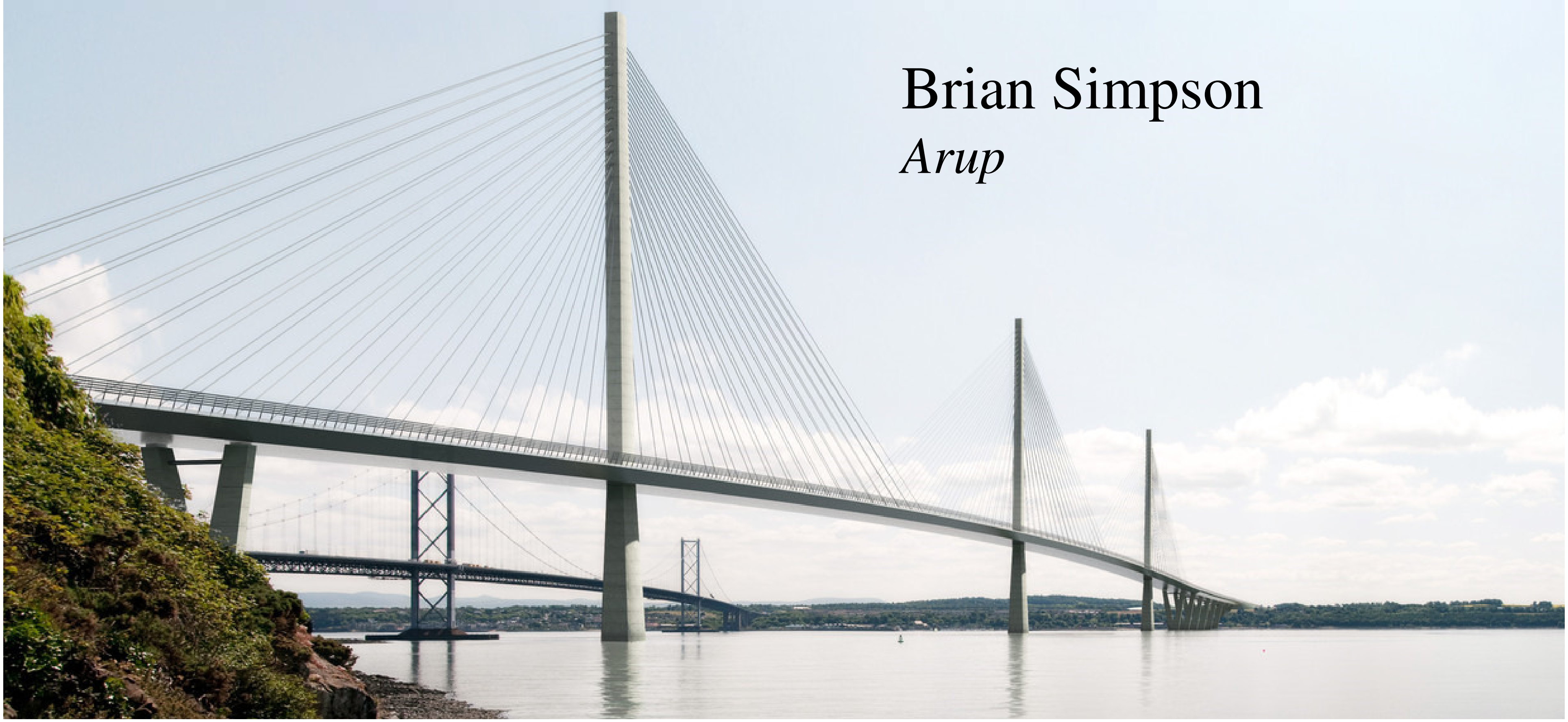
8th Lumb Lecture

Eurocode 7 – Good practice in geotechnical design

Brian Simpson
Arup



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Eurocode 7 – Good practice in geotechnical design

- Limit state design
- Holistic design – structures and ground
- Practical approach to characteristic values of soil parameters
- ULS and SLS design requirements
- Water pressures
- Ground anchors
- Retaining structures – numerical analysis
- The future

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Eurocode 7 – Good practice in geotechnical design

- **Limit state design**
- Holistic design – structures and ground
- Practical approach to characteristic values of soil parameters
- ULS and SLS design requirements
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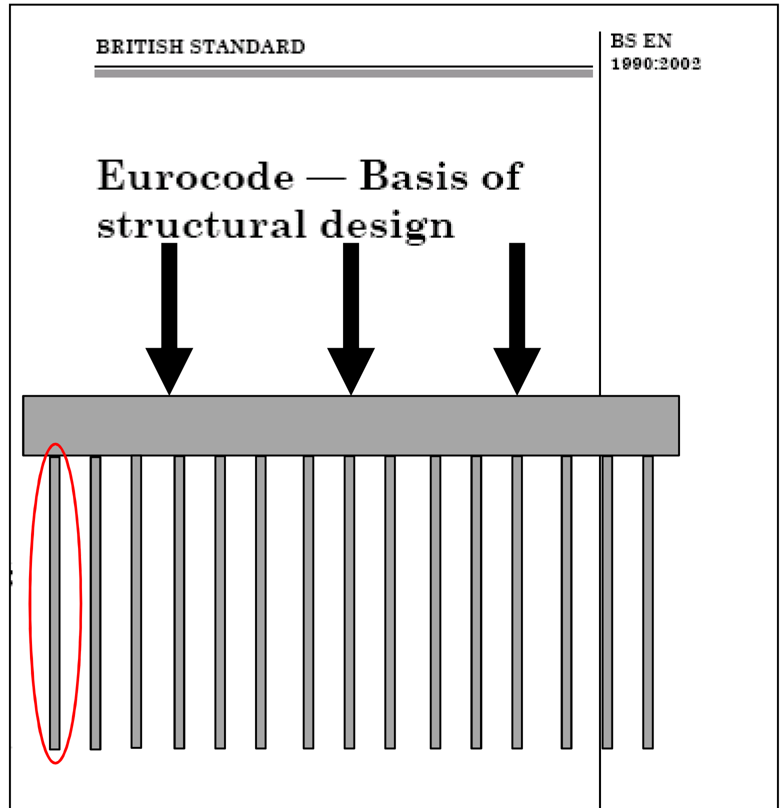
Limit state design

- “states beyond which the structure no longer satisfies the relevant design criteria”
- partial factor design ?
- probabilistic design ?
- concentration on what might go wrong



EN1990 3.3 (3)
States prior to structural collapse, which, for simplicity, are considered in place of the collapse itself, may be treated as ultimate limit states.

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EN 1990 3.3 Ultimate limit states

(4)P The following ultimate limit states shall be verified where they are relevant :

- loss of equilibrium of the structure or any part of it, considered as a rigid body ;
- failure by excessive deformation, transformation of the structure or any part of it into a mechanism, rupture, loss of stability of the structure or any part of it, including supports and foundations ;
- failure caused by fatigue or other time-dependent effects.

Serious failures involving risk of injury or major cost.

Must be rendered very unlikely. An "unrealistic" possibility.

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EN 1990 3.3 Ultimate limit states

Time to run away

(4)P The following ultimate limit states … relevant :

– loss of equilibrium of the … ered as a rigid body ;

– failure by ex… on of the structure or any part of it into

– … ability of the structure or any part of it, including

… ons ;

– … sed by fatigue or other time-dependent effects.

Serious failures involving risk of injury or major cost.

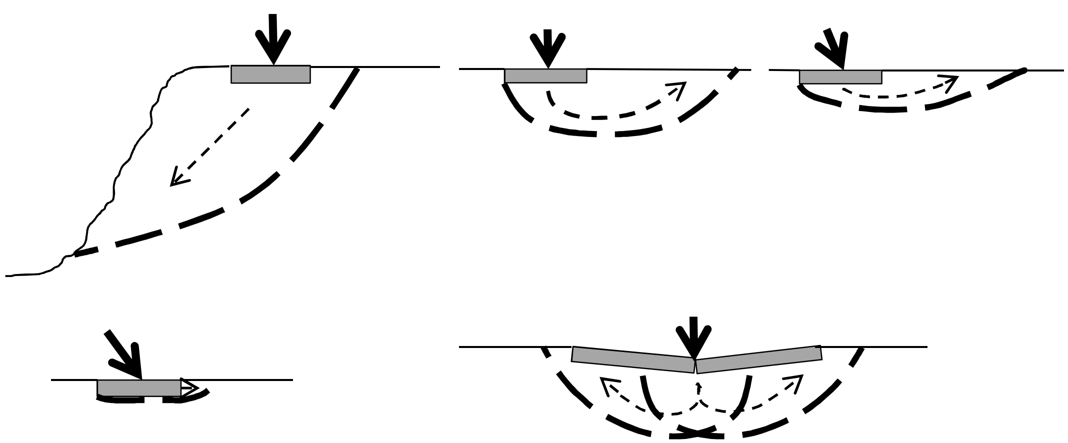
Must be rendered very unlikely. An "unrealistic" possibility.

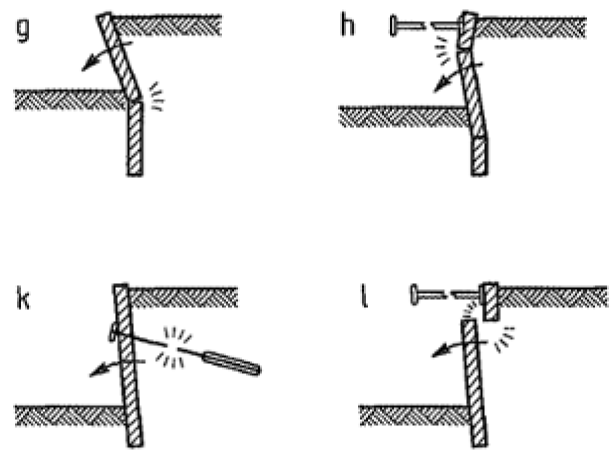
EN1997-1 2.4.7 Ultimate limit states – STR, GEO

— internal failure or excessive deformation of the structure or structural elements, including e.g. footings, piles or basement walls, in which the strength of structural materials is significant in providing resistance (STR);

— failure or excessive deformation of the ground, in which the strength of soil or rock is significant in providing resistance (GEO);

NOTE Limit state GEO is often critical to the sizing of structural elements involved in foundations or retaining structures and sometimes to the strength of structural elements.





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EN1990 3.4 Serviceability limit states

(1)P The limit states that concern :
– the functioning of the structure or structural members under normal use ;
– the comfort of people ;
– the appearance of the construction works,
shall be classified as serviceability limit states.

Inconveniences, disappointments and more manageable costs.

Should be rare, but it might be uneconomic to eliminate them completely.

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EN1990 3.4 Serviceability limit states

(1)P The limit states that concern :

– the functioning of the stru… under normal use ;

– the comfort of…

– th… …ction works,

… serviceability limit states.

Time to call your insurer

Inconveniences, disappointments and more manageable costs.

Should be rare, but it might be uneconomic to eliminate them completely.

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Limit state design

- An understanding of limit state design can be obtained by contrasting it with "working state design".
- Working state design: Analyse the expected, working state, then apply margins of safety.
- Limit state design: Analyse the unexpected states at which the structure has reached an unacceptable limit.
- Make sure the limit states are unrealistic (or at least unlikely).

Soil failure without geometrical instability (large displacements)??

Fundamental limit state requirement

$$E_d \leq R_d$$

$$E\{ \; F_d \; ; \; X_d \; ; a_d\} = E_d \leq R_d = R\{ \; F_d \; ; \; X_d \; ; a_d\}$$

$$E\{\gamma_F F_{rep}; X_k/\gamma_M; a_d\} = E_d \leq R_d = R\{\gamma_F F_{rep}; X_k/\gamma_M; a_d\}$$

or $E\{\gamma_F F_{rep}; X_k/\gamma_M; a_d\} = E_d \leq R_d = R_k/\gamma_R = R_n\phi_R$ (LRFD)

or $\gamma_E E_k = E_d \leq R_d = R_k/\gamma_R$

so in total

$$\gamma_E E\{\gamma_F F_{rep}; X_k/\gamma_M; a_d\} = E_d \leq R_d = R\{\gamma_F F_{rep}; X_k/\gamma_M; a_d\}/\gamma_R$$

E = action effects

F = actions (loads)

R = resistance (=capacity)

X = material properties

a = dimensions/geometry

d = design (= factored)

k = characteristic (= unfactored)

rep = representative

Partial factors recommended in EN1997-1 Annex A (+UKNA)

Values of partial factors recommended in EN1997-1 Annex A (+ UKNA)

			Design approach 1										Design approach 2					Design approach 3			
			Combination 1			Combination 2			Combination 2 - piles & anchors				DA2 - Comb 1			DA2 - Slopes		DA3			
			A1	M1	R1	A2	M2	R1	A2	M1 or …	M2	R4	A1	M1	R2	A1	M=R2	A1	A2	M2	R3
Actions	Permanent	unfav	1,35										1,35			1,35		1,35			
		fav																			
	Variable	unfav	1,5			1,3			1,3				1,5			1,5		1,5	1,3		
Soil	tan φ'						1,25				1,25							Structural actions	Geotech actions	1,25	
	Effective cohesion						1,25				1,25									1,25	
	Undrained strength						1,4				1,4									1,4	
	Unconfined strength						1,4				1,4									1,4	
	Weight density																				
Spread footings	Bearing														1,4						
	Sliding														1,1						
Driven piles	Base											1,3			1,1						
	Shaft (compression)											1,3			1,1						
	Total/combined											1,3			1,1						
	Shaft in tension											1,6			1,15						1,1
Bored piles	Base											1,6			1,1						
	Shaft (compression)											1,3			1,1						
	Total/combined											1,5			1,1						
	Shaft in tension											1,6			1,15						1,1
CFA piles	Base											1,45			1,1						
	Shaft (compression)											1,3			1,1						
	Total/combined											1,4			1,1						
	Shaft in tension											1,6			1,15						1,1
Anchors	Temporary											1,1			1,1						
	Permanent											1,1			1,1						
Retaining walls	Bearing capacity														1,4						
	Sliding resistance														1,1						
	Earth resistance														1,4						
Slopes	Earth resistance																1,1				

[green box] indicates partial factor = 1.0

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Partial factors recommended in EN1997-1 Annex A

Values of partial factors recommended in EN1997-1 Annex A

			Design approach 1 Combination 1			Combination 2			Combination 2 - piles & anchors				Design approach 2 DA2 - Comb 1			DA2 - Slopes		Design approach 3 DA3			
			A1	M1	R1	A2	M2	R1	A2	M1 or …	M2	R4	A1	M1	R2	A1	M=R2	A1	A2	M2	R3
Actions	Permanent	unfav	1,35			□			□				1,35			1,35		1,35	□		
		fav	□			□			□				□			□		□	□		
	Variable	unfav	1,5			1,3			1,3				1,5			1,5		1,5	1,3		
Soil	tan φ'			□			1,25			□	1,25			□				Structural actions	Geotech actions	1,25	
	Effective cohesion			□			1,25			□	1,25			□						1,25	
	Undrained strength			□			1,4			□	1,4			□						1,4	
	Unconfined strength			□			1,4			□	1,4			□						1,4	
	Weight density			□			□			□	□			□						□	
Spread footings	Bearing				□			□							1,4						□
	Sliding				□			□							1,1						□
Driven piles	Base				□							1,3			[illegible]						□
	Shaft (compression)				□							1,3			1,1						□
	Total/combined				□							1,3			1,1						□
	Shaft in tension				1,25							1,6			1,15						1,1
Bored piles	Base				1,25							1,6			[illegible]						□
	Shaft (compression)				1,0							1,3			[illegible]						□
	Total/combined				1,15							[illegible]			1,1						□
	Shaft in tension				1,25							1,6			1,15						1,1
CFA piles	Base				1,1							1,45			1,1						□
	Shaft (compression)				1,0							1,3			1,1						□
	Total/combined				[illegible]							1,4			1,1						□
	Shaft in tension				1,25							1,6			1,15						1,1
Anchors	Temporary				1,1							1,1			1,1						□
	Permanent				1,1							1,1			1,1						□
Retaining walls	Bearing capacity				□			□							1,4						□
	Sliding resistance				□			□							1,1						□
	Earth resistance				□			□							1,4						□
Slopes	Earth resistance				□			□									1,1				□

□ indicates partial factor = 1.0

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Design approach is a national choice

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Partial factors for DA1 – UK National Annex

			Design approach 1 Combination 1---------------			Combination 2 --------------			Combination 2 - piles & anchors				
			A1	M1	R1	A2	M2	R1	A2	M1 or …	M2	R4 (UKNA)	EC7 values
Actions	Permanent	unfav	1,35										
		fav											
	Variable	unfav	1,5			1,3			1,3				
Soil	tan φ'						1,25				1,25		
	Effective cohesion						1,25				1,25		
	Undrained strength						1,4				1,4		
	Unconfined strength						1,4				1,4		
	Weight density												
Spread footings	Bearing												
	Sliding												
Driven piles	Base											1,7/1.5	1,3
	Shaft (compression)											1.5/1.3	1,3
	Total/combined											1.7/1.5	1,3
	Shaft in tension											2.0/1.7	1.6
Bored piles	Base											2.0/1.7	1,6
	Shaft (compression)											1.6/1.4	1,3
	Total/combined											2.0/1.7	1.5
	Shaft in tension											2.0/1.7	1.6
CFA piles	Base											As	1.45
	Shaft (compression)											for	1.3
	Total/combined											bored	1.4
	Shaft in tension											piles	1.6
Anchors	Temporary											1,1	1,1
	Permanent											1,1	1,1
Retaining walls	Bearing capacity												
	Sliding resistance												
	Earth resistance												
Slopes	Earth resistance												

[green box] indicates partial factor = 1.0

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2.4.7 Ultimate Limit States

2.4.7.1 General

(1)P Where relevant, it shall be verified that the following limit states are not exceeded:

— loss of equilibrium of the structure or the ground, considered as a rigid body, in which the strengths of structural materials and the ground are insignificant in providing resistance (EQU);

— internal failure or excessive deformation of the structure or structural elements, including e.g. footings, piles or basement walls, in which the strength of structural materials is significant in providing resistance (STR);

— failure or excessive deformation of the ground, in which the strength of soil or rock is significant in providing resistance (GEO);

— loss of equilibrium of the structure or the ground due to uplift by water pressure (buoyancy) or other vertical actions (UPL)

— hydraulic heave, internal erosion and piping in the ground caused by hydraulic gradients (HYD).

DA1 Combinations 1 and 2 correspond to STR and GEO?

			Design approach 1									
			Combination 1----------------			Combination 2 ---------------			Combination 2 - piles & anchors			
			A1	M1	R1	A2	M2	R1	A2	M1 or …	M2	R4
Actions	Permanent	unfav	1,35									
		fav										
	Variable	unfav	1,5			1,3			1,3			
Soil	tan φ'						1,25				1,25	
	Effective cohesion						1,25				1,25	
	Undrained strength						1,4				1,4	
	Unconfined strength						1,4				1,4	
	Weight density											

2.4.7 Ultimate Limit States

STR GEO

2.4.7.3 Verification of resistance for structural and ground limit states in persistent and transient situations

2.4.7.3.4.2 Design Approach 1

(1)P Except for the design of axially loaded piles and anchors, it shall be verified that a limit state of rupture or excessive deformation will not occur with either of the following combinations of sets of partial factors:

Combination 1: *A1* "+" *M1* "+" *R1*

Combination 2: *A2* "+" *M2* "+" *R1*

where "+" implies: "to be combined with".

STR and GEO both designed for the same partial factors

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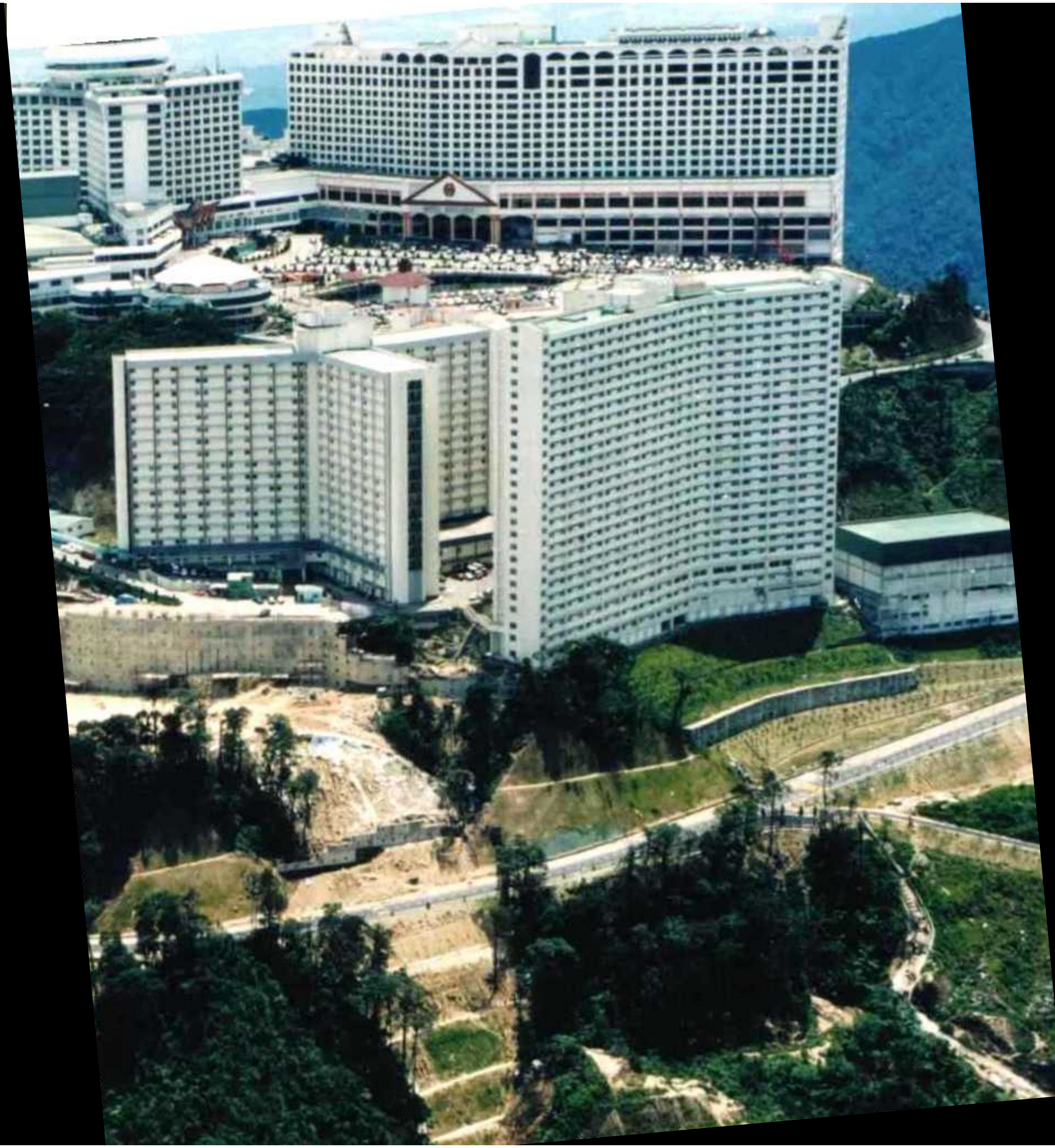
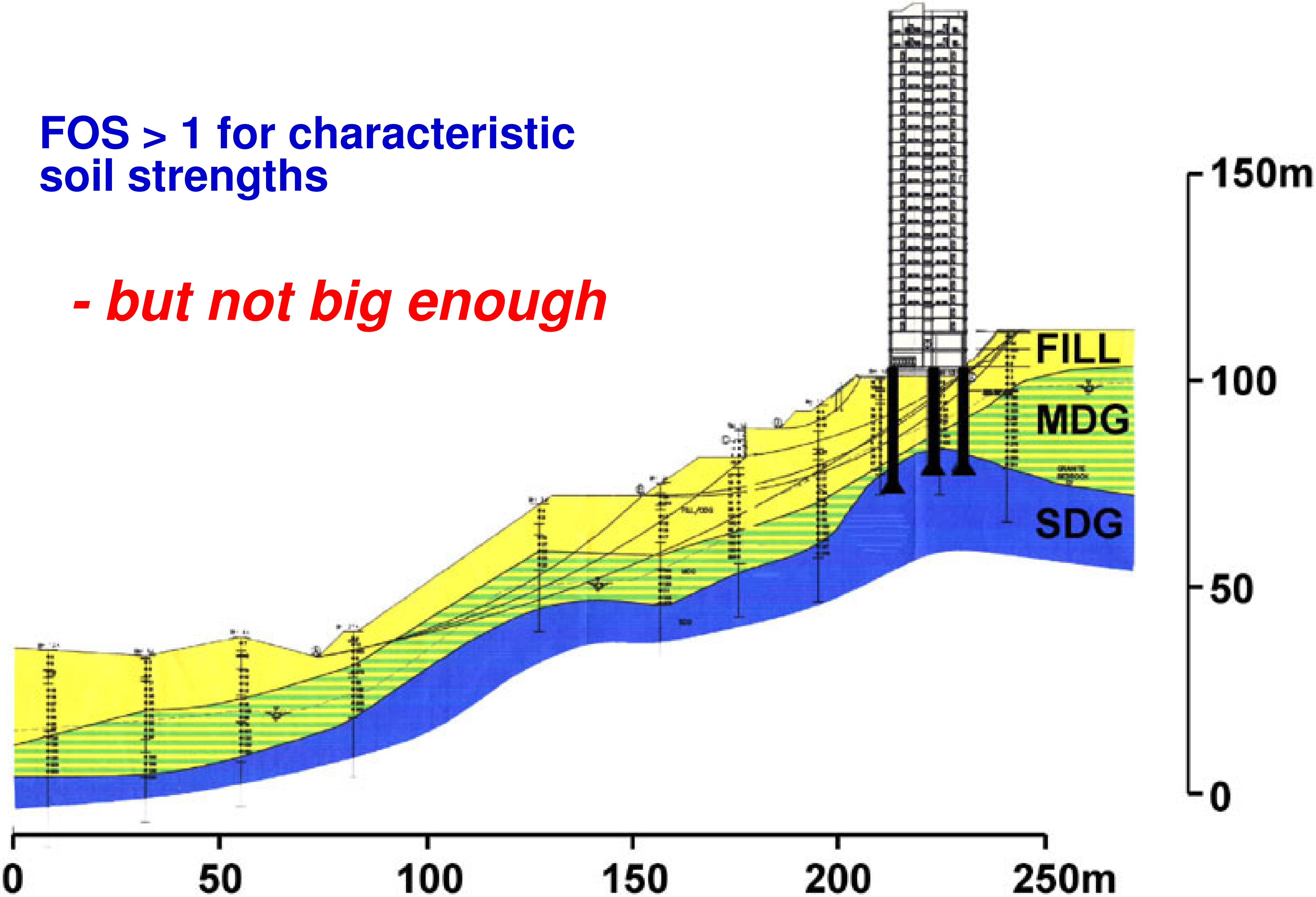


FOS > 1 for characteristic soil strengths

- but not big enough



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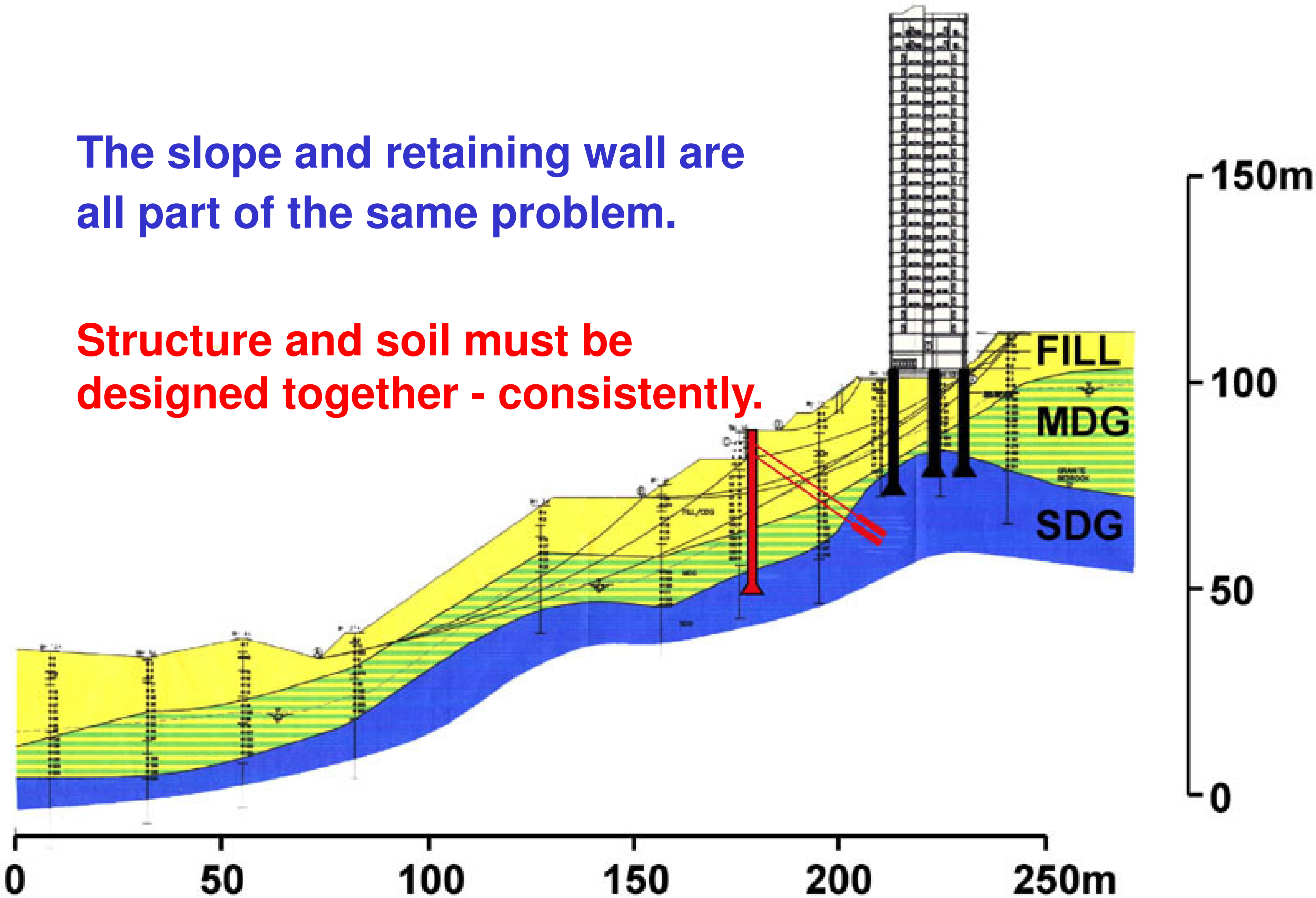
The slope and retaining wall are all part of the same problem.

