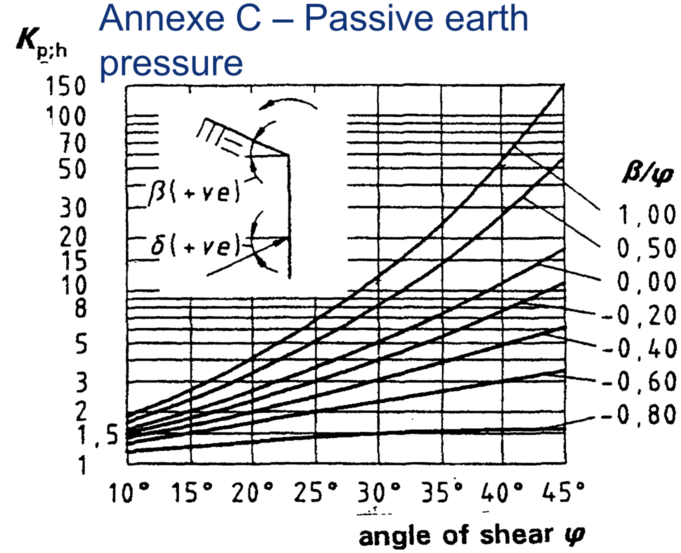
Informative annexes

(b) $\delta = 0$



Annex C
Active
earth
pressure

Annexe C – Passive earth pressure



(e) $\delta = 2/3\ \varphi$

Annexes D & E : Bearing capacity of foundations

$$R/A' = c' \times N_c \times b_c \times s_c \times i_c +$$

$$q' \times N_q \times b_q \times s_q \times i_q +$$

$$0{,}5 \times \gamma' \times B' \times N_\gamma \times b_\gamma \times s_\gamma \times i_\gamma$$

$$R/A' = \sigma_{v0} + k \times p^*_{le}$$

Annexe F : Settlement of foundations

$$s = p \times b \times f / E_m$$

Contents of Part 2 (EN 1997-2)

Section 1 General

Section 2 Planning and reporting of ground investigations

Section 3 Drilling, sampling and gw measurements

Section 4 Field tests in soils and rocks

Section 5 Laboratory tests on soils and rocks

Section 6 Ground investigation report

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1997-2

March 2007

ICS 91.060.01; 91.120.20

Supersedes ENV 1997-2:1999, ENV 1997-3:1999

English Version

Eurocode 7 - Geotechnical design - Part 2: Ground investigation and testing

Eurocode 7 - Calcul géotechnique - Partie 2: Reconnaissance des terrains et essais

Eurocode 7 - Entwurf, Berechnung und Bemessung in der Geotechnik - Teil 2: Erkundung und Untersuchung des Baugrunds

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> Also a number of Informative annexes

Clauses on :

CPT(U), PMT, FDT, SPT, DP, WST, FVT, DMT, PLT

Objectives, specific requirements, evaluation of test results, use of test results and derived values

Annexes with examples on use of results and derived values for geotechnical design

EN 1997- 2
Laboratory tests on soils and rocks (Section 5)

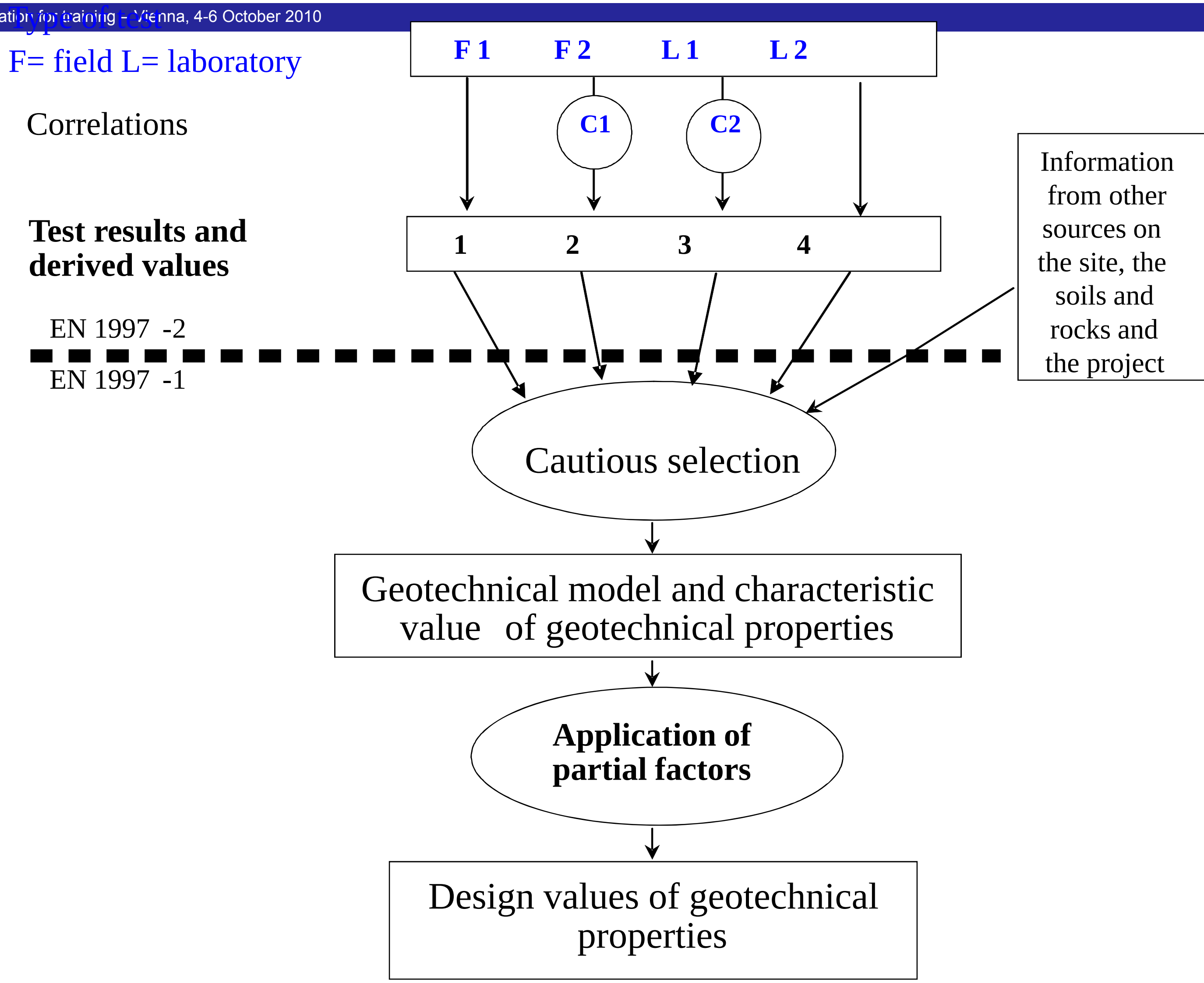
preparation of soil specimens for testing
preparation of rock specimens for testing
tests for classification, identification and description of soils
chemical testing of soils and groundwater
strength index testing of soils
strength testing of soils
compressibility and deformation testing of soils
compaction testing of soils
permeability testing of soils
tests for classification of rocks
swelling testing of rock material
strength testing of rock material

Results of test standards
EN 1997-2 Annex A

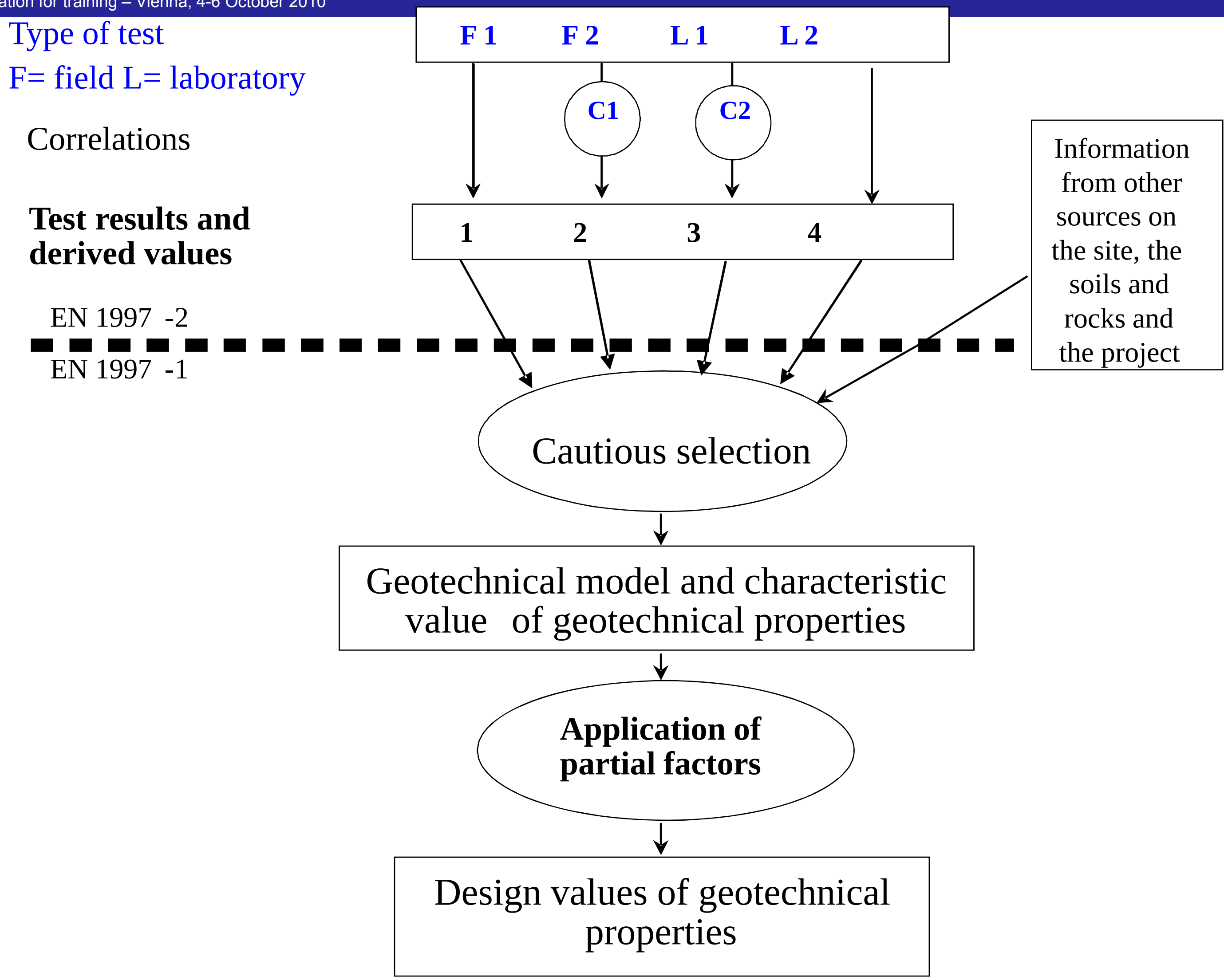
Field test	Test results
CPT/CPTU	q_c , f_s , R_f (CPT) / q_t , f_s , u (CPTU)
Dynamic probing	N_{10} (DPL, DPM, DPH); N_{10} or N_{20} (DPSH)
SPT	N , E_r (SPT), soil description
Pressuremeters (PMT)	E_M ,,p_f , p_{IM} (MPM); expansion curve (all)
Flexible dilatometer (FDT)	E_{FDT}, deformation curve
Field vane test (FVT)	c_{fv} , c_{rv} , torque-rotation curve
Weight sounding test (WST)	continuous record of penetration depth or N_b
Plate loading test	p_u
Flta dilatometer test	P_0 , p_1 , E_{DMT} , I_{DMT} , K_{DMT} (DMT)

