COMITÉ FRANÇAIS DE MÉCANIQUE DES SOLS ET DE GÉOTECHNIQUE

ACADÉMIE DES SCIENCES
INSTITUT DE FRANCE

ACADÉMIE DES TECHNOLOGIES
POUR UN PROGRÈS RAISONNÉ, CHOISI ET PARTAGÉ

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LES TRAVAUX PUBLICS FÉDÉRATION NATIONALE

Charles-Augustin COULOMB - A geotechnical tribute

Paris, september 25 & 26, 2023

Workshop #1: Design methods for retaining walls

Design of gravity walls: 50 years of French practice

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Content

1. Main evolution stages for the design of gravity walls
2. The approach of the virtual back
3. Calculation of active earth pressures
4. Limit state consideration
5. Conclusions and Perspectives

Design of gravity walls: main stages during 50 years

1. Years 1960/1970: development of methods for the design of gravity walls in line with the construction of highway infrastructure (MUR 73)

2. Years 1980/1990: evolution of the shallow foundation design (DTU 13.12, Fascicule 62 Titre V)

3. Years 1990/2000: development of a specific method for the gravity walls with the perspective of the Eurocodes (Ad Hoc Group / French Expert Group)

4. Years 2000/2010: development of the national standard for the implementation of the Eurocode 7 in France (NF P 94-281)

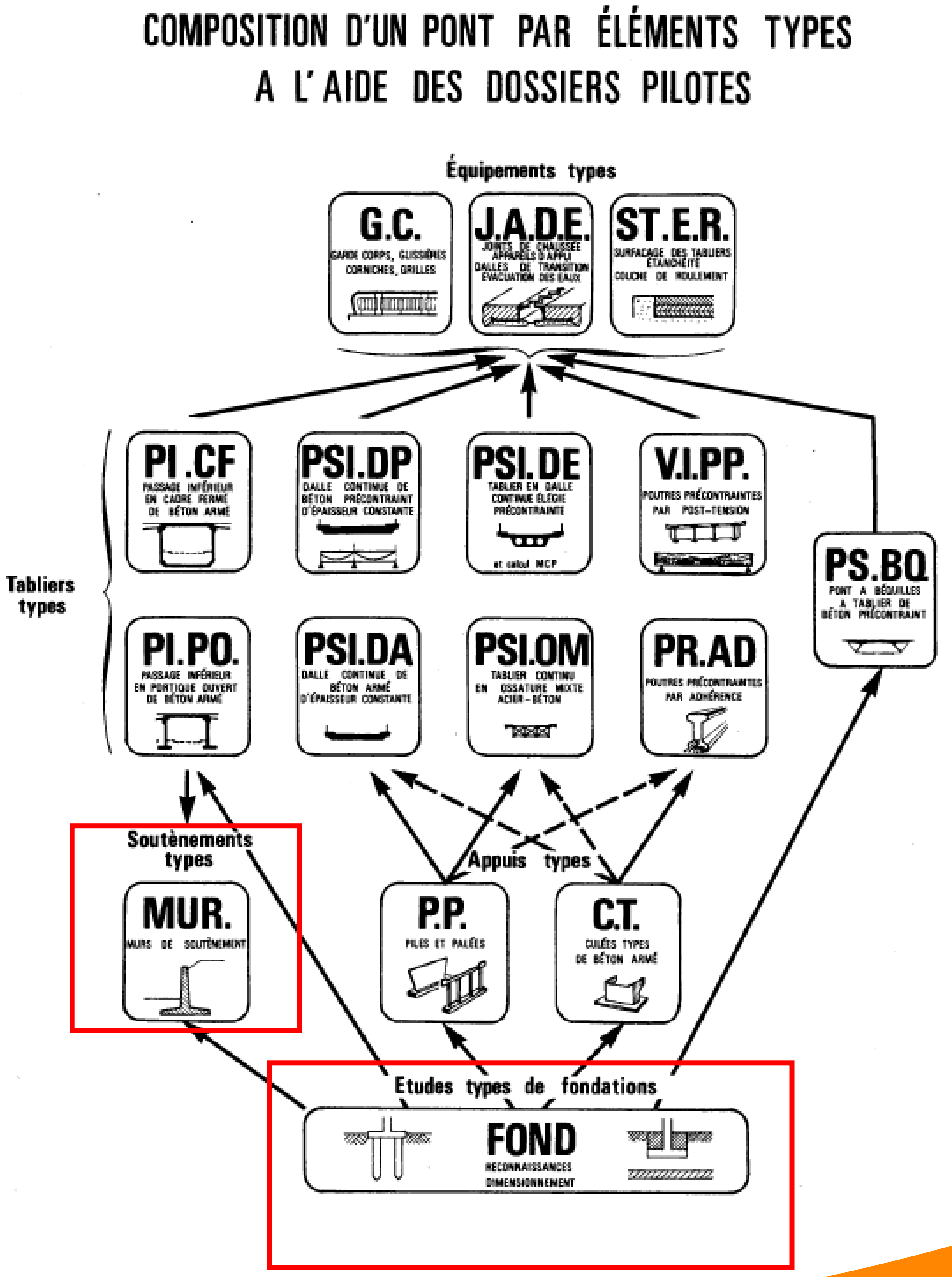
1970s: Construction of highway infrastructure

1. Public policy for the rapid and huge development of highway infrastructure

2. The objective is to have a design method for an industrial policy: relevancy, reliability and robustness

→ Need of efficiency

1. Establishment of standard procedure for the design of structures (SETRA and LCPC)
   - Identification of typical structures or typical part of structures
   - Elaboration of a specific verification method for each specific structure:
     - Background report with prescriptions and explanations to assist the designer
     - First dedicated softwares

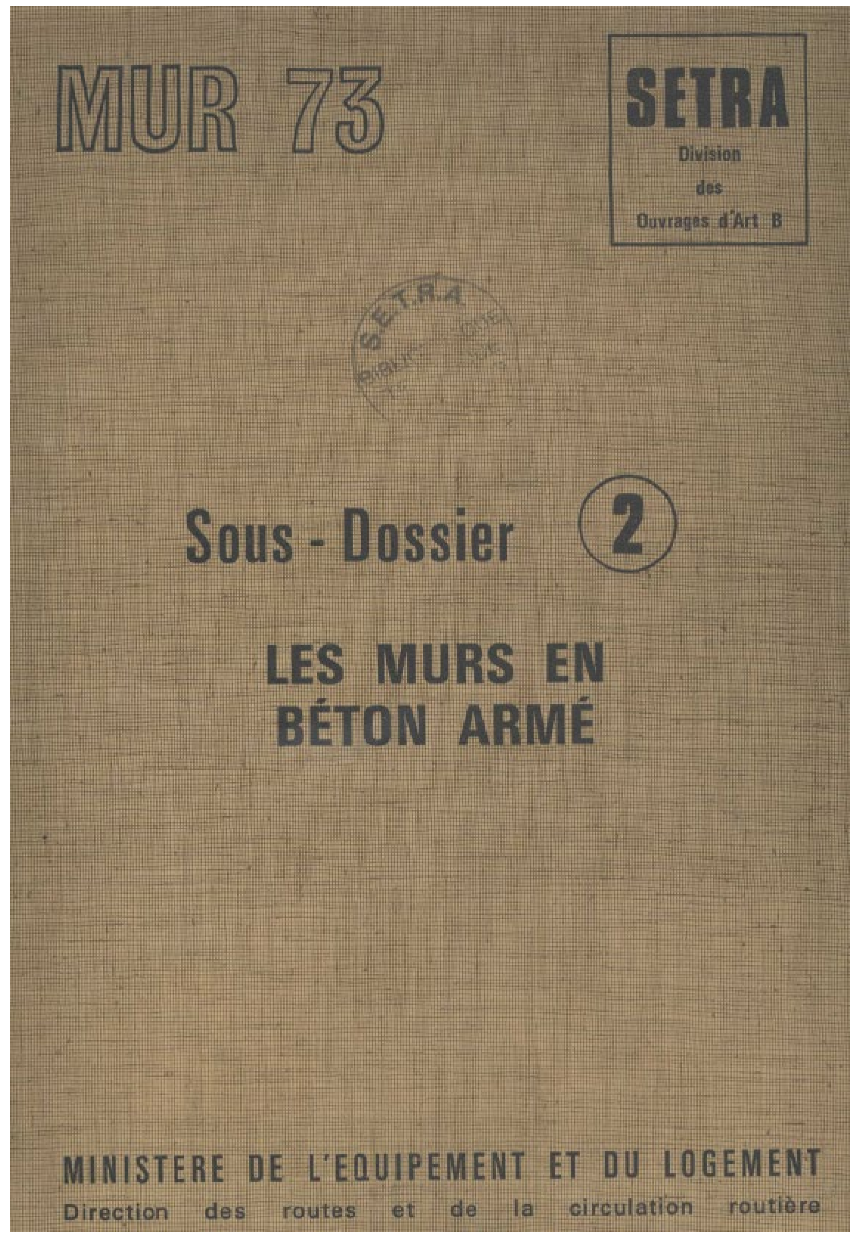


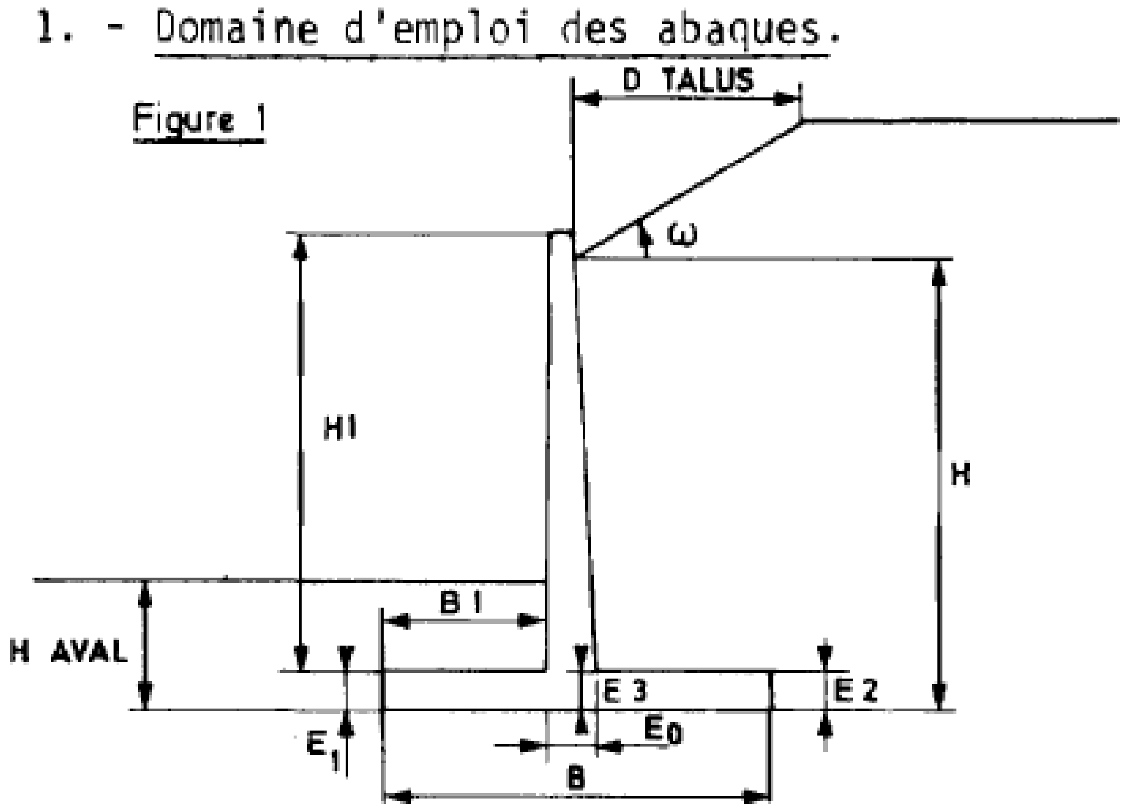
1970s: MUR73 for the design of gravity walls