Structure and soil must be designed together - consistently.



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Partial factors for DA1 – UK and MS National Annex

			Design approach 1 Combination 1 A1	M1	R1	Combination 2 A2	M2	R1	Combination 2 - piles & anchors A2	M1 or	… M2	R4 UKNA	EC7 values
Actions	Permanent	unfav	1,35										
		fav											
	Variable	unfav	1,5			1,3			1,3				
Soil	tan φ'						1,25				1,25		
	Effective cohesion						1,25				1,25		
	Undrained strength						1,4				1,4		
	Unconfined strength						1,4				1,4		
	Weight density												
Spread footings	Bearing												
	Sliding												
Driven piles	Base											1,7/1.5	1,3
	Shaft (compression)											1.5/1.3	1,3
	Total/co											1.7/1.5	1,3
	Shaft in											2.0/1.7	1.6
Bored piles	Base											2.0/1.7	1,6
	Shaft (c											1.6/1.4	1,3
	Total/co											2.0/1.7	1.5
	Shaft in											2.0/1.7	1.6
CFA piles	Base											As	1.45
	Shaft (c											for	1.3
	Total/co											bored	1.4
	Shaft in											piles	1.6
Anchors	Temporary											1,1	1,1
	Permanent											1,1	1,1
Retaining walls	Bearing capacity												
	Sliding resistance												
	Earth resistance												
Slopes	Earth resistance												

[green box] indicates partial factor = 1.0

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- Should DA1-1 and DA1-2 give the same result?
- Then what's the point in doing two calculations?

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EN1990 – choice of partial factor values

C7 Approach for calibration of design values

(2) Design values should be based on the values of the basic variables at the FORM design point, which can be defined as the point on the failure surface ($g = 0$) closest to the average point in the space of normalised variables (as diagrammatically indicated in Figure C2).

(3) The design values of action effects E_d and resistances R_d should be defined such that the probability of having a more unfavourable value is as follows :

$$P(E > E_d) = \Phi(+\alpha_E \beta) \quad \text{(C.6a)}$$

$$P(R \leq R_d) = \Phi(-\alpha_R \beta) \quad \text{(C.6b)}$$

Design consistently at β standard deviations from the mean

where :

β is the target reliability index (see C6).

α_E and α_R, with $|\alpha| \leq 1$, are the values of the FORM sensitivity factors. The value of α is negative for unfavourable actions and action effects, and positive for resistances.

0.7 and 0.8 or 1.0 and 0.4 ?

α_E and α_R may be taken as - 0,7 and 0,8, respectively, provided

$$0{,}16 < \sigma_E/\sigma_R < 7{,}6 \qquad \text{(C.7)}$$

Provided the uncertainties of loads and resistances are reasonably similar …

where σ_E and σ_R are the standard deviations of the action effect and resistance, respectively, in expressions (C.6a) and (C.6b). This gives :

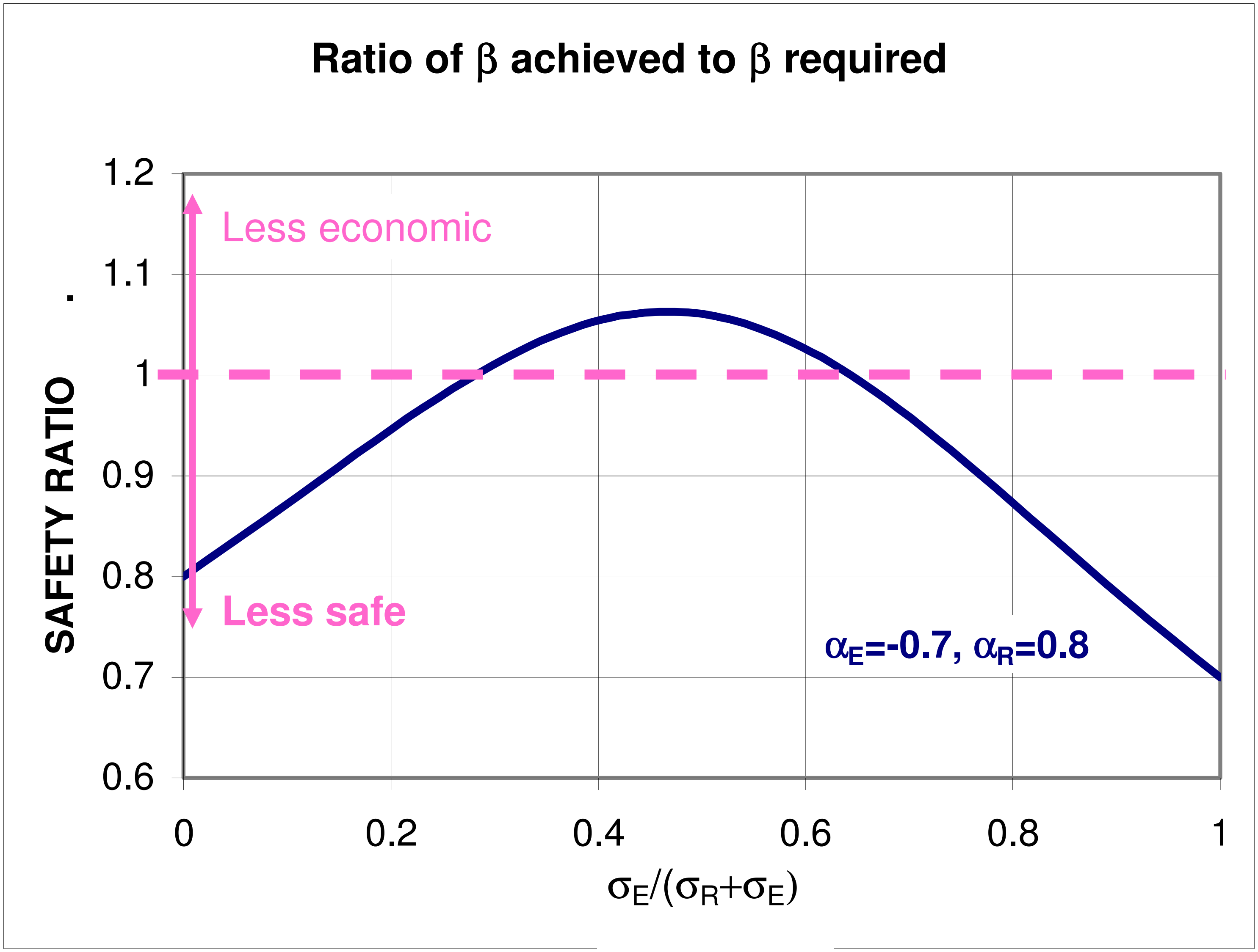
$$P(E > E_d) = \Phi(-0{,}7\beta) \qquad \text{(C.8a)}$$

… use this approach

$$P(R \le R_d) = \Phi(-0{,}8\beta) \qquad \text{(C.8b)}$$

But if one type of uncertainty is really dominant …

(4) Where condition (C.7) is not satisfied $\alpha = \pm\ 1{,}0$ should be used for the variable with the larger standard deviation, and $\alpha = \pm\ 0{,}4$ for the variable with the smaller standard deviation.



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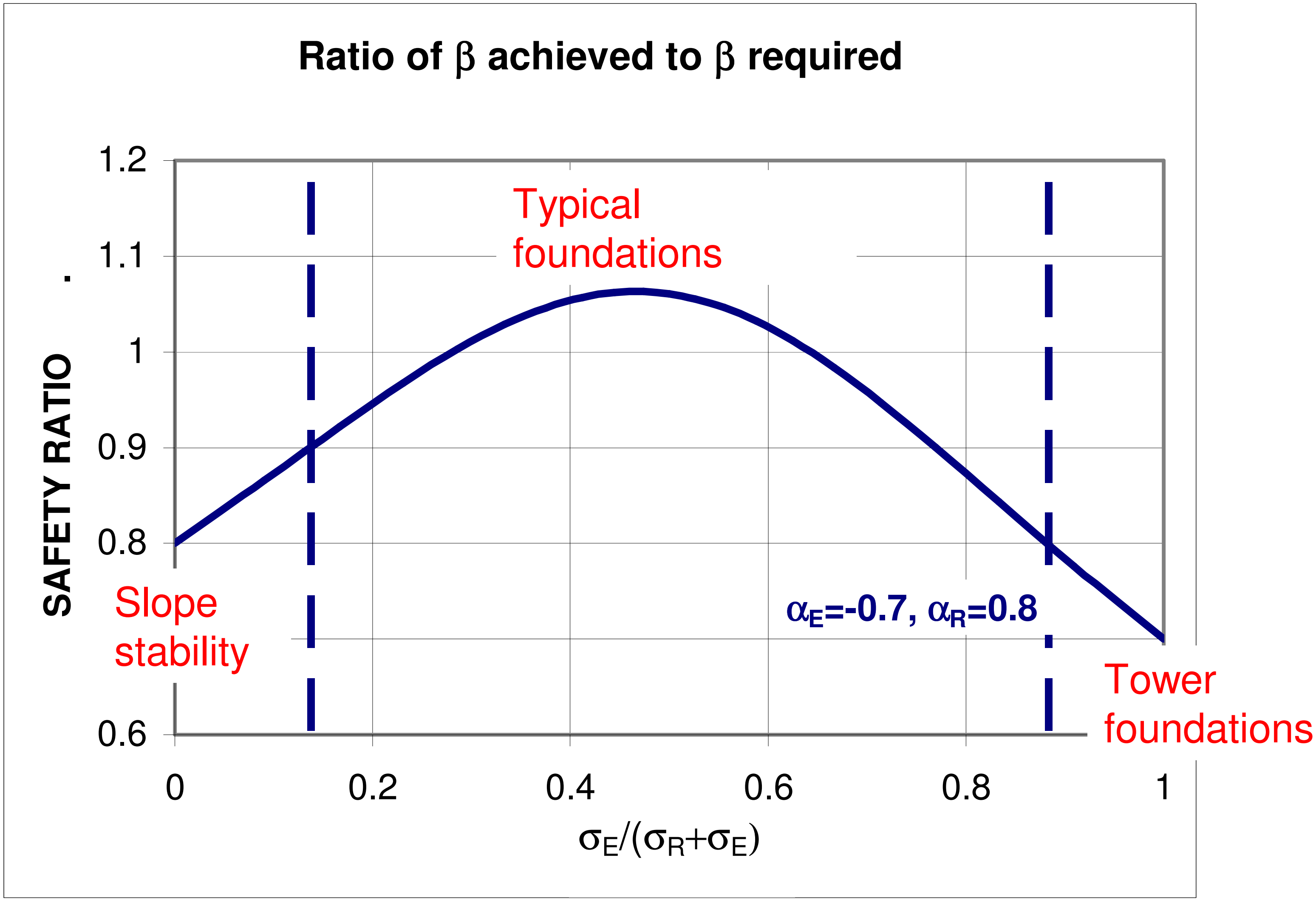

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0.7 and 0.8 or 1.0 and 0.4 ?

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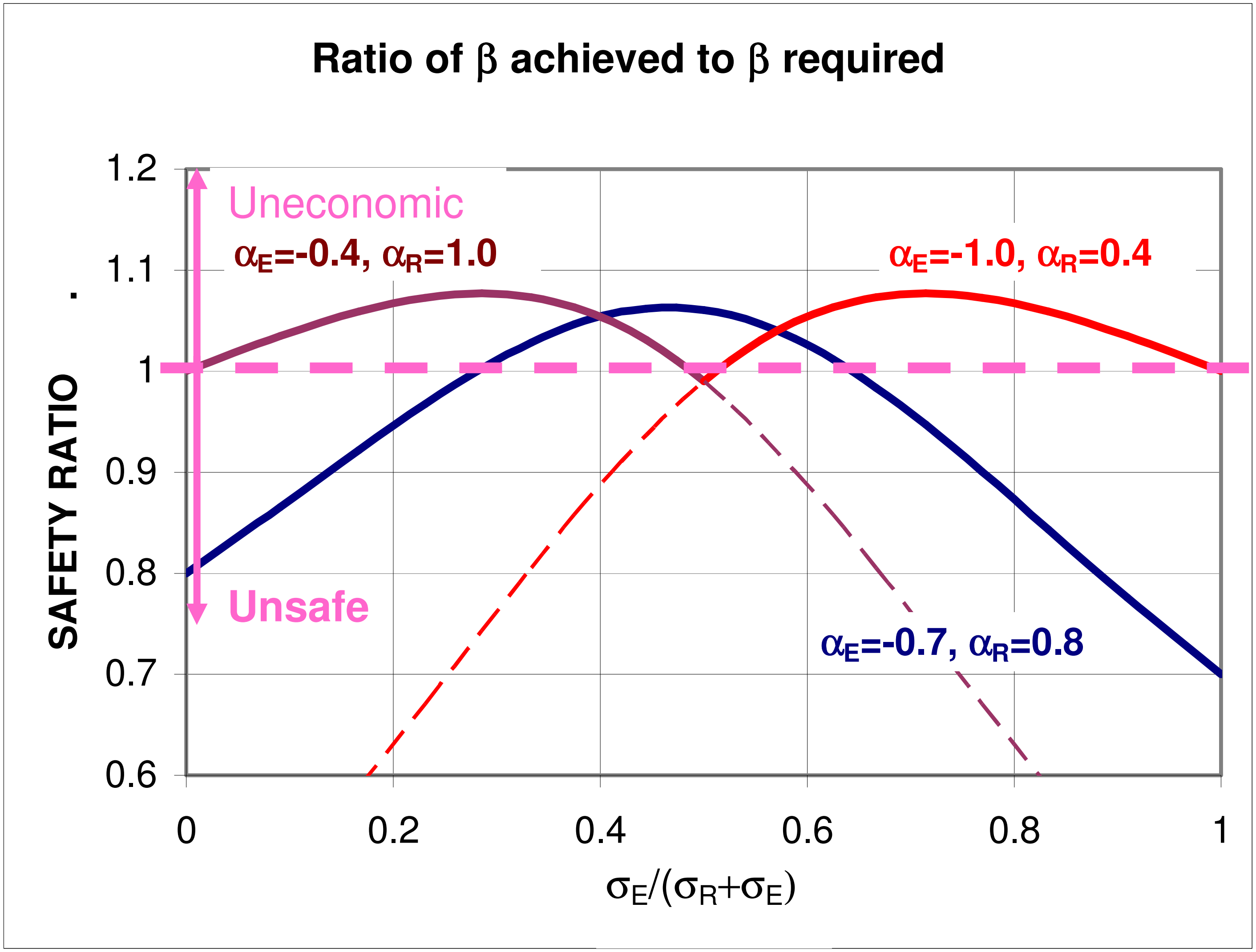
$$P(E > E_d) = \Phi(-0{,}7\beta) \qquad \text{(C.8a)}$$

… use this approach

$$P(R \le R_d) = \Phi(-0{,}8\beta) \qquad \text{(C.8b)}$$

But if one type of uncertainty is really dominant …

(4) Where condition (C.7) is not satisfied $\alpha = \pm\ 1{,}0$ should be used for the variable with the larger standard deviation, and $\alpha = \pm\ 0{,}4$ for the variable with the smaller standard deviation.



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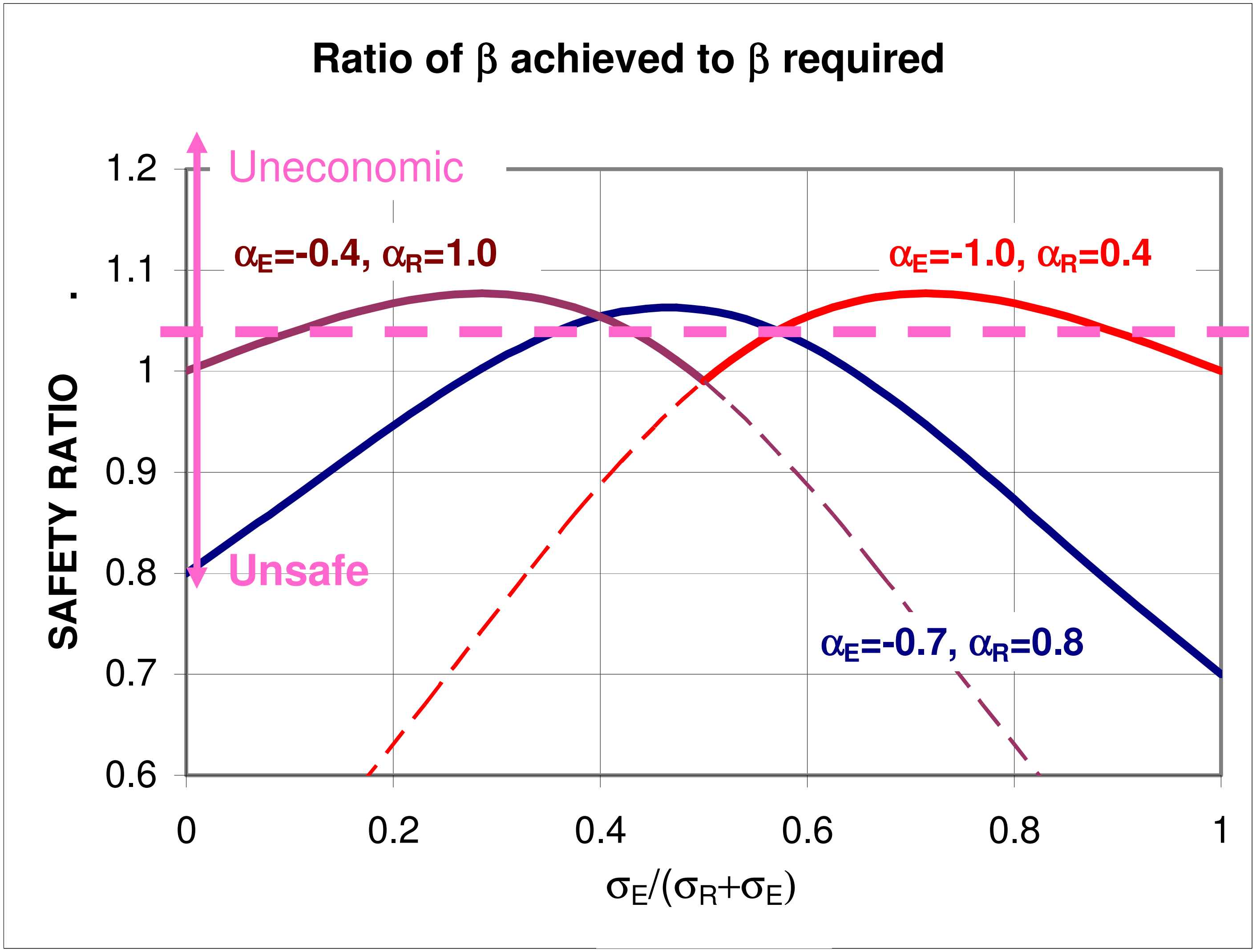

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Combinations 1 and 2 in EC7 - DA1

			Design approach 1 Combination 1			Combination 2			Combination 2 - piles & anchors			
			A1	M1	R1	A2	M2	R1	A2	M1 or …	M2	R4
Actions	Permanent	unfav	1,35									
		fav										
	Variable	unfav	1,5			1,3			1,3			
Soil	tan ϕ'						1,25				1,25	
	Effective cohesion						1,25				1,25	
	Undrained strength						1,4				1,4	
	Unconfined strength						1,4				1,4	
	Weight density											

- Just like load combinations, extended to include variables on the resistance side.
- All designs must comply with both combinations in all respects, both geotechnical and structural
- Turkstra's principle for load combinations - extended

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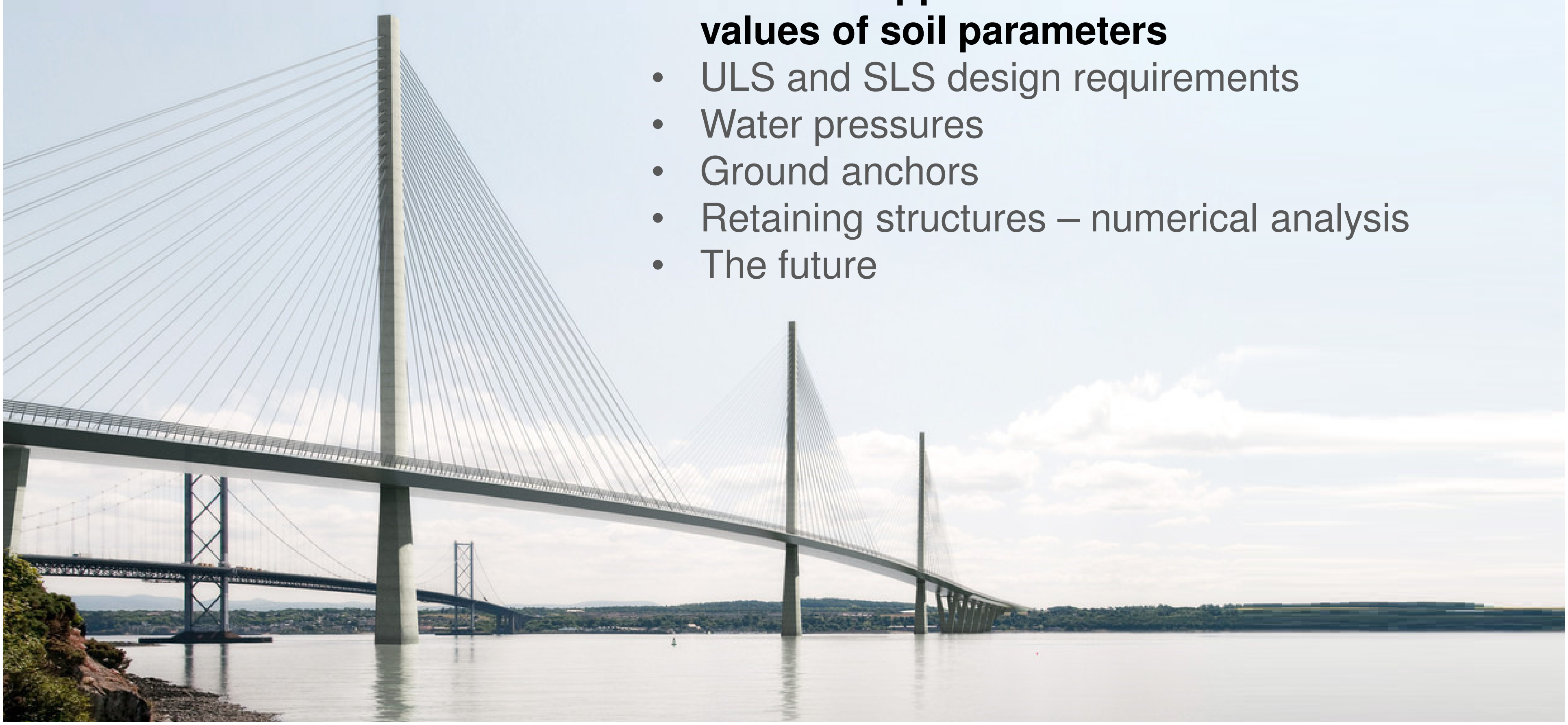

Fundamental limit state requirement

$$E_d \le R_d$$

$$E\{\ F_d\ ;\ X_d\ ;\ a_d\} = E_d \le R_d = R\{\ F_d\ ;\ X_d\ ;\ a_d\}$$

$$E\{\gamma_F\ F_{rep};\ X_k/\gamma_M;\ a_d\} = E_d \le R_d = R\{\gamma_F\ F_{rep};\ X_k/\gamma_M;\ a_d\}$$

or $E\{\gamma_F\ F_{rep};\ X_k/\gamma_M;\ a_d\} = E_d \le R_d = R_k/\gamma_R = R_n \phi_R$ (LRFD)

or $\gamma_E\ E_k = E_d \le R_d = R_k/\gamma_R$

so in total

$$\gamma_E\ E\{\gamma_F\ F_{rep};\ X_k/\gamma_M;\ a_d\} = E_d \le R_d = R\{\gamma_F\ F_{rep};\ X_k/\gamma_M;\ a_d\}/\gamma_R$$

E = action effects

F = actions (loads)

R = resistance (=capacity)

X = material properties

a = dimensions/geometry

d = design (= factored)

k = characteristic (= unfactored)

rep = representative

Fundamental limit state requirement

$$E_d \leq R_d$$

$$E\{\ F_d\ ;\ X_d\ ;\ a_d\} = E_d \leq R_d = R\{\ F_d\ ;\ X_d\ ;\ a_d\}$$

$$E\{\gamma_F\ F_{rep};\ X_k/\gamma_M;\ a_d\} = E_d \leq R_d = R\{\gamma_F\ F_{rep};\ X_k/\gamma_M;\ a_d\}$$

or $$E\{\gamma_F\ F_{rep};\ X_k/\gamma_M;\ a_d\} = E_d \leq R_d = R_k/\gamma_R = R_n\phi_R \quad \text{(LRFD)}$$

or $$\gamma_E\ E_k = E_d \leq R_d = R_k/\gamma_R$$

so in total

$$\gamma_E\ E\{\gamma_F\ F_{rep};\ X_k/\gamma_M;\ a_d\} = E_d \leq R_d = R\{\gamma_F\ F_{rep};\ X_k/\gamma_M;\ a_d\}/\gamma_R$$

Concrete and steel: 2 standard deviations from the mean test result.

Characteristic values in EC7

2.4.5.2 Characteristic values of geotechnical parameters

(1)P The selection of characteristic values for geotechnical parameters shall be based on derived values resulting from laboratory and field tests, complemented by well-established experience.

(2)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.

(3)P The greater variance of c' compared to that of tanφ' shall be considered when their characteristic values are determined.

(4)P The selection of characteristic values for geotechnical parameters shall take account of the following:

-- geological and other background information, such as data from previous projects;
-- the variability of the measured property values and other relevant information, e.g. from existing knowledge;
-- the extent of the field and laboratory investigation;
-- the type and number of samples;
-- the extent of the zone of ground governing the behaviour of the geotechnical structure at the limit state being considered;
-- the ability of the geotechnical structure to transfer loads from weak to strong zones in the ground.

(5) Characteristic values can be lower values, which are less than the most probable values, or upper values, which are greater.

(6)P For each calculation, the most unfavourable combination of lower and upper values of independent parameters shall be used.

(7) The zone of ground governing the behaviour of a geotechnical structure at a limit state is usually much larger than a test sample or the zone of ground affected in an in situ test. Consequently the value of the governing parameter is often the mean of a range of values covering a large surface or volume of the ground. The characteristic value should be a cautious estimate of this mean value.

(8) If the behaviour of the geotechnical structure at the limit state considered is governed by the lowest or highest value of the ground property, the characteristic value should be a cautious estimate of the lowest or highest value occurring in the zone governing the behaviour.

(9) When selecting the zone of ground governing the behaviour of a geotechnical structure at a limit state, it should be considered that this limit state may depend on the behaviour of the supported structure. For instance, when considering a bearing resistance ultimate limit state for a building resting on several footings, the governing parameter should be the mean strength over each individual zone of ground under a footing, if the building is unable to resist a local failure. If, however, the building is stiff and strong enough, the governing parameter should be the mean of these mean values over the entire zone or part of the zone of ground under the building.

(10) If statistical methods are employed in the selection of characteristic values for ground properties, such methods should differentiate between local and regional sampling and should allow the use of a priori knowledge of comparable ground properties.

(11) 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%.

NOTE In this respect, a cautious estimate of the mean value is a selection of the mean value of the limited set of geotechnical parameter values, with a confidence level of 95%; where local failure is concerned, a cautious estimate of the low value is a 5% fractile.

(12)P When using standard tables of characteristic values related to soil investigation parameters, the characteristic value shall be selected as a very cautious value.

Characteristic values in EC7 – definition (2.4.5.2)

(1)P The selection of characteristic values for geotechnical parameters shall be based on results and derived values from laboratory and field tests, complemented by well-established experience.

(2)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.

(4)P The selection of characteristic values for geotechnical parameters shall take account of the following:

— geological and other background information, such as data from previous projects;

— the variability of the measured property values and other relevant information, e.g. from existing knowledge;

— the extent of the field and laboratory investigation;

— the type and number of samples;

— the extent of the zone of ground governing the behaviour of the geotechnical structure at the limit state being considered;

— the ability of the geotechnical structure to transfer loads from weak to strong zones in the ground.

Characteristic values in EC7

2.4.3(4) also mentions:

- — many geotechnical parameters are not true constants but depend on stress level and mode of deformation;
- — soil and rock structure (e.g. fissures, laminations, or large particles) that may play a different role in the test and in the geotechnical structure;
- — time effects;
- — the softening effect of percolating water on soil or rock strength;
- — the softening effect of dynamic actions;
- — the brittleness or ductility of the soil and rock tested;
- — the method of installation of the geotechnical structure;
- — the influence of workmanship on artificially placed or improved ground;
- — the effect of construction activities on the properties of the ground.

Characteristic values in EC7

2.4.5.2 Characteristic values of geotechnical parameters

(5) Characteristic values can be lower values, which are less than the most probable values, or upper values, which are greater.

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"Cautious" – worse than most probable.

Characteristic values in EC7 – zone of ground

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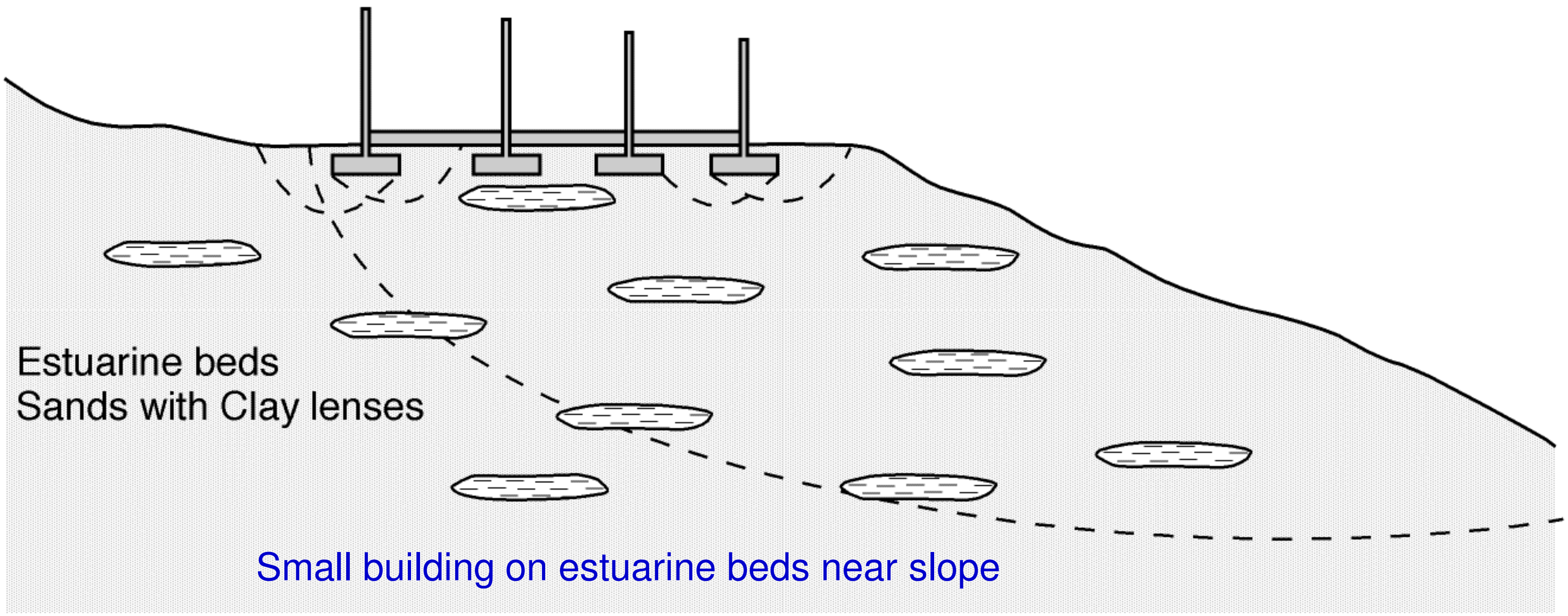
"Cautious" – worse than most probable.