Laboratory tests
Soils: w ; ρ ; ρ_s ; grain size distribution curve ; w_P , w_L ; e_{max} , e_{min} , I_D ; C_{OM} ; C_{CaCO3} ; $C_{SO4}{}^{2-}$, $C_{SO3}{}^{2-}$; C_{cl} ; pH ; compressibility, consolidation, creep curves, E_{oed}, σ'_p or C_s, C_c, σ'_p, C_α ; c_u (lab vane) ; c_u (fall cone) ; q_u ; c_u (UU) ; σ-ε and u curves, σ–paths, Mohr circles ; c', φ' or c_u, c_u=f(σ'c), E' or E_u ; σ-u curve, τ-σ diagram, c', φ', residual parameters ; I_{CBR} ; k (direct lab, field or oedometer) Rocks: w ; ρ and n ; swelling results ; σ_c, E and ν ; I_{s50} ; σ-u curve, Mohr diagram, c', φ', res par ; σ_T ; σ-ε curve, σ–paths, Mohr circles ; c', φ', E and ν

Geotechnical properties



Geotechnical properties



Some aspects of Eurocode 7-1

Characteristic values

and design values

ULS Design Approaches

SLS and deformations of structures

Characteristic value of geotechnical parameters

P The characteristic value of a geotechnical parameter shall be selected as a cautious estimate of the value affecting the occurrence of the limit state.

If statistical methods are used, the characteristic value should be derived such that the calculated probability of a worse value governing the occurrence of the limit state under consideration is not greater than 5%.

Design values of geotechnical parameters

Design value of a parameter : $X_d = X_k / \gamma_M$

Design values of actions and resistances

fulfilling for STR/GEO ULS : $E_d \leq R_d$

$E_d = E\{\gamma_F . F_k\}$ and $R_d = R\{X_k / \gamma_M\}$

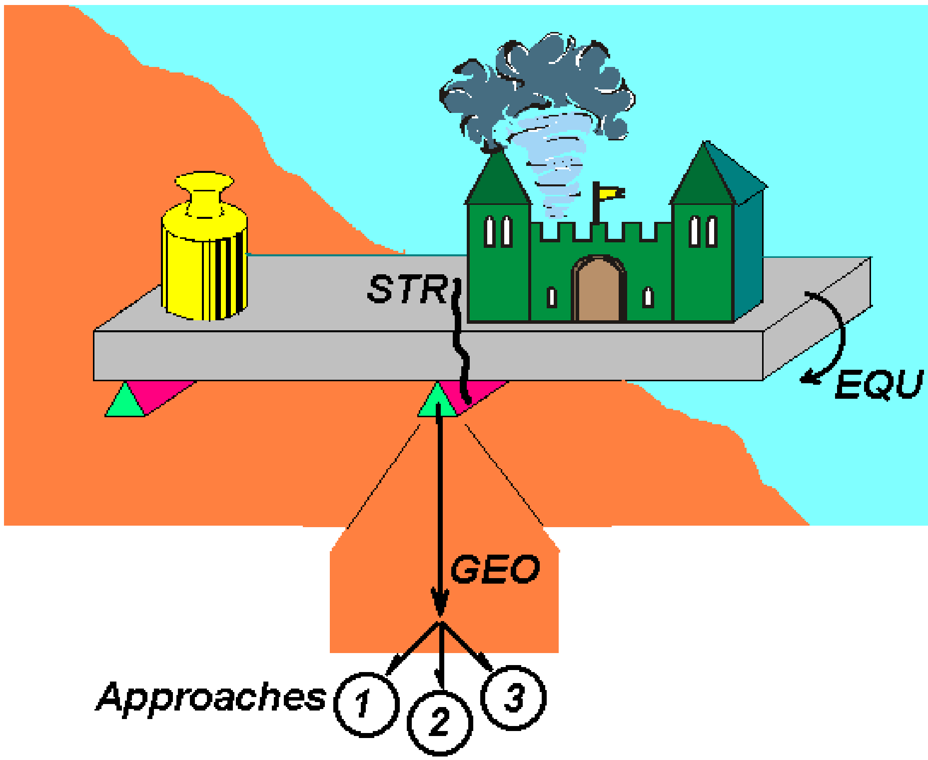
(= "at the source")

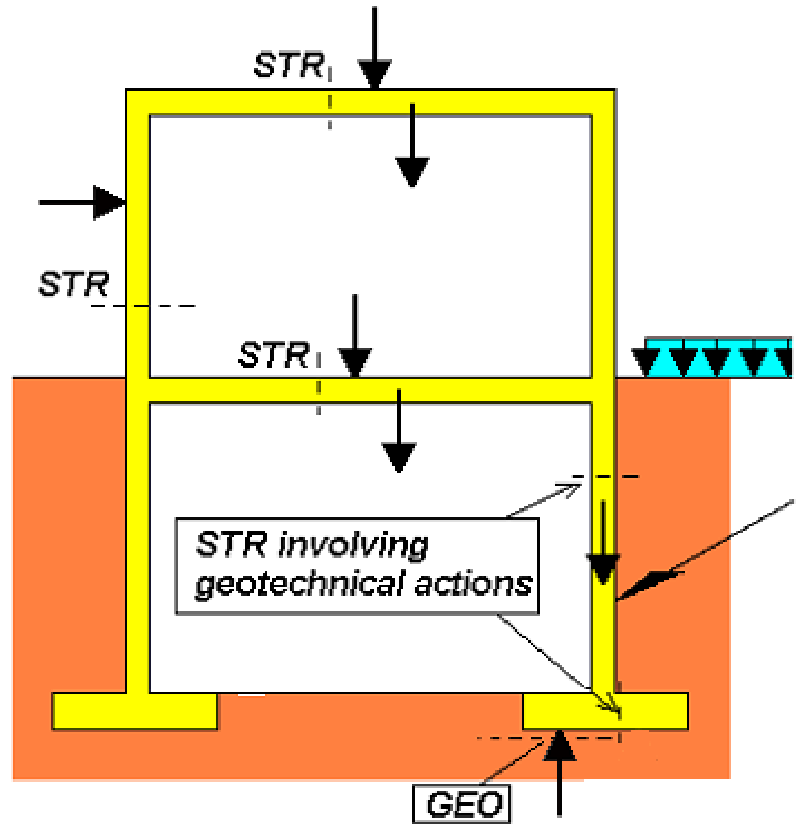
or $E_d = \gamma_E . E\{F_k\}$ and $R_d = R\{X_k\} / \gamma_R$

Ultimate limit states – Eurocode 7-1

- EQU : loss of equilibrium of the structure
- STR : internal failure or excessive deformation of the structure or structural elements
- GEO : failure or excessive deformation of the ground
- UPL : loss of equilibrium due to uplift by water pressure (buoyancy) or other vertical actions
- HYD : hydraulic heave, internal erosion and piping caused by hydraulic gradients

EN1990 - Ultimate limit states
EQU and STR/GEO





$E_d < R_d$

J.A Calgaro

ULS - STR/GEO : persistent and transient situations

The 3 Design Approaches – Format : $E_d < R_d$

Appro-aches	Combinations
1	A1 "+" M1 "+" R1 & A2 "+" M2 "+" R1 Or A2 "+" M1 or M2"+" R4
2	A1 "+" M1 "+" R2
3	A1 or A2 "+" M2 "+" R3

Action (γ_F)	Symbol	Set A1	Set A2
Permanent			
Unfavourable	γ_G	1,35	1,00
Favourable	γ_G	1,00	1,00
Variable			
Unfavourable	γ_Q	1,50	1,30
Favourable	γ_Q	0	0

Soil parameter (γ_M)	Symbol	Set M1	Set M2
Angle of shearing resistance	$\gamma_{\varphi'}$	1,00	1,25
Effective cohesion	$\gamma_{c'}$	1,00	1,25
Undrained shear strength	γ_{cu}	1,00	1,40
Unconfined strength	γ_{qu}	1,00	1,40
Weight density	γ_γ	1,00	1,00

Resistance (γ_R)	Symbol	Set R1	Set R2	Set R3
Bearing capacity	γ_{Rv}	1,00	1,4	1,00
Sliding	γ_{Rh}	1,00	1,1	1,00

← γ_R for Spread foundations

EN1990 - Serviceability limit states SLS

Verifications :