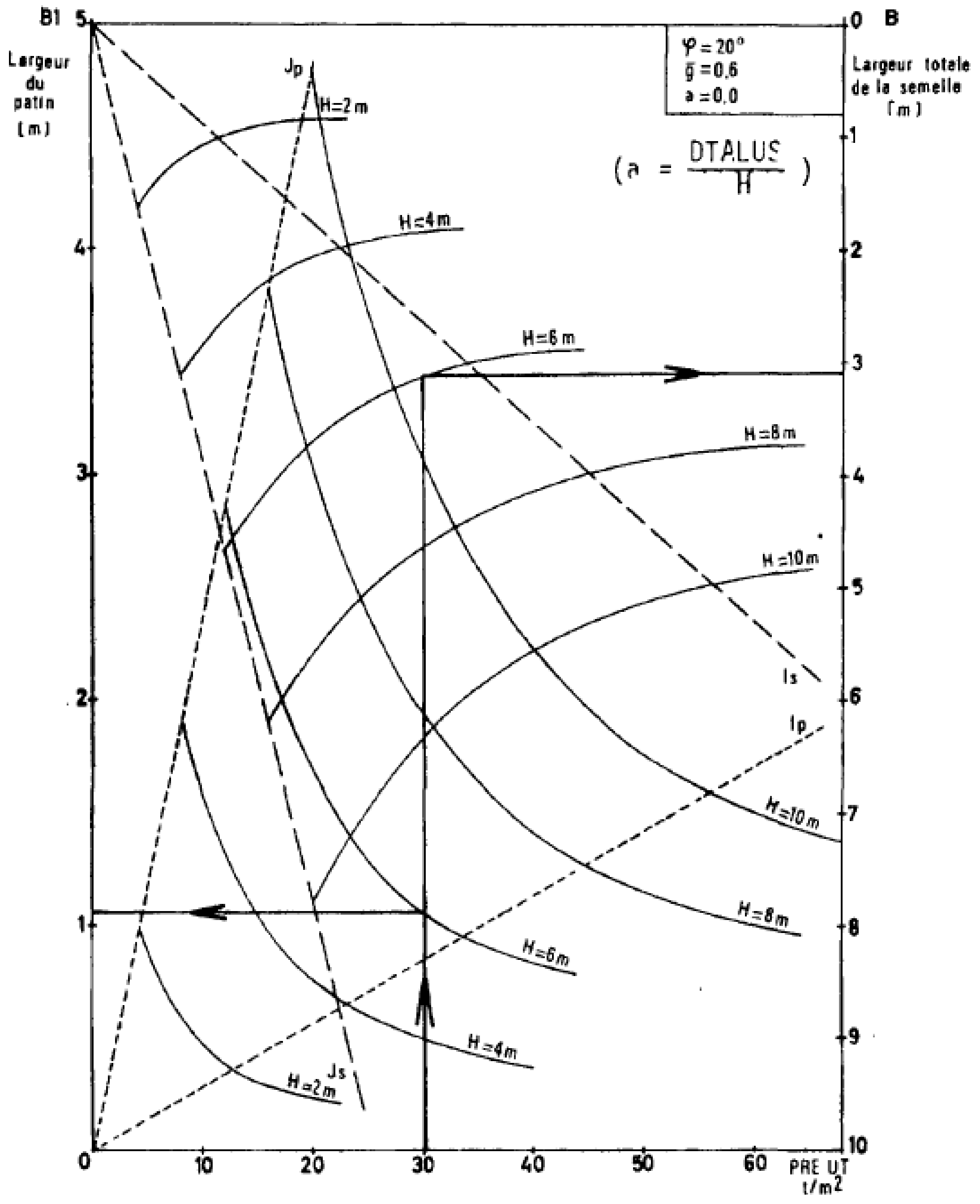
Before: only theortical soil mechanics books without practical calculation method or standard → Each wall is different

Content of MUR73:

- •Overview of calculation methods (including active earth pressureassessment)
- •Detailed method of the gravity walls linked to bridges (wing walls)
- •Design charts
- •Interaction with FOND72 (the first French standard for foundation design)



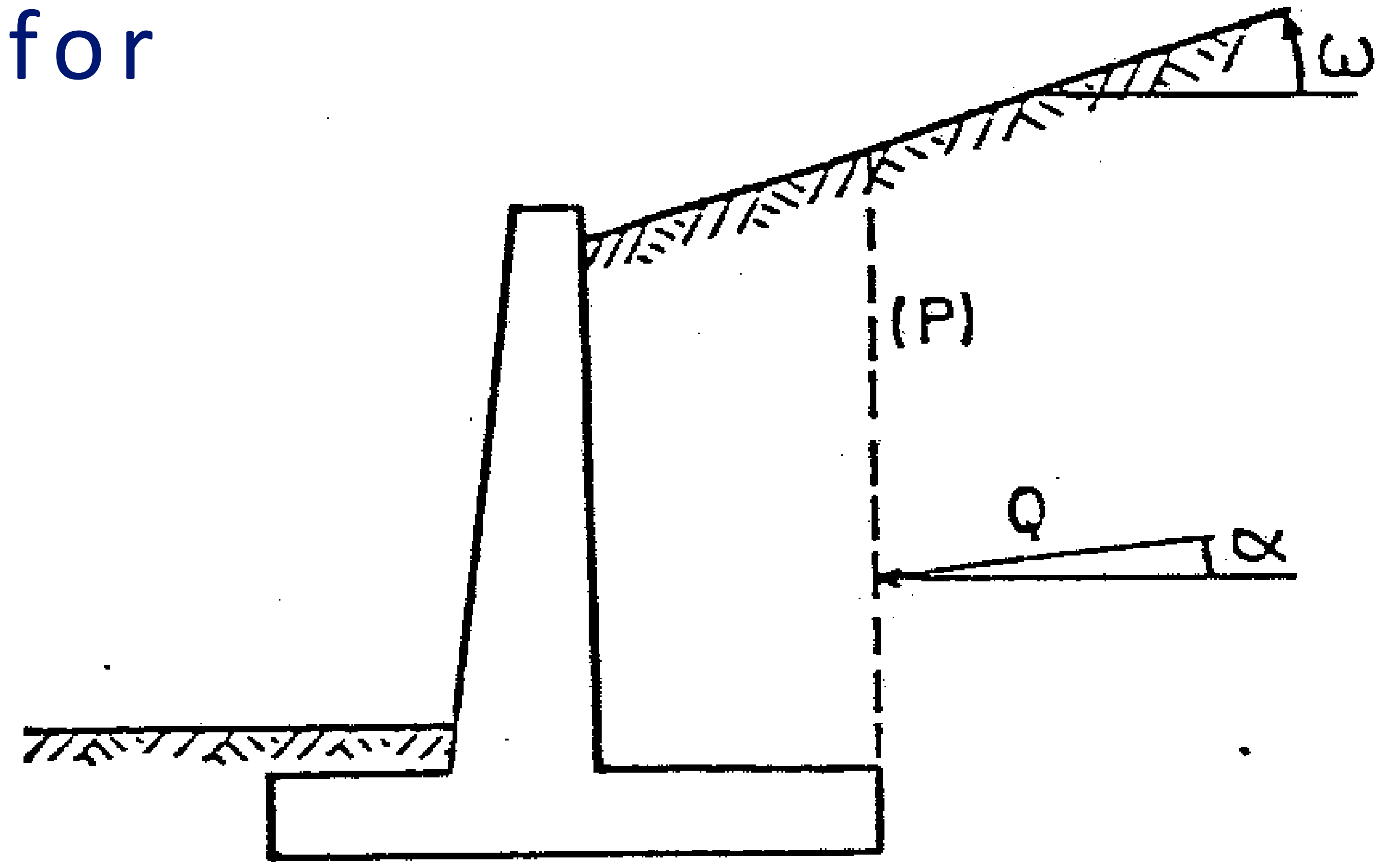




1970s: MUR73 for the design of gravity walls

Main influences for the choice of a method for the gravity walls:

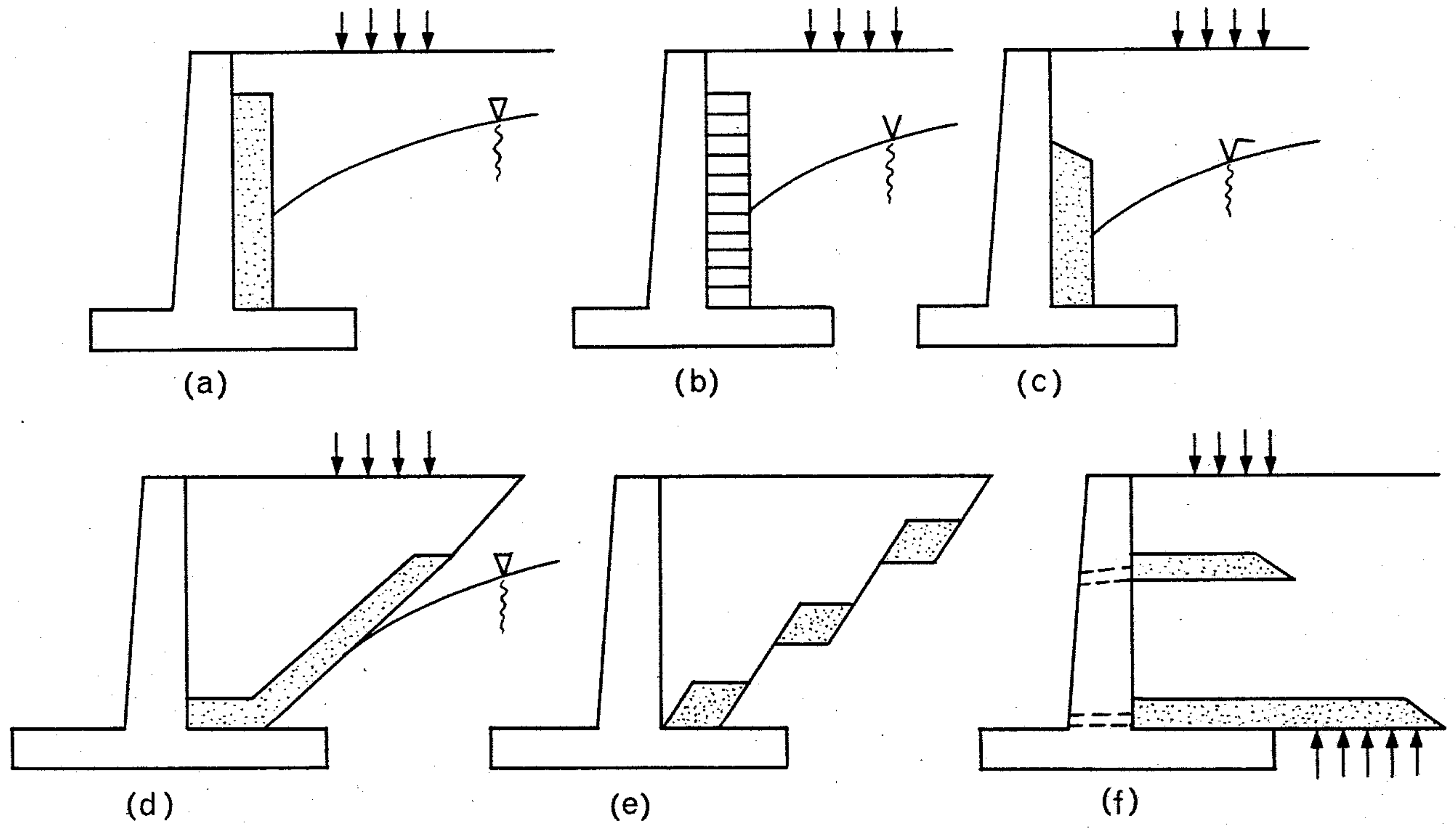
- First approaches for the calculation with limit state framework (Directives Communes de la Construction : DCC 1971): active earth pressures are modified by considering +/-25% for compaction effects, +/- 20 % for shear properties, +/-15 % for density.
- Earth pressure:
  - Caquot-Kerisel or Coulomb
  - Introduction of the virtual back with adaptation of the stress inclination (α)
- Bearing capacity:
  - From laboratory tests
  - From *in-situ* tests
  - Introduction of inclination reduction factor