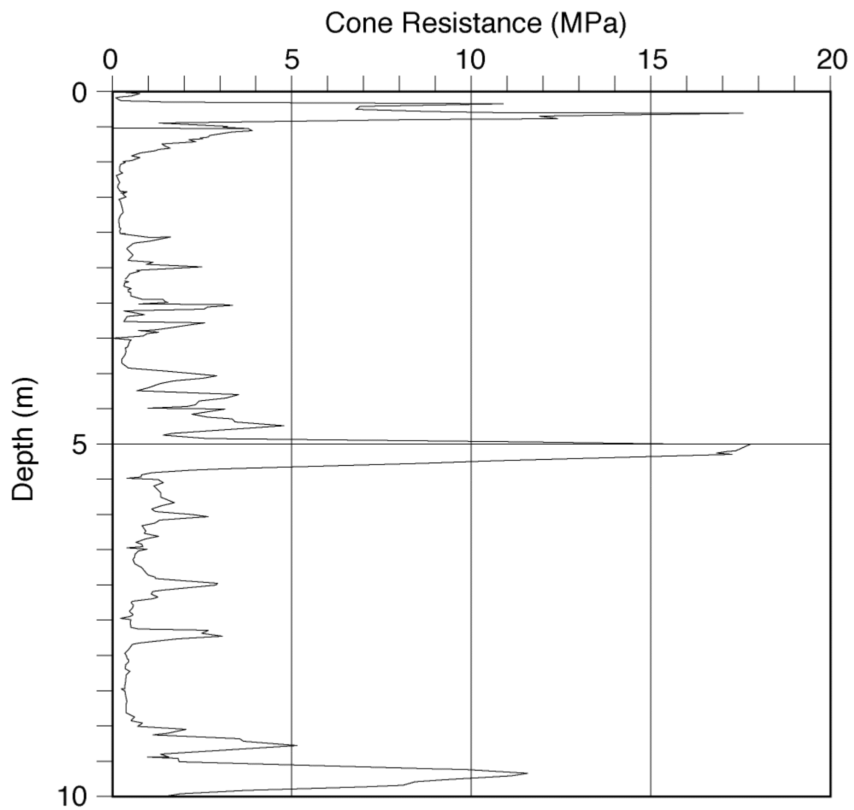


Small building on estuarine beds near slope

ARUP

Characteristic values in EC7 – zone of ground

(7) The zone of ground governing the behaviour of a geotechnical structure at a limit state is usually much larger than a test sample or the zone of ground affected in an in situ test. Consequently the value of the governing parameter is often the mean of a range of values covering a large surface or volume of the ground. The characteristic value should be a cautious estimate of this mean value.



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Characteristic values in EC7 – zone of ground

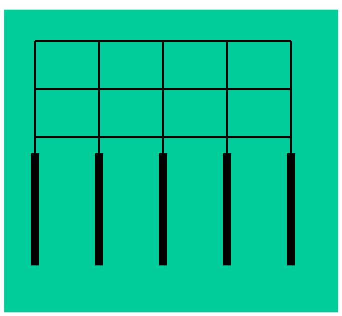
2.4.5.2 Characteristic values of geotechnical parameters

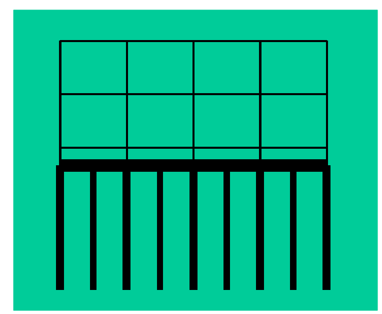
(9) When selecting the zone of ground governing the behaviour of a geotechnical structure at a limit state, it should be considered that this limit state may depend on the behaviour of the supported structure. For instance, when considering a bearing resistance ultimate limit state for a building resting on several footings, the governing parameter should be the mean strength over each individual zone of ground under a footing, if the building is unable to resist a local failure. If, however, the building is stiff and strong enough, the governing parameter should be the mean of these mean values over the entire zone or part of the zone of ground under the building.

Thoughtful interpretation – not simple averaging

7.6.2.2

(9) For structures having sufficient stiffness and strength to transfer loads from "weak" to "strong" piles, the values of ξ_1 and ξ_2 may be divided by 1,1, provided that ξ_1 is never less than 1,0.





Characteristic values in EC7 – definition (2.4.5.2)

(2)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.

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(11) 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%.

NOTE In this respect, a cautious estimate of the mean value is a selection of the mean value of the limited set of geotechnical parameter values, with a confidence level of 95%; where local failure is concerned, a cautious estimate of the low value is a 5% fractile.

(12)P When using standard tables of characteristic values related to soil investigation parameters, the characteristic value shall be selected as a very cautious value.

0.5 SD below the mean?

A suggestion:

When:

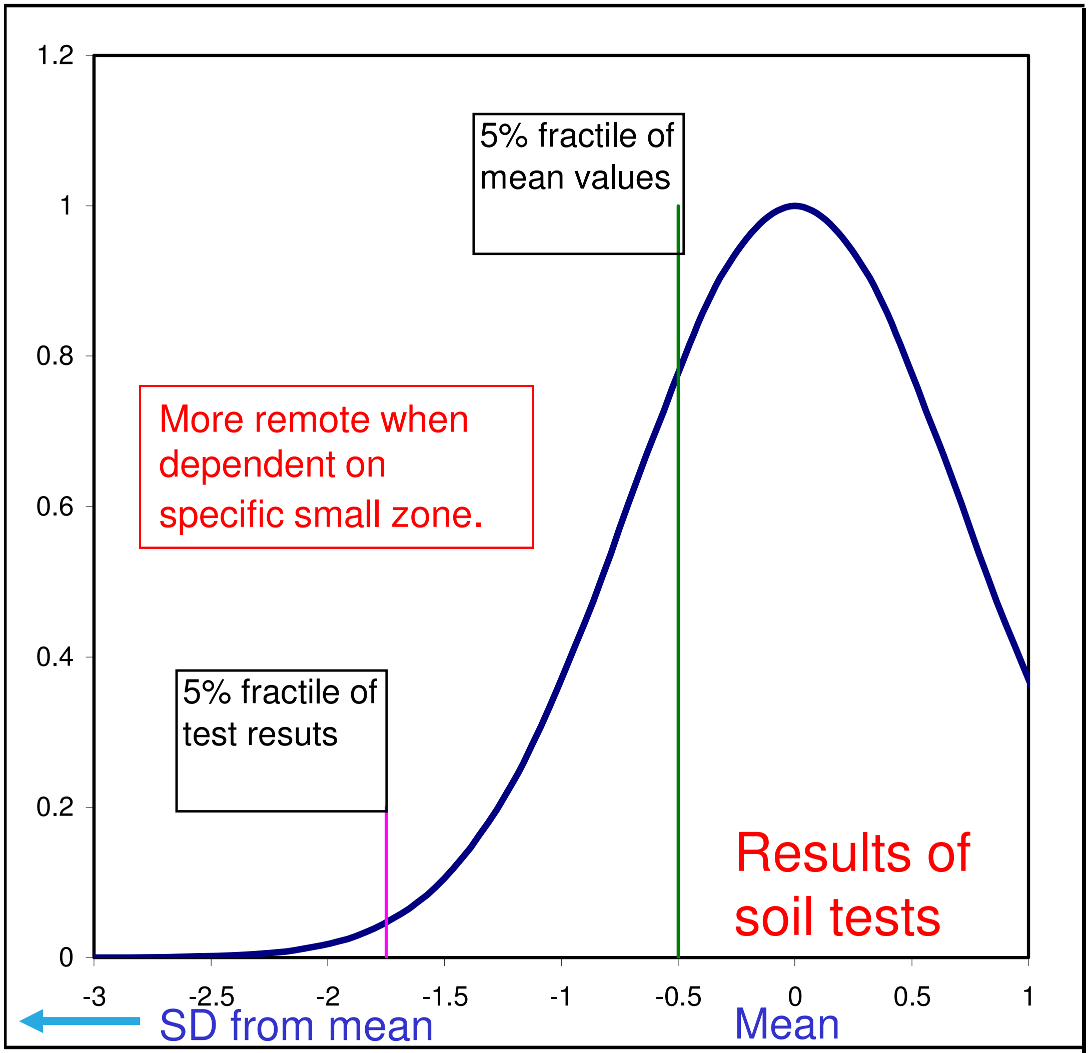
- a limit state depends on the value of a parameter averaged over a large amount of ground (ie a mean value), and
- the ground property varies in a homogeneous, random manner, and
- at least 10 test values are available

Then: A value 0.5SD below the mean of the test results provides a useful indication of the characteristic value

(Contribution to Discussion Session 2.3, XIV ICSMFE, Hamburg. Balkema., Schneider H R (1997) Definition and determination of characteristic soil properties. Discussion to ISSMFE Conference, Hamburg.)

0.5 SD below the mean?

- a useful consideration, not a rule



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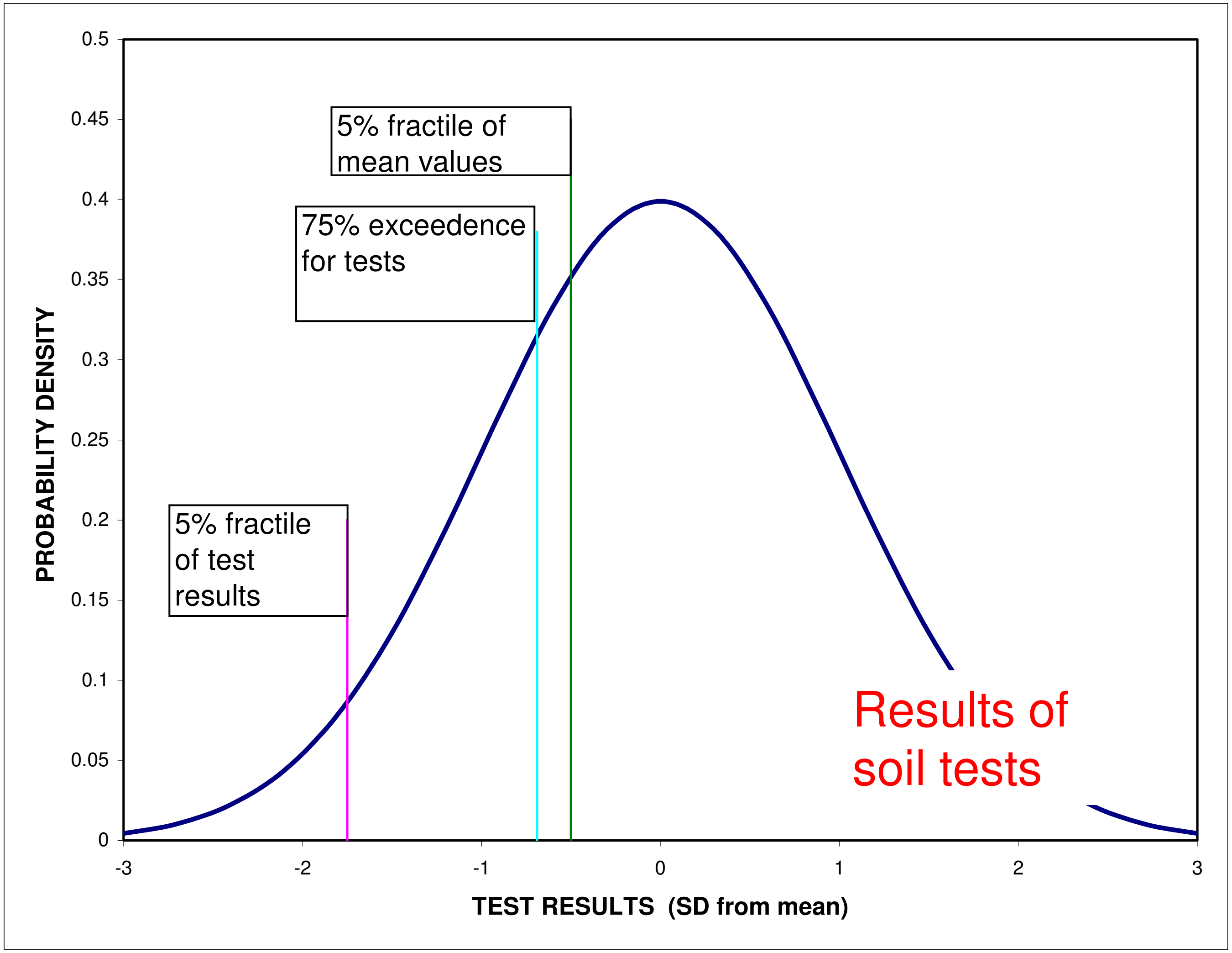
A USA proposal – 25% fractile



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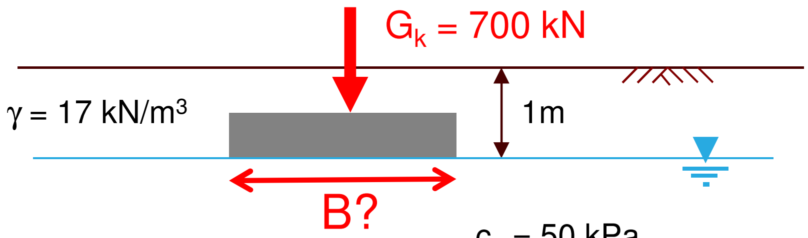
Characteristic values in EC7

- NOT a fractile of the results of particular, specified laboratory tests on specimens of material.
- A cautious estimate of the value affecting the occurrence of the limit state
- Take account of time effects, brittleness, soil fabric and structure, the effects of construction processes and the extent of the body of ground involved in a limit state
- The designer's expertise and understanding of the ground are all encapsulated in the characteristic value
- Consider both project-specific information and a wider body of geotechnical knowledge and experience.
- Characteristic = moderately conservative = representative (BS8002) = what good designers have always done.

Eurocode 7 – Good practice in geotechnical design

- Limit state design
- Holistic design – structures and ground
- Practical approach to characteristic values of soil parameters
- **ULS and SLS design requirements**
- Water pressures
- Ground anchors
- Retaining structures – numerical analysis
- The future

Square footing



c_u = 50 kPa

c'=0, φ' = 25°

γ = 20 kN/m³

Limiting settlements:

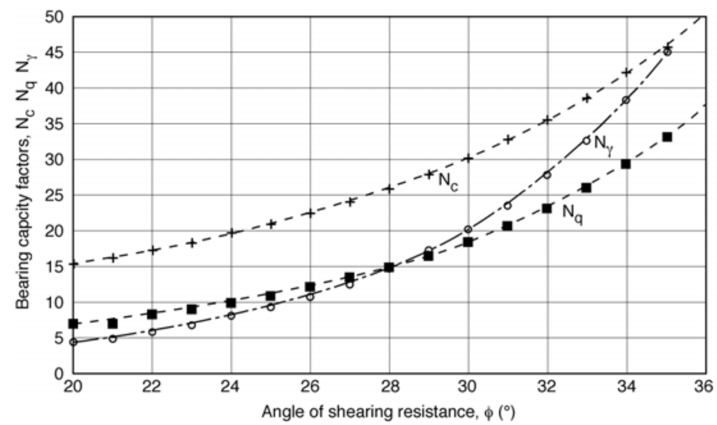
20 mm short term (undrained)

30 mm long term (drained)

Ultimate bearing capacity

Undrained: $R/B = (\pi+2)\ c_u s_u + q$

Drained: $R/B = c'\ N_c s_c + q'\ N_q s_q + 0.5\ \gamma' B\ N_\gamma s_\gamma$



Partial factors $\gamma_{Cu} = 1.4$ $\gamma_{\varphi}=1.25$

To satisfy ULS requirements:

(5)P A limiting value for a particular deformation is the value at which a serviceability limit state, such as unacceptable cracking or jamming of doors, is deemed to occur in the supported structure. This limiting value shall be agreed during the design of the supported structure.

6.6 Serviceability limit state design

6.6.1 General

(1)P Account shall be taken of displacements caused by actions on the foundation, such as those listed in 2.4.2(4).

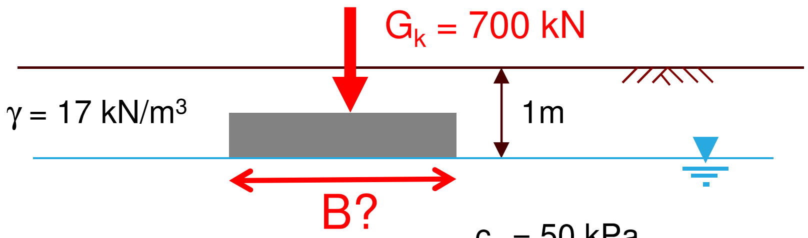
(2)P In assessing the magnitude of foundation displacements, account shall be taken of comparable experience, as defined in 1.5.2.2. If necessary, calculations of displacements shall also be carried out.

(3)P For soft clays, settlement calculations shall always be carried out.

(4) For spread foundations on stiff and firm clays in Geotechnical Categories 2 and 3, calculations of vertical displacement (settlement) should usually be undertaken. Methods that may be used to calculate settlements caused by loads on the foundation are given in 6.6.2.

(16) For conventional structures founded on clays, the ratio of the bearing capacity of the ground, at its initial undrained shear strength, to the applied serviceability loading should be calculated (see 2.4.8(4)). If this ratio is less than 3, calculations of settlements should always be undertaken. If the ratio is less than 2, the calculations should take account of non-linear stiffness effects in the ground.

Square footing



c_u = 50 kPa

c'=0, φ' = 25°

γ = 20 kN/m³

Limiting settlements:

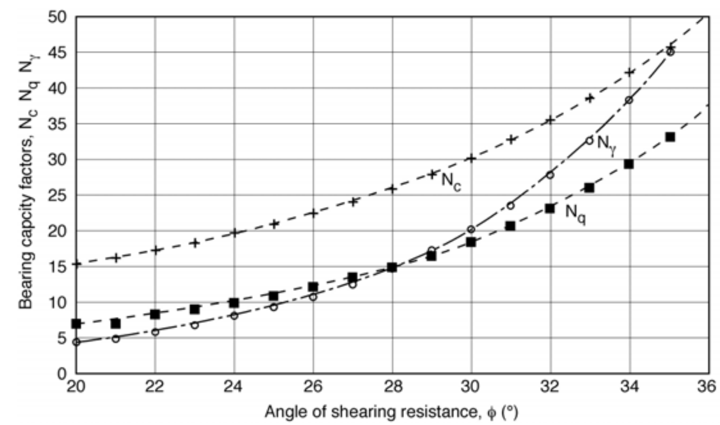
20 mm short term (undrained)

30 mm long term (drained)

Ultimate bearing capacity

Undrained: $R/B = (\pi+2)\ c_u s_u\ +\ q$

Drained: $R/B = c'\ N_c s_c\ + q'\ N_q s_q\ + 0.5\ \gamma'\ B\ N_\gamma s_\gamma$



Partial factors $\gamma_{Cu} = 1.4$ $\gamma_\varphi = 1.25$

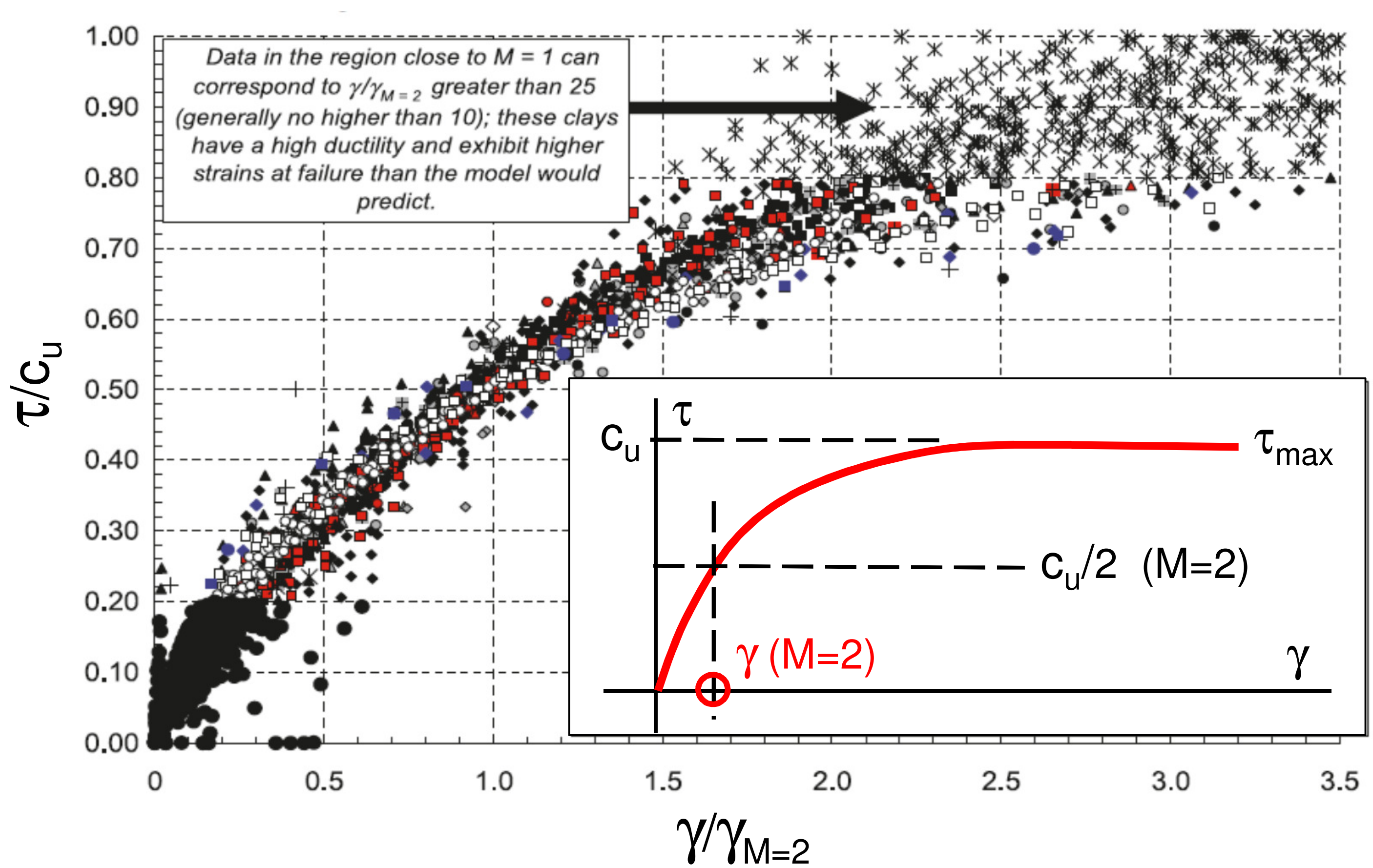
To satisfy ULS requirements:

Undrained:	B = 1.73 m	Working bearing pressure = 237 kPa
Drained:	B = 2.02 m	Working bearing pressure = 174 kPa

SLS:

SLS using $c_u/3$	B = 2.44 m	Working bearing pressure = 120 kPa
SLS using $c_u/2$	B = 2.04 m	Working bearing pressure = 171 kPa

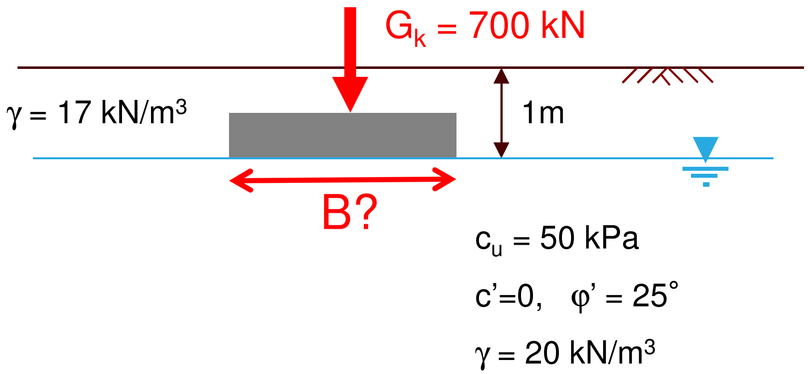
Settlement prediction by Bolton et al



Vardanega, P.J. and Bolton, M.D. (2011) Strength mobilization in clays and silts. Canadian Geotechnical Journal 48(10):1485-1503.

McMahon, B.T., Haigh, S.K., Bolton, M.D. (2014) Bearing capacity and settlement of circular shallow foundations using a nonlinear constitutive relationship. Canadian Geotechnical Journal 51 (9): 995-1003.

Square footing



Limiting settlements:

20 mm short term (undrained)

30 mm long term (drained)

- Design for undrained ULS only – likely to fail at SLS.
- Design for ULS drained – marginal at SLS
- $c_u/3$ – small settlements
- $c_u/2$ – non-linear

Criterion	Width B required	Working bearing pressure	Undrained settlement		Drained settlement	
			Bolton $\gamma_{M=2} = 1\%$	$E/c_u = 300$	Bolton $\gamma_{M=2} = 1\%$	$E/c_u = 200$
	m	kPa	mm	mm	mm	mm
ULS undrained	1.73	237				
ULS drained	2.02	171				
SLS $c_u/3$	2.44	120				
SLS $c_u/2$	2.04	171				

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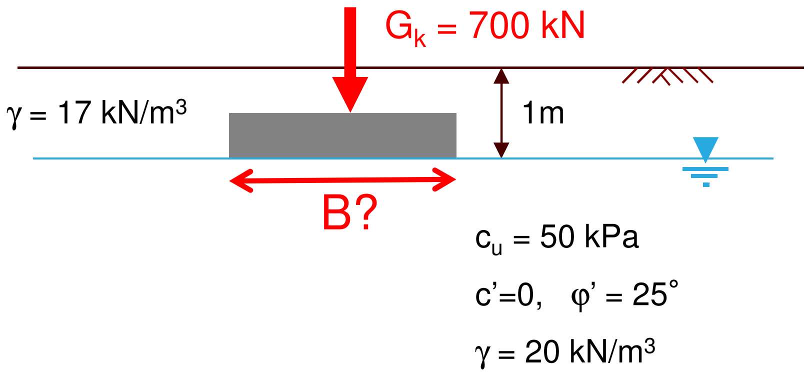
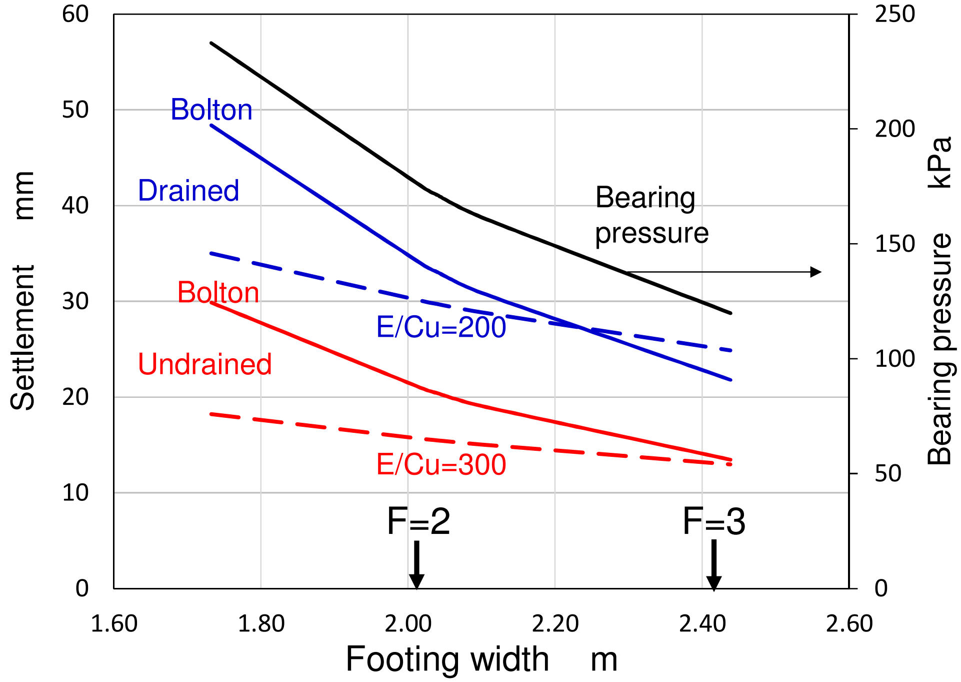
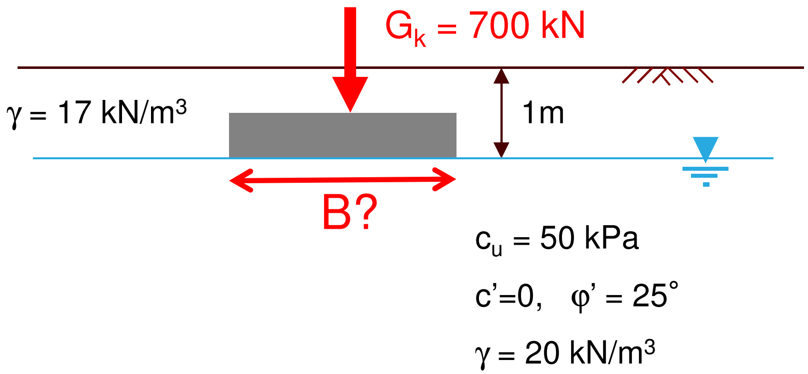
Square footing