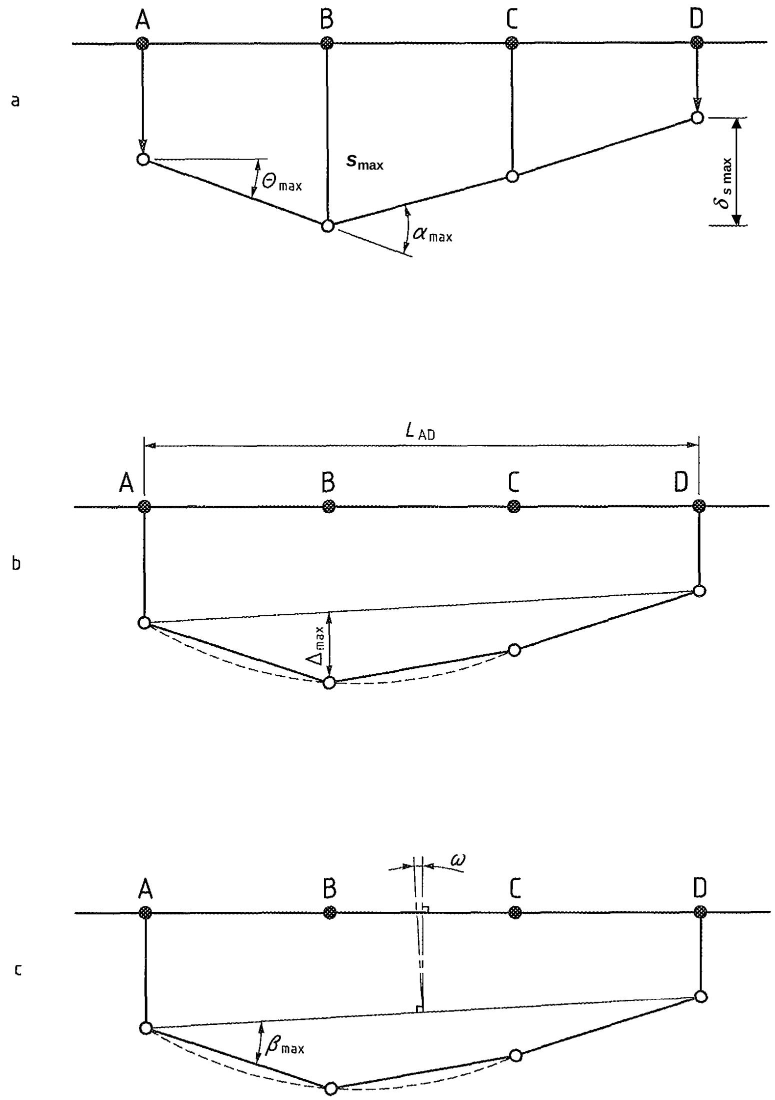
$$E_d \leq C_d$$

C_d = limiting design value of the relevant serviceability criterion

E_d = design value of the effects of actions specified in the serviceability criterion, determined on the basis of the relevant combination

all γ_F and γ_M = 1.0

EN 1997-1 annex H
Movements and deformations of structures



settlement s, differential settlement δs, rotation θ and angular strain α

relative deflection Δ and deflection ratio Δ/L

ω and relative rotation (angular distortion) β

(after Burland and Wroth, 1975)

Allowable movements of foundations

Foundations of buildings (Eurocode 7, 1994)

- Serviceability limit states (SLS) : $\beta_{max} \approx 1/500$
- Ultimate limit states (ULS) : $\beta_{max} \approx 1/150$
- $s_{max} \approx 50$ mm $\delta_{smax} \approx 20$ mm

Foundations of bridges

Moulton (1986) for 314 bridges in the US and Canada :

- $\beta_{max} \approx 1/250$ (continuous deck bridges)

and $\beta_{max} \approx 1/200$ (simply supported spans)

- $s_{Hmax} \approx 40$ mm

In France, in practice :

ULS : $\beta_{max} \approx 1/250$

SLS : $\beta_{max} \approx$ 1/1000 à 1/500

Spread foundations

STR/GEO Ultimate limit states (ULS)

Bearing resistance:

$$V_d \leq R_d = R_k \ / \gamma_{Rv}$$

(R_k : analytical, semi-empirical or prescriptive)

Sliding resistance :

$$H_d \leq R_d + R_{pd}$$

$$[+ \ \mathrm{R_d} \leq 0{,}4 \ \mathrm{V_d} \ ]$$

Design approach 2:

$$\mathrm{R_d} = (\mathrm{V'_d} \tan \delta_k) / \gamma_{Rh} \ \underline{\text{or}} \ \mathrm{R_d} = (\mathrm{A_c} \ c_{uk}) / \gamma_{Rh}$$

STR/GEO Ultimate limit states (ULS cntd)

Overall stability

Large eccentricities : special precautions if :

e/B > 1/3 (or 0,6 f)

Structural failure due to foundation movement

Structural design of spread foundation:
see EN 1992

STR/GEO persistent and transient design situations (spread foundations without geotechnical actions)

Design approach	Actions on/from the structure γ_F	Geotechnical resistance γ_R or γ_M at the source)
1	1,35 and 1,5	γ_{Rv} = 1,0 γ_{Rh} = 1,0
	1,0 and 1,3	γ_M = 1,25 or 1,4
2	1,35 and 1,5	γ_{Rv} = 1,4 γ_{Rh} = 1,1
3	1,35 and 1,5	γ_M = 1,25 or 1,4

Serviceability limit states (SLS)

Include both immediate and delayed settlements

Assess differential settlements and relative rotations

Check that limit values for the structure are not reached

Verifications to carry out for spread foundations

Direct method :

- check each limit states (ULS and SLS)
- check the settlement for the SLSs

Indirect method :

- only a SLS calculation based on experience

Prescriptive method : - example of the presumed bearing resistance on rocks (Annex G)

Annexes relevant to spread foundations in EN 1997-1

Annex A (normative) Safety factors for ultimate limit states

Informative annexes :

Annex D A sample analytical method for bearing resistance calculation

Annex E A sample semi-empirical method for bearing resistance estimation

Annex F Sample methods for settlement evaluation

Annex G A sample method for deriving presumed bearing resistance for spread foundations on rock

Annex H Limiting foundation movements and structural deformation

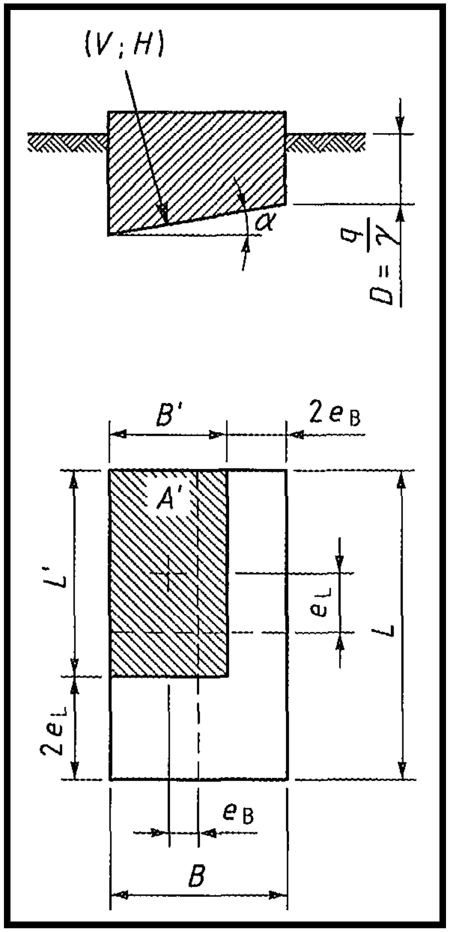
EN 1997-1 annexes D, E, F
Bearing capacity and settlement of foundations

"c-φ" model (annex D)

$$R/A' = c' \times N_c \times b_c \times s_c \times i_c$$
$$+ q' \times N_q \times b_q \times s_q \times i_q$$
$$+ 0{,}5 \times \gamma' \times B' \times N_\gamma \times b_\gamma \times s_\gamma \times i_\gamma$$

Pressuremeter model *(annexe E)*

$$R/A' = \sigma_{v0} + k \times p^*_{le}$$

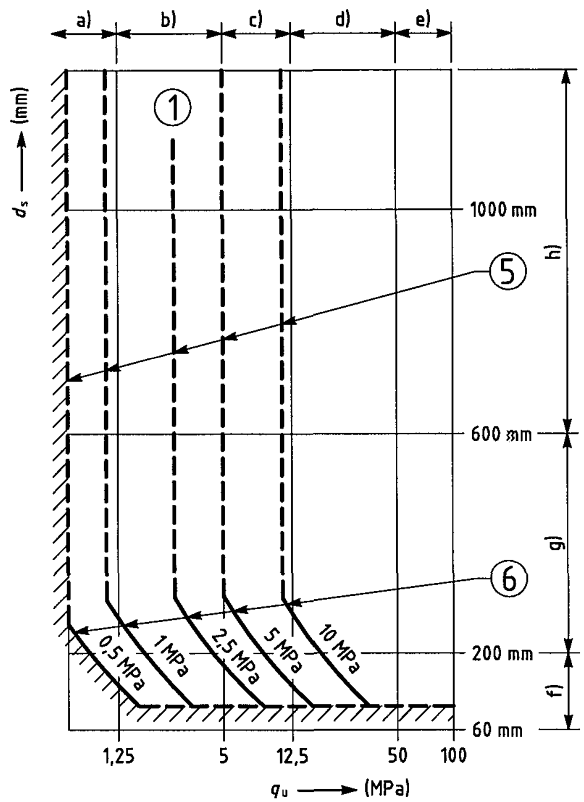


Settlement of foundations (Annex F)

$$s = p \times b \times f / E_m$$

EN 1997-1 annex G
Bearing resistance on rocks

Group	Type of rock
1	Pure limestones and dolomites Carbonate sandstones of low porosity
2	Igneous Oolitic and marly limestones Well cemented sandstones Indurated carbonate mudstones Metamorphic rocks, including slates and schist (flat cleavage/foliation)
3	Very marly limestones Poorly cemented sandstones Slates and schists (steep cleavage/foliation)
4	Uncemented mudstones and shales



5 Allowable bearing pressure not to exceed uniaxial compressive strength of rock if joints are tight or 50 % of this value if joints are open,

6 Allowable bearing pressures: a) very weak rock, b) weak rock c) moderately weak rock d) moderately strong rock, e) strong rock