1970s: MUR73 for the design of gravity walls

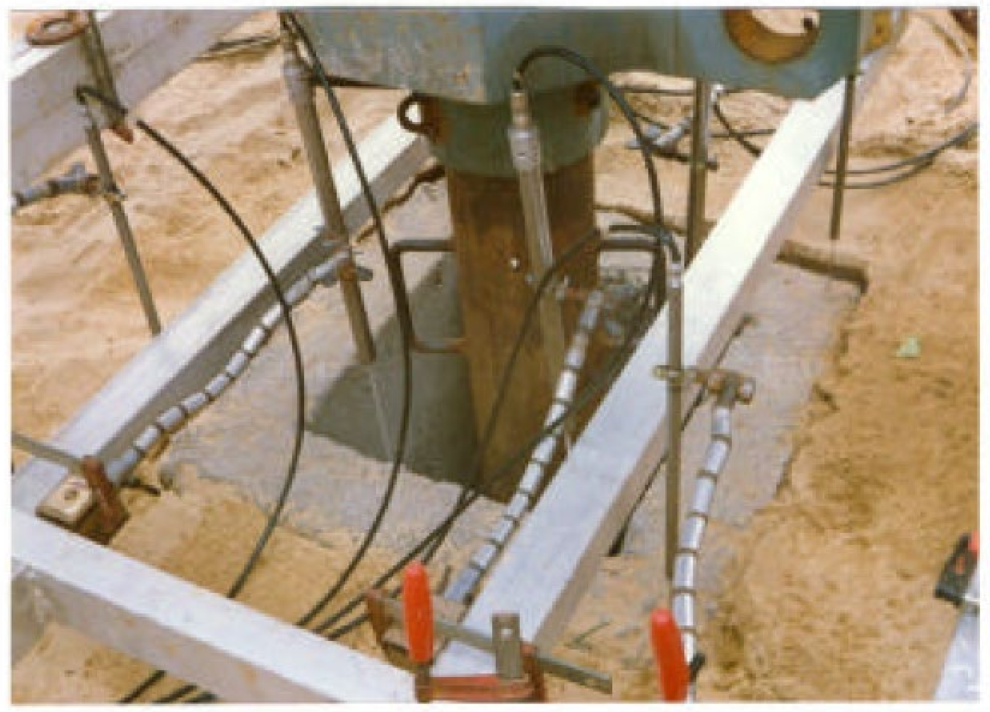
Prescriptive and execution rules:

- Drainage
- Criteria for engineered fill
- Earthwork execution
- Road safety barrier, highway noise barrier

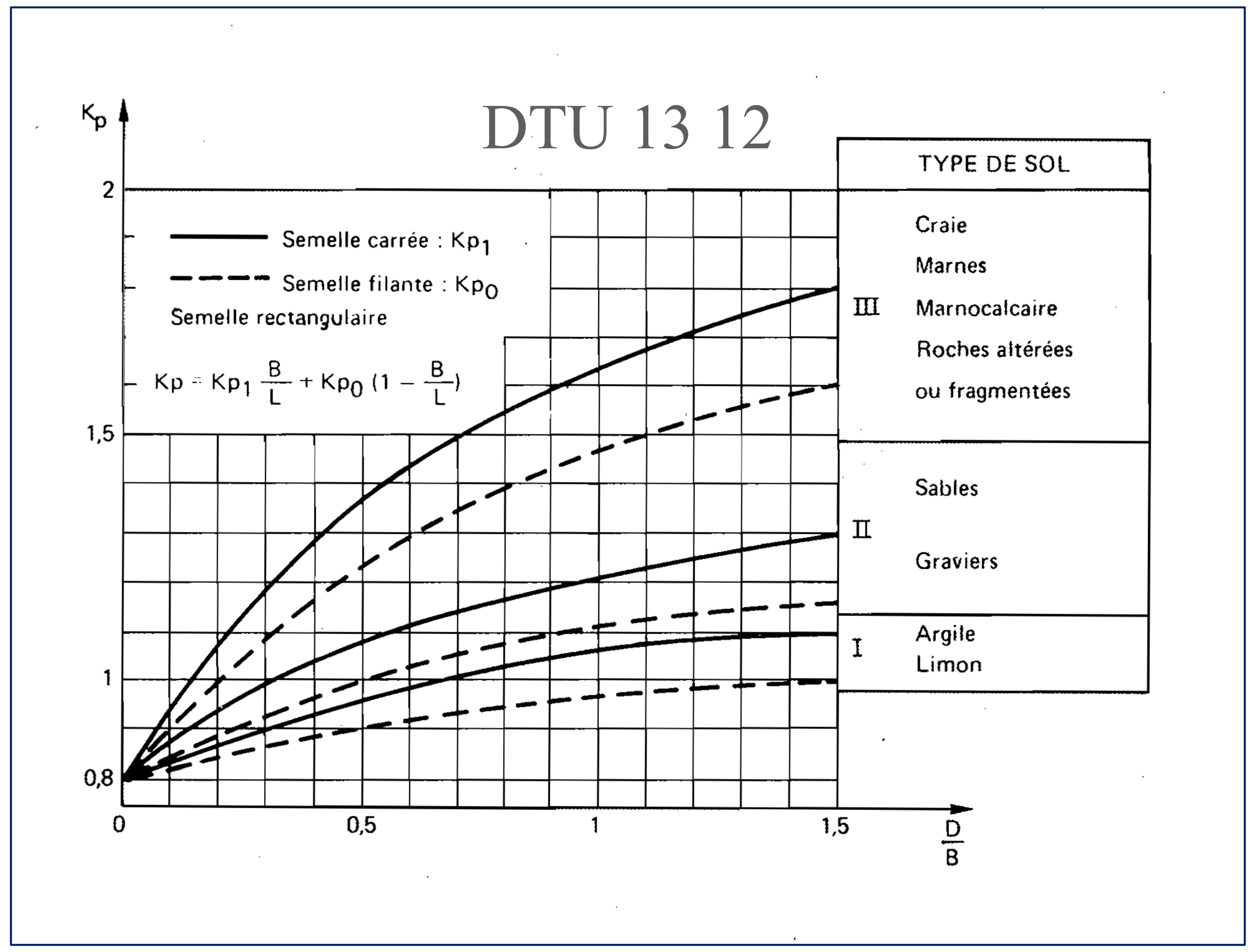


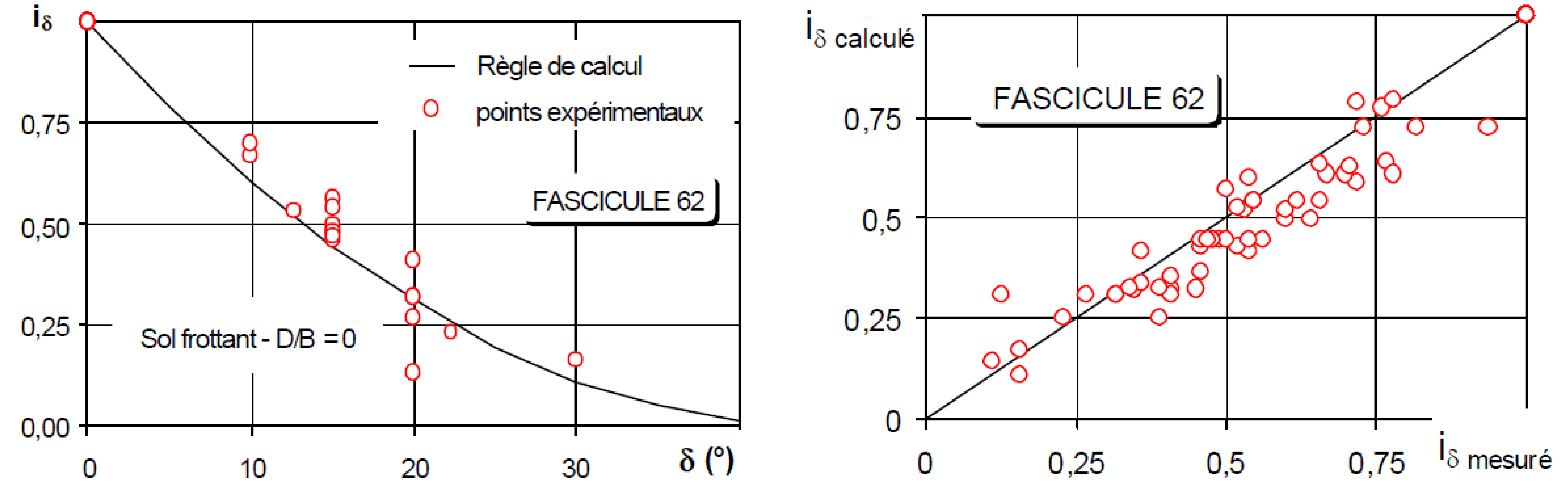
1980s: Evolution of shallow foundation design

- Elaboration of national standards for the design of shallow foundations:
    - Fascicule 62 Titre V
    - DTU 13.12
- Limit state framework
- Semi-empirical method (pressuremeter test) from in situ tests (both full scale and centrifuge tests)
- Reduction factor accounting for load inclination



(a) - Essai de chargement de semelle coulée pleine fouille (Site de Labenne - Sable de dune)





(a) - Semelles non encastrées (D/B = 0) établies sur sol frottant (c' = 0)

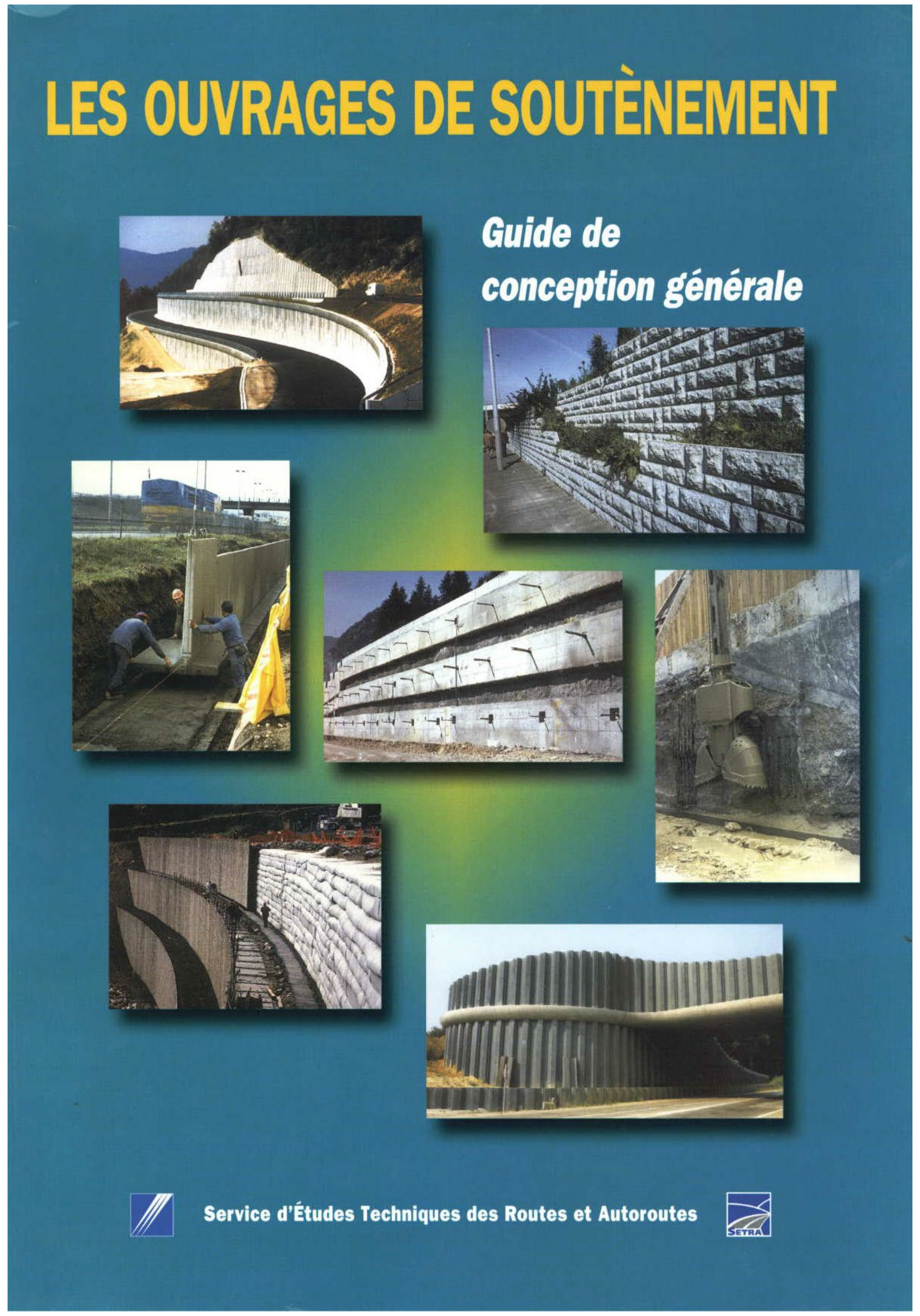
(b) - Semelles encastrées ou non établies sur sol frottant