Criterion	Width B required	Working bearing pressure	Undrained settlement		Drained settlement	
			Bolton $\gamma_{M=2} = 1\%$	$E/c_u = 300$	Bolton $\gamma_{M=2} = 1\%$	$E/c_u = 200$
	m	kPa	mm	mm	mm	mm
ULS undrained	1.73	237	30	18	48	35
ULS drained	2.02	171	20	15	33	29
SLS $c_u/3$	2.44	120	13	13	22	25
SLS $c_u/2$	2.04	171	20	15	33	30
Settlement limits	2.10	159	19	15	30	28

Square footing



Limiting settlements:

20 mm short term (undrained)

30 mm long term (drained)

- Design for undrained ULS only – likely to fail at SLS.
- Design for ULS drained – marginal at SLS
- $c_u/3$ – small settlements
- $c_u/2$ – non-linear
- Necessary to check both ULS and SLS: SLS may govern

Criterion	Width B required	Working bearing pressure	Undrained settlement		Drained settlement	
			Bolton $\gamma_{M=2} = 1\%$	$E/c_u = 300$	Bolton $\gamma_{M=2} = 1\%$	$E/c_u = 200$
	m	kPa	mm	mm	mm	mm
ULS undrained	1.73	237	30	18	48	35
ULS drained	2.02	171	20	15	33	29
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Settlement limits	2.10	159	19	15	30	28

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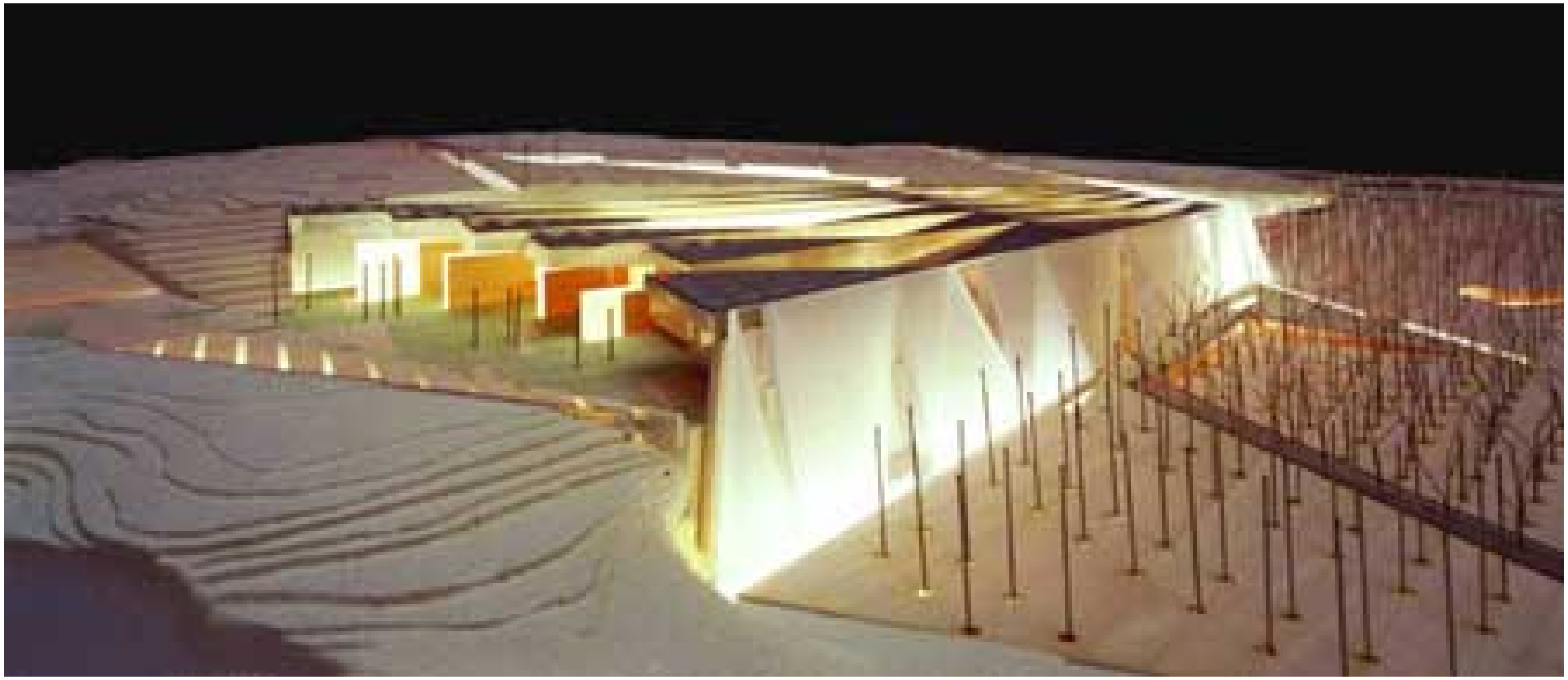
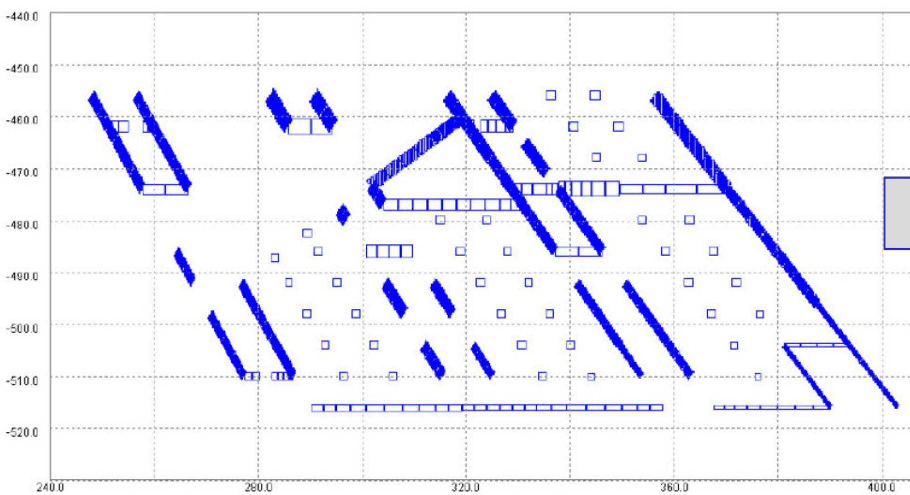
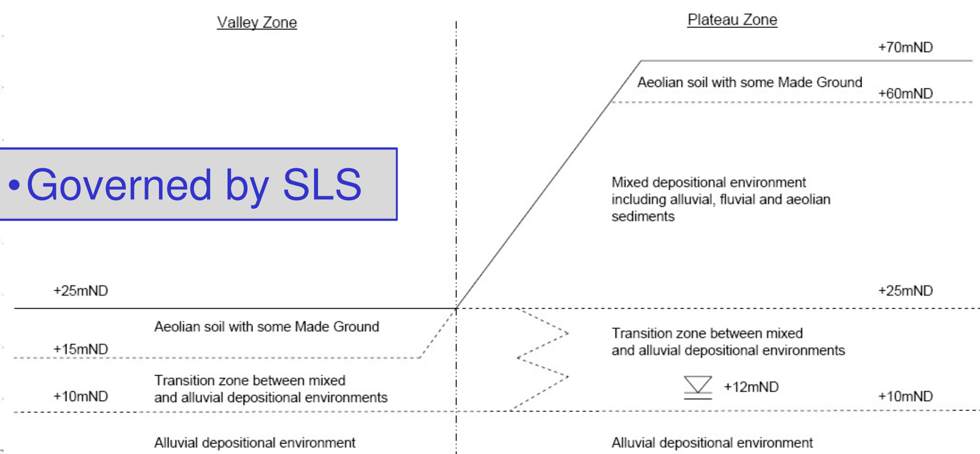
Grand Egyptian Museum





- Governed by SLS



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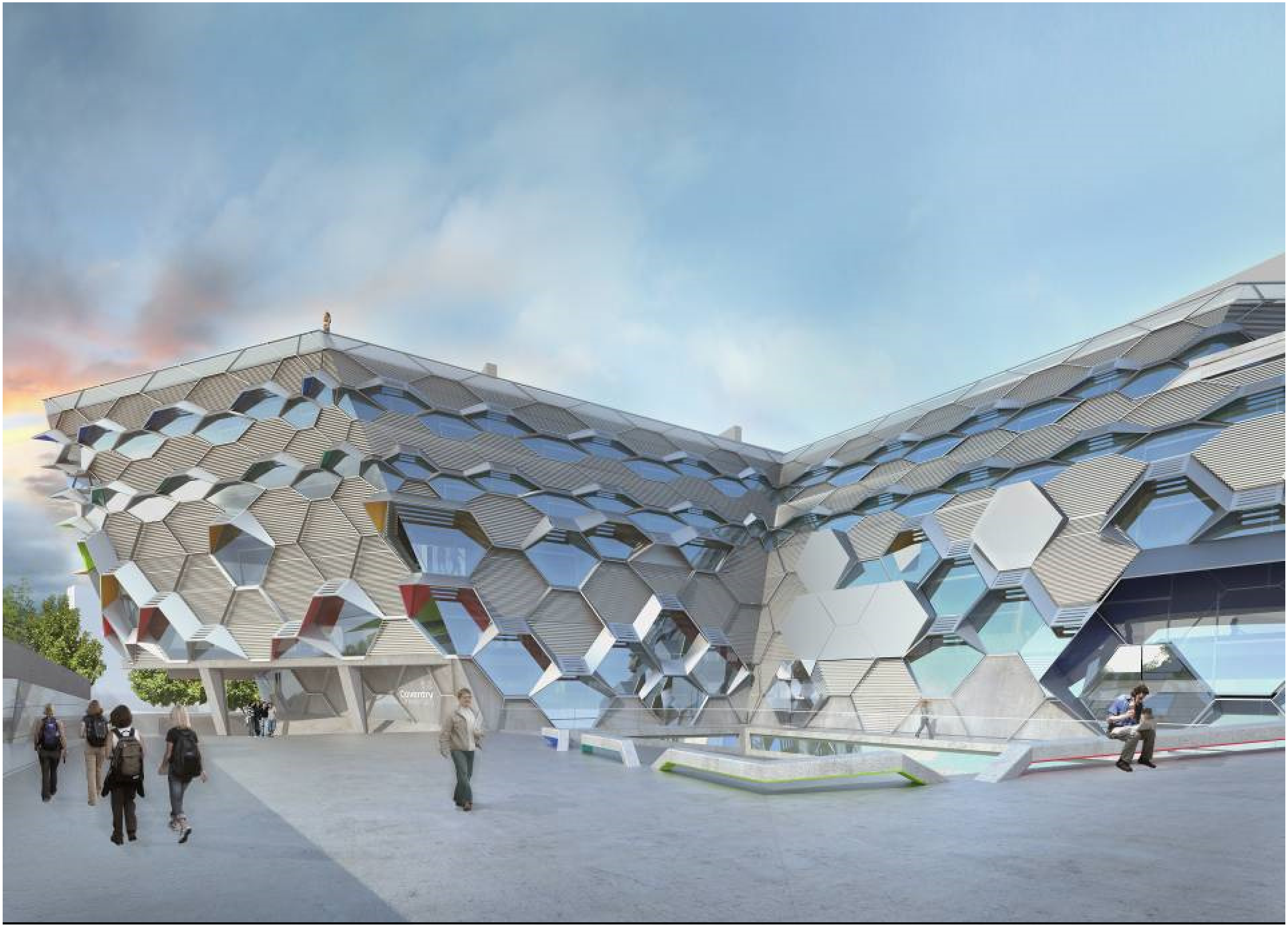
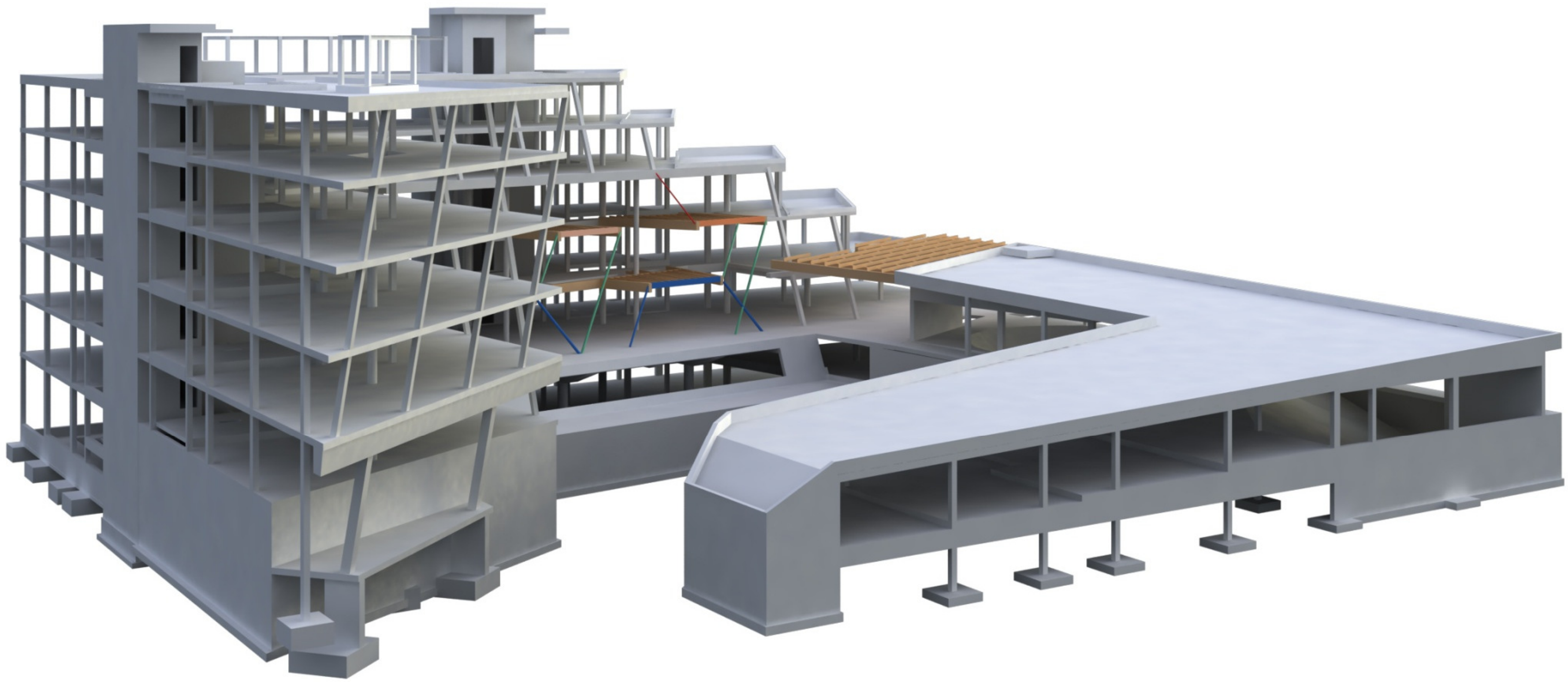


Coventry University Engineering and Computing Building

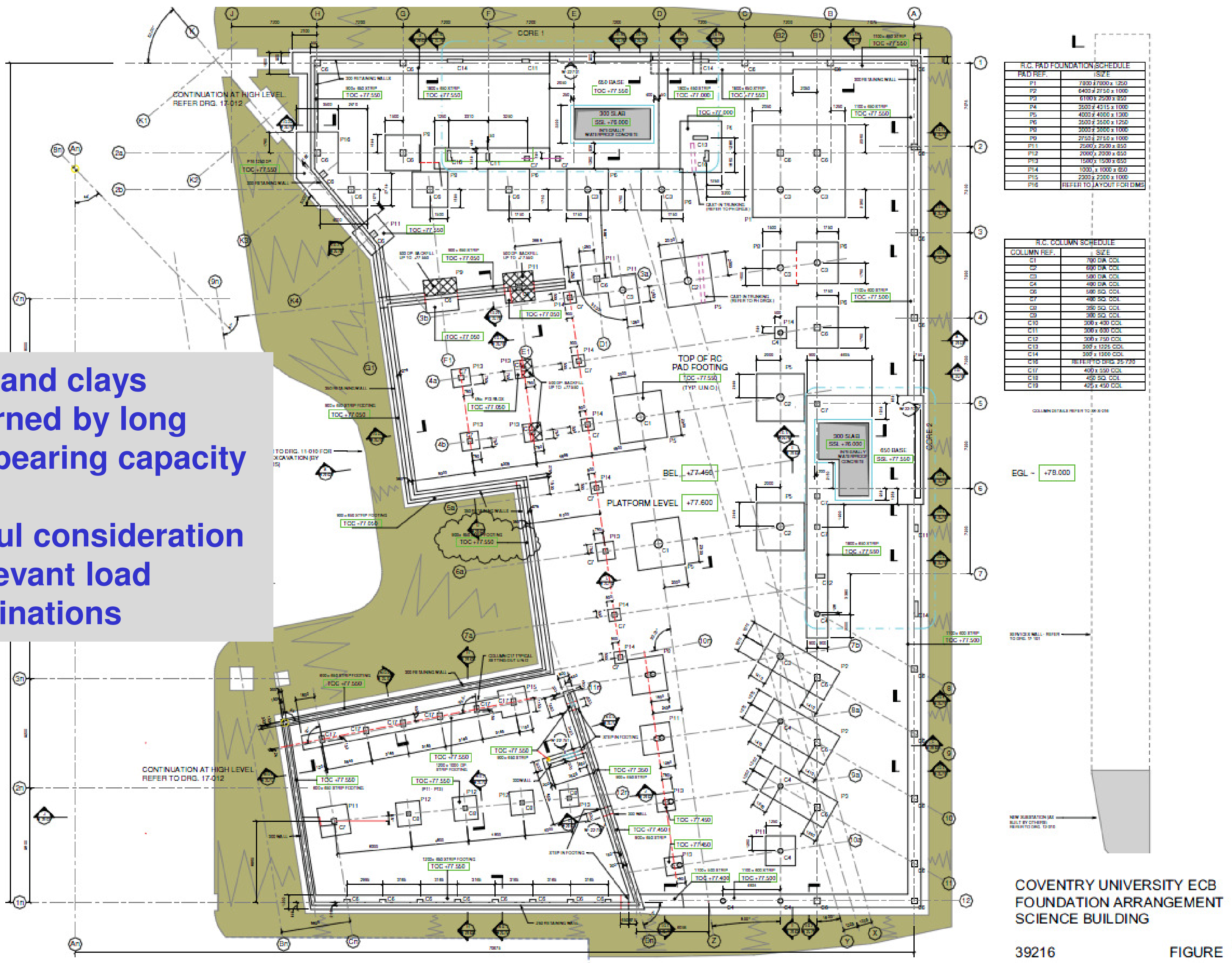
Arup Associates

Design for Collaborative Learning

Detailed Design



- Sand and clays
- Governed by long term bearing capacity (ULS)
- Careful consideration of relevant load combinations



Greengate Public Realm

- footbridge near Manchester

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Section 7 – Pile foundations

7.6.1.1 Limit state design

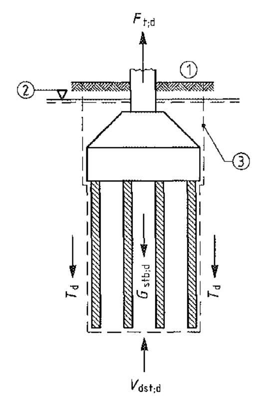
(1)P The design shall demonstrate that exceeding the following limit states is sufficiently improbable:

— ultimate limit states of compressive or tensile resistance failure of a single pile;

— ultimate limit states of compressive or tensile resistance failure of the pile foundation as a whole;

— ultimate limit states of collapse or severe damage to a supported structure caused by excessive displacement or differential displacements of the pile foundation;

— serviceability limit states in the supported structure caused by displacement of the piles.



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SLS also covered by ULS factors

7.6.4 Vertical displacements of pile foundations (Serviceability of supported structure)

7.6.4.1 General

(1)P Vertical displacements under serviceability limit state conditions shall be assessed and checked against the requirements given in 2.4.8 and 2.4.9.

(2) When calculating the vertical displacements of a pile foundation, the uncertainties involved in the calculation model and in determining the relevant ground properties should be taken into account. Hence it should not be overlooked that in most cases calculations will provide only an approximate estimate of the displacements of the pile foundation.

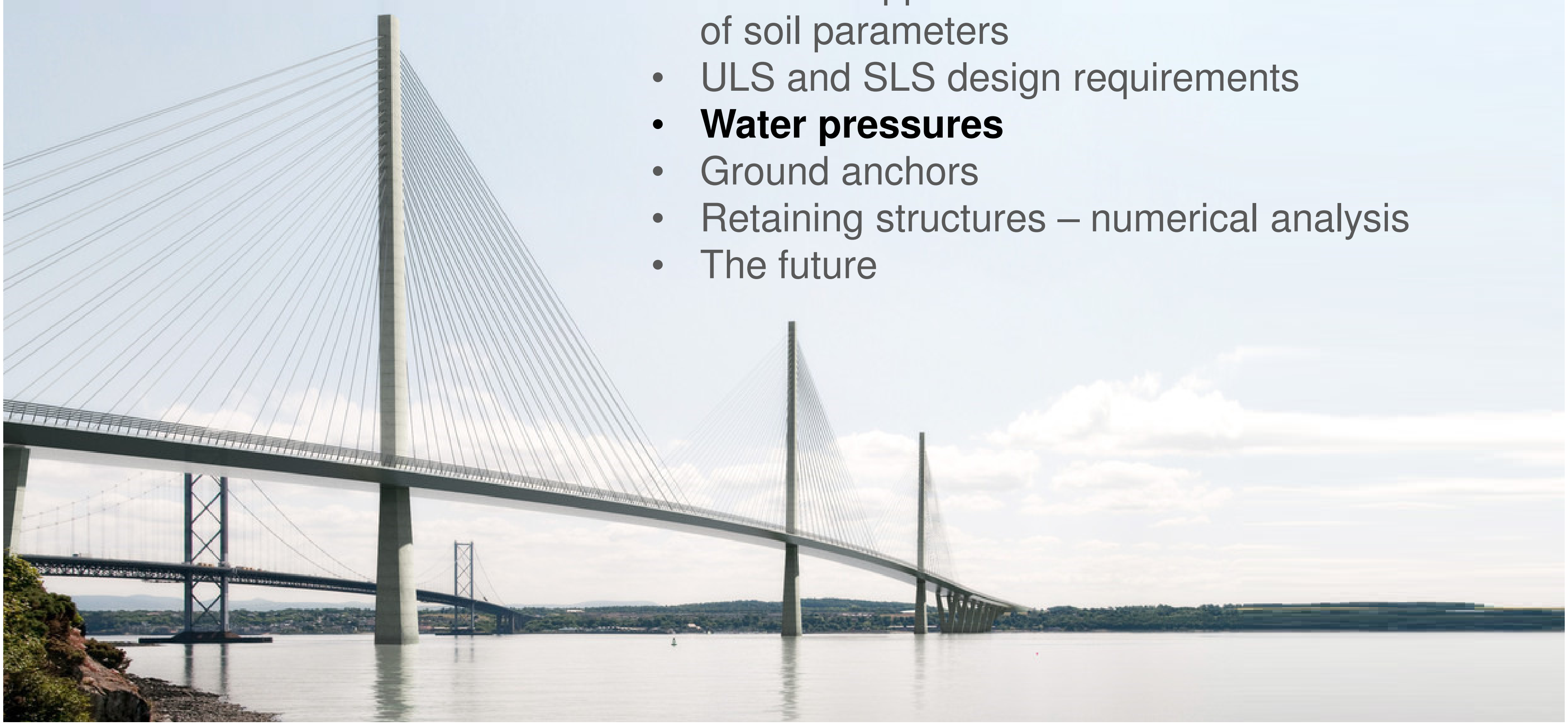
NOTE For piles bearing in medium-to-dense soils and for tension piles, the safety requirements for the ultimate limit state design are normally sufficient to prevent a serviceability limit state in the supported structure.

HKIE

8th Lumb Lecture

Eurocode 7 – Good practice in geotechnical design

- Limit state design
- Holistic design – structures and ground
- Practical approach to characteristic values of soil parameters
- ULS and SLS design requirements
- **Water pressures**
- Ground anchors
- Retaining structures – numerical analysis
- The future



Water has a way of seeping between any two theories!

2.4.7 Ultimate Limit States

2.4.7.1 General

(1)P Where relevant, it shall be verified that the following limit states are not exceeded:

— loss of equilibrium of the structure or the ground, considered as a rigid body, in which the strengths of structural materials and the ground are insignificant in providing resistance (EQU);

— internal failure or excessive deformation of the structure or structural elements, including e.g. footings, piles or basement walls, in which the strength of structural materials is significant in providing resistance (STR);

— failure or excessive deformation of the ground, in which the strength of soil or rock is significant in providing resistance (GEO);

— loss of equilibrium of the structure or the ground due to uplift by water pressure (buoyancy) or other vertical actions (UPL)

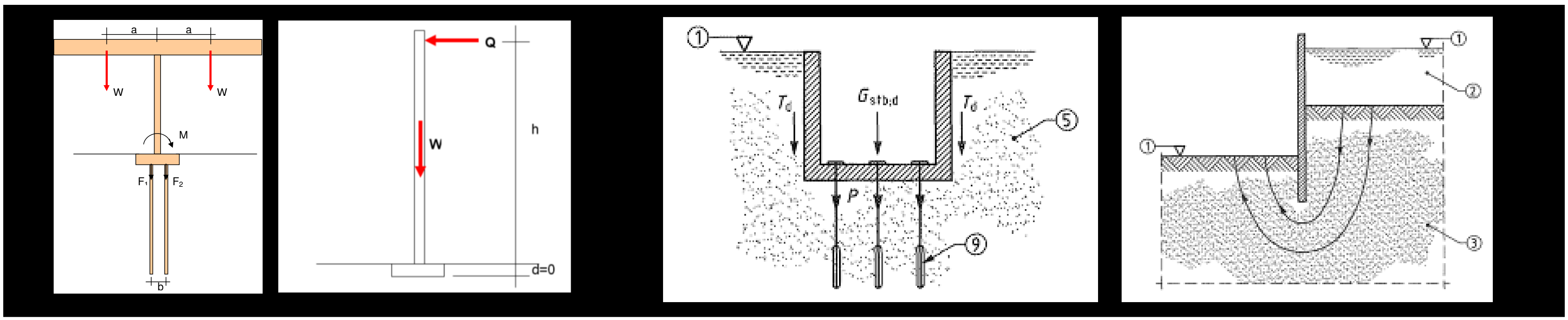
— hydraulic heave, internal erosion and piping in the ground caused by hydraulic gradients (HYD).

2.4.7 Ultimate Limit States

2.4.7.1 General

(1)P Where relevant, it shall be verified that the following limit states are not exceeded:

— loss of equilibrium of the structure or the ground, considered as a rigid body, in which the strengths of structural materials and the ground are insignificant in providing resistance (EQU);



— loss of equilibrium of the structure or the ground due to uplift by water pressure (buoyancy) or other vertical actions (UPL)

— hydraulic heave, internal erosion and piping in the ground caused by hydraulic gradients (HYD).

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(1)P Where relevant, it shall be verified that the following limit states are not exceeded:

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— internal failure or excessive deformation of the structure or structural elements, including e.g. footings, piles or basement walls, in which the strength of structural materials is significant in providing resistance (STR);

γ_F = 1.0, 1.35, 1.5 etc

— failure or excessive deformation of the ground, in which the strength of soil or rock is significant in providing resistance (GEO);

γ_F = 1.0, 1.35, 1.5 etc

— loss of equilibrium of the structure or the ground due to uplift by water pressure (buoyancy) or other vertical actions (UPL)

$\gamma_{F,dst}$ = 1.0/1.1, $\gamma_{F,stb}$ = 0.9

— hydraulic heave, internal erosion and piping in the ground caused by hydraulic gradients (HYD).

$\gamma_{F,dst}$ = 1.35, $\gamma_{F,stb}$ = 0.9

“Design” water pressures in EC7

(6)P When dealing with ground-water pressures for limit states with severe consequences (generally ultimate limit states), design values shall represent the most unfavourable values that could occur during the design lifetime of the structure. For limit states with less severe consequences (generally serviceability limit states), design values shall be the most unfavourable values which could occur in normal circumstances.

(7) In some cases extreme water pressures complying with 1.5.3.5 of EN 1990:2002, may be treated as accidental actions.

(8) Design values of ground-water pressures may be derived either by applying partial factors to characteristic water pressures or by applying a safety margin to the characteristic water level in accordance with 2.4.4(1)P and 2.4.5.3(1)P.

2.4.2 – Actions The "single source principle"

(9)P Actions in which ground- and free-water forces predominate shall be identified for special consideration with regard to deformations, fissuring, variable permeability and erosion.

NOTE Unfavourable (or destabilising) and favourable (or stabilising) permanent actions may in some situations be considered as coming from a single source. If they are considered so, a single partial factor may be applied to the sum of these actions or to the sum of their effects.