Spacings: f) closely spaced discontinuities g) medium spaced discontinuities h) widely spaced dicontinuities

For types of rock in each of four groups, see Table G.1. Presumed bearing resistance in hatched areas to be assessed after inspection and/or making tests on rock. (from BS 8004)

Annexes relevant to spread foundations in EN 1997-2

Informative annexes :

D.3 Example of a method to determine the settlement for spread foundations from CPT
D.4 Example of a correlation between the oedometer modulus and the cone penetration resistance from CPT
D.5 Examples of establishing the stress-dependent oedometer modulus from CPT results
E.1 Example of a method to calculate the bearing resistance of spread foundations from PMT
E.2 Example of a method to calculate the settlements for spread foundations from PMT
F.3 Example of a method to calculate the settlement of spread foundations from SPT
G.3 Example of establishing the stress-dependent oedometer modulus from DP results
J Flat dilatometer test (DMT)
K.4 Example of a method to calculate the settlement of spread foundations in sand from (PLT)

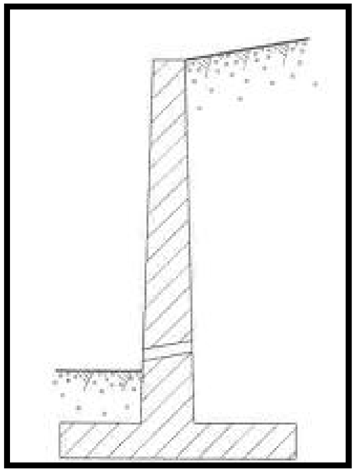
Retaining structures

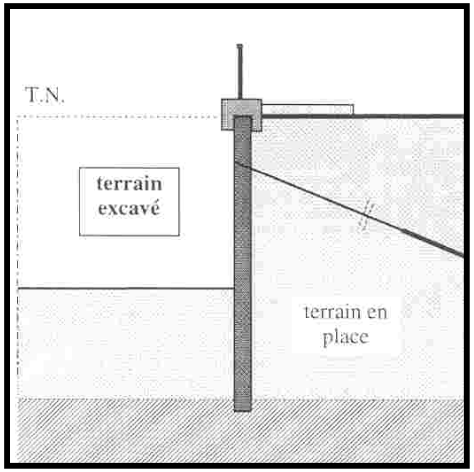
Scope of Eurocode 7 (Section 9)

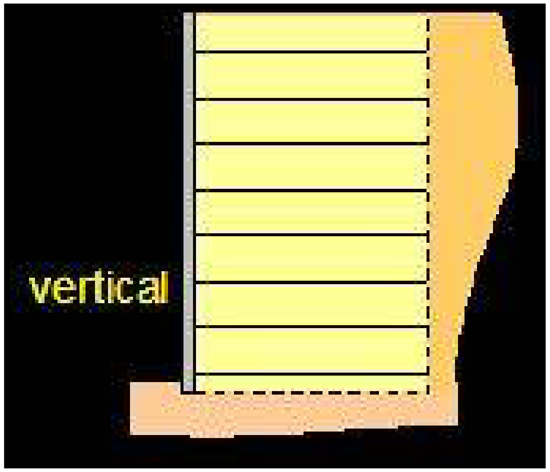
Gravity walls (in stone, concrete, reinforced concrete)

Embedded walls (sheet pile walls, slurry trench walls ; cantilever or supported walls)

Composite retaining structures (walls composed of elements, double wall cofferdams, reinforced earth structures)

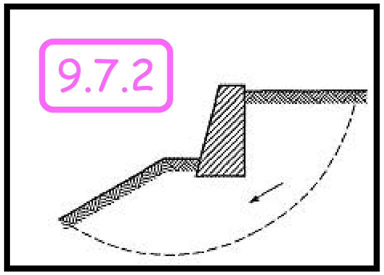




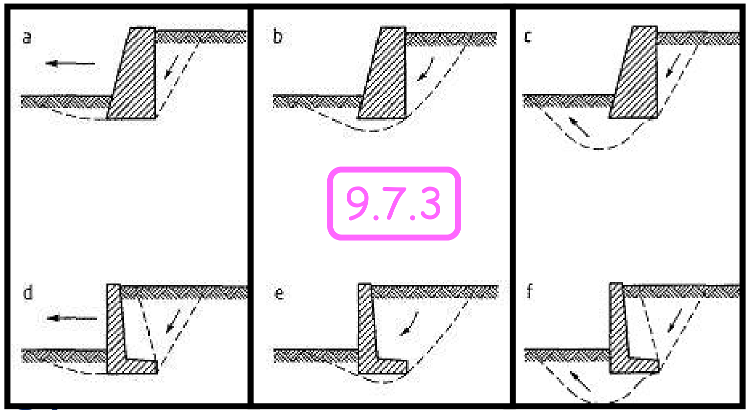


Ultimate limit states of gravity walls

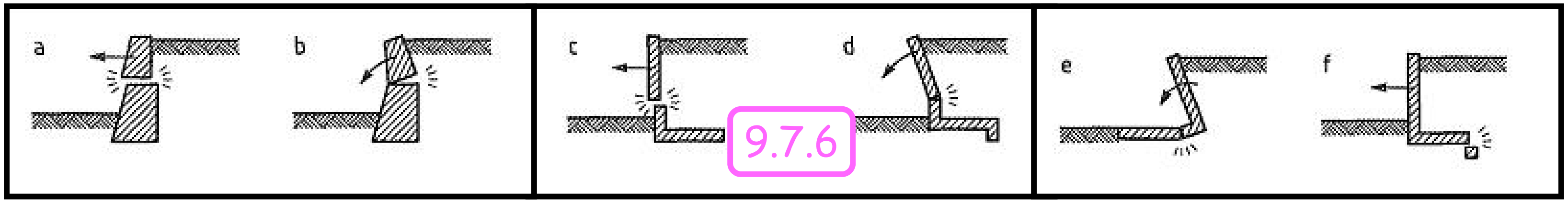
9.7.2 Overall stability
(principles of section 11)



9.7.3 Foundation failure of gravity walls (principles of section 6)



9.7.6 Structural design
(in accordance with
EC 2, EC 3, EC5 and EC6)



Geometrical data – clause 9.3.2

Ground surface

ULS with passive pressure (ie rotational failure): the level of the resisting soil depends on the degree of site control over the level of the surface

($\Delta a = 0$, if surface controlled, otherwise $\Delta a > 0$)

Recommended values Δa :

equal to 10 % of the wall height above excavation level , limited to a maximum of 0,5 m

Geometrical data – clause 9.3.2

Water levels

The water levels to be selected shall be based on the data for the hydraulic and hydrogeological conditions at the site

Nota : The variability of water levels is taken into account through the various design situations considered

Determination of earth pressures (clause 9.5)

Magnitudes and directions of forces resulting from earth pressures shall take account of

- the amount and direction of the relative ground-wall movement

- the horizontal as well as vertical equilibrium for the entire retaining structure

Range of inclinations recommended

< 2/3 φ (steel sheet piles) ; < φ (concrete cast against soil)

Allowed or recommended models :

At rest values : $K_0 = (1\text{-}\sin\varphi')(R_{oc})^{0,5}$

Limiting values : Caquot-Kérisel-Absi (Annex C)

Intermediate values (subgrade reaction, FEM)

Water pressures – clause 9.6

For structures retaining earth of medium or low permeability (silts and clays), water pressures shall correspond to a water table at the surface of the retained material, unless:
a reliable drainage system is installed or infiltration is prevented

Where sudden changes in a free water level may occur, both the non-steady condition occurring immediately after the change and the steady condition shall be examined.

STR/GEO : persistent and transient situations

The 3 Design Approaches – Format : $E_d < R_d$

Appro-aches	Combinations
1	A1 "+" M1 "+" R1 & A2 "+" M2 "+" R1 Or A2 "+" M1 or M2"+" R4
2	A1 "+" M1 "+" R2
3	A1 or A2 "+" M2 "+" R3

Action (γ_F)	Symbol	Set A1	Set A2
Permanent			
Unfavourable	γ_G	1,35	1,00
Favourable	γ_G	1,00	1,00
Variable			
Unfavourable	γ_Q	1,50	1,30
Favourable	γ_Q	0	0

Soil parameter (γ_M)	Symbol	Set M1	Set M2
Angle of shearing resistance	$\gamma_{\varphi'}$	1,00	1,25
Effective cohesion	$\gamma_{c'}$	1,00	1,25
Undrained shear strength	γ_{cu}	1,00	1,40
Unconfined strength	γ_{qu}	1,00	1,40
Weight density	γ_γ	1,00	1,00

Resistance (γ_R)	Symbol	Set R1	Set R2	Set R3
Bearing capacity	γ_{Rv}	1,0	1,4	1,0
Sliding resistance	γ_{Rh}	1,0	1,1	1,0
Earth resistance		1,0	1,4	1,0

← γ_R for Retaining structures

Serviceability limit states - SLS

Principle : P Design values of earth pressures shall be derived using characteristic values of all soil parameters

Displacement : The design shall be justified by a more detailed investigation including displacement calculations where :

- the initial estimate exceeds the limiting values,
- where nearby structures and services are unusually sensitive to displacement;
- where comparable experience is not well established.