Figure 30 - Confrontation des résultats expérimentaux obtenus avec les règles de calculs pressiométrique (Fascicule 62, 1993)

Canepa et Garnier (2003)

1990s: towards a standard for the implementation of Eurocode 7 (gravity walls)

- Need of harmonization for gravity wall design
  - Introduction of limit state and use of new standards (DTU and Fascicule 62 Titre V)
  - Use of partial factors for bearing capacity and sliding
- Scope of the Expert Group in the perspective of Eurocode 7 implementation:
  - Failure mechanisms
  - Uncertainties
  - Calculation method /Engineering judgement
- SETRA Guidelines:
  - Only SLS verifications (without ULS)
  - Use of partial factors : $2.0 + i_{\delta}^2$ close to 2.3 (value recommended by the Expert Group)



2000-2014: National standard NF P 94-281 (Eurocode 7)

- Elaboration of national standards (CNJOG)
  - NF P 94-261: shallow foundations (2013)
  - NF P 94-281: gravity walls (2014)

- Synthesis of the previous standards :
  - Earth pressure calculation: MUR73
  - Verification of the foundation: NF P 94261/Fascicule 62 Titre V/DTU 13.12
  - Partial factors: see the Expert Group conclusions

 NF P94-281:2014-04

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norme française

NF P 94-281
26 Avril 2014

Indice de classement : **P 94-281**

ICS : 91.010.30 ; 93.020

Justification des ouvrages géotechniques — Normes d'application nationale de l'Eurocode 7 — Ouvrages de soutènement — Murs

E : Justification of geotechnical work — National application standards for the implementation of Eurocode 7 — Retaining structures — Walls
D : Rechtfertigung von geotechnischen Bauwerken — Normen für die nationale Anwendung von Eurocode 7 — Stützanlagen — Wände

Norme française homologuée

par décision du Directeur Général d'AFNOR.

Correspondance À la date de publication du présent document, il n'existe pas de travaux de normalisation internationaux ou européens traitant du même sujet.

Résumé Le présent document constitue la norme d'application nationale de l'Eurocode 7 pour ce qui concerne les fondations des murs de soutènement. Il définit la terminologie et les notations employées. Il décrit leur comportement et fournit les règles de justification et de dimensionnement de ce type d'ouvrage aux états limites ultimes et aux états limites de service en ce qui concerne les aspects géotechniques.

Descripteurs **Thésaurus International Technique :** GEOTECHNIQUE, OUVRAGE, SOL, SOL DE FONDATION, RENFORCEMENT, REMBLAIEMENT, MUR, DEFINITION, CALCUL, CONTRAINTE ADMISSIBLE, LIMITE, RUPTURE, DEPLACEMENT, STABILITE, GLISSEMENT, RESISTANCE AU CISAILLEMENT, VERIFICATION, MATERIAU DE RENFORCEMENT, BETON, BETON ARME, BETON CELLULAIRE.

Modifications

Corrections

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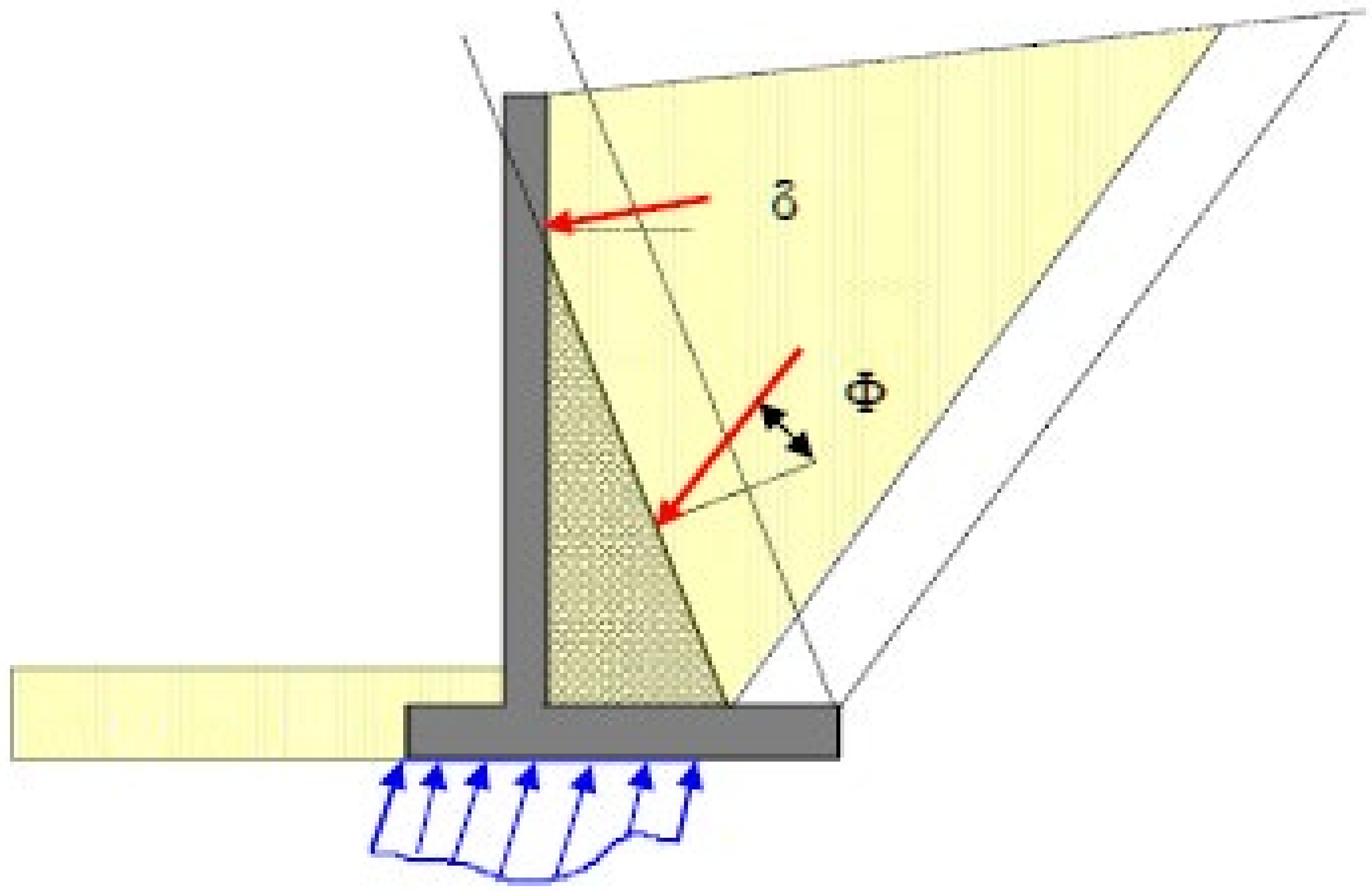
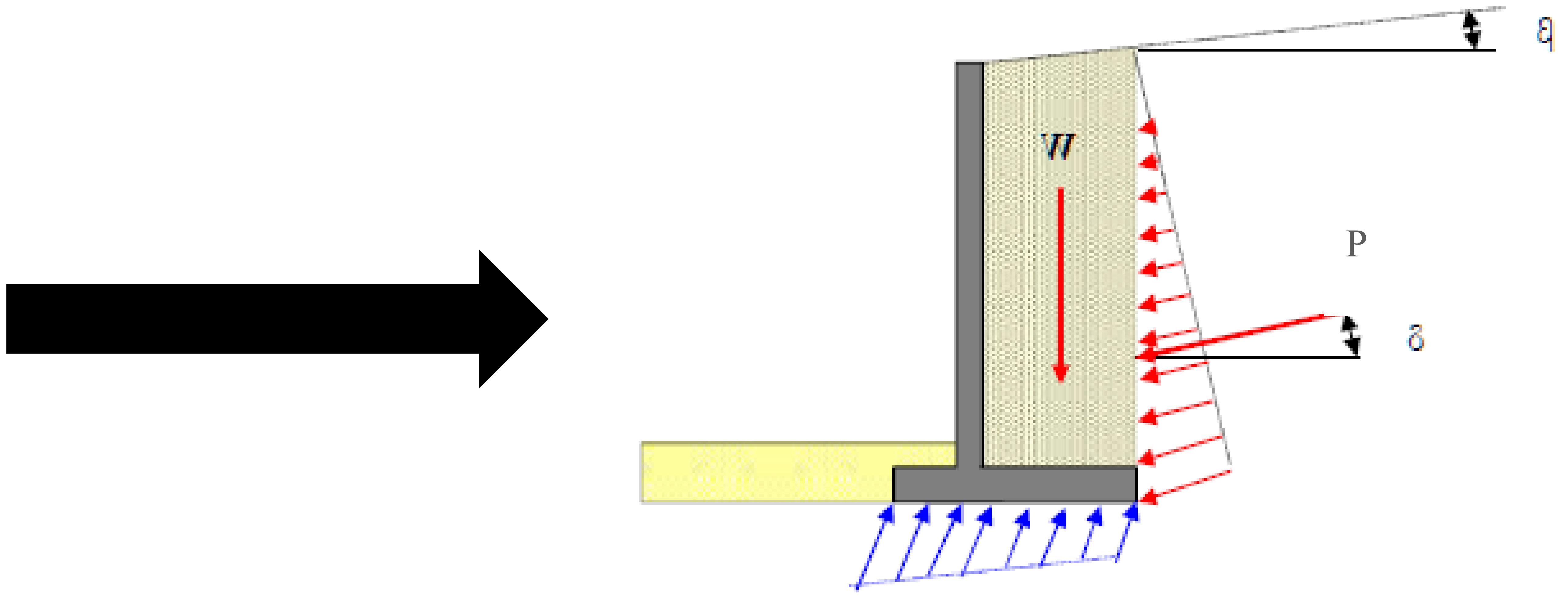
 Version de 2014-04-P