Geotechnical safety in relation to water pressures

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Zentrum Geotechnik, Munich, Germany

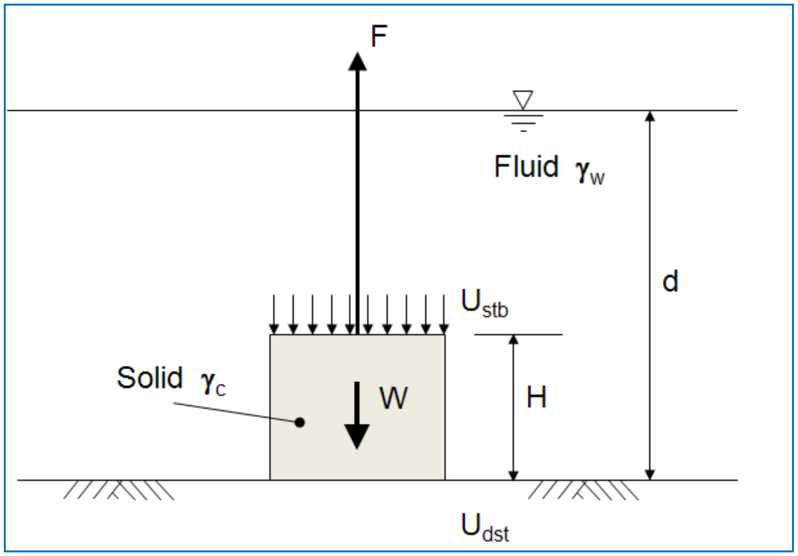
A. J. van Seters

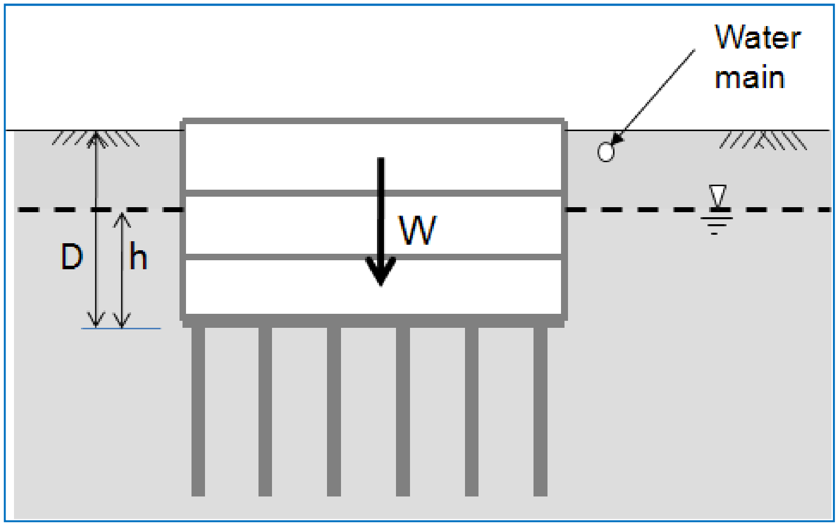
Fugro GeoServices, The Netherlands

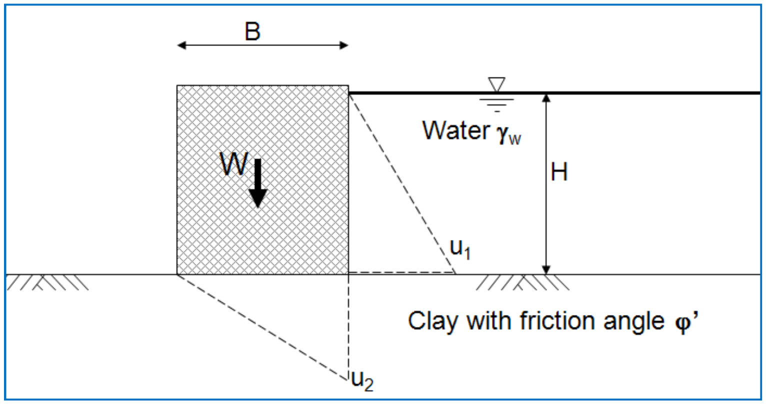
Simpson, B, Vogt, N & van Seters AJ (2011) Geotechnical safety in relation to water pressures. Proc 3rd Int Symp on Geotechnical Safety and Risk, Munich, pp 501-517.

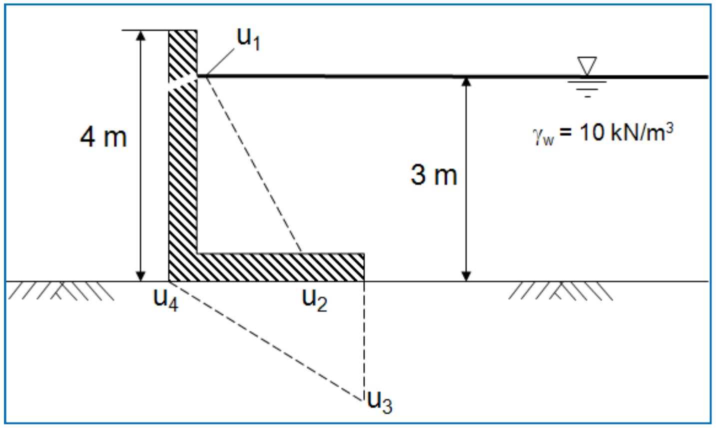
ARUP

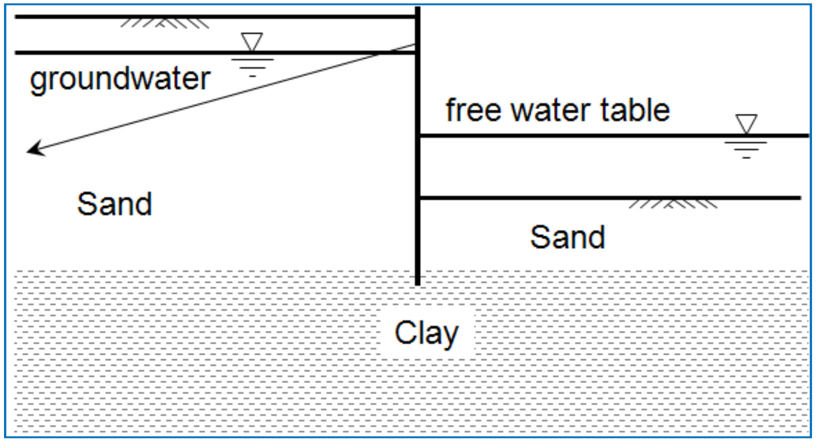
Very “simple” problems











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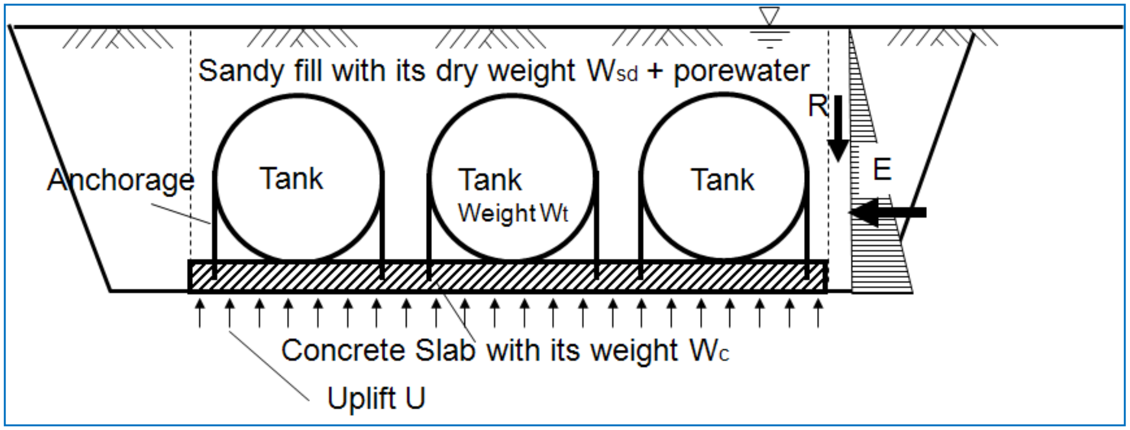
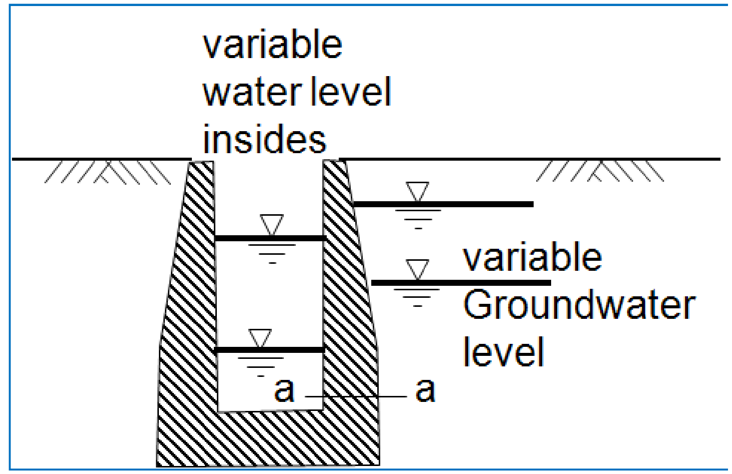
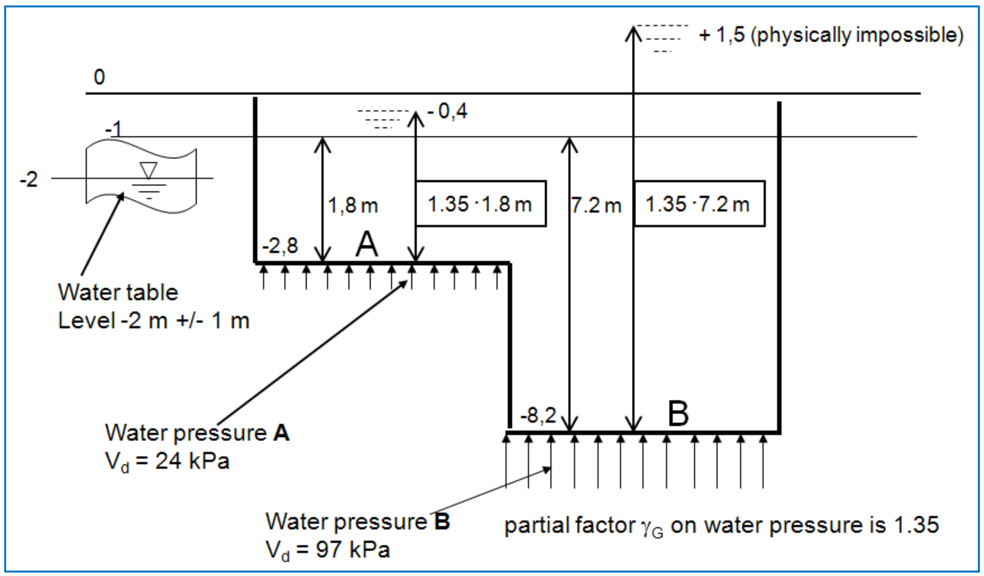
Slightly more complex problems







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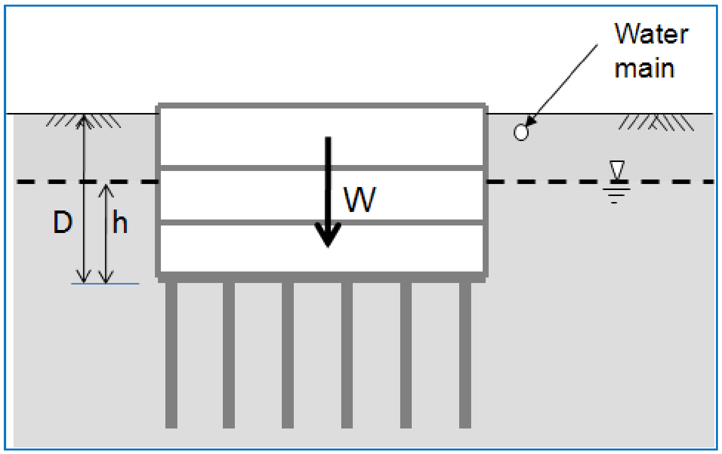
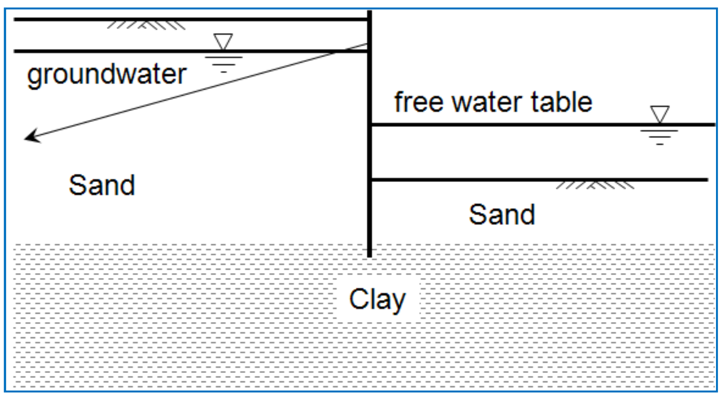
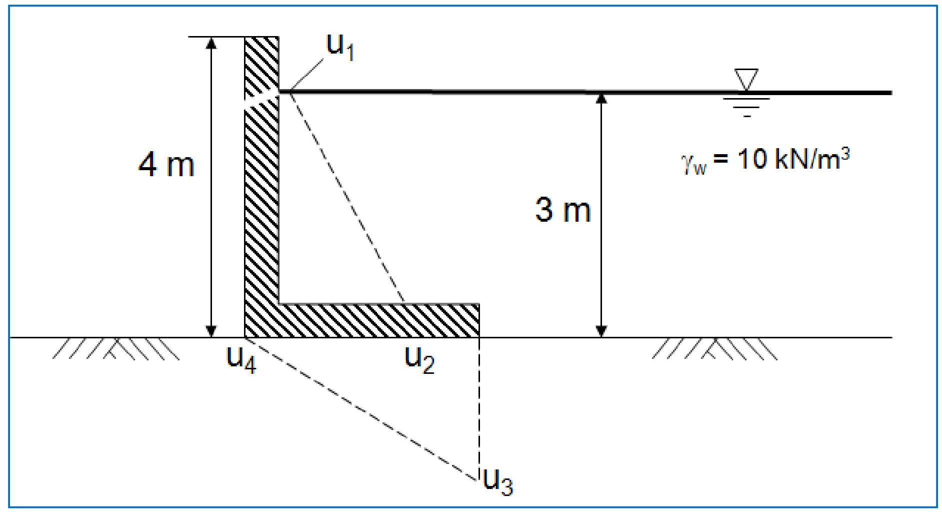
Explicitly accommodate the worst water pressures that could reasonably occur

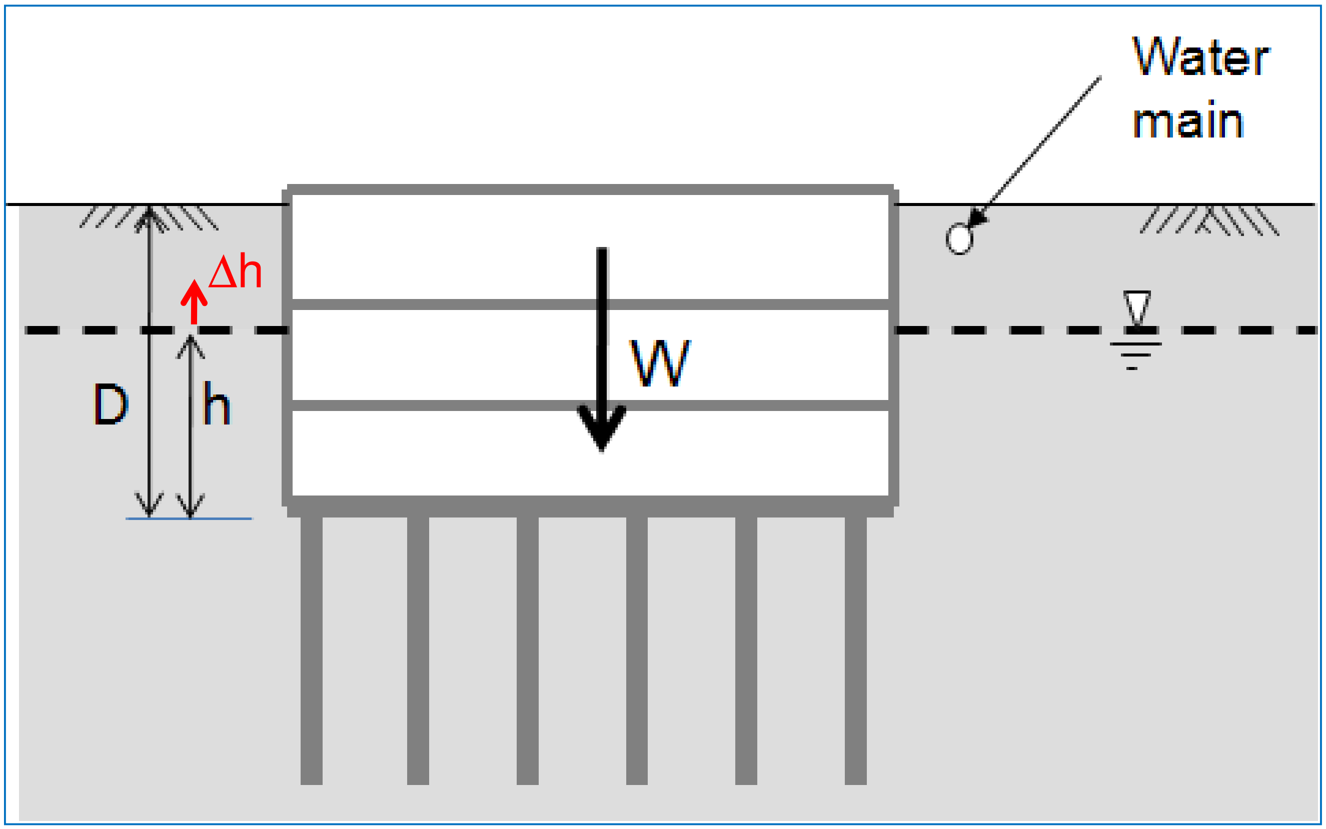




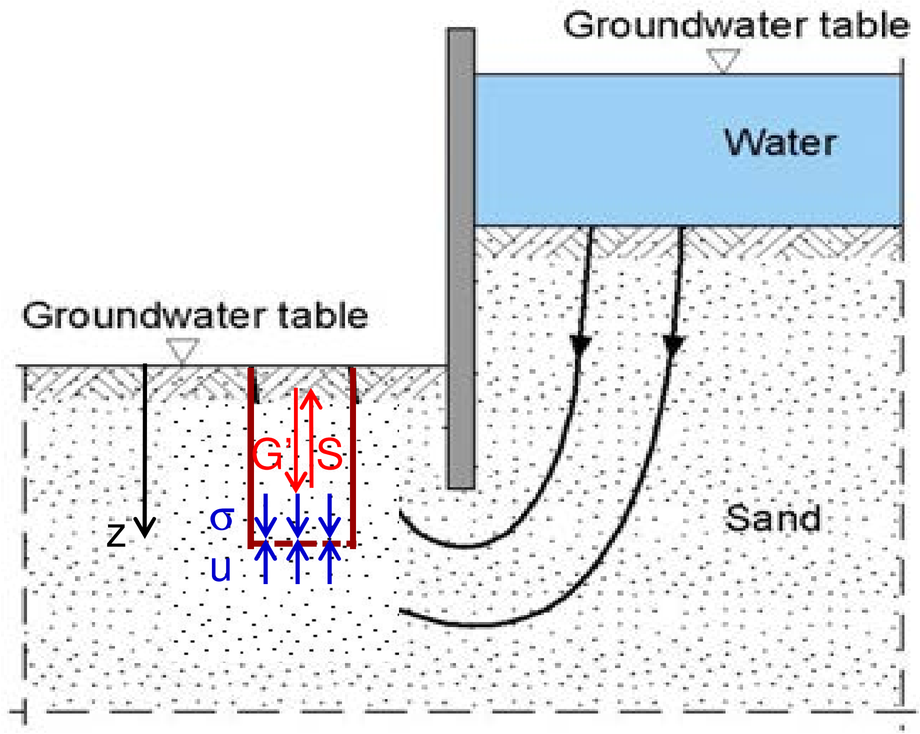


1m rise in water level multiplies BM by about 2.5 – outside the range allowed by factors on the water pressure or water force.

Use of an offset in water level?



HYD – Equation 2.9

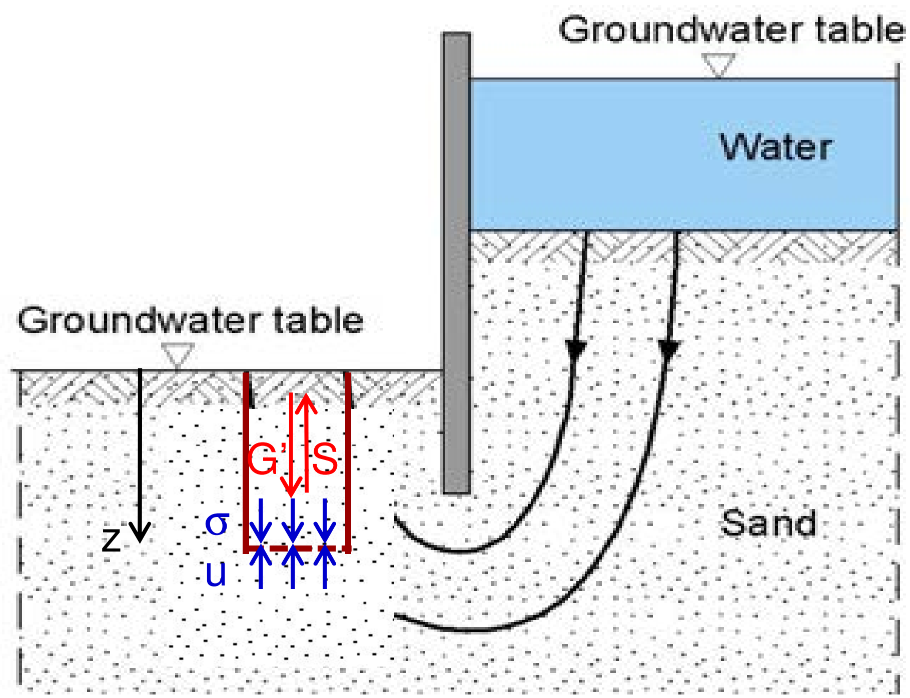


EC7 {2.4.7.5(1)P} states: "When considering a limit state of failure due to heave by seepage of water in the ground (HYD, see 10.3), it shall be verified, for every relevant soil column, that the design value of the destabilising total pore water pressure ($u_{dst;d}$) at the bottom of the column, or the design value of the seepage force ($S_{dst;d}$) in the column is less than or equal to the stabilising total vertical stress ($\sigma_{stb;d}$) at the bottom of the column, or the submerged weight ($G'_{stb;d}$) of the same column:

$u_{dst;d} \leq \sigma_{stb;d}$ (2.9a) – total stress (at the bottom of the column)

$S_{dst;d} \leq G'_{stb;d}$ (2.9b)" – effective weight (within the column)

HYD – Equation 2.9



Annex A of EC7 provides values for partial factors to be used for HYD, $\gamma_{G;dst} = 1.35$ and $\gamma_{G;stb} = 0.9$. But the code does not state what quantities are to be factored. Maybe:

$$\gamma_{G;dst}\, u_{dst;k} \le \gamma_{G;stb}\, \sigma_{stb;k} \qquad (2.9a)$$

and

$$\gamma_{G;dst}\, S_{dst;k} \le \gamma_{G;stb}\, G'_{stb;k} \qquad (2.9b)$$

1.35/0.9 = 1.5

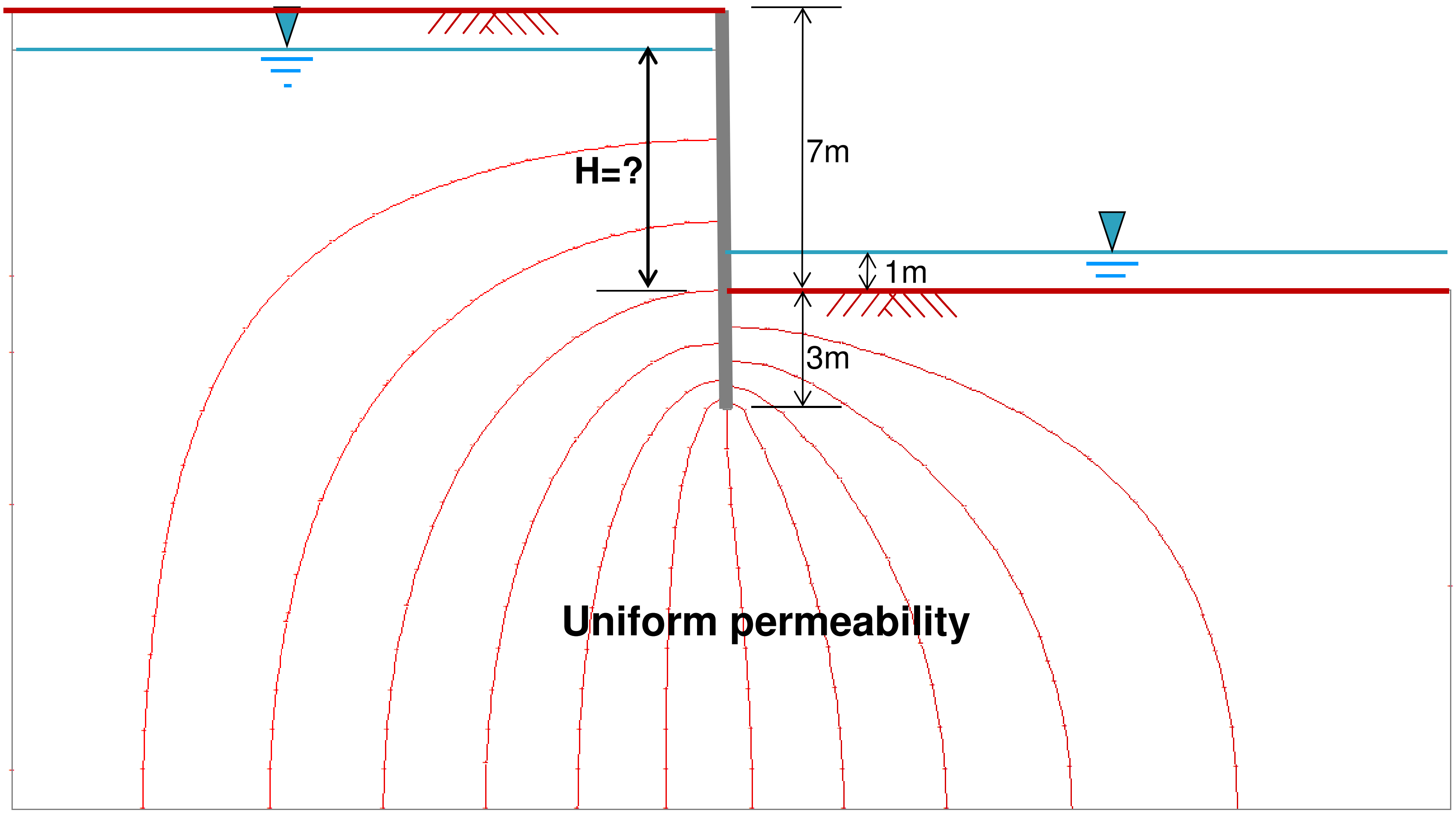
<u>In this format, the factors are applied to different quantities in 2.9 a and b.</u>

$$u_{dst;d} \le \sigma_{stb;d} \qquad (2.9a)$$ – total stress (at the bottom of the column)

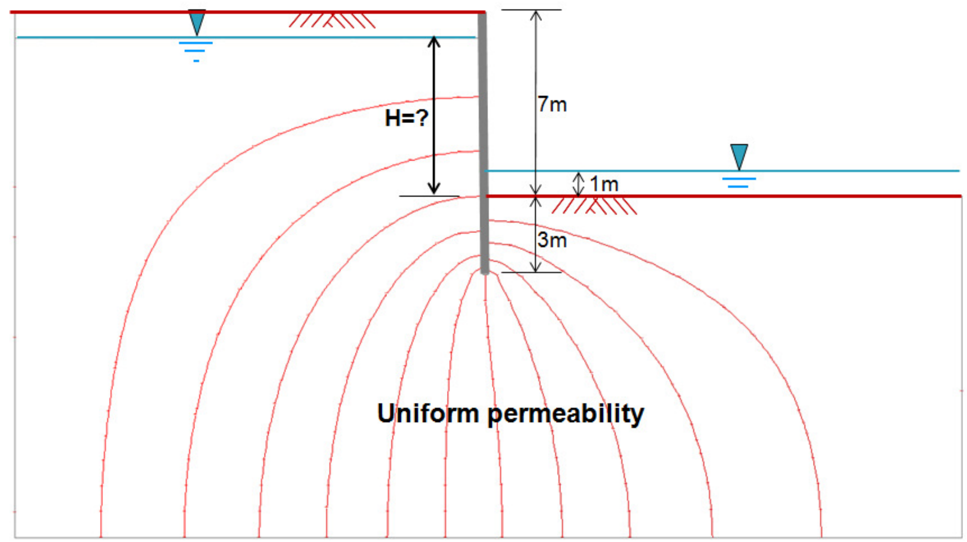
$$S_{dst;d} \le G'_{stb;d} \qquad (2.9b)"$$ – effective weight (within the column)

HYD – Equation 2.9

Orr, TLL (2005) Model Solutions for Eurocode 7 Workshop Examples. Trinity College, Dublin.



HYD – Equation 2.9



$u_{dst;d} \leq \sigma_{stb;d}$ (2.9a) – total stress (at the bottom of the column)

$S_{dst;d} \leq G'_{stb;d}$ (2.9b)" – effective weight (within the column)

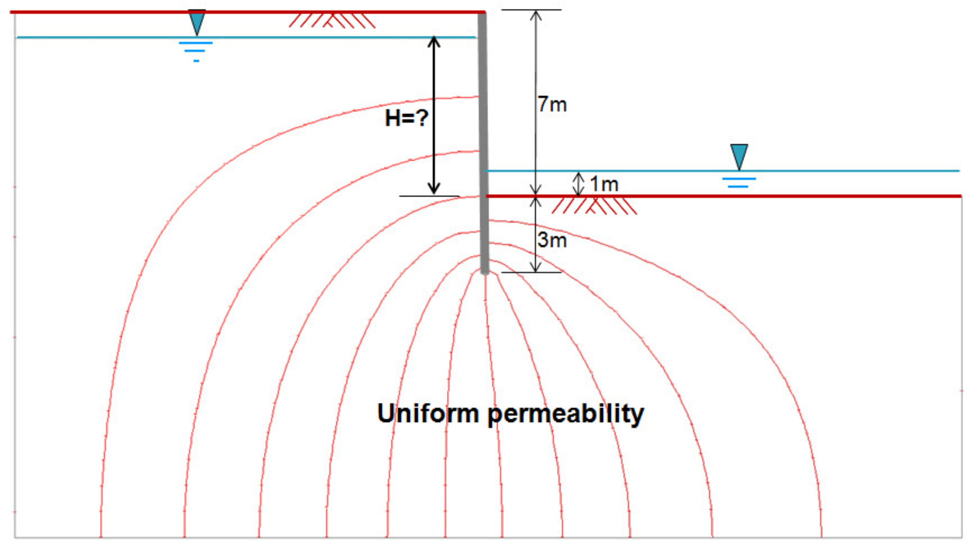
Apply $\gamma_{G;dst} = 1.35$ to:	Apply $\gamma_{G;stb} = 0.9$ to:	H
Pore water pressure $u_{dst;k}$	Total stress $\sigma_{stb;k}$	2.78
Seepage force $S_{dst;k}$	Buoyant weight $G'_{stb;k}$	6.84

$$\gamma_{G;dst}\, u_{dst;k} \leq \gamma_{G;stb}\, \sigma_{stb;k} \qquad (2.9a)$$

$$\gamma_{G;dst}\, S_{dst;k} \leq \gamma_{G;stb}\, G'_{stb;k} \qquad (2.9b)$$

Orr, T.L.L. 2005.
Model Solutions for Eurocode 7 Workshop Examples.
Trinity College, Dublin.