Annexes relevant to retaining structures in EN 1997-1

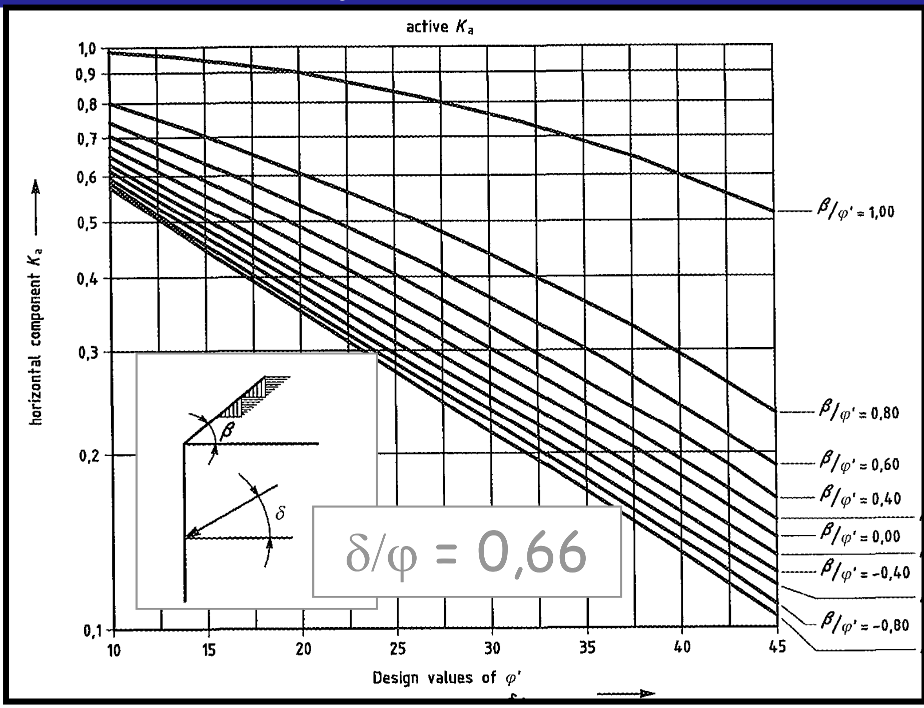
Annex A (normative) Safety factors for ultimate limit states

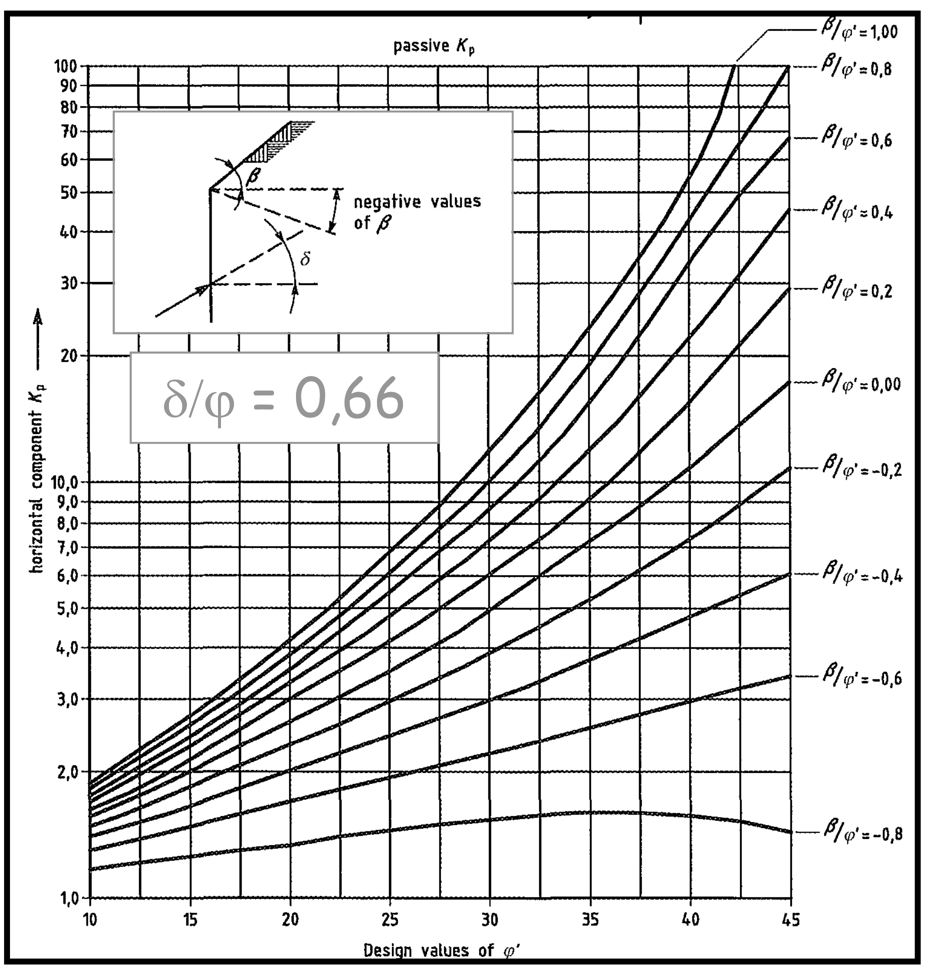
Informative annexes :