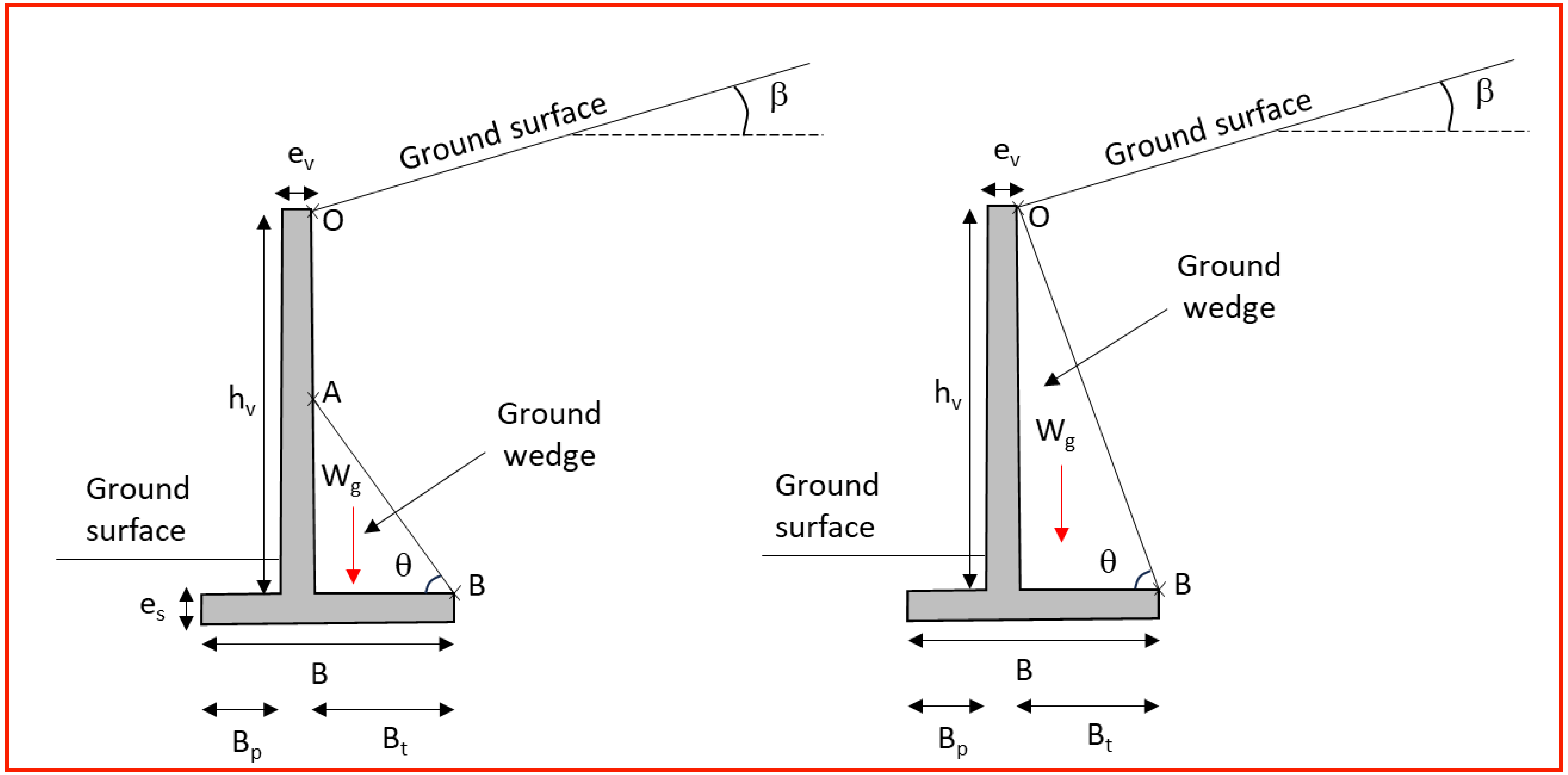
Method of the virtual back

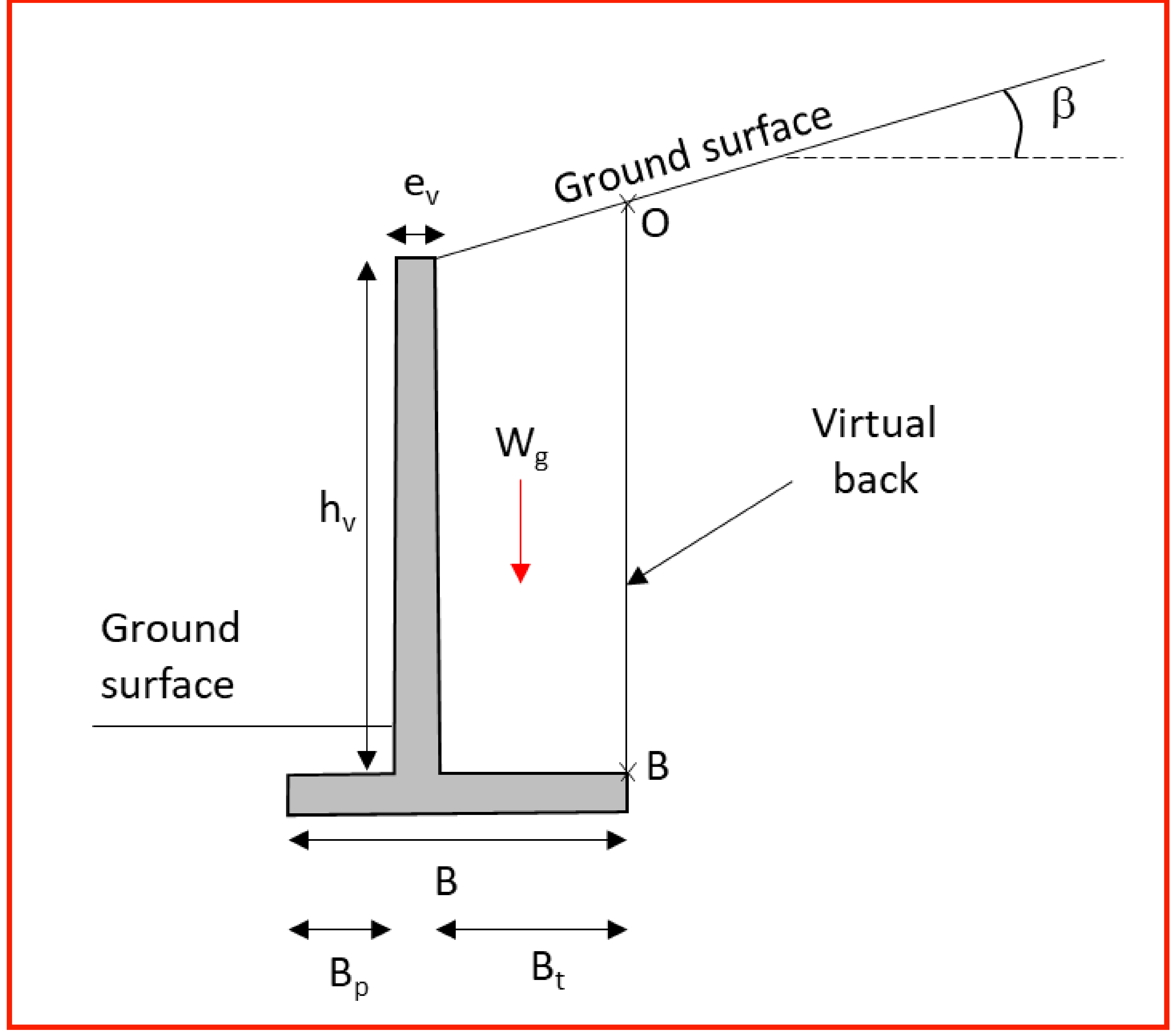
- This method was introduced by MUR73
- The « true » mechanism is simplified by the use of a virtual back
- The stress inclination on the virtual back is defined in order to obtain actions and loads that are equivalent to those obtained by considering the « true » mechanisms





Method of the virtual back





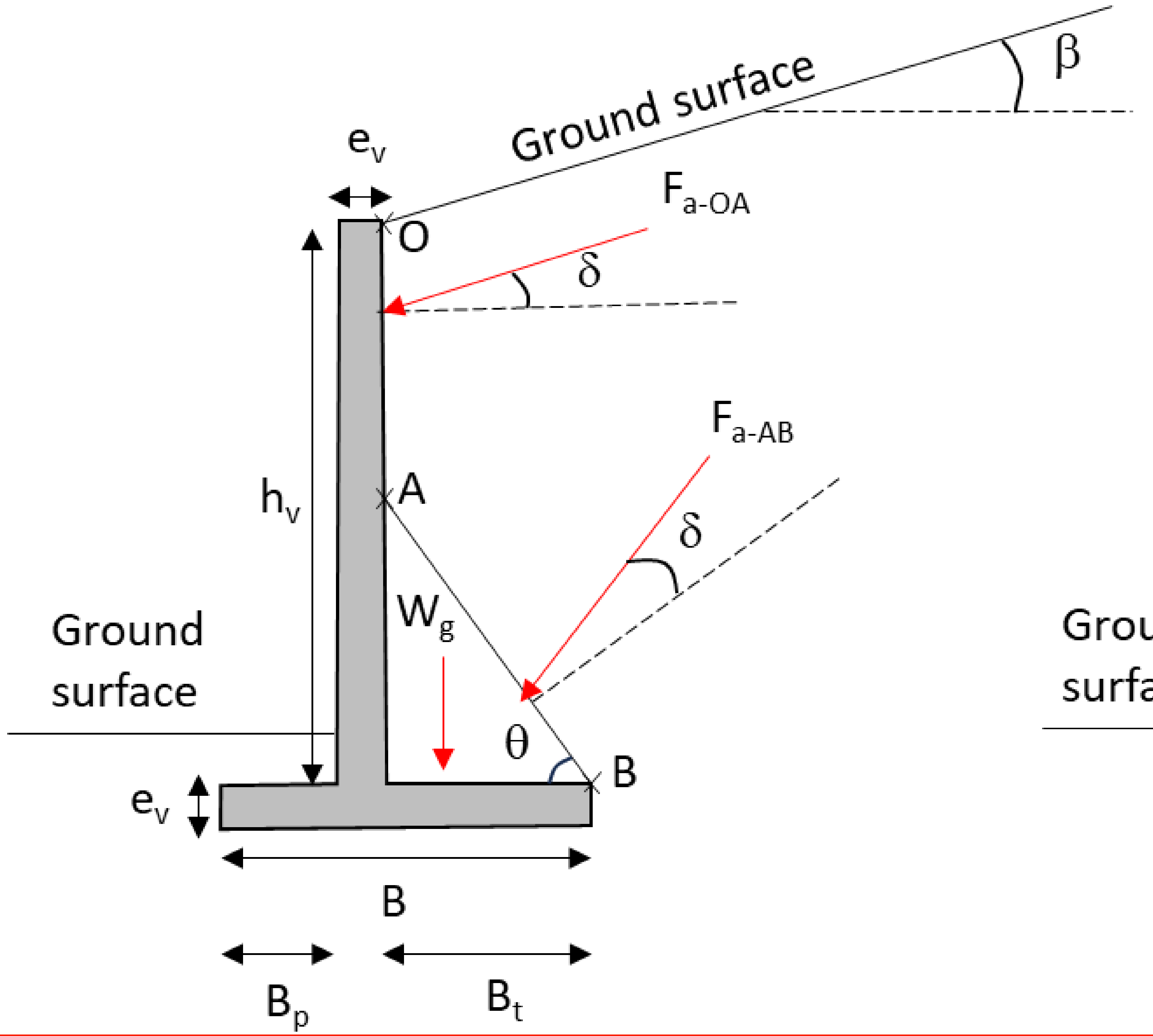
$$\theta = \frac{\pi}{4} + \frac{\varphi}{2} + \frac{(\gamma - \beta)}{2} \text{ and } \gamma = arcsin\left(\frac{sin\beta}{sin\varphi}\right)$$