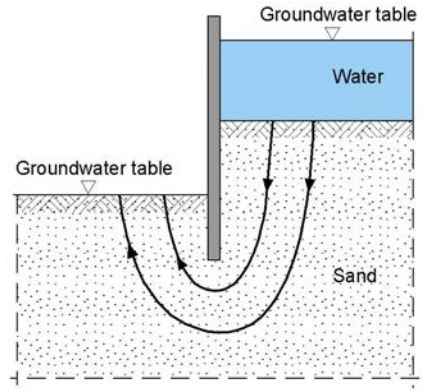
HYD – Equation 2.9



$u_{dst;d} \leq \sigma_{stb;d}$ (2.9a) – total stress (at the bottom of the column)

$S_{dst;d} \leq G'_{stb;d}$ (2.9b)" – effective weight (within the column)

Apply $\gamma_{G;dst} = 1.35$ to:	Apply $\gamma_{G;stb} = 0.9$ to:	H
Pore water pressure $u_{dst;k}$	Total stress $\sigma_{stb;k}$	2.78
Seepage force $S_{dst;k}$	Buoyant weight $G'_{stb;k}$	6.84
Excess pore pressure $u_{dst;k} - \gamma_w z$	Buoyant density	6.84
Excess head $(u_{dst;k} - \gamma_w z) / \gamma_w$	Buoyant density	6.84
Excess pore pressure or excess head	Total density	6.1

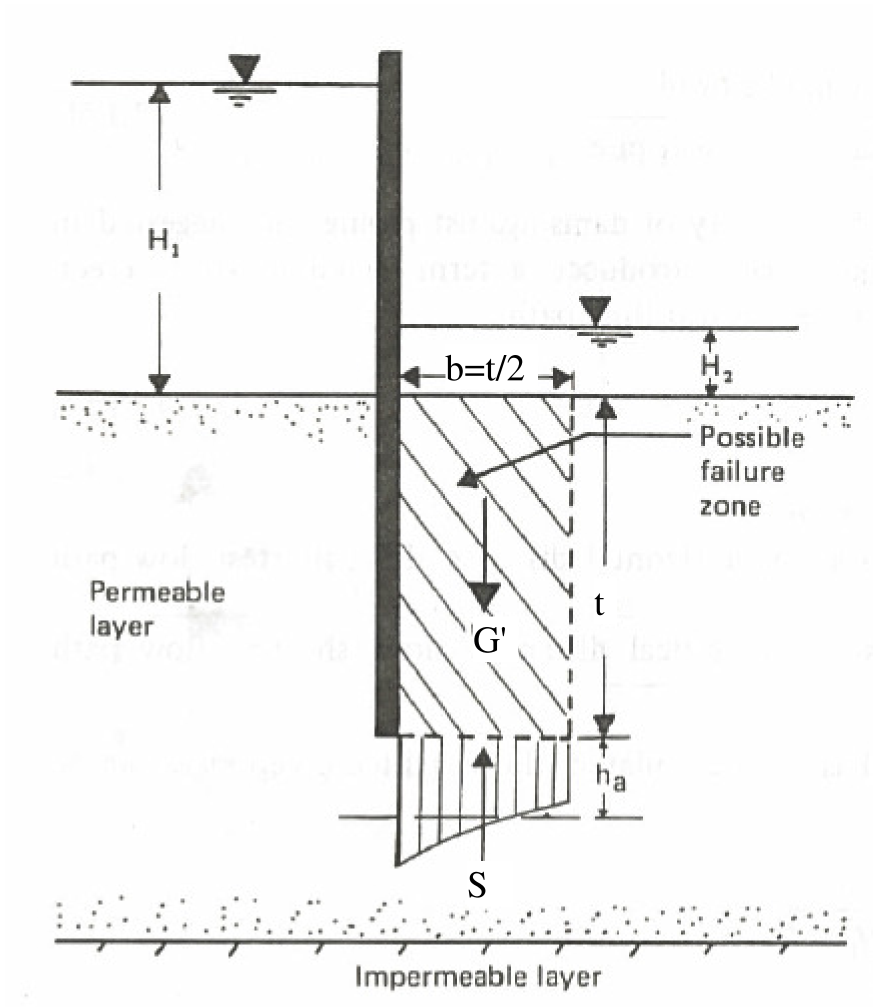


Conclusions

Not good to factor total water pressures

- Factoring differential **or excess** water pressure may be OK. (ie excess over hydrostatic)

Terzhagi's rectangular block



Das (1983) Fig 2.47

G' = buoyant weight
S = seepage force
due to excess water pressure

Dimensions t x t/2

$$F_T = G'/S$$

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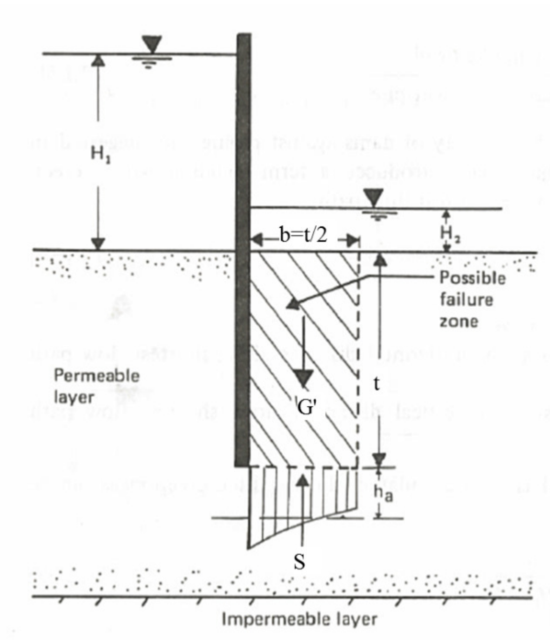
Factors of safety for HYD

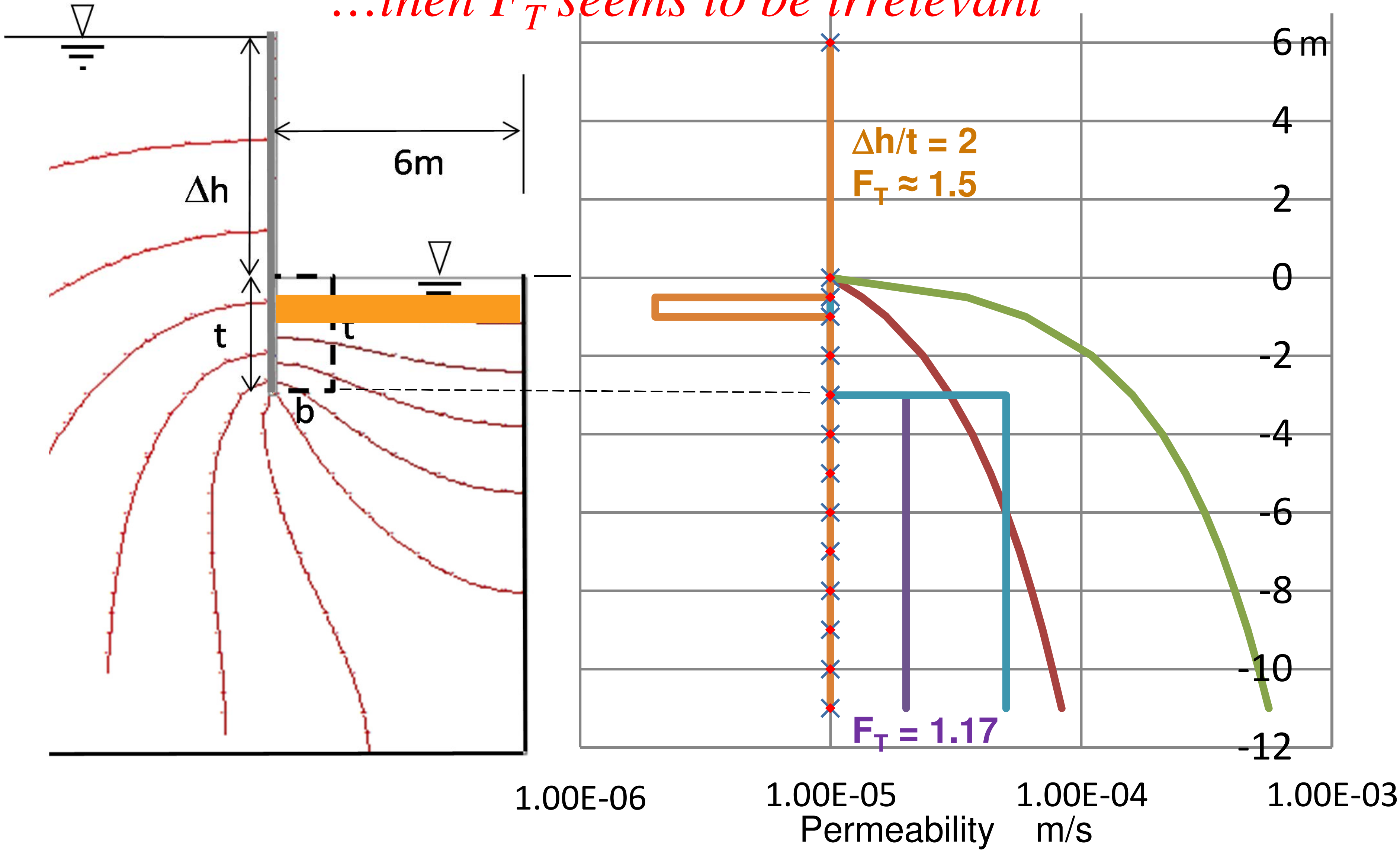


Das (1983) Fig 2.47

Publication and any limitations		Values
Williams B P & Waite D (1993) for clean sands		1.5 to 2.0
Kashef, Abdel-Aziz Ismail (1986)		4 to 5
Harr, M E. (1962)		4 to 5
German practice	– unfavourable soils	1.9
(DIN 1054/A2 2014)	– favourable soils	1.42
Swedish practice	– coarse soils	1.5
(Ryner et al 1996)	– silty material	2.5
Dutch practice (van Seters 2013)		2.8
Das (1983), quoting Harr (1962)		4 to 5

Essential to assess correct water pressures (permeabilities)

…then F_T seems to be irrelevant



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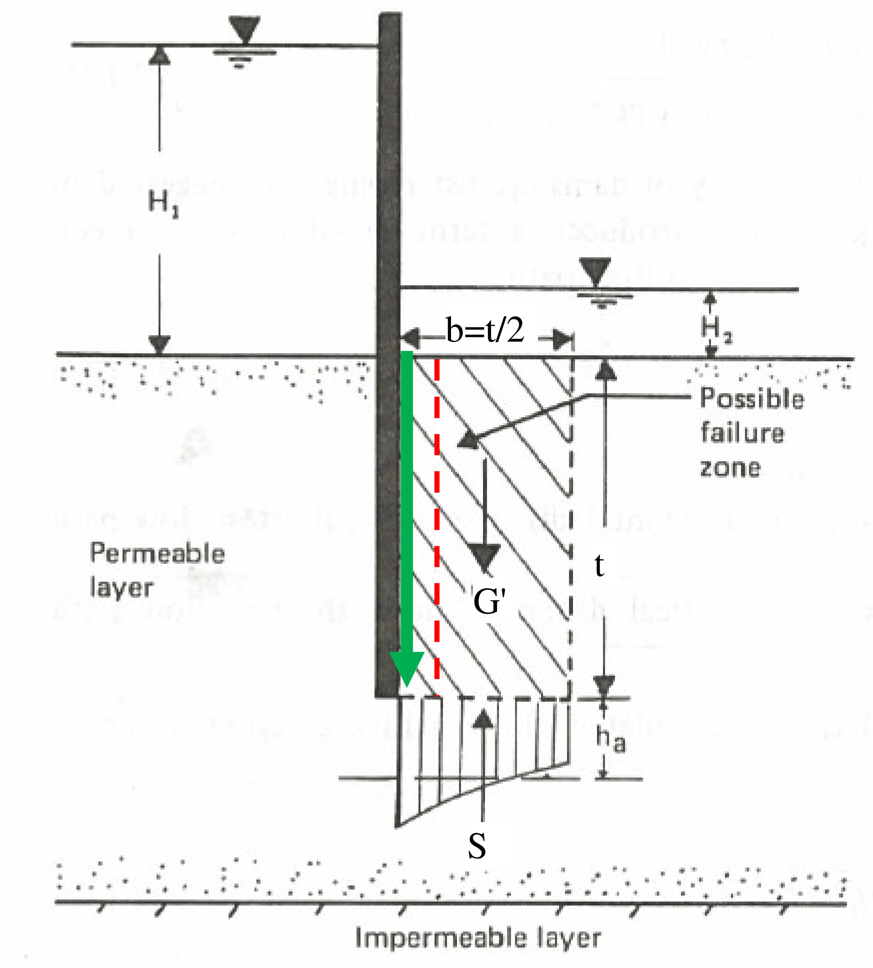
Why b=t/2? A narrower block would be more critical. Include friction on the side of the block?



Das (1983) Fig 2.47

G' = buoyant weight

S = seepage force

due to excess water pressure

Dimensions t x t/2

F_T = G'/S

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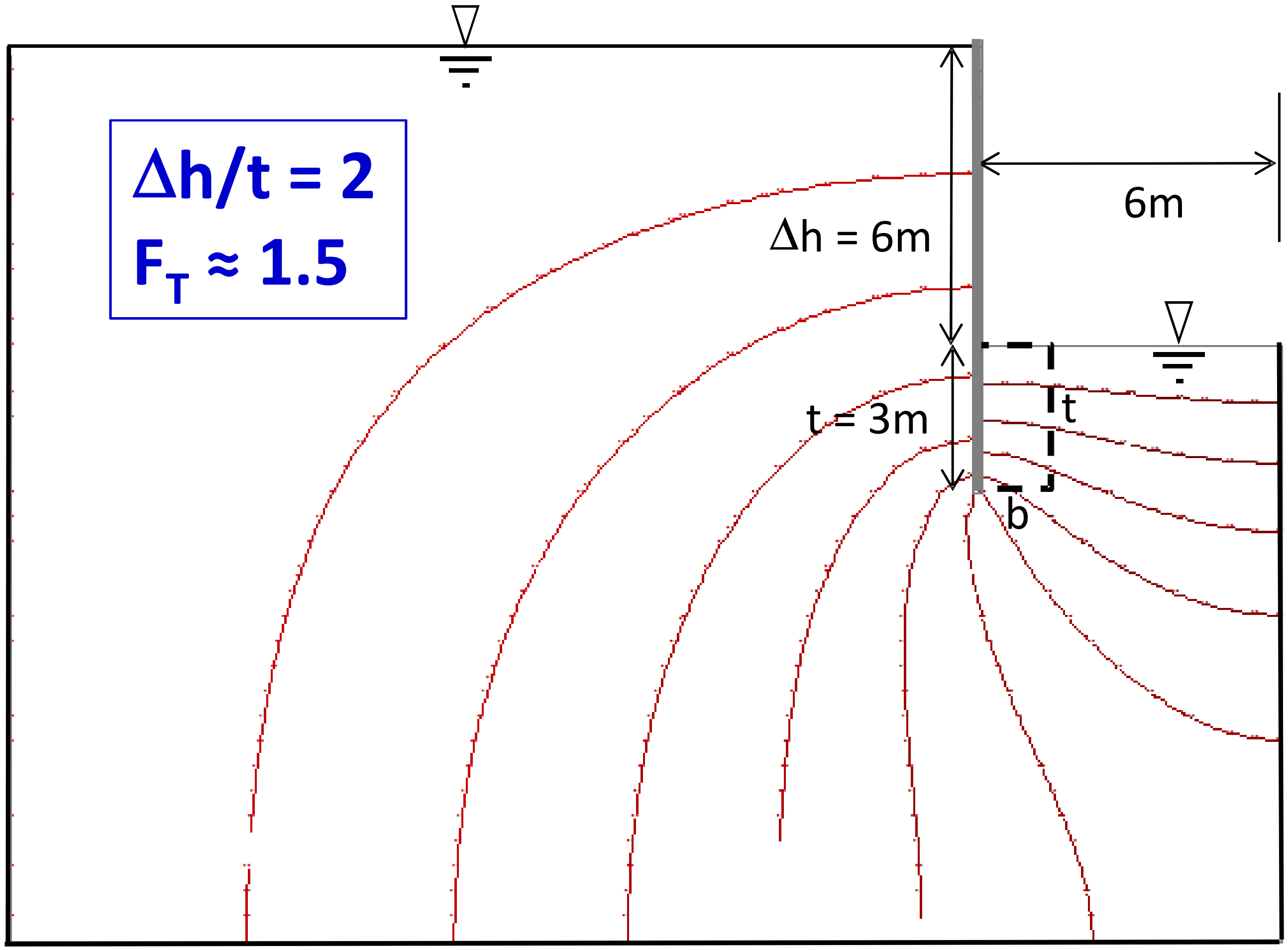
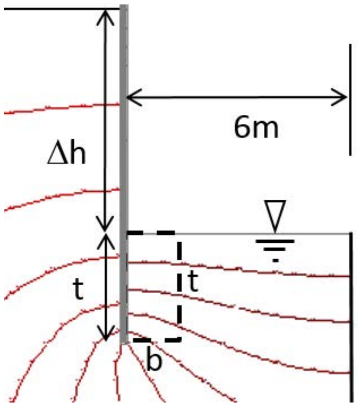
Equipotentials for uniform permeability – $F_T = 1.5$



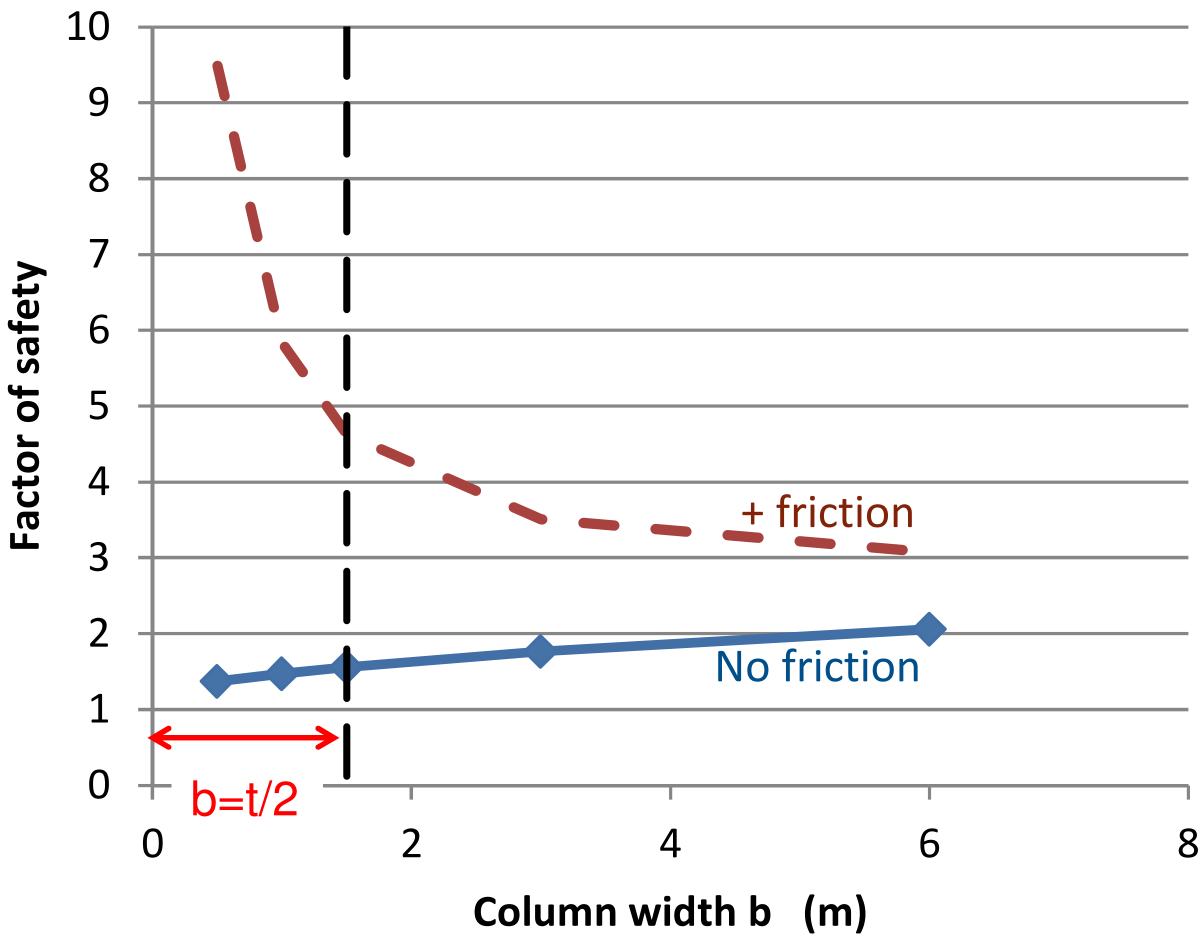
Simpson, B & Katsigiannis, G (2015) Safety considerations for the HYD limit state. Submitted for ECSMGE, Edinburgh.

Effect of friction on the Terzaghi block



$\Delta h/t = 2$

$F_T \approx 1.5$



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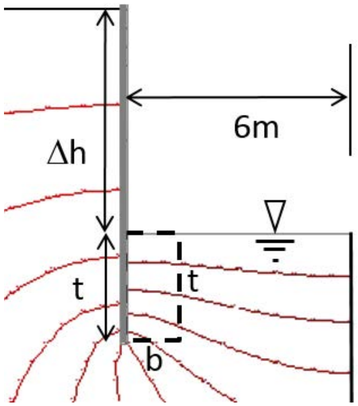
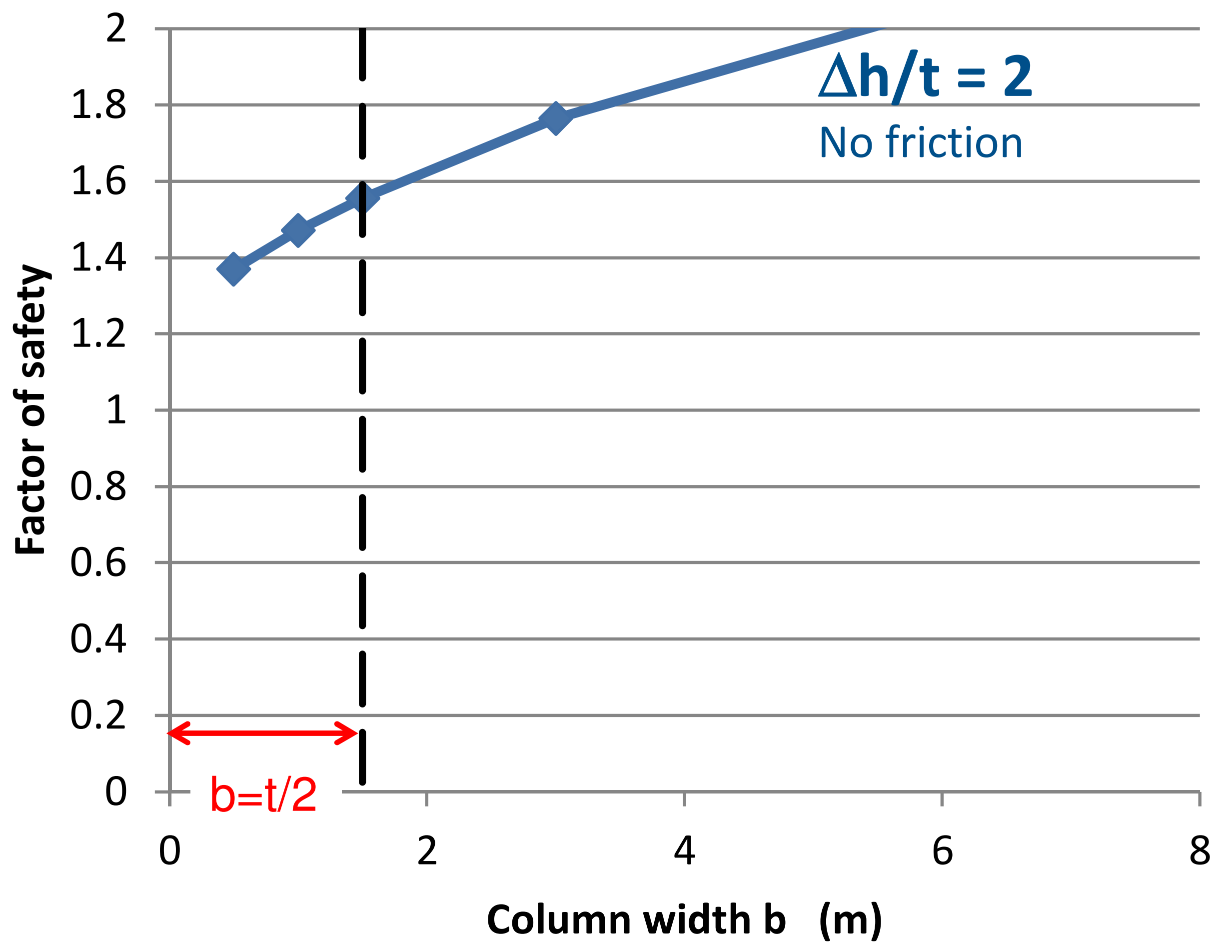
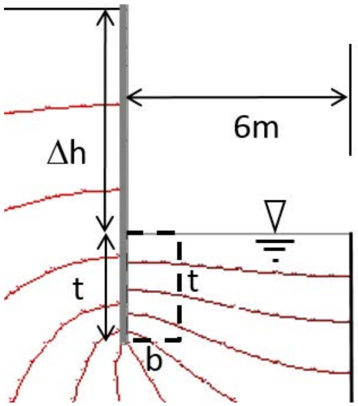
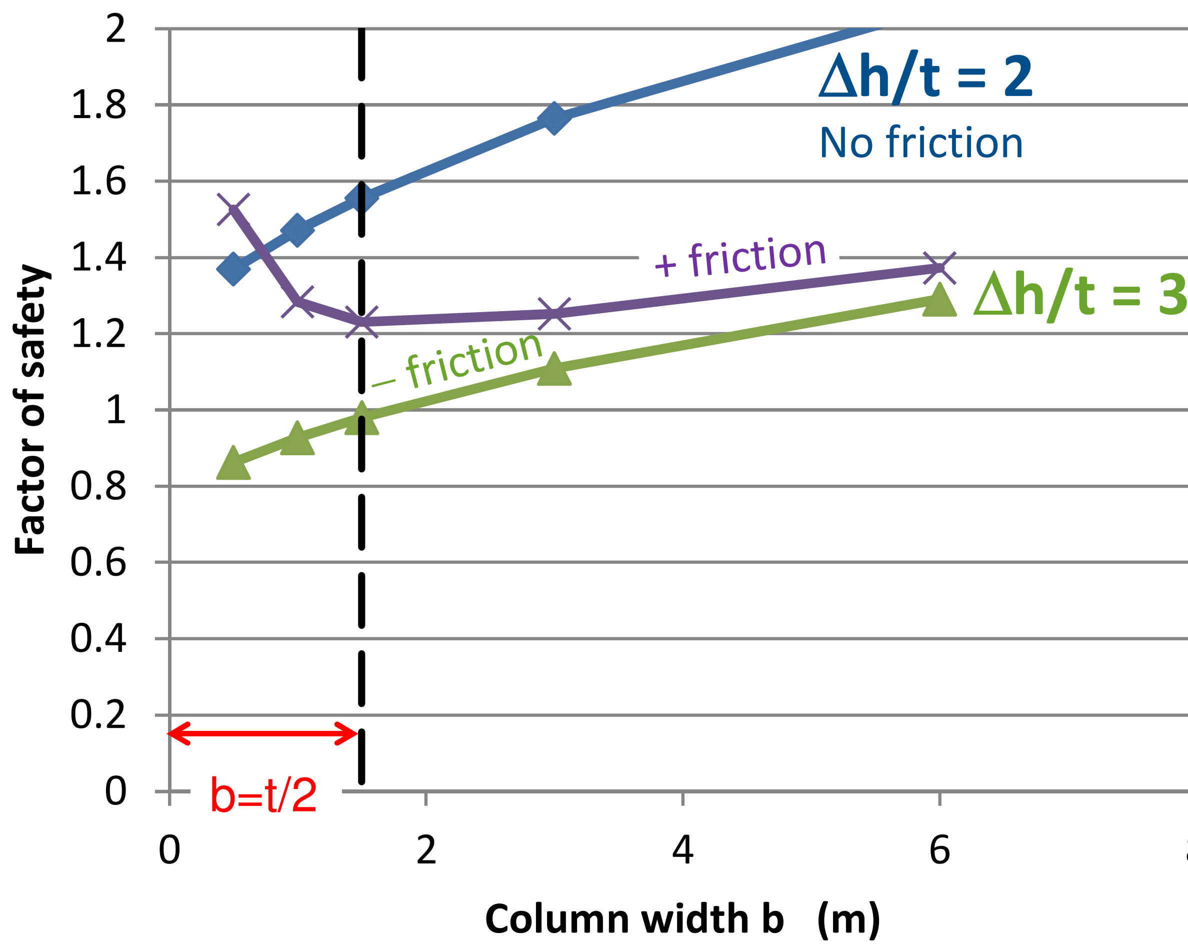
Effect of friction on the Terzaghi block