Annex C Limit values of earth pressures on vertical walls

Annex H Limiting foundation movements and structural deformation

Active /Passive earth pressures - annex C



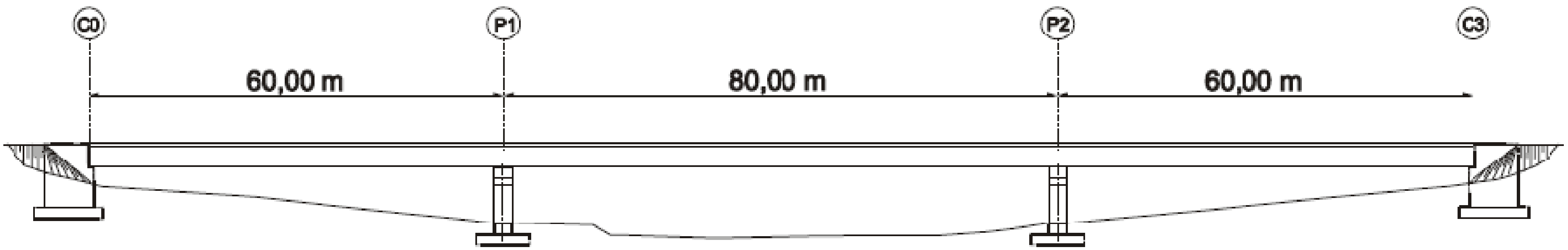


Active/Passive earth pressures

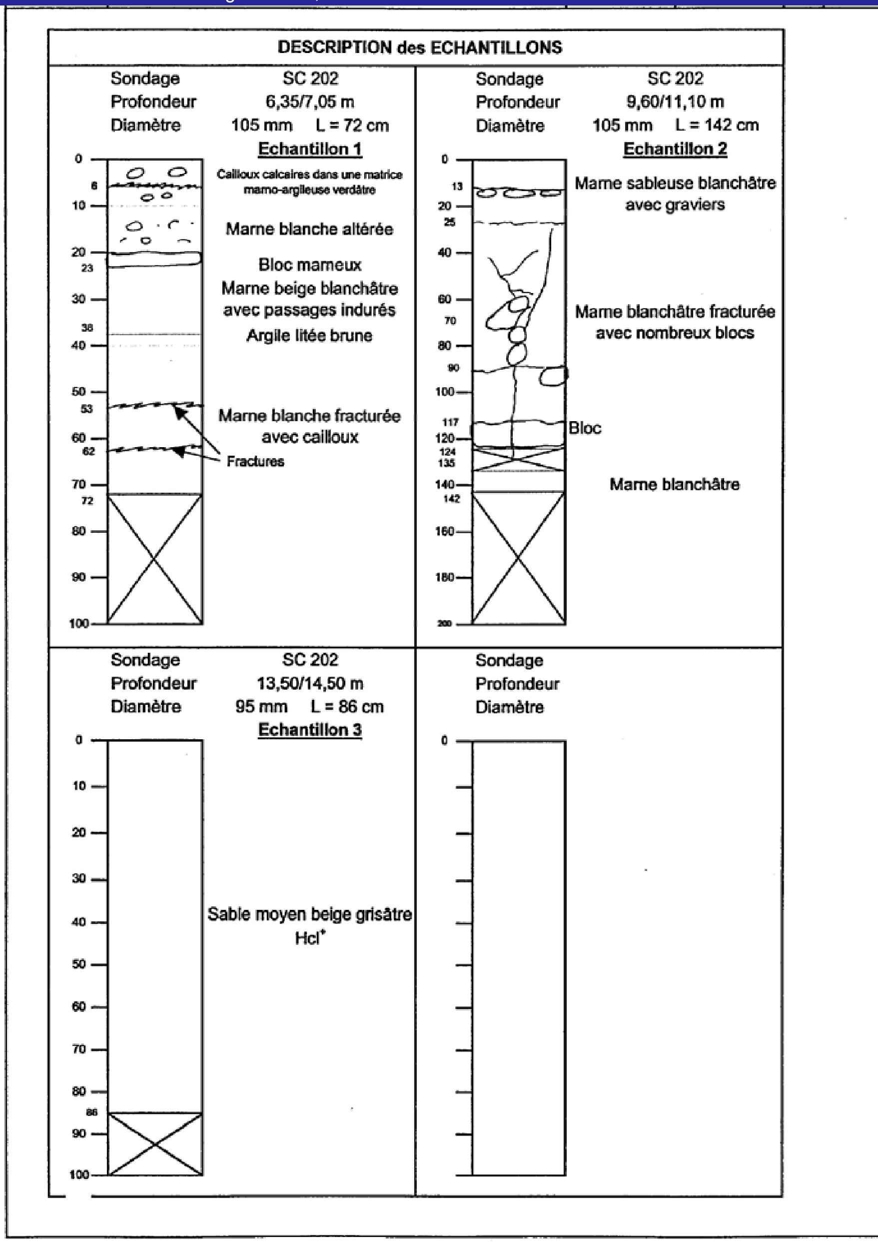
β = - φ à + φ

δ = 0 ; 2/3φ et φ

Bridge design

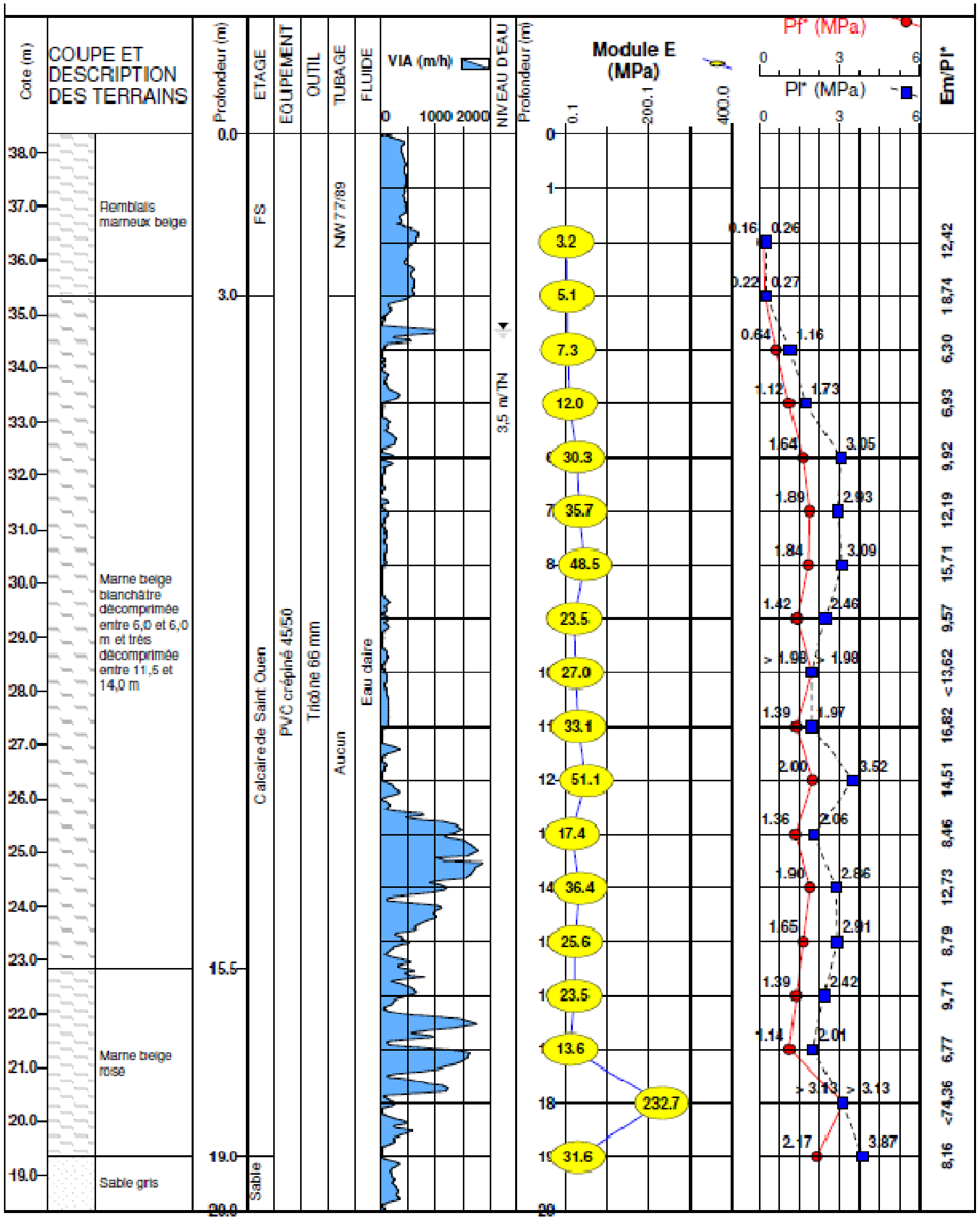


Geotechnical data



Identification of soils : core sampling results between abutment C0 and pier P1

Geotechnical data



Results of pressuremeter tests between abutment C0 and pier P1

Geotechnical data for C0 and P1

Normally fractured calcareous marl (at 2,5 m depth and 3 m depth):

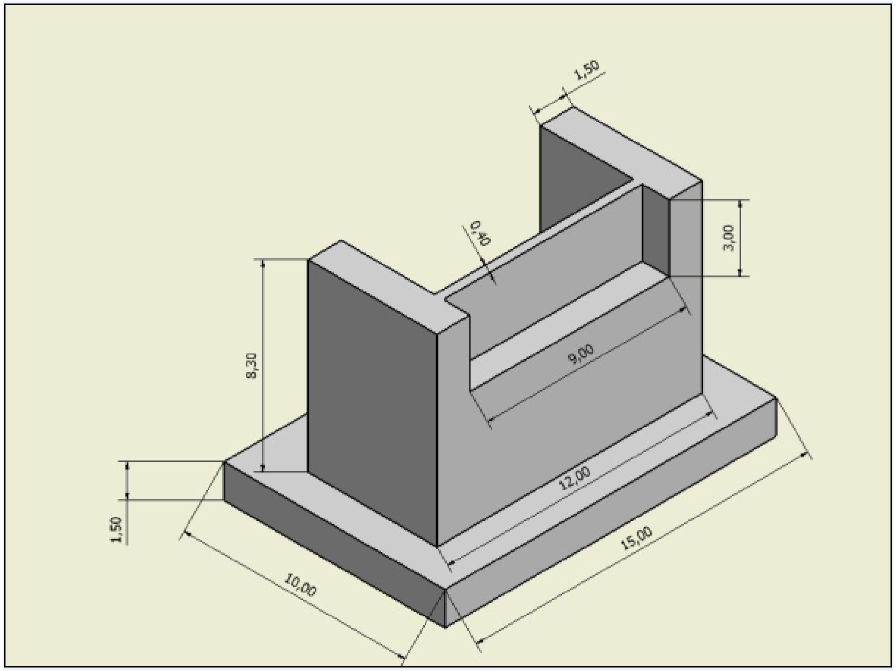
- $c'_{kg} = 0$
- $\varphi'_{kg} = 30°$
- $\gamma_{kg} = 20$ kN/m3

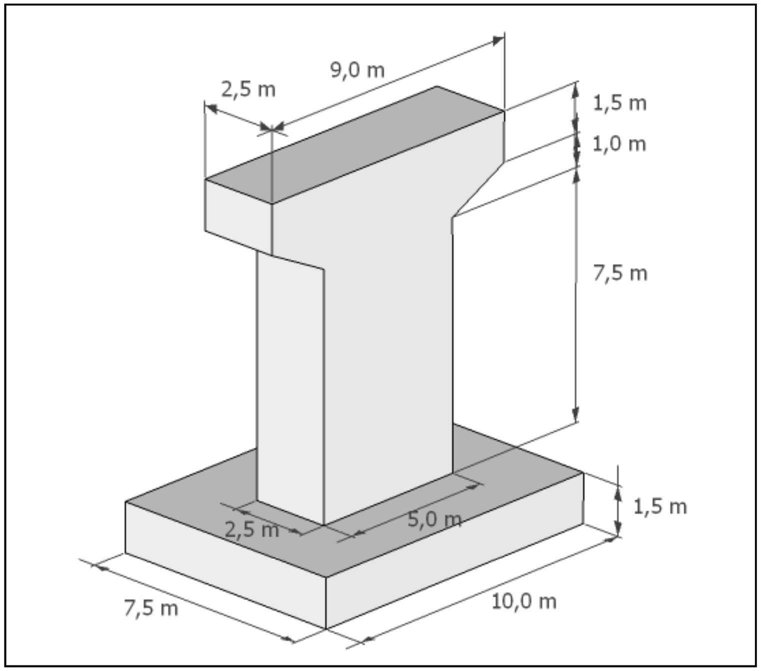
From ground level to base of foundation: $\gamma = 20 kN/m^3$.

Water level is assumed to be one metre below the foundation level in both cases.

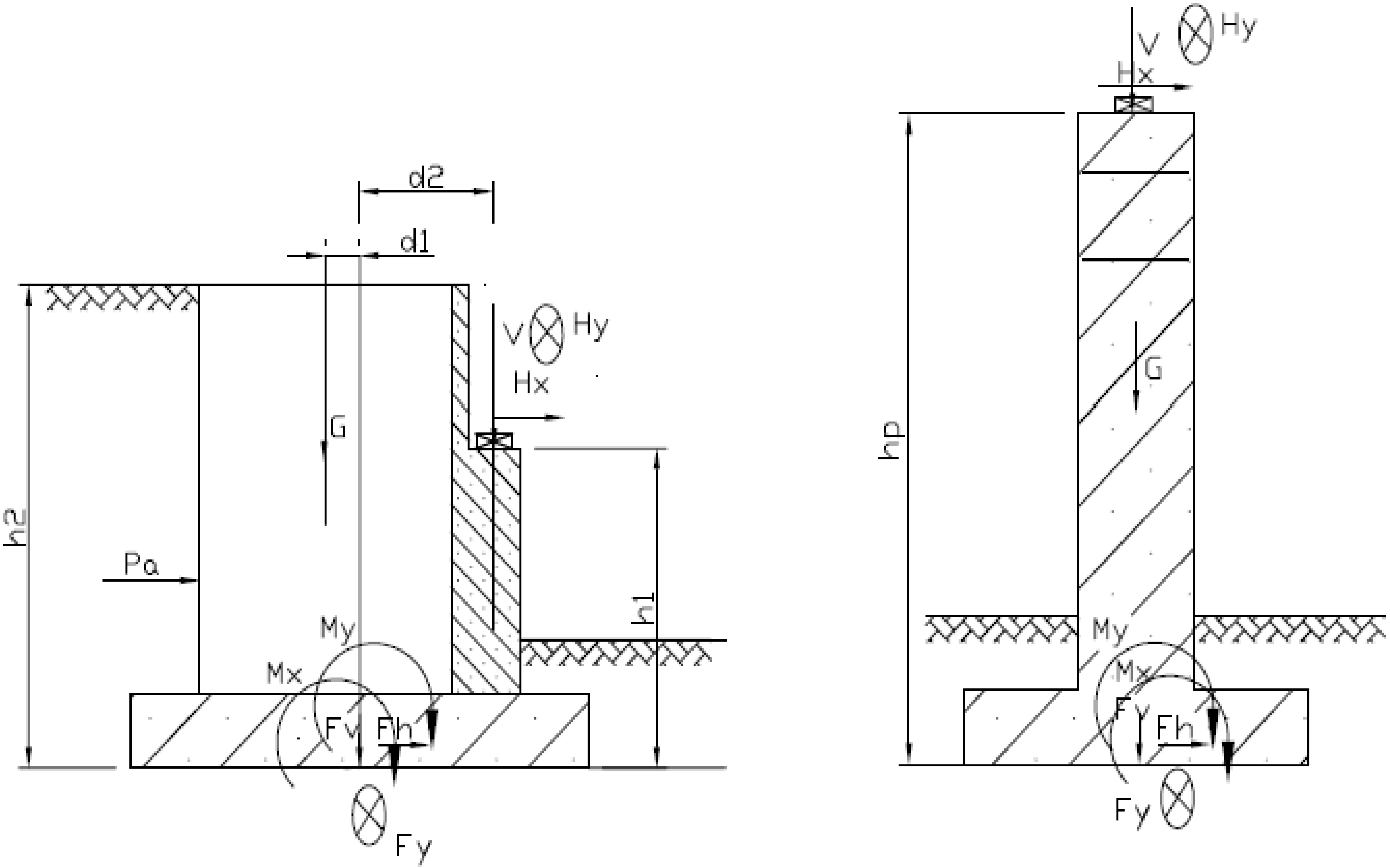
Fill material : - $c'_{kf} = 0$; $\varphi'_{kf} = 30°$; $\gamma_{kf} = 20\ kN/m^3$