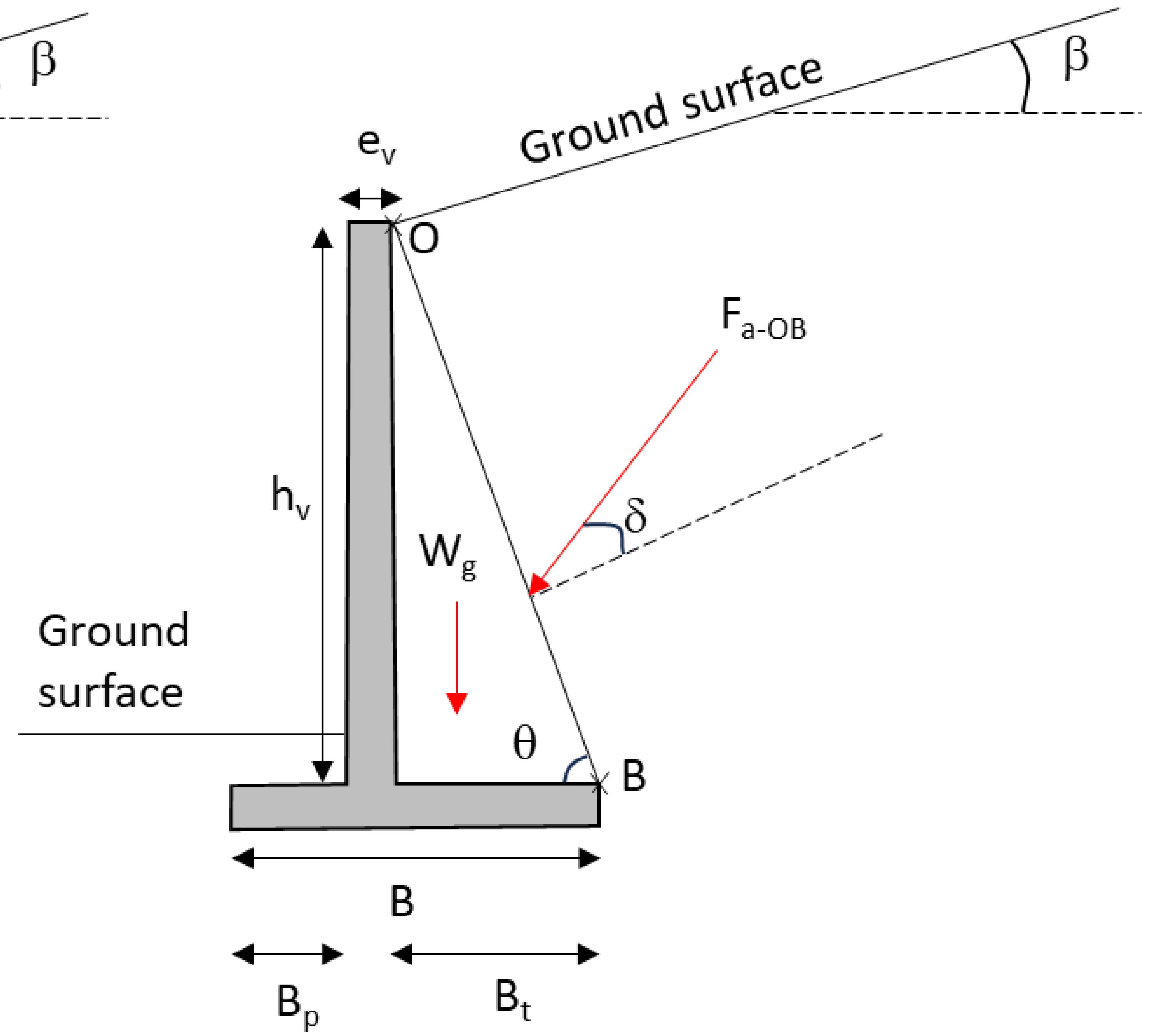
Method of the virtual back

$$\delta_a = \beta \text{ if } B_t \tan(\theta) > h_v$$

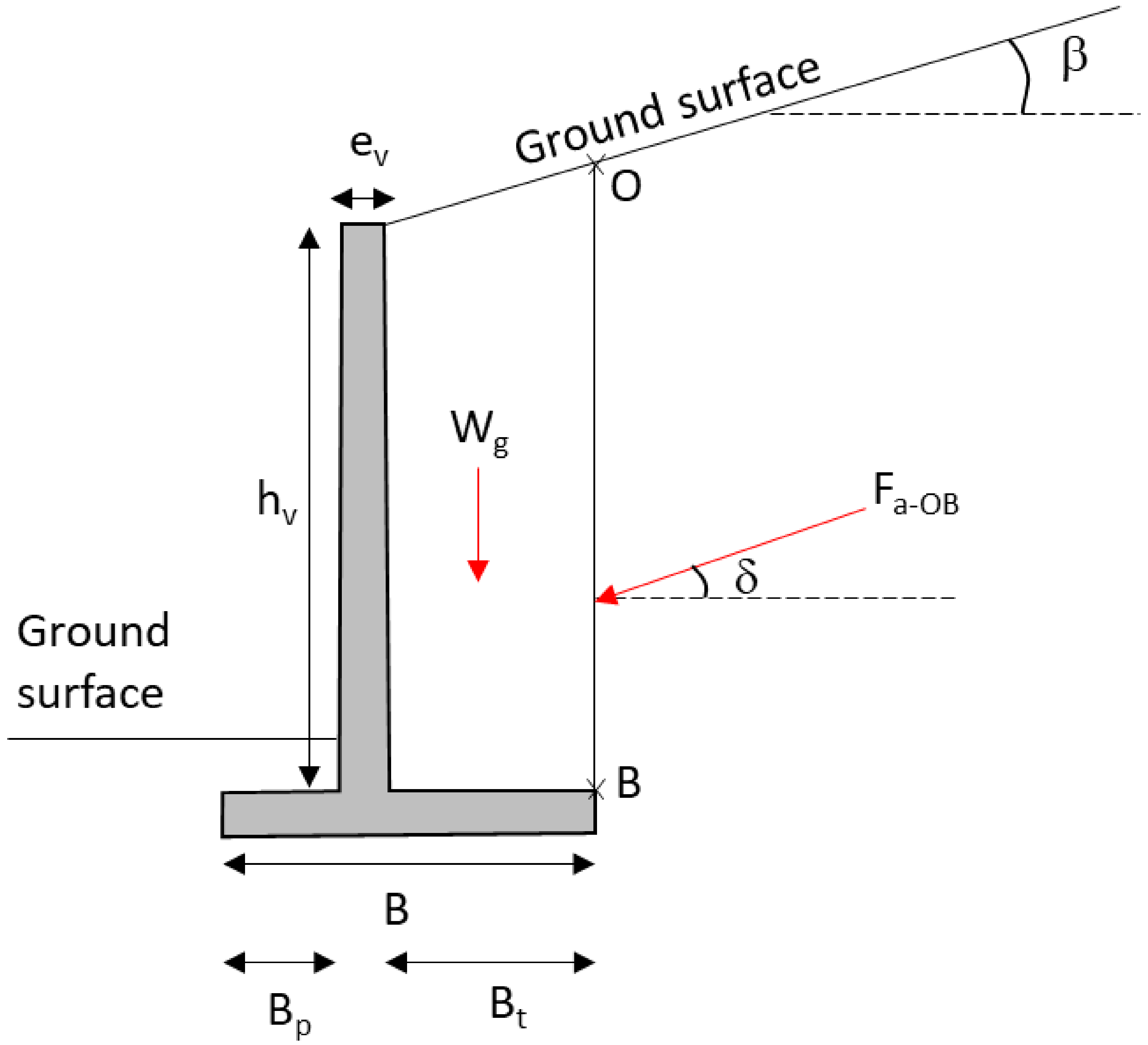
$$\delta_a = \beta + (\delta_0 - \beta)\left(1 - \frac{B_t \tan(\theta)}{h_v}\right)^2 \text{ if } B_t \tan(\theta) < h_v$$

$$\text{with } \delta_0 = \max\left(\beta, \frac{2}{3}\varphi\right)$$





ΣM_t, ΣV_t, ΣH_t ΣF_t, e_t, δ_t



ΣM_v, ΣV_v, ΣH_v ΣF_v, e_v, δ_v

Method of the virtual back

Parametric study :
$e_v = e_s = H/15$
$B_p = B/\alpha$ with $1.25 < \alpha < 20$
$27° \leq \varphi \leq 39°$
B=0.3H

Resultant force

φ - B_p=B/α	1.25	1.5	2	3	5	10	20
27	0,02	-0,05	-0,03	0,02	0,06	0,08	0,09
28.5	0,02	-0,04	-0,01	0,05	0,09	0,10	0,11
30	0,02	-0,03	0,01	0,07	0,11	0,12	0,13
31.5	0,02	-0,02	0,02	0,09	0,12	0,14	0,14
33	0,02	-0,02	0,04	0,10	0,14	0,15	0,15
34.5	0,01	-0,01	0,05	0,11	0,15	0,15	0,15
36	0,01	-0,01	0,05	0,12	0,15	0,16	0,16
37.5	0,02	-0,01	0,06	0,12	0,15	0,16	0,15
39	0,02	-0,01	0,06	0,12	0,15	0,15	0,15

$(\Sigma F_v - \Sigma F_t)/F_t$ in %

Load inclination

φ - B_p=B/α	1.25	1.5	2	3	5	10	20
27	0,08	-0,38	-0,81	-1,08	-1,17	-1,18	-1,17
28.5	0,09	-0,40	-0,85	-1,12	-1,20	-1,21	-1,19
30	0,09	-0,42	-0,88	-1,14	-1,22	-1,22	-1,20
31.5	0,09	-0,43	-0,90	-1,17	-1,24	-1,22	-1,19
33	0,10	-0,44	-0,92	-1,18	-1,24	-1,21	-1,18
34.5	0,10	-0,44	-0,93	-1,18	-1,23	-1,19	-1,16
36	0,10	-0,44	-0,92	-1,17	-1,21	-1,17	-1,12
37.5	0,09	-0,44	-0,91	-1,15	-1,18	-1,13	-1,08
39	0,09	-0,42	-0,89	-1,12	-1,14	-1,08	-1,03

$(\delta_v - \delta_t)/\delta_t$ in %

Eccentricity

φ - B_p=B/α	1.25	1.5	2	3	5	10	20
27	0,01	-0,02	-0,03	-0,03	-0,03	-0,03	-0,03
28.5	0,01	-0,02	-0,03	-0,03	-0,03	-0,03	-0,03
30	0,01	-0,02	-0,03	-0,03	-0,03	-0,03	-0,03
31.5	0,00	-0,02	-0,03	-0,03	-0,03	-0,03	-0,03
33	0,00	-0,02	-0,03	-0,03	-0,03	-0,03	-0,02
34.5	0,00	-0,02	-0,03	-0,03	-0,03	-0,02	-0,02
36	0,00	-0,02	-0,03	-0,03	-0,03	-0,02	-0,02
37.5	0,00	-0,01	-0,02	-0,03	-0,02	-0,02	-0,02
39	0,00	-0,01	-0,02	-0,02	-0,02	-0,02	-0,02

$(e_v - e_t)/B$ in %

Method of the virtual back

Parametric study :
$e_v = e_s = H/15$
$B_p = B/\alpha$ with $1.25 < \alpha < 20$
$27° \leq \varphi \leq 39°$
B=0.6H

φ - B_p=B/α	1.25	1.5	2	3	5	10	20
27	-0,03	0,04	0,10	0,09	0,06	0,03	0,02
28.5	-0,01	0,07	0,12	0,10	0,06	0,03	0,02
30	0,00	0,08	0,13	0,10	0,05	0,02	0,01
31.5	0,01	0,10	0,14	0,10	0,05	0,02	0,01
33	0,02	0,11	0,15	0,10	0,04	0,01	0,00
34.5	0,02	0,12	0,15	0,09	0,03	0,01	0,00
36	0,02	0,13	0,15	0,08	0,03	0,00	0,00
37.5	0,02	0,13	0,15	0,08	0,02	0,00	0,00
39	0,02	0,13	0,14	0,07	0,01	0,00	0,00

$(\Sigma F_v - \Sigma F_t)/F_t$ in %

Resultant force

Load inclination

φ - B_p=B/α	1.25	1.5	2	3	5	10	20
27	-0,58	-1,08	-1,15	-0,84	-0,49	-0,26	-0,16
28.5	-0,61	-1,12	-1,16	-0,81	-0,45	-0,22	-0,13
30	-0,63	-1,15	-1,16	-0,78	-0,40	-0,17	-0,09
31.5	-0,65	-1,16	-1,15	-0,74	-0,35	-0,13	-0,06
33	-0,66	-1,17	-1,13	-0,69	-0,30	-0,09	-0,03
34.5	-0,67	-1,17	-1,10	-0,63	-0,24	-0,06	-0,01
36	-0,67	-1,16	-1,07	-0,57	-0,19	-0,03	0,00
37.5	-0,66	-1,14	-1,02	-0,51	-0,14	-0,01	0,00
39	-0,64	-1,11	-0,96	-0,44	-0,09	0,00	0,00

$(\delta_v - \delta_t)/\delta_t$ in %

φ - B_p=B/α	1.25	1.5	2	3	5	10	20
27	-0,01	-0,02	-0,01	-0,01	0,00	0,00	0,00
28.5	-0,01	-0,02	-0,01	-0,01	0,00	0,00	0,00
30	-0,01	-0,02	-0,01	-0,01	0,00	0,00	0,00
31.5	-0,01	-0,01	-0,01	-0,01	0,00	0,00	0,00
33	-0,01	-0,01	-0,01	-0,01	0,00	0,00	0,00
34.5	-0,01	-0,01	-0,01	-0,01	0,00	0,00	0,00
36	-0,01	-0,01	-0,01	0,00	0,00	0,00	0,00
37.5	-0,01	-0,01	-0,01	0,00	0,00	0,00	0,00
39	-0,01	-0,01	-0,01	0,00	0,00	0,00	0,00