Effect of friction on the Terzaghi block





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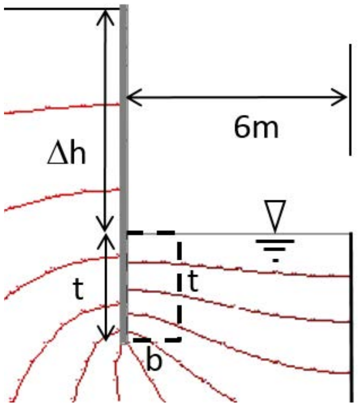
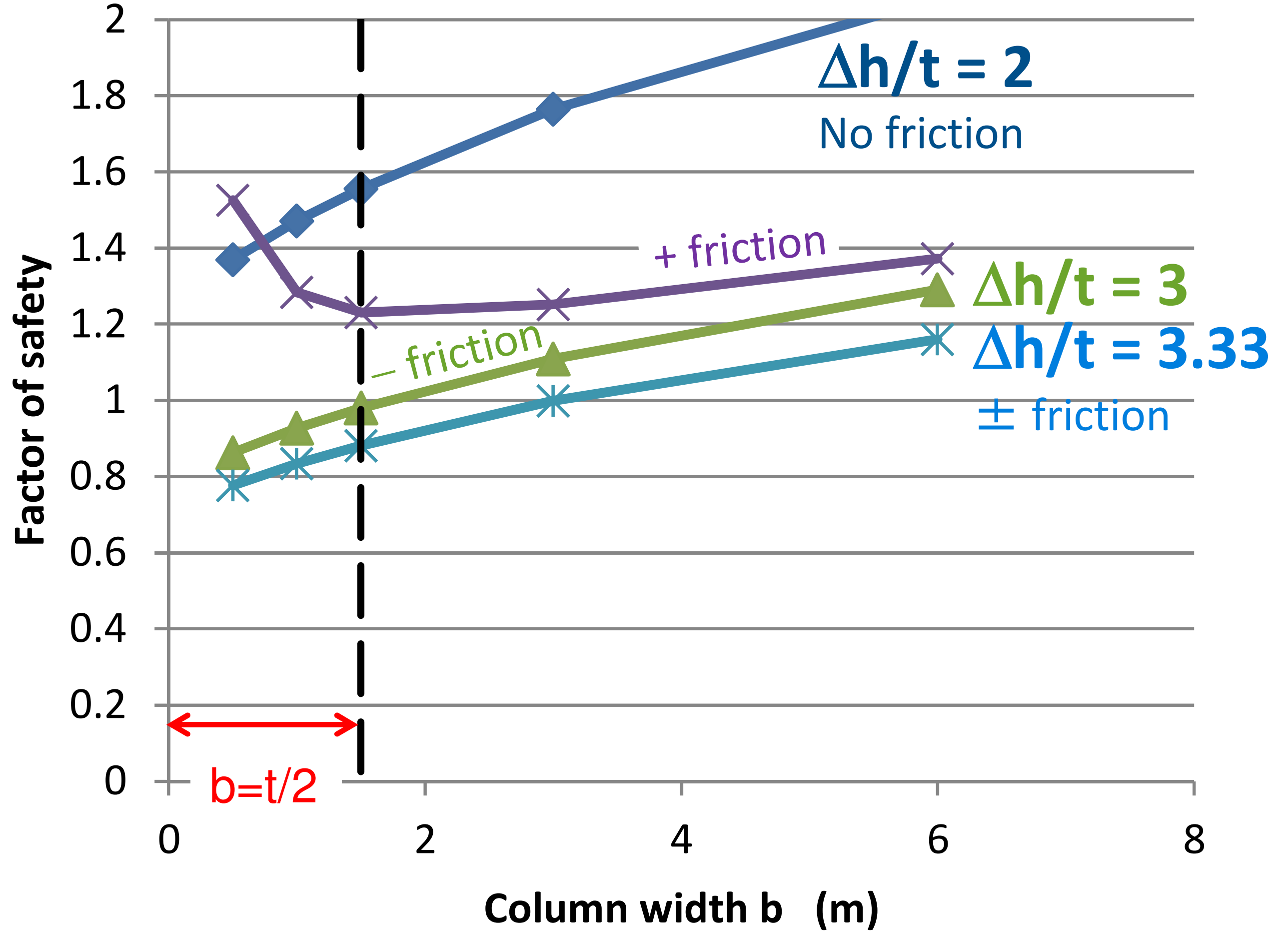
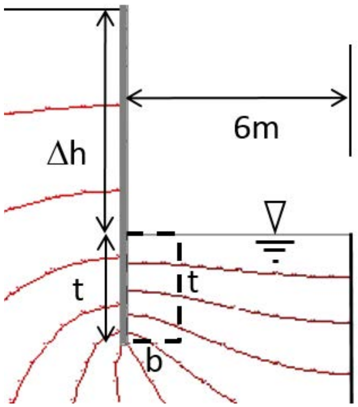
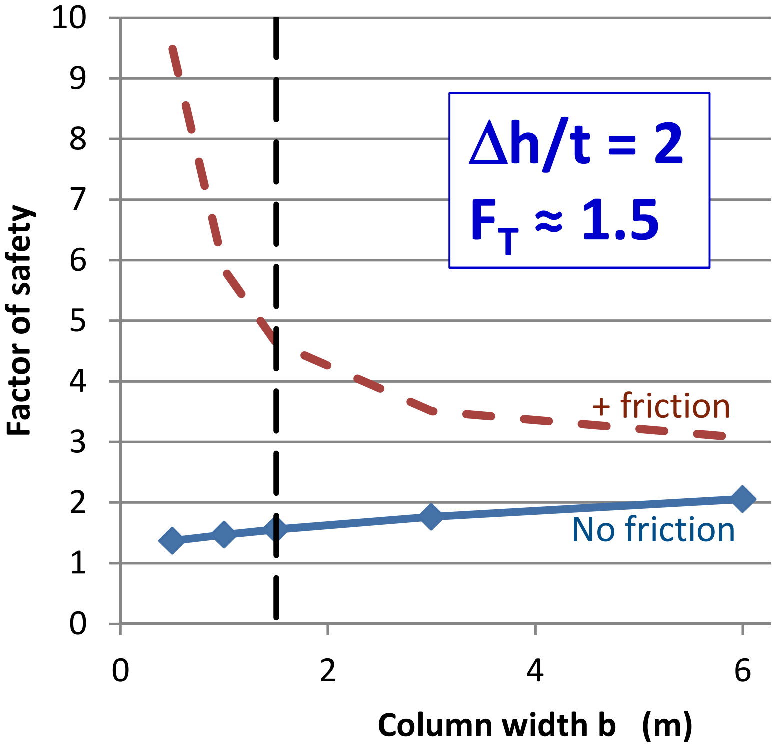
Effect of friction on the Terzaghi block

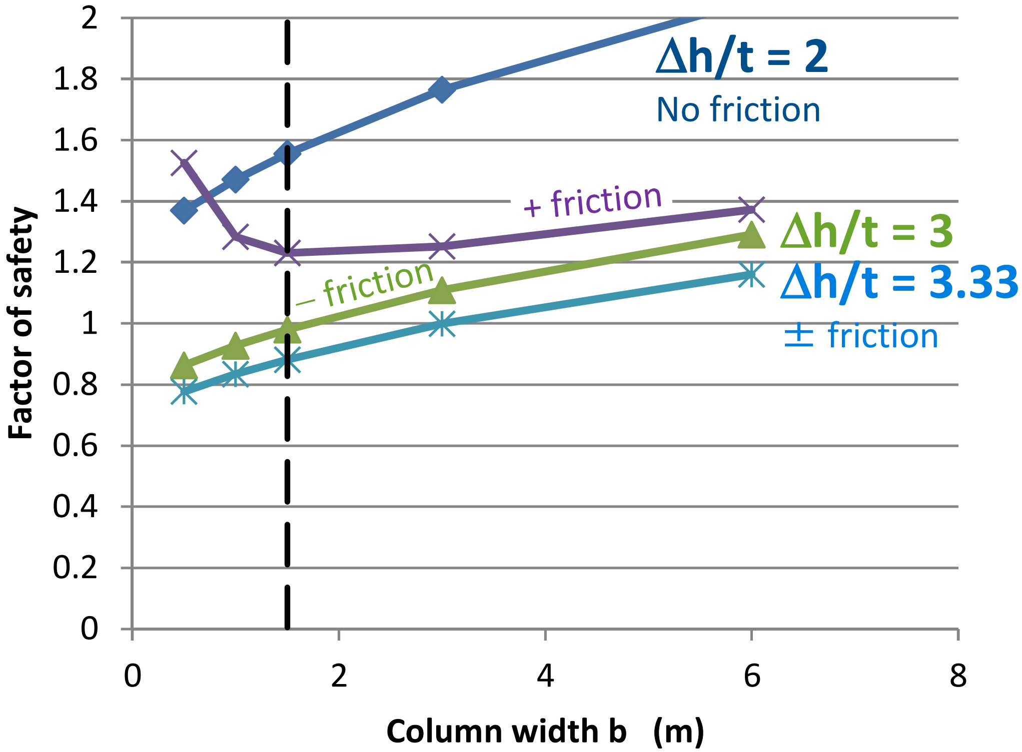




Effect of friction on the Terzaghi block







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Conclusions of EG9

- Not good to factor total water pressures
  - Factoring differential water pressure may be OK.
- Design for F=… is no use if the pore pressures (permeability distribution) are not properly understood.
- ULS design water pressure derived without factors (1% chance)
  - No factors on effects of water pressure – eg seepage force S.
  - But could be factors on structural effects of water pressures – eg BM
- Take directly assessed ULS design water pressures (1% chance) with factored strengths of materials. Consider all failure mechanisms. Simple!
- Special case: Terzaghi block – only consider one mechanism so add a factor of safety (1.5?).

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Eurocode 7 – Good practice in geotechnical design

- Limit state design
- Holistic design – structures and ground
- Practical approach to characteristic values of soil parameters
- ULS and SLS design requirements
- Water pressures
- **Ground anchors**
- Retaining structures – numerical analysis
- The future

Ground anchors – EC7 Section 8 and the new UKNA

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EC7 Section 8 – Anchorages (existing)

EN 1997-1:2004(E)

Section 8 Anchorages

8.1 General

8.1.1 Scope

(1)P This Section applies to the design of temporary and permanent anchorages used:

— to support a retaining structure;

— to provide the stability of slopes, cuts or tunnels;

— to resist uplift forces on structures.

by transmitting a tensile force to a load bearing formation of soil or rock.

Not usable - Not used

(2)P This Section is applicable to;

— pre-stressed anchorages consisting of an anchor head, a tendon free length and a tendon bond length bonded to the ground by grout;

— non pre-stressed anchorages consisting of an anchor head, a tendon free length and a restraint such as a fixed anchor length bonded to the ground by grout, a deadman anchorage, a screw anchor or a rock bolt.

(3) This Section should not be applied to soil nails.

(4)P Section 7 shall apply to the design of anchorages comprising tension piles.

EC7 “Evolution Groups”

EG0	Management and oversight
EG1	Anchors
EG2	Maintenance and simplification
EG3	Model solutions
EG4	Numerical models
EG5	Reinforced soil
EG6	Seismic design
EG7	Pile design
EG8	Harmonization
EG9	Water pressures
EG10	Calculation models
EG11	Characterization
EG12	Tunnelling
EG13	Rock mechanics
EG14	Ground improvement

Three European documents

- EN 1537

  Execution of special geotechnical work – **Ground anchors**

- EN ISO 22477-5

  Geotechnical investigation and testing — Testing of geotechnical structures — Part 5:
  Testing of anchorages

- Eurocode 7 – EN 1997-1 – Section 8 – **Anchors** **+ UKNA**

And the existing British code

- BS 8081 **– Ground anchorages** (being revised as NCCI)

EN 1997-1:2004/A1:2013
Eurocode 7 (2004) with amendment (2013)

Section 8 - Anchors

8.1 General

8.2 Limit states

8.3 Design situations and actions

8.4 Design and construction considerations

8.5 Limit state design of anchors

8.6 Tests on anchors

8.7 Lock-off load for pre-stressed anchors

8.8 Supervision, monitoring and maintenance

+UKNA

Motherhood and apple pie?

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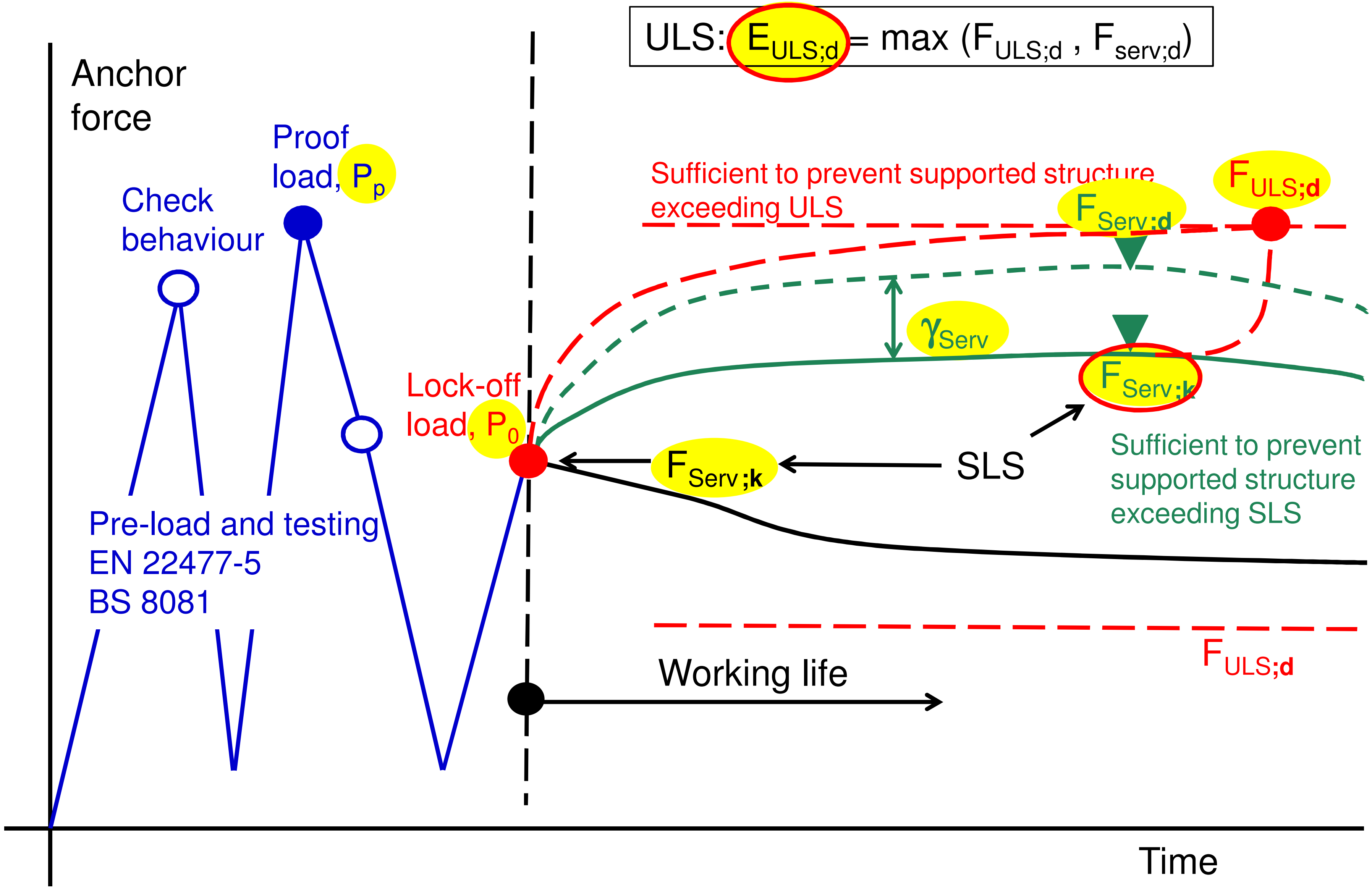
Anchor force

The life story of a ground anchor

Time



F_{ULS} – the force required to prevent any ultimate limit state in the supported structure

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8.5 Limit state design of anchors

8.5.1 General

(1)P The design value of the geotechnical ultimate limit state resistance of an anchor, $R_{ULS;d}$, shall satisfy the following inequality:

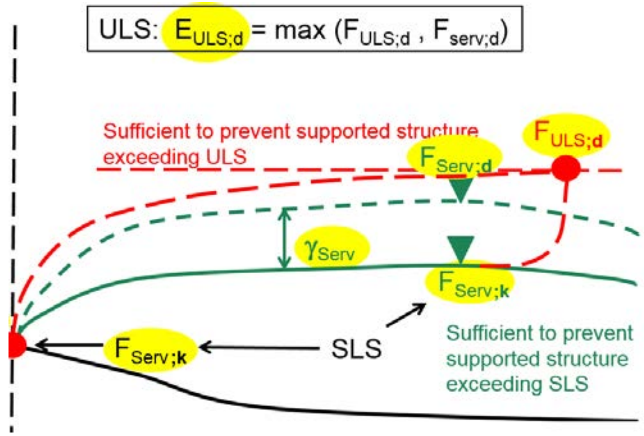
$$E_{ULS;d} \leq R_{ULS;d} \quad (8.1)$$

where:

$$E_{ULS;d} = \max\left(F_{ULS;d}; F_{Serv;d}\right) \quad (8.2)$$

and where:

$$F_{Serv;d} = \gamma_{Serv} \times F_{Serv;k} \quad (8.3)$$



NOTE 1 The value of partial factor γ_{Serv} may be set by the National Annex. The recommended value for persistent and transient situations is given in Table A.18.

(2)P When a separate evaluation of the serviceability limit state of the anchor is required the evaluation shall be carried out using Formula (8).4).

$$F_{Serv;k} \leq R_{SLS;d} \quad (8.4)$$

NOTE 1 The National Annex may set whether a separate evaluation of the serviceability limit state of the anchor is required.

NOTE 2 The National Annex may set whether the verifications for ultimate limit state and serviceability limit state are to be carried out separately or in a combined procedure.

8.5.1 General

(1)P The design value of the geotechnical ultimate limit state resistance of an anchor, $R_{ULS;d}$, shall satisfy the following inequality:

$$E_{ULS;d} \le R_{ULS;d} \qquad (8.1)$$

$R_{ULS;d}$ design value of the resistance of an anchor complying with ultimate limit state criteria

Small factor $\gamma_{a;ULS}$

$R_{ULS;k}$ characteristic value of the resistance of an anchor complying with ultimate limit state criteria

Take the worst

$R_{ULS;m}$ measured value of the resistance of an anchor complying with ultimate limit state criteria

8.5.2 Geotechnical ultimate limit state resistance

(1)P The measured geotechnical ultimate limit state resistance of an anchor as defined in 8.5.2(2)P shall be determined from a number of investigation or suitability tests (*n*) carried out in accordance with EN ISO 22477-5.

NOTE The test method to be used to determine the measured resistance and the number of tests *n* may be set in the National Annex.

- Investigation or suitability tests must be used to check $E_{ULS;d}$
  - Investigation tests not used much on small contracts. Suitability tests on working anchors.
- Investigation or suitability tests may optionally check behaviour at $F_{serv;k}$ (NA)
- All grouted anchors must have acceptance tests
- Acceptance tests may check $E_{ULS;d}$ and/or $F_{serv;k}$ (NA)

8.5.1 General

(1)P The design value of the geotechnical ultimate limit state resistance of an anchor, $R_{ULS;d}$, shall satisfy the following inequality:

$$E_{ULS;d} \leq R_{ULS;d} \tag{8.1}$$

$R_{ULS;d}$ design value of the resistance of an anchor complying with ultimate limit state criteria

Small factor $\gamma_{a;ULS}$

$R_{ULS;k}$ characteristic value of the resistance of an anchor complying with ultimate limit state criteria

Take the worst

$R_{ULS;m}$ measured value of the resistance of an anchor complying with ultimate limit state criteria

8.5.2 Geotechnical ultimate limit state resistance

(2)P The measured ultimate limit state resistance of an anchor $R_{ULS;m}$ shall be determined by load tests as the lesser of the proof load or the load causing a limiting condition (R_m). The limiting condition depends on the test method and may be:

— the asymptote to the creep rate versus load curve, or;

— the load corresponding to a limit value of the creep rate (α_{ULS}), or;

— the load corresponding to a limit value of load loss ($k_{l;ULS}$).

Thus:

$$R_{ULS;m} = \min\left\{R_m\left(\alpha_{ULS} \text{ or } k_{l;ULS}\right) \text{ and } P_p\right\} \tag{8.5}$$

NOTE The limit value of the creep rate (α_{ULS}) or load loss ($k_{l;ULS}$) may be set by the National Annex, which may

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(2)P When a separate evaluation of the serviceability limit state of the anchor is required the evaluation shall be carried out using Formula (8 .4).

$$F_{Serv;k} \leq R_{SLS;d} \quad (8.4)$$

NOTE 1 The National Annex may set whether a separate evaluation of the serviceability limit state of the anchor is required.

NOTE 2 The National Annex may set whether the verifications for ultimate limit state and serviceability limit state are to be carried out separately or in a combined procedure.

Table A.NA.21 — Limiting criteria for investigation, suitability and acceptance tests for persistent and transient design situations at the ultimate and serviceability limit states

Test Method [a]	**Limiting criterion**	**Investigation and suitability tests**		**Acceptance tests**	
		ULS (Eq. 8.5)	**SLS** (Eq. 8.8)	**ULS** (Eq. 8.13)	**SLS** (Eq. 8.14)
2	k_l	5% per log cycle of time	2% per log cycle of time[e]	5% per log cycle of time	2% per log cycle of time[e]
	α_2[b]	$5\%\Delta_{eULS}$[c] per log cycle of time	$2\%\Delta_{eSLS}$[d] per log cycle of time	$5\%\Delta_{eULS}$ per log cycle of time	$2\%\Delta_{eSLS}$ per log cycle of time

[a] For a description of the test methods see EN ISO 22477-5, or EN 1537:2013. Pending the publication of EN ISO 22477-5, the procedures of BS8081 may be substituted for Test Method 2, adopting the limiting criteria shown in this table.

[b] α_2 is the creep rate determined by Test Method 2, from the displacement per log cycle of time at constant anchor load (as defined in EN ISO 22477-5).

8.5.2 Geotechnical ultimate limit state resistance

$$R_{ULS;m} = \min\{R_m(\alpha_{ULS} \text{ or } k_{l;ULS}) \text{ and } P_p\} \quad (8.5)$$

NOTE The limit value of the creep rate (α_{ULS}) or load loss ($k_{l;ULS}$) may be set by the National Annex, which may specify the use of an asymptote to the creep rate versus load curve in place of a specified value for α_{ULS}. Recommended values for persistent and transient situations are given in Table A.21.

(3)P The characteristic value of the ultimate limit state geotechnical resistance of an anchor, $R_{ULS;k}$, shall be derived from:

$$R_{ULS;k} = \frac{(R_{ULS;m})\min}{\xi_{ULS}} \quad (8.6)$$

CEN value: $\xi_{ULS} = 1.0$

UK value: $\xi_{ULS} = 1.35\, F_{serv;k}/E_{ULS;d}$

< 1.0, if $E_{ULS;d} > 1.35F_{serv;k}$

NOTE 1 Values of the correlation factor ξ_{ULS} may be set by the National Annex. Recommended values for persistent and transient situations are given in Table A.20.

NOTE 2 The minimum number of investigation and suitability tests n to be carried out to determine $(R_{ULS;m})_{min}$ may be set by the National Annex. Recommended values for persistent and transient situations are given in Table A.20.

(4) Investigation tests should normally be loaded to the estimated ultimate resistance of the ground/grout interface and may require tendons and other structural components of greater capacity than used in suitability or acceptance tests.

(5)P The design value of the geotechnical ultimate limit state resistance of an anchor shall be derived from:

$$R_{ULS;d} = \frac{R_{ULS;k}}{\gamma_{a;ULS}}$$

CEN value: $\gamma_{a;ULS} = 1.1$ = UK value

So $R_{ULS;m} = 1.1\text{x}R_{ULS;d} \geq 1.1E_{ULS;d}$

›› $F_{serv;k}$??

So $R_{ULS;m} = 1.1\text{x}\ (R_{ULS;d} \geq E_{ULS;d})\text{x}1.35\ F_{serv;k}/E_{ULS;d} \approx 1.5F_{Serv;k}$

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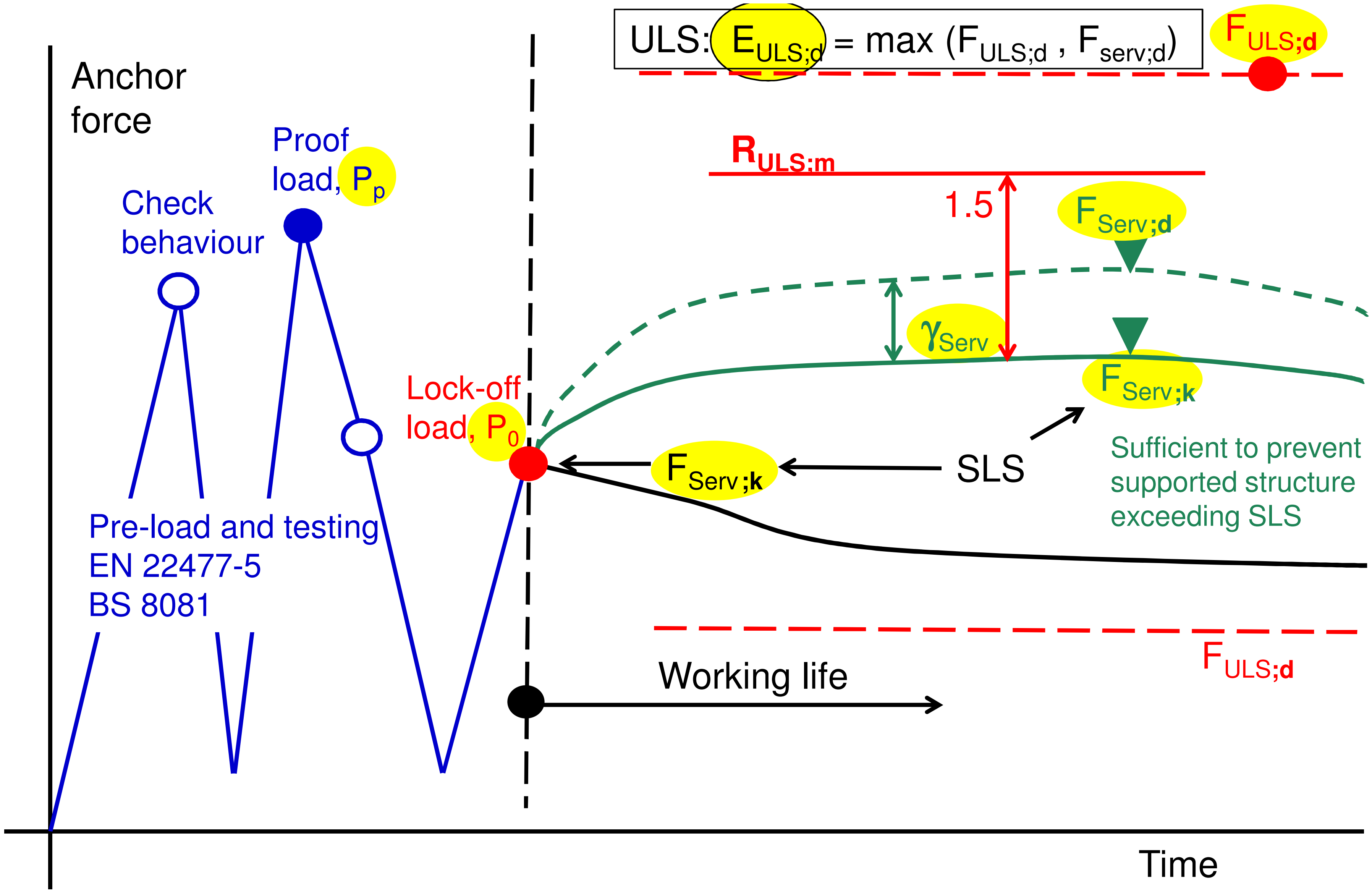

F_{ULS} – the force required to prevent any ultimate limit state in the supported structure

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$\mathbf{R_{ULS;m}} = 1.1x\ (R_{ULS;d} \geq E_{ULS;d})x1.35\ F_{serv;k}/E_{ULS;d} = \mathbf{1.5F_{Serv;k}}$

$\mathbf{R_{SLS;m} = F_{serv;k}}$

Table A.NA.21 — Limiting criteria for investigation, suitability and acceptance tests for persistent and transient design situations at the ultimate and serviceability limit states

Test Method [a]	Limiting criterion	Investigation and suitability tests		Acceptance tests	
		ULS (Eq. 8.5)	SLS (Eq. 8.8)	ULS (Eq. 8.13)	SLS (Eq. 8.14)
2	k_l	5% per log cycle of time	2% per log cycle of time[e]	5% per log cycle of time	2% per log cycle of time[e]
	α_2[b]	5%Δ_{eULS}[c] per log cycle of time	2%Δ_{eSLS}[d] per log cycle of time	5%Δ_{eULS} per log cycle of time	2%Δ_{eSLS} per log cycle of time

Advice on design of anchors to achieve these performance requirements will be provided in BS 8081 (2015).

Summary

- Anchor validation based only on testing – no reliance on calculations.
- No requirement for big overall FOS.
- But contractor will need to be confident that every anchor will pass the acceptance test. Low creep at <u>fairly</u> high loads.
- So he might introduce extra margins to be sure of this.
- EC7 gives the test criteria, but doesn’t advise how to achieve them. BS8081 will do this.