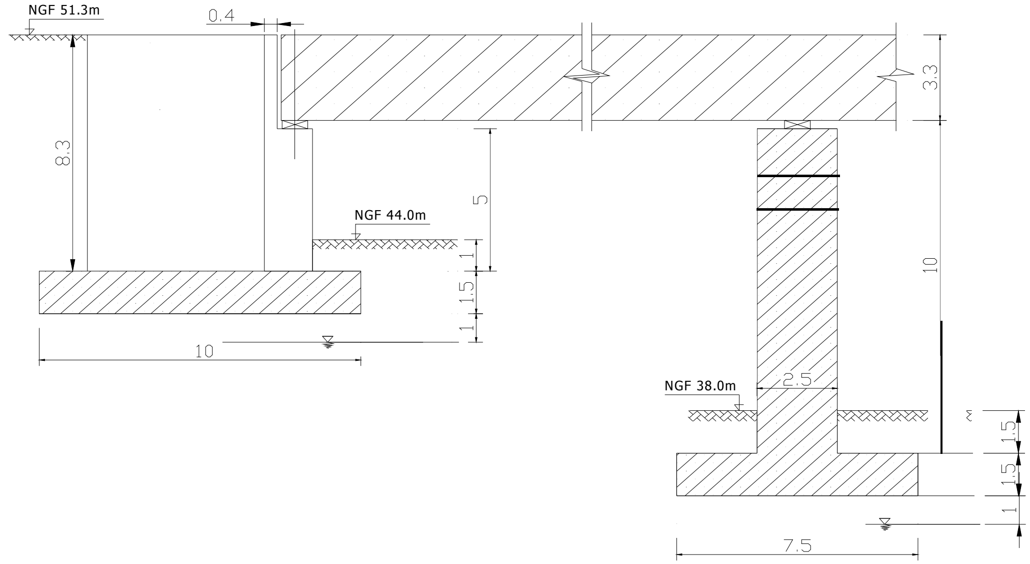
Abutment C0 and pier P1 (squat pier)

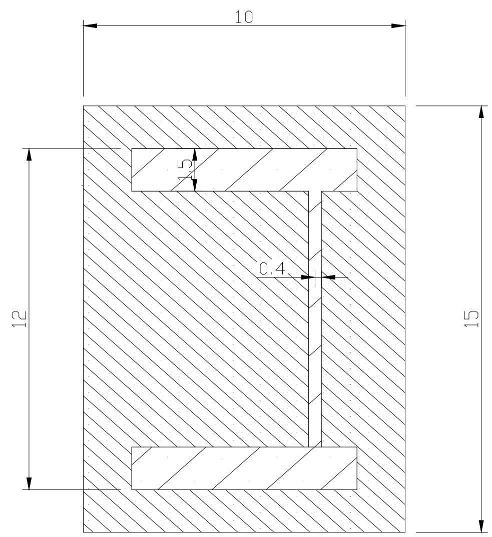


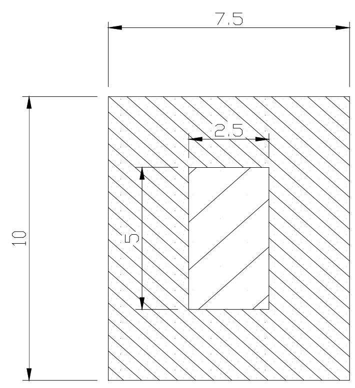


Forces and notations




NGF 51.3m
0.4
8.3
3.3
5
NGF 44.0m
1
1.5
1
10
10
NGF 38.0m
2.5
1.5
1.5
1
7.5


10
1.5
0.4
12
15


7.5
2.5
5
10

Support reactions for static analysis (Davaine, Malakatas)

Table 1. Vertical 'structural' actions for half of the bridge deck (Davaine, 2010b et c)

Load cases	Designation	C0 (MN)	P1 (MN)
Self weight (structural steel + concrete)	$G_{k,1}$	1.1683	5.2867
Nominal non structural equipments	$G_{k,2}$	0.39769	1.4665
3 cm settlement on support P1	S_k	0.060	-0.137
Traffic UDL	$Q_{vk,1}$ max/min	0.97612/-0.21869	2.693/-0.15637
Traffic TS	$Q_{vk,2}$ max/min	0.92718/-0.11741	0.94458/-0.1057

Horizontal traffic action effects

The horizontal longitudinal reactions $Q_{xk,1} + Q_{xk,2}$ on abutments and piers due to traffic loads UDL and TS are, for half of the bridge deck (Davaine, 2010b) :

	min	max	
Braking :	-0,90658	0	MN
Acceleration :	0	0,90658	MN

Support reactions for static analysis (Davaine, Malakatas)

Transverse horizontal wind action effects (Malakatas, 2010 and Davaine 2010c)

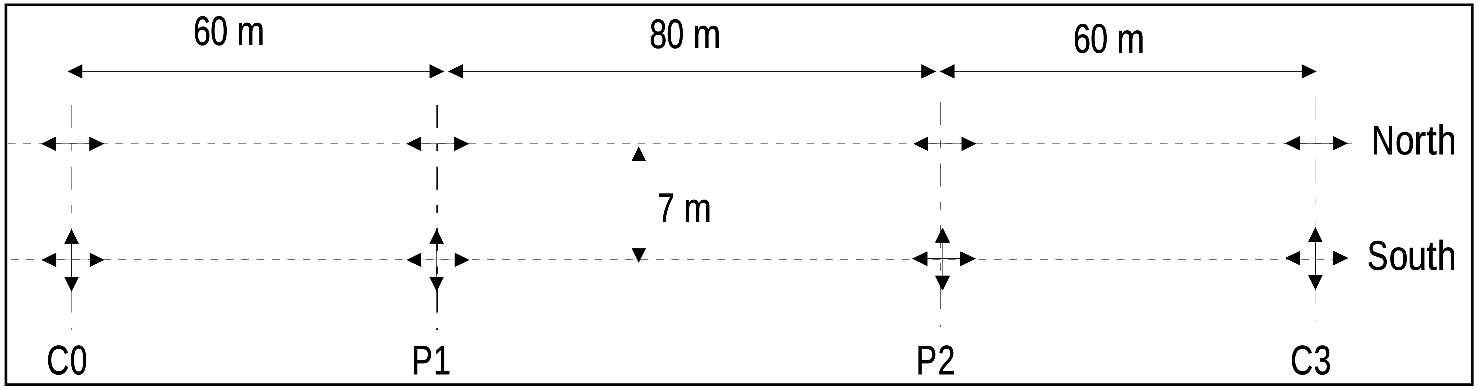


Fig. 7. Displacement conditions of the bridge (Davaine, 2010b and 2010c)

Table 2. Transverse horizontal variable actions H_{ykw} due to wind (Davaine, 2010c)

Transverse horizontal force H_y due to:	C0	P1
$F_{wk,1}$ without traffic load	164 kN	596 kN
$F_{wk,2}$ with traffic load	206.7 kN	751.3 kN

Abutment C0

- **ULS - Bearing capacity**
- **ULS – Sliding resistance**

C0 – ULS Bearing capacity

Geotechnical actions

Weight of the wall : $G_{wall,k} = 26.4$ MN

Active earth pressure:

$P_{ad} = \gamma_{G,sup} \times 0,5\ K_{ad}\ \gamma_{kf} h_2^2 L_a$

$K_{ad} = \tan(\pi/4 - \varphi_{df}/2)^2$

- for DA1-1 and DA2 : $\varphi_{df} = \varphi_{kf} = 30°$; $K_{ad} = 0,333$
  $\gamma_{kd} = \gamma_{kf} = 20$ kN/m^3 and
  $P_{ad} = 1.35 \times 3,84 = 5.18$ MN
- for DA1-2 and DA3 : $\tan \varphi_{df} = (\tan \varphi_{kf})/1.25 = \tan 30°/1.25$ and $\varphi_{df} = 24.8°$;
  $K_{ad} = 0,409$ and $P_{ad} = 1.00 \times 4,71 = 4.71$ MN

C0 – ULS Bearing capacity

Resultant actions

$$F_v = V + G_{wall}$$
$$F_x = H_x + P_a$$
$$F_y = H_y$$
$$M_y = P_a(h_2/3) + H_x h_1 – G_{wall} d_1 + Vd_2$$
$$M_x = H_y h_1$$

Resistance

$$R = (B\text{-}2e_B).\ (L\text{-}2e_L)\ \{q' N_q(\varphi')s_q i_q + 0{,}5\gamma'(B\text{-}2e_B)N_\gamma(\varphi')s_\gamma i_\gamma\}$$

and $R_d = R / \gamma_{R;v}$

C0 – ULS Bearing capacity

For DA1-1 : $\varphi'_{dg} = \varphi'_{kg} = 30°$

$F_{vd} = 9.88 + 35.64 = 45.52$ MN

$F_{xd} = 2.43 + 5.18 = 7.61$ MN

$F_{yd} = 0.19$ MN

$\gamma_{R;v} = 1.0$

Thus, $e_B = 1.04$ m, $e_L = 0.03$ m and $R_d = 150.2/1.0 = 150.2$ MN

For DA1-2 : $\tan \varphi'_{dg} = (\tan \varphi'_{kg})/ 1.25$, thus $\varphi'_{dg} = 24.8°$