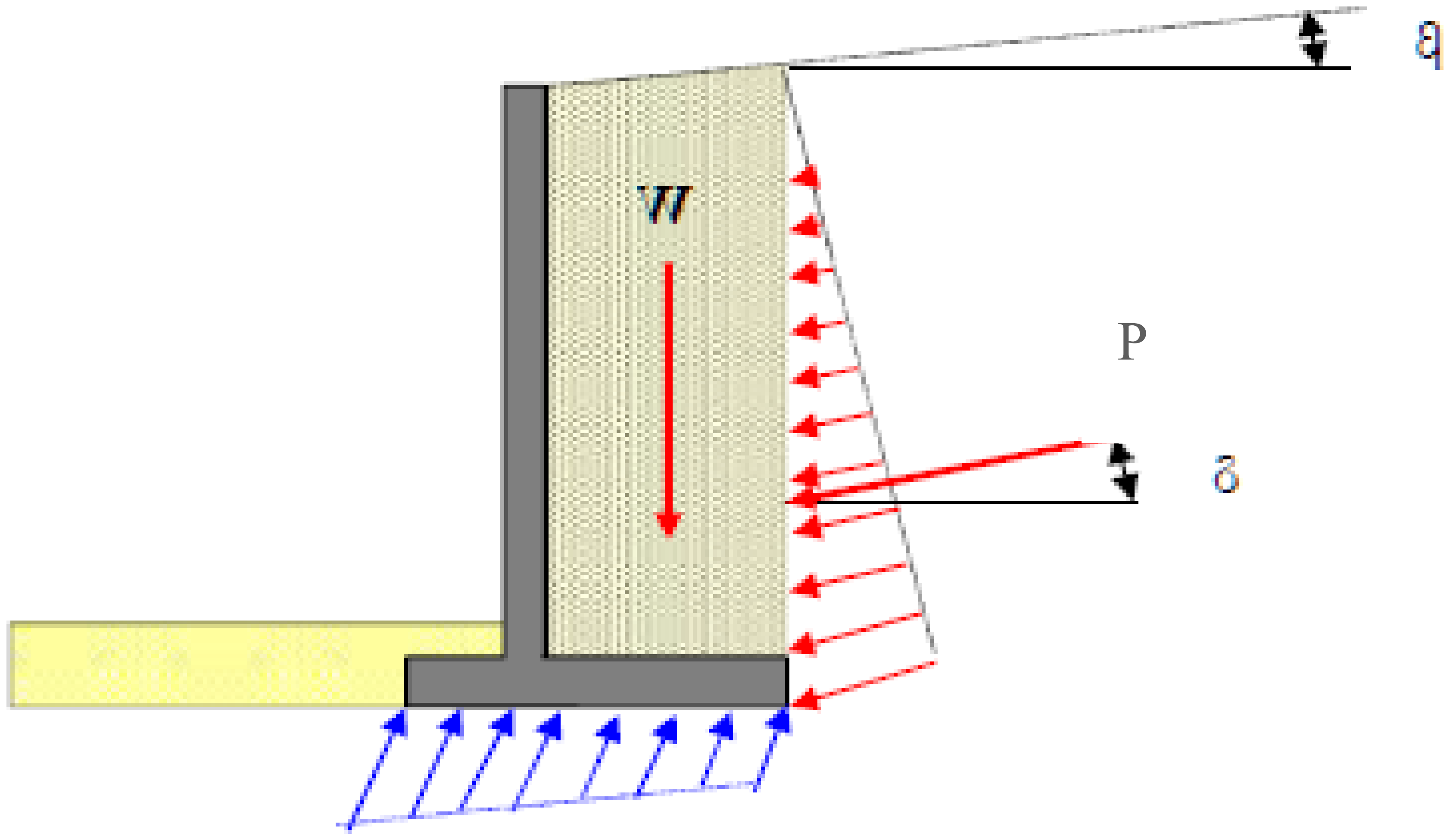
$(e_v - e_t)/B$ in %

Eccentricity

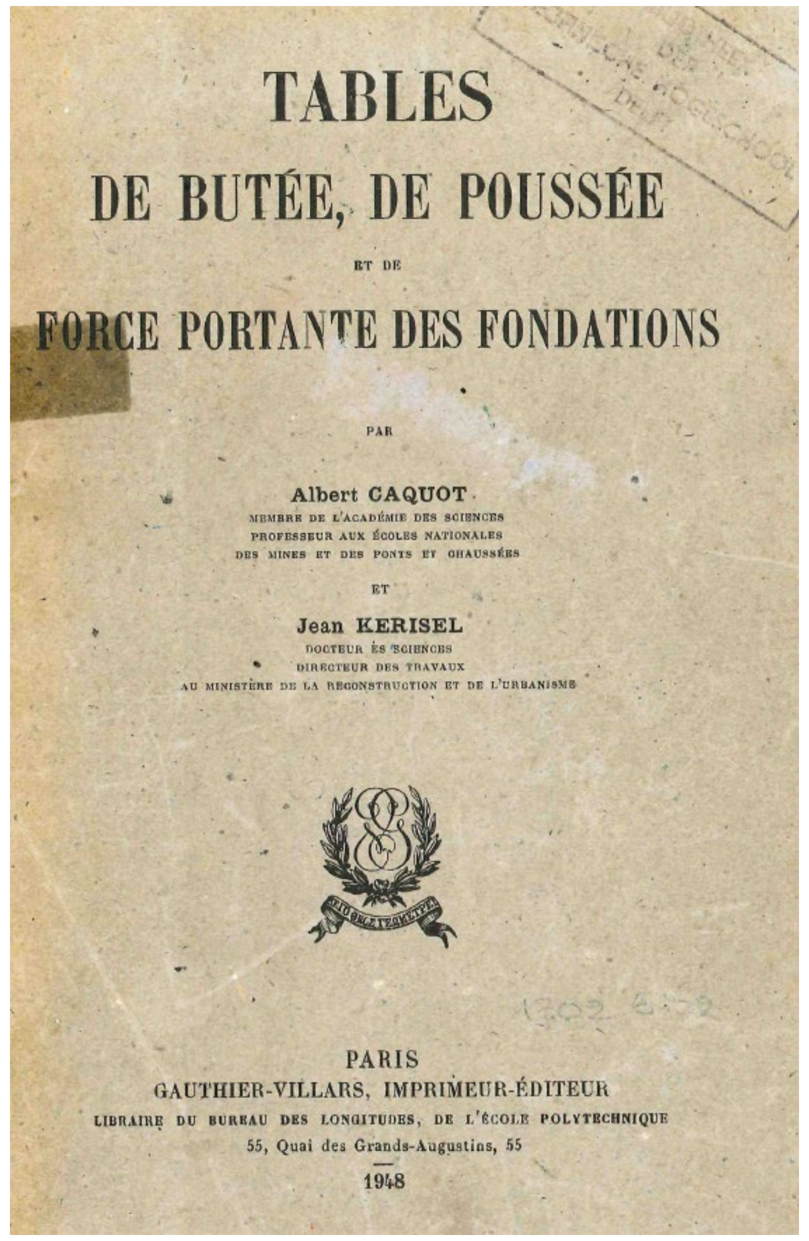
Method of the virtual back

- The actions calculated with the theoretical approach and the virtual back approach are very close: the foundation is subjected to the same actions.

- The inclination of the active earth pressures on the virual back may be significant and has a strong influence on the calculation results: considering a null inclination increases a lot the horizontal action and reduces to zero the vertical action, which is very conservative.

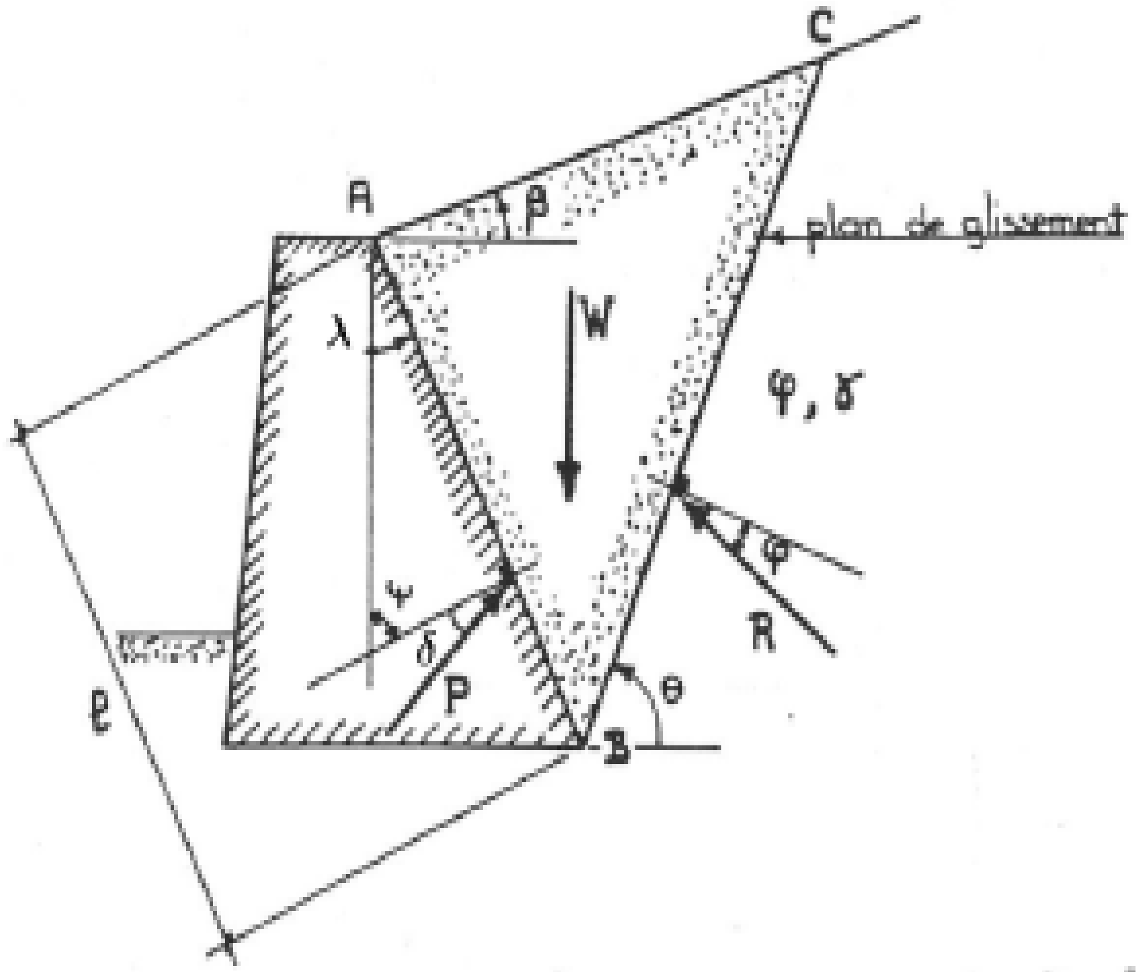


Active earth pressure calculation



- Caquot-Kerisel tables

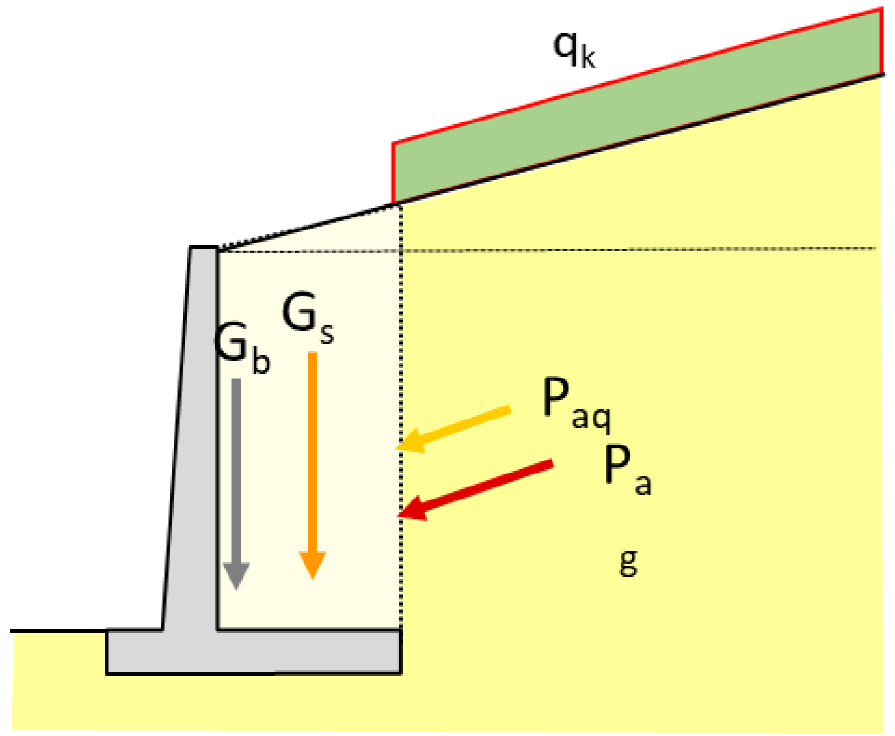
- Coulomb calculation (complex geometry, external loads on the ground surface)



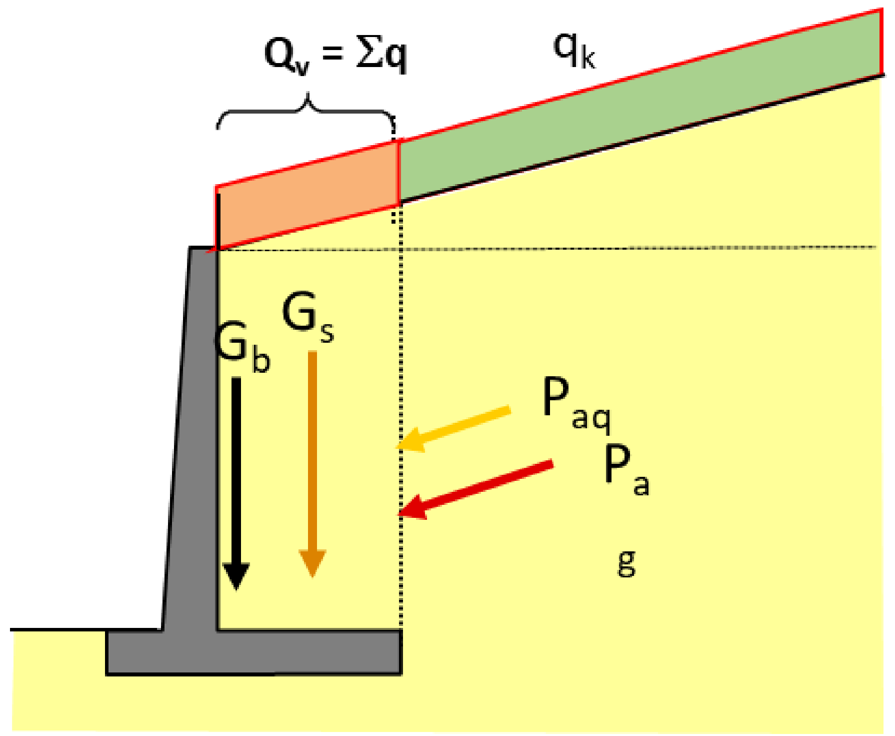
$$K_a = \frac{\cos^2(\lambda - \varphi)}{\cos(\lambda + \delta)\left(1 + \sqrt{\frac{\sin(\varphi + \delta)\sin(\varphi - \beta)}{\cos(\lambda + \delta)\cos(\beta - \lambda)}}\right)^2}$$

Limit state calculations: comparisons of various methods

Partial factors on actions	**Combination G_{min} (1)**	**Combination G_{max} (2)**
Partial factors γ_G on G_s and G_b	1	1.35
Partial factors γ_Q on Q_v (Σq at the virtual back)	0	1.5
Partial factors γ_G on $P_{ah,g}$ and $P_{av,g}$ (3)	1.35	1.35
Partial factors γ_Q on $P_{ah,q}$ and $P_{av,q}$	1.5	1.5



G min



G max

(1) : G_{min} (1) : the vertical actions are favourable

(2) : G_{max} (2) : the vertical actions are unfavourable

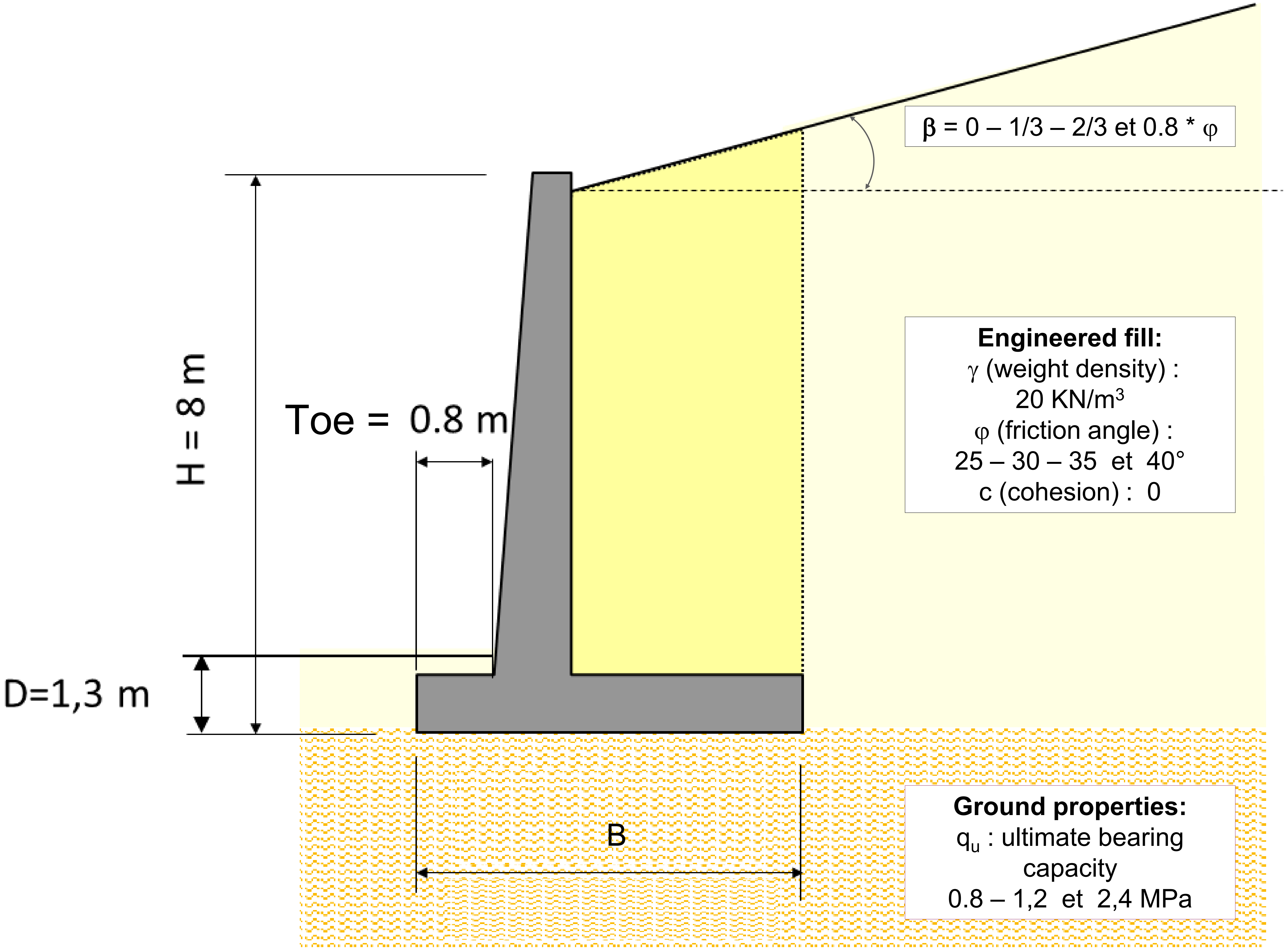
(3) : **the active earth pressures are always unfavourable**

Limit state calculations: comparisons of various methods

- The implementation of the Eurocode 7 has required to calibrate the partial factors used until 2000.
- Several issues should be checked:
  - Partial factors for the bearing capacity and the sliding
  - Model factors
  - The virtual back approach is more conservative than the theoretical approach since the vertical actions are less increased whereas the horizontal actions are identical to the real case.

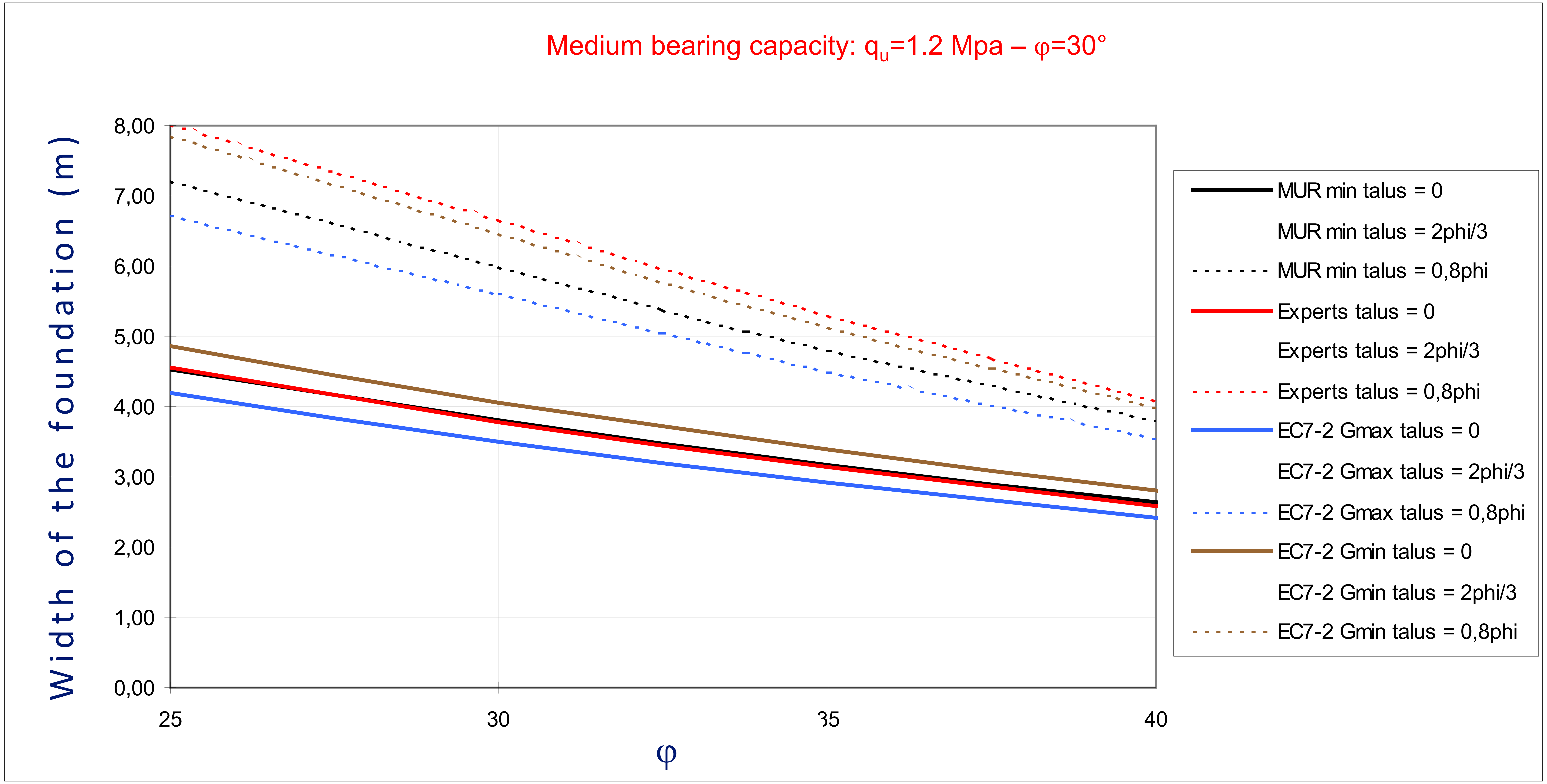
→ Need to compare the various methods

Limit state calculations: comparisons of various methods



- Methods:
  - MUR min : calculation with the software MUR (SETRA – ULS bearing capacity factor $1,5+0,5i_{\delta}^2$)
  - Experts recommendations (SLS coef 2 ,3)
  - EC7 G_{max} : : calculation with NF P 94-281 - G_{max}
  - EC7 G_{min} : calculation with NF P 94-281 - G_{min}

Limit state calculations: comparisons of various methods



The results are close.

The most conservative method is EC7-G_{min}, which is consistent with the previous comment about the role of the virtual back.

	gamma d	gamma Gmur	gamma sol	gamma Gsol	gamma Psol	gamma Q	gamma Pq	gam, phi,r	A	B	gamma(phi)	gamma (C)
MUR min	1,125	0,9	0,9	1	1,2	0	1,6	1	1,5	0,5	1,2	1,4
Experts	1	1	1	1	1	0	1	1	2,3	0	1,3	1,5
EC7-2 Gmax	1	1,35	1	1,35	1,35	1,5	1,5	1	1,4	0	1,1	1,1
EC7-2 Gmin	1	1	1	1	1,35	0	1,5	1	1,4	0	1,1	1,1

Conclusions and perspectives

- The evolution of the design methods was continuous during the last 50 years with the elaboration of an harmonized design method as a first step, the consideration of inclined loadings as a second step and the use of limite state framework as a third step.

- The virtual back method and the use of partial factors might be maybe improved by analysing the role of the ground mass above the heel.

- The calculation method includes some simplifications that are necessary for an efficient design and take into account the uncertainties about the ground properties and the execution.

- The knowledge of the previous calculation methods is fundamental for:
    - the maintenance and the reparation of the existing structures,
    - the possibility to propose future evolutions.

cfms

COMITÉ FRANÇAIS DE MÉCANIQUE DES SOLS ET DE GÉOTECHNIQUE

Thank you for your attention