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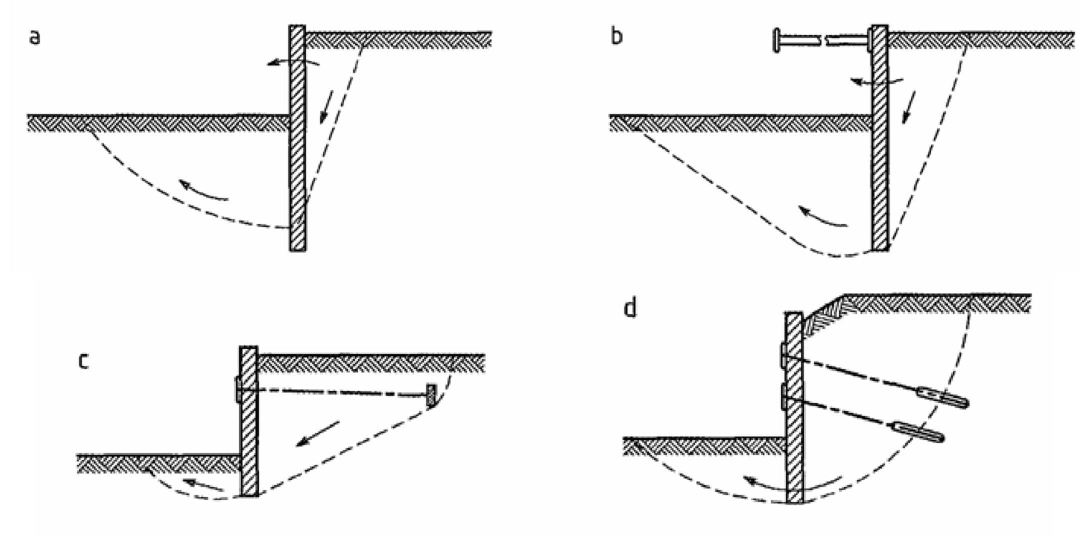
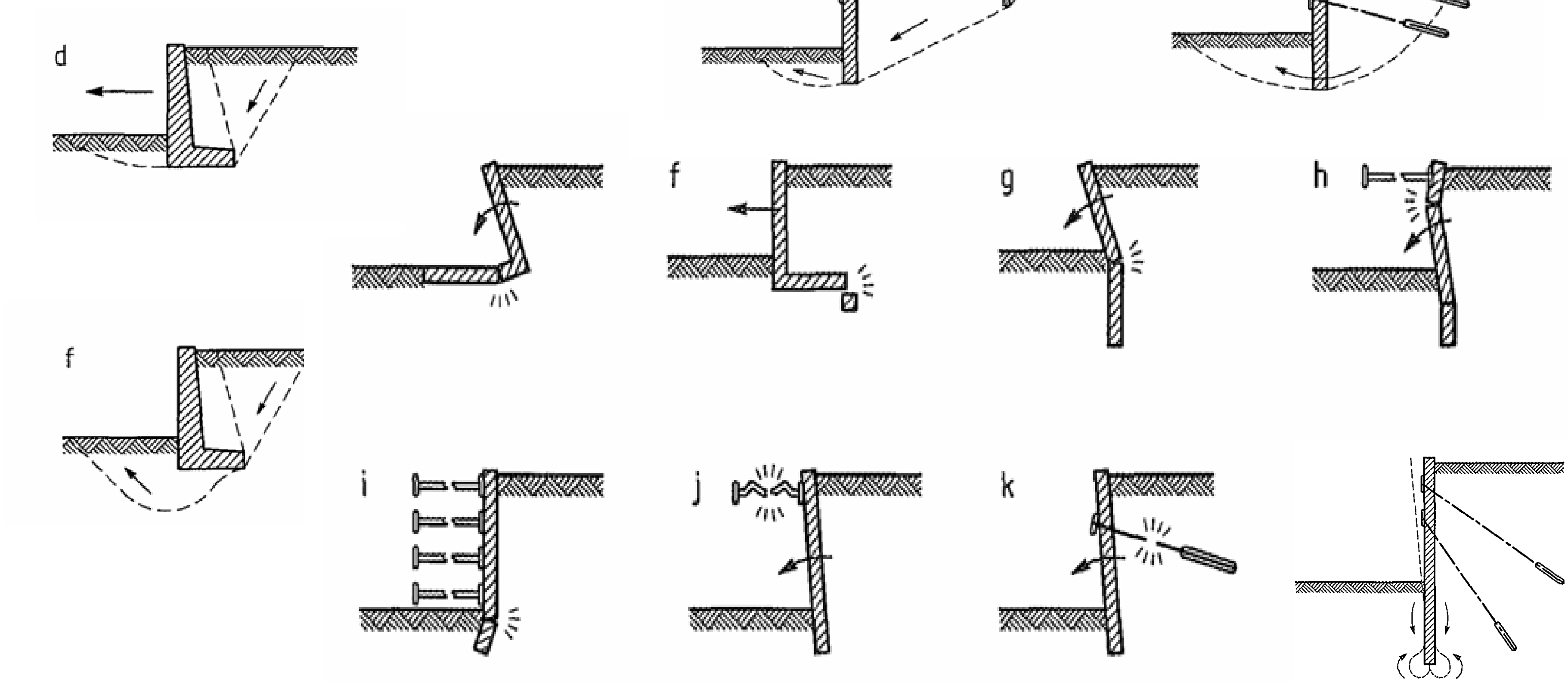
8th Lumb Lecture

Eurocode 7 – Good practice in geotechnical design

- Limit state design
- Holistic design – structures and ground
- Practical approach to characteristic values of soil parameters
- ULS and SLS design requirements
- Water pressures
- Ground anchors
- **Retaining structures** – numerical analysis
- The future

How retaining walls fail – ULS (Eurocode 7)





Which governs – ULS or SLS? Always SLS?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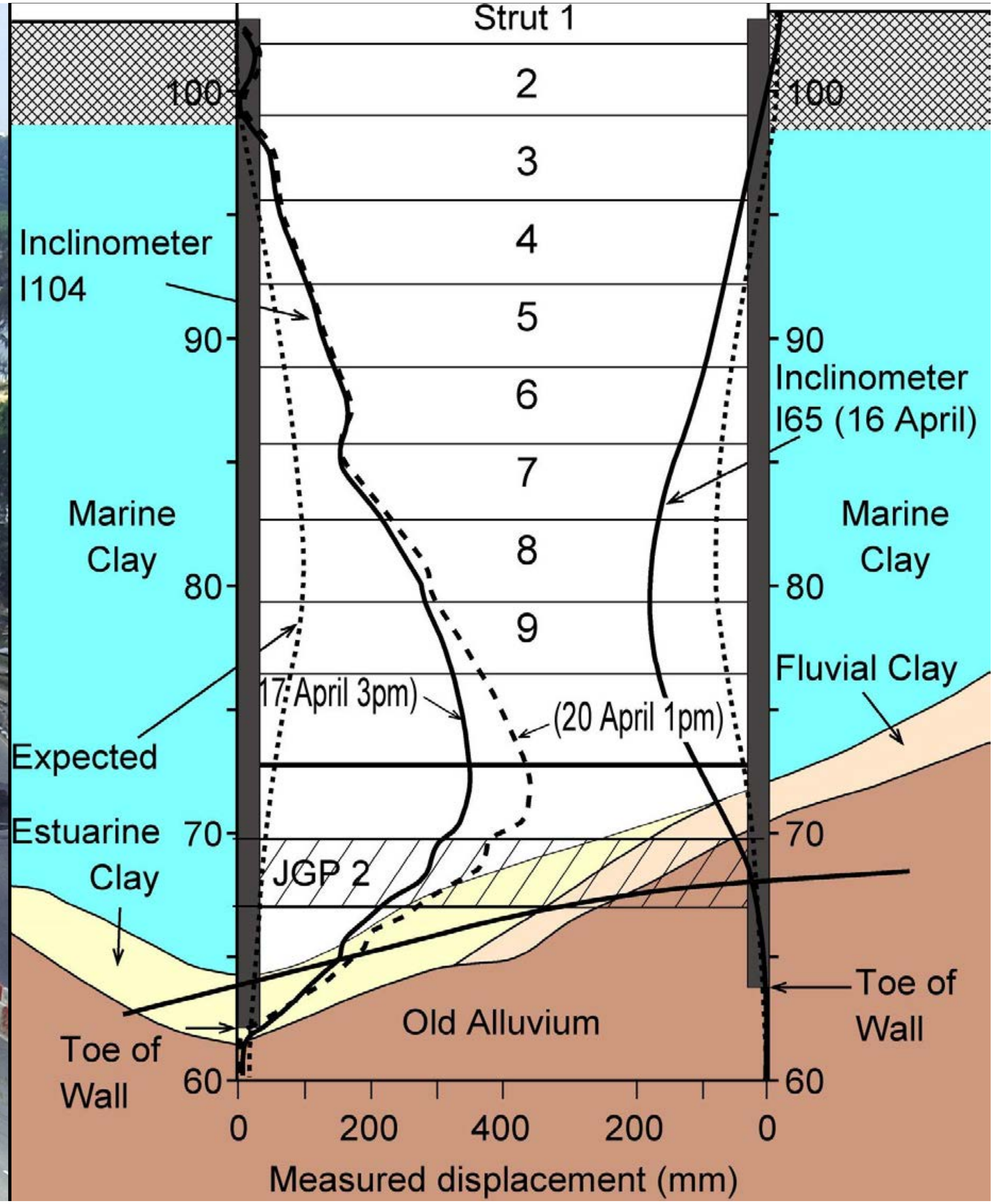
Strut 1
2
3
4
5
6
7
8
9
Inclinometer
I104
Marine
Clay
Expected
Estuarine
Clay
Toe of
Wall
17 April 3pm)
(20 April 1pm)
JGP 2
Old Alluvium
Inclinometer
I65 (16 April)
Marine
Clay
Fluvial Clay
Toe of
Wall
100
90
80
70
60
0
200
400
200
0
Measured displacement (mm)

9.8 Serviceability limit state design

9.8.1 General

(1)P The design of retaining structures shall be checked at the serviceability limit state using the appropriate design situations as specified in 9.3.3.

(2)P Design values of earth pressures for the serviceability limit state shall be derived using characteristic values of all soil parameters.

(5) The design values of earth pressures should be derived taking account of the allowable deformation of the structure at its serviceability limit state. These pressures may not necessarily be limiting values.

9.8.2 Displacements

(1)P Limiting values for the allowable displacements of walls and the ground adjacent to them shall be established in accordance with 2.4.8, taking into account the tolerance to displacements of supported structures and services.

(2)P A cautious estimate of the distortion and displacement of retaining walls, and the effects on supported structures and services, shall always be made on the basis of comparable experience. This estimate shall include the effects of construction of the wall. The design may be justified by checking that the estimated displacements do not exceed the limiting values.

(3)P If the initial cautious estimate of displacement exceeds the limiting values, the design shall be justified by a more detailed investigation including displacement calculations.

(4)P It shall be considered to what extent variable actions, such as vibrations caused by traffic loads behind the retaining wall, contribute to the wall displacement.

(5)P A more detailed investigation, including displacement calculations, shall be undertaken in the following situations:

— where nearby structures and services are unusually sensitive to displacement;

— where comparable experience is not well established.

(8) The behaviour of materials assumed in displacement calculations should be calibrated by comparable experience with the same calculation model. If linear behaviour is assumed, the stiffnesses adopted for the ground and structural materials should be appropriate for the degree of deformation computed. Alternatively, complete stress-strain models of the materials may be adopted.

Eurocode 7 – Good practice in geotechnical design

- Limit state design
- Holistic design – structures and ground
- Practical approach to characteristic values of soil parameters
- ULS and SLS design requirements
- Water pressures
- Ground anchors
- **Retaining structures – numerical analysis**
- The future

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(3)P If the initial cautious estimate of displacement exceeds the limiting values, the design shall be justified by a more detailed investigation including displacement calculations.

Numerical analysis often used for SLS.
Nothing new in EC7.

(5)P A more detailed investigation, including displacement calculations, shall be undertaken in the following situations:

— where nearby structures and services are unusually sensitive to displacement;

— where comparable experience is not well established.

(8) The behaviour of materials assumed in displacement calculations should be calibrated by comparable experience with the same calculation model. If linear behaviour is assumed, the stiffnesses adopted for the ground and structural materials should be appropriate for the degree of deformation computed. Alternatively, complete stress-strain models of the materials may be adopted.

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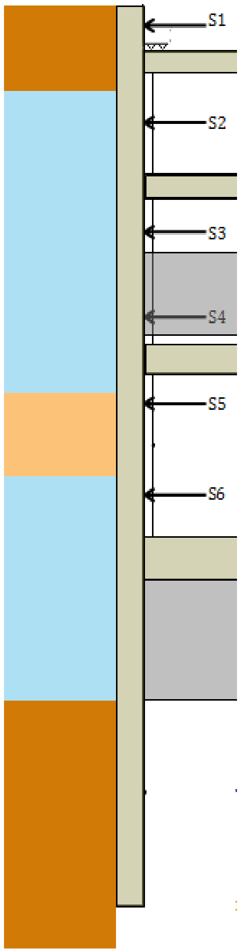
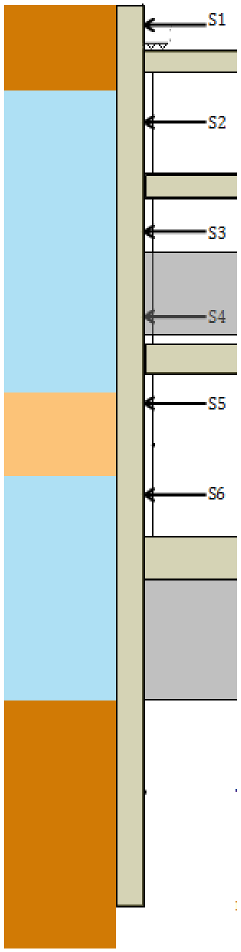


- **Use of numerical methods for ULS**
  - Can numerical methods be used for all design approaches?
  - How should strength factors be applied?
  - Does FEM give the wrong failure mechanism?
  - Use of advanced soil models for ULS
  - Undrained behaviour and consolidation
  - K_0 and soil stiffness
  - Staged construction

- **Simpson, B and Junaideen, SM (2013)**
  Use of numerical analysis with Eurocode 7.
  18th South East Asia Geotechnical Conference, Singapore.

Eurocode 7 – Good practice in geotechnical design



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Partial factors recommended in EN1997-1 Annex A (+UKNA)

Values of partial factors recommended in EN1997-1 Annex A (+ UKNA)

			Design approach 1 Combination 1 A1	M1	R1	Combination 2 A2	M2	R1	Combination 2 - piles & anchors A2	M1 or …	M2	R4	Design approach 2 DA2 - Comb 1 A1	M1	R2	DA2 - Slopes A1	M=R2	Design approach 3 DA3 A1	A2	M2	R3
Actions	Permanent	unfav	1,35										1,35			1,35		1,35			
		fav																			
	Variable	unfav	1,5			1,3			1,3				1,5			1,5		1,5	1,3		
Soil	tan φ'						1,25				1,25							Structural actions	Geotech actions	1,25	
	Effective cohesion						1,25				1,25									1,25	
	Undrained strength						1,4				1,4									1,4	
	Unconfined strength						1,4				1,4									1,4	
	Weight density																				
Spread footings	Bearing														1,4						
	Sliding														1,1						
Driven piles	Base											1,3			1,1						
	Shaft (compression)											1,3			1,1						
	Total/combined											1,3			1,1						
	Shaft in tension											1,6			1,15						1,1
Bored piles	Base											1,6			1,1						
	Shaft (compression)											1,3			1,1						
	Total/combined											1,5			1,1						
	Shaft in tension											1,6			1,15						1,1
CFA piles	Base											1,45			1,1						
	Shaft (compression)											1,3			1,1						
	Total/combined											1,4			1,1						
	Shaft in tension											1,6			1,15						1,1
Anchors	Temporary											1,1			1,1						
	Permanent											1,1			1,1						
Retaining walls	Bearing capacity														1,4						
	Sliding resistance														1,1						
	Earth resistance														1,4						
Slopes	Earth resistance																1,1				

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DA2 unsuitable for numerical analysis

- Easy to factor primary input – material strengths and actions
- Difficult to factor geotechnical resistances and action effects

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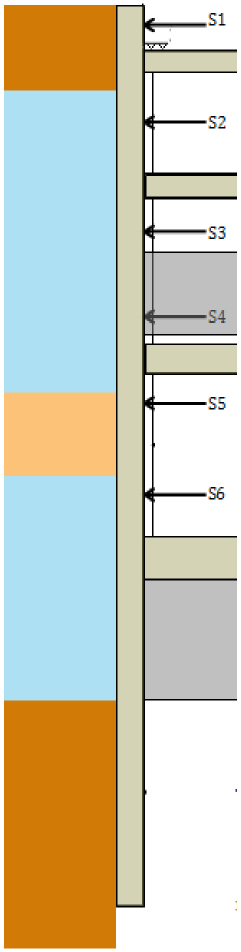
Eurocode 7 – Good practice in geotechnical design



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  - Staged construction

Fundamental limit state requirement

$$E_d \leq R_d$$

$$E\{ \; F_d \; ; \; X_d \; ; a_d\} = E_d \leq R_d = R\{ \; F_d \; ; \; X_d \; ; a_d\}$$

$$E\{\gamma_F \, F_{rep}; X_k/\gamma_M; a_d\} = E_d \leq R_d = R\{\gamma_F \, F_{rep}; X_k/\gamma_M; a_d\}$$

or $E\{\gamma_F \, F_{rep}; X_k/\gamma_M; a_d\} = E_d \leq R_d = R_k/\gamma_R = R_n\phi_R$ (LRFD)

or $\gamma_E \, E_k = E_d \leq R_d = R_k/\gamma_R$

so in total

$$\gamma_E \, E\{\gamma_F \, F_{rep}; X_k/\gamma_M; a_d\} = E_d \leq R_d = R\{\gamma_F \, F_{rep}; X_k/\gamma_M; a_d\}/\gamma_R$$

- (a) Reduce strength, increase the loads, and check equilibrium

  OR

- (b) Find the remaining FOS?

  OR

- (b) “c-ϕ reduction”

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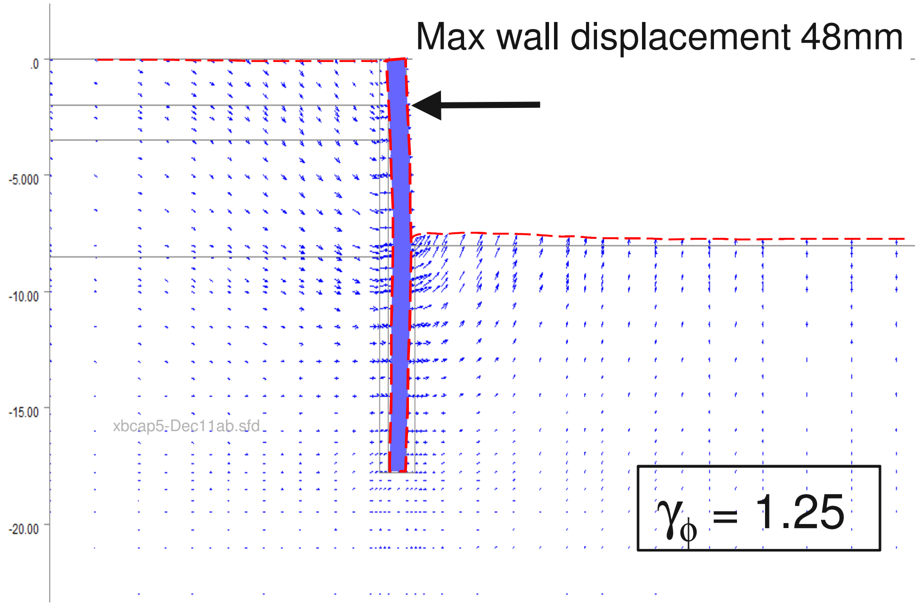
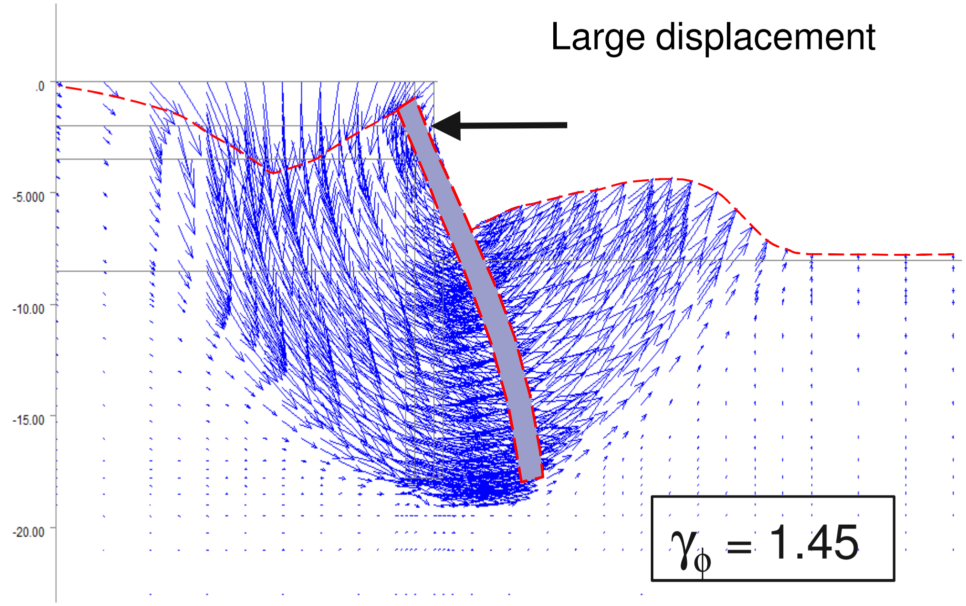
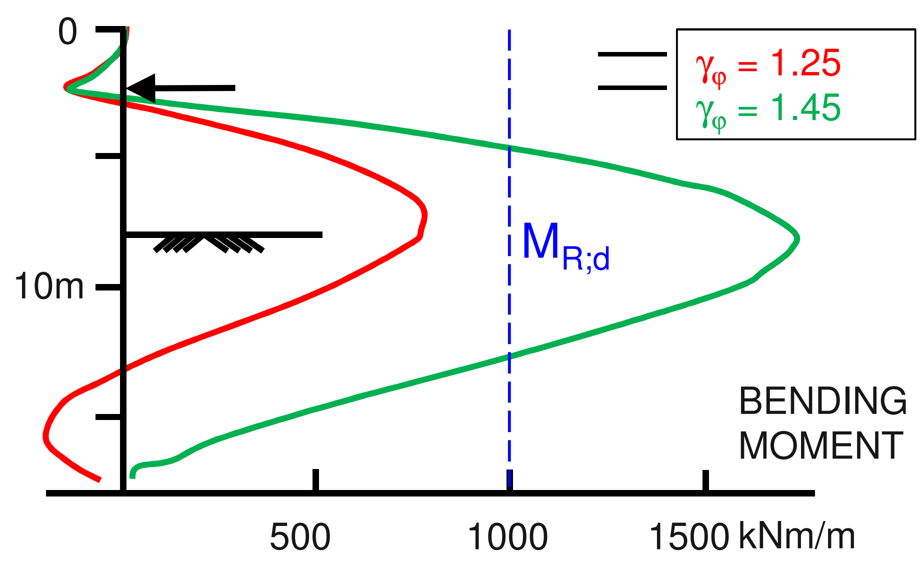
Pre-factored strength, or c-ϕ reduction?







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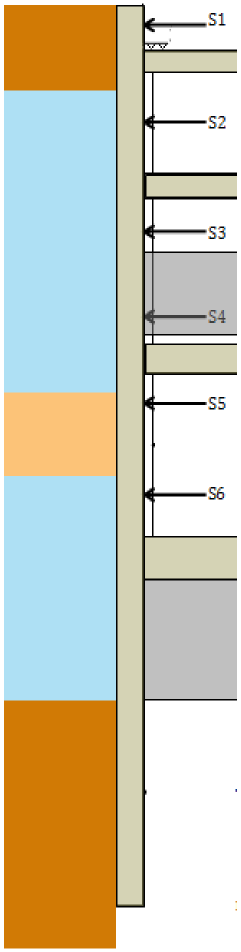

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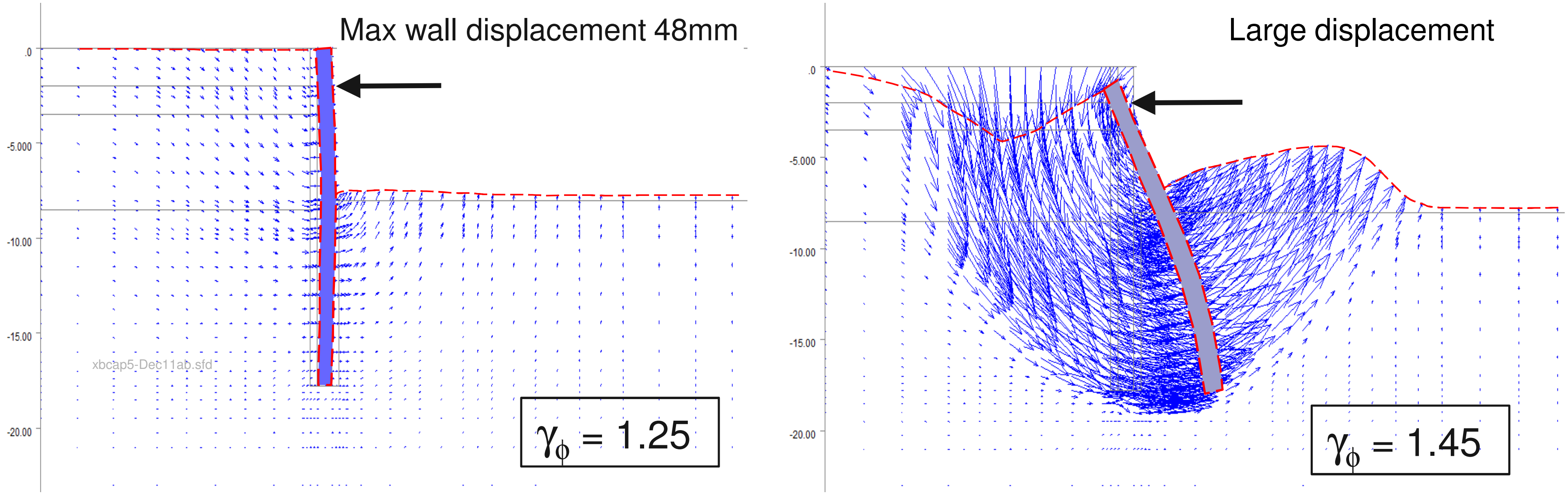
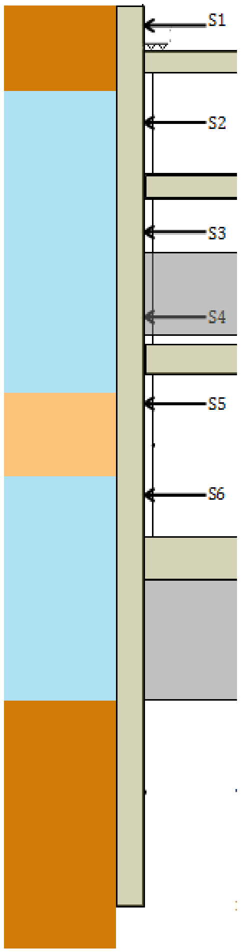
Wrong failure mechanism?



- There is no "right" failure mechanism
  - Because failure isn't the "right" answer!
- EC7 is interested in proving success, not failure.
- Finding FOS useful for design refinement, but not for final verification.
- Plastic models of structural elements useful in ULS analysis.

Eurocode 7 – Good practice in geotechnical design



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Factoring advanced models – ϕ', c', c_u not explicit parameters

- eg Cam Clay, BRICK, Lade etc
- Change to Mohr-Coulomb for the factored calculation?
- If $\gamma_{c'}=\gamma_{\phi'}$ this is the code factor on drained strength, however derived.
- Consider: is the model's drained strength more or less reliable than those used in conventional practice?
  - eg the model might take good account of combinations of principal stresses, direction (anisotropy), stress level etc.
  - Possibly modify factors in the light of this.

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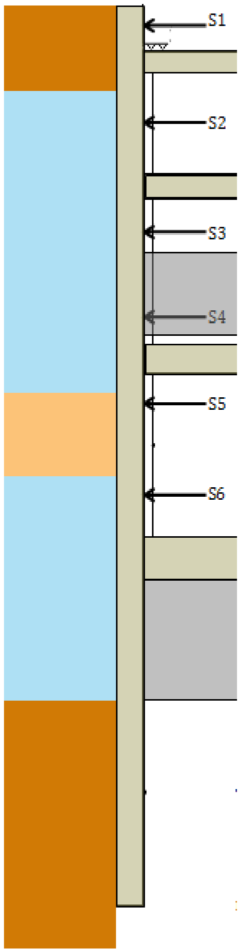

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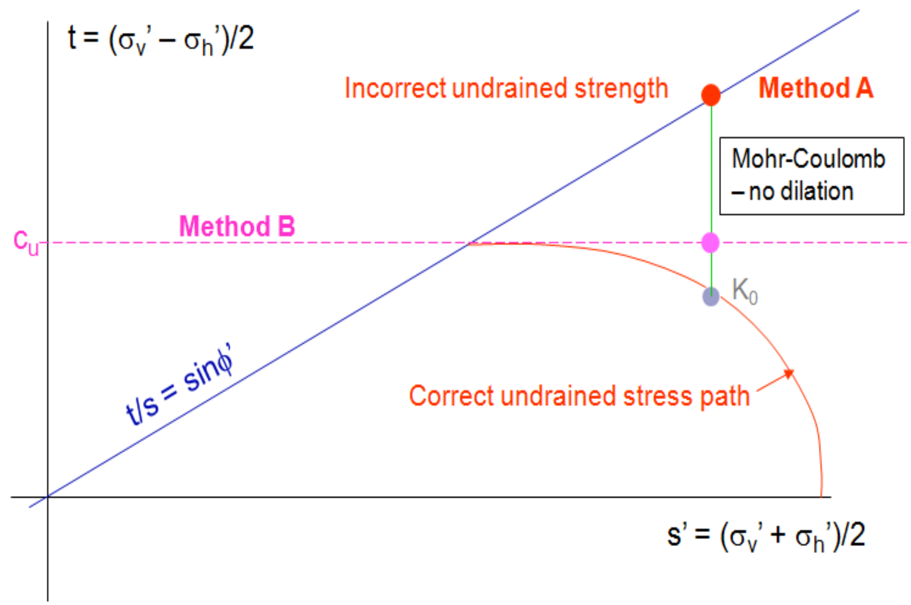
Undrained strength in effective stress models

Reliable computation of undrained strength from effective stress parameters is very difficult.

EC7 generally requires a higher factor on undrained strength (eg 1.4 on c_u) than on effective stress parameters (eg 1.25 on c', $\tan\phi'$).



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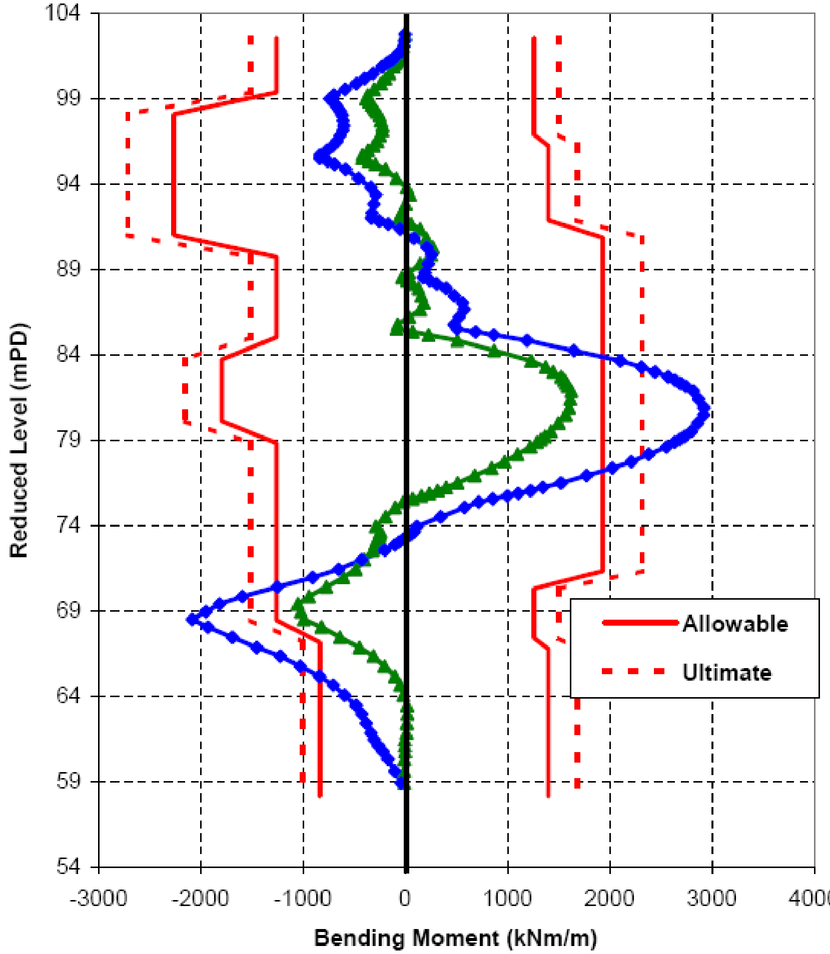