$F_{vd} = 7.86 + 26.4 = 34.26$ MN

$F_{xd} = 2.07 + 4.71 = 6.78$ MN

$F_{yd} = 0.16$ MN

$\gamma_{R;v} = 1.0$

Thus, $e_B = 1.21$ m, $e_L = 0,03$ m and $R_d = 67.3/1.0 = 67.3$ MN

For DA2 : $\varphi'_{dg} = \varphi'_{kg} = 30°$

$F_{vd} = 9.88 + 35.64 = 45.52$ MN

$F_{xd} = 2.43 + 5.18 = 7.61$ MN

$F_{yd} = 0.19$ MN

$\gamma_{R;v} = 1.4$

Thus, $e_B = 1.05$ m, $e_L = 0,03$ m and $R_d = 150.2/1.4 = 107.3$ MN

For DA3 : $\tan \varphi'_{dg} = (\tan \varphi'_{kg})/ 1.25$, thus $\varphi'_{dg} = 24.8°$

$F_{vd} = 9.88 + 35.64 = 45.52$ MN

$F_{xd} = 2.43 + 4.71 = 7.14$ MN

$F_{yd} = 0.19$ MN

$\gamma_{R;v} = 1.0$

Thus, $e_B = 1.01$ m, $e_L = 0.03$ m and $R_d = 79.6/1.0 = 79.6$ MN

C0 – ULS Bearing capacity

$F_{vd} \leq R_d$

- fulfilled for all Design Approaches
- for DA1, combination 2 is governing
- DA3 the most conservative approach

All eccentricities are small: the maximum is $e_B = 1.21$ m

C0 – ULS Sliding resistance

$F_{xd} \leq R_d + R_{p;d}$

where

F_{xd} horizontal component in the longitudinal direction
R_d is the sliding resistance
$R_{p;d}$ is the passive earth force in front of the spread foundation.

$R_d = \{F'_{vd} (\tan\delta_k)/\gamma_M\}/\gamma_{R;h}$

where

- F'_{vd} favourable effective vertical force
- δ_d is the concrete-ground friction angle, assumed $\delta_k = 2/3\ \varphi_{kg}$

C0 – ULS Sliding resistance

Actions

$F'_{vd} = V_{d,min} + G_{wall,d}$

- for DA1-1, DA2 and DA3 : $V_{d,min} = G_{k,1}+0.8364\ G_{k,2}+1.35(Q_{vk,1}+ Q_{vk,2})$ =1.047 x 2 = 2.09 MN

- for DA1-2 : $V_{d,min} = G_{k,1}+0.8364\ G_{k,2}+1.15\ (Q_{vk,1}+Q_{vk,2})$ =1.114 x 2 = 2.23 MN

- and for all DAs : $G_{wall,d} = 1.0\ G_{wall,k}$ = 26.4 MN

DA1-1 : F_{xd} = 7.61 MN and F'_{vd} = 2.09 + 26.4 = 28.49 MN

DA1-2 : F_{xd} = 6.78 MN and F'_{vd} = 2.23 + 26.4 = 28.63 MN

DA2 : F_{xd} = 7.61 MN and F'_{vd} = 2.09 + 26.4 = 28.49 MN

DA3 : F_{xd} = 7.14 MN and F'_{vd} = 2.09 + 26.4 = 28.49 MN

Sliding resistances

DA1-1 : γ_M = 1.0 and $\gamma_{R;h}$ = 1.0, thus R_d = {28.49 x 0.364/1.0} /1.0 = 10.37 MN

DA1-2 : γ_M = 1.25 and $\gamma_{R;h}$ = 1.0, thus R_d = {28.63 x 0.364/1.25}/1.0 = 8.33 MN

DA2 : γ_M = 1.0 and $\gamma_{R;h}$ = 1.1, thus R_d = {28.49 x 0.364/1.0} /1.1 = 9.42 MN

DA3 : γ_M = 1.25 and $\gamma_{R;h}$ = 1.0, thus R_d = {28.49 x 0.364/1.25}/1.0 = 8.29 MN

Pier P1 (squat pier)

- **ULS - Bearing capacity (DA2 only)**
- **SLS – Settlement**

P1 – ULS Bearing capacity

$G_{pier,k} = 8.3$ MN

for DA2 :

$G_{pier,d} = 1.35 \times 8.3 = 11.2$ MN

At base of foundation :

$$F_v = V + G_{pier}$$
$$F_x = H_x$$
$$F_y = H_y$$
$$M_y = H_x h_p$$
$$M_x = H_y h_p$$

P1 – ULS Bearing capacity

For DA2 : F_{vd} = 28.9 + 11.2 = 40.1 MN
F_{xd} = 2.45 MN
F_{yd} = 0.68 MN

one obtains, for DA 2 :
e_B= 0.70 m, e_L = 0.20 m and R_k = 101.2 MN and
$R_d = R=/\gamma_{R;v}$ = 101.2/1.4 = 72.3 MN

The ULS condition in permanent and transient design situation $F_{vd} \leq R_d$ is fulfilled,
as 40.1 MN < 72.3 MN.

P1 – SLS Settlement

SLS-QP combination:

Q = $G_{k,1}$ + $G_{k,2}$ = (5.2867 + 1.4665) x 2 = 6.75 x 2
= 13.5 MN

Ménard pressuremeter (MPM) method is used (Annex D2 of EN 1997-2)

The settlement is expressed as :

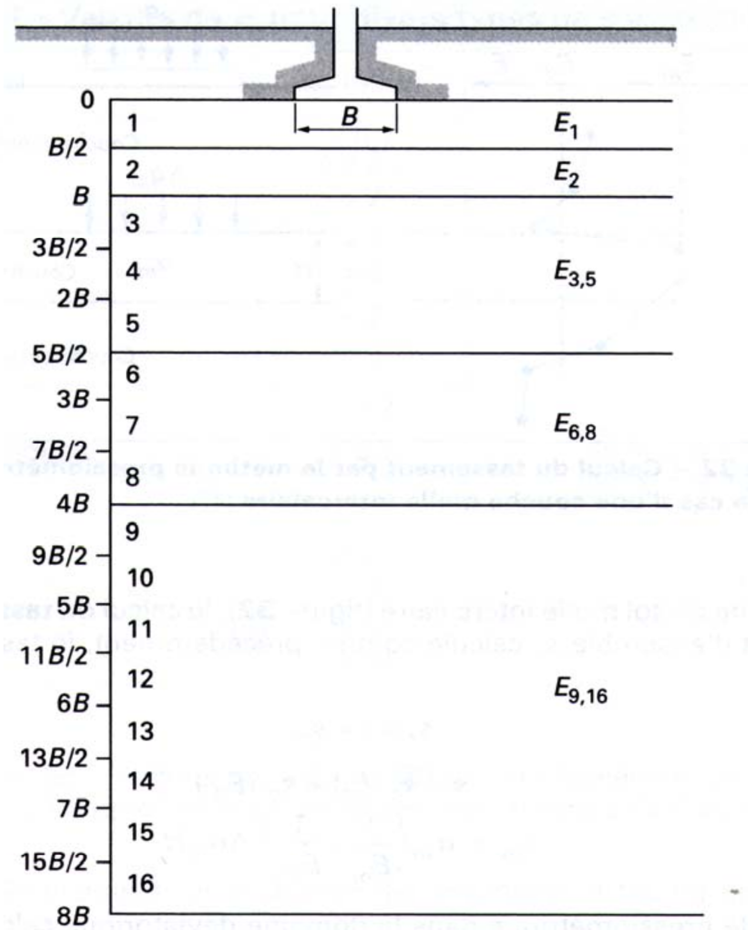
$$s = \left(q - \sigma_{v0}\right) \times \left[\frac{2B_0}{9E_d} \times \left(\frac{\lambda_d B}{B_0} \right)^a + \frac{\alpha \lambda_c B}{9E_c} \right]$$

Selection of moduli E_C and E_D

$$E_c = E_1$$

$$\frac{4}{E_d} = \frac{1}{E_1} + \frac{1}{0{,}85\ E_2} + \frac{1}{E_{3,5}} + \frac{1}{2{,}5\ E_{6,8}} + \frac{1}{2{,}5\ E_{9,16}}$$

$$\frac{3{,}0}{E_{3,5}} = \frac{1}{E_3} + \frac{1}{E_4} + \frac{1}{E_5}$$



Or

$$\frac{3{,}6}{E_d} = \frac{1}{E_1} + \frac{1}{0{,}85\ E_2} + \frac{1}{E_{3,5}} + \frac{1}{2{,}5\ E_{6,8}}$$

Or

$$\frac{3{,}2}{E_d} = \frac{1}{E_1} + \frac{1}{0{,}85\ E_2} + \frac{1}{E_{3,5}}$$

P1 – SLS Settlement

$s = (0.18 – 0.06) [1.2 (1.26x7.5/0.6)^{0.5} /(9x14.65) + 0.5x1.13x7.5/9x7.3]$

$= 0.12 [0.036 + 0.065] = 0.012$ m = 12 mm,

(preliminary rough estimate, with $E_c = E_d = 6$ MPa $\sigma_{vo} = 0$: s = 0.030 m = 3 cm!)

Seismic design situations (EN 1998-5)

- no liquefiable layer – see Figs. 2 and 3

Annexes in Eurocode 8 – Part 5:
- Annex E (Normative) 'Simplified analysis for retaining structures',
- Annex F (Informative) 'Seismic bearing capacity of shallow foundations'

A_{ED} seismic action effects come from the capacity design of the superstructure (see Kolias 2010a and 2010b)

The recommended values of γ_M seem very conservative:
γ_{cu} = 1,4, $\gamma_{\tau cu}$ = 1,25, γ_{qu} = 1,4, and $\gamma_{\phi'}$ = 1,25.

The NA for Greece, for instance, requires : all γ = 1,0 !

and to conclude :

It should be considered that knowledge of the ground conditions depends on the extent and quality of the geotechnical investigations. Such knowledge and the control of workmanship are usually more significant to fulfilling the fundamental requirements than is precision in the calculation models and partial factors.

Thank you for your kind and patient attention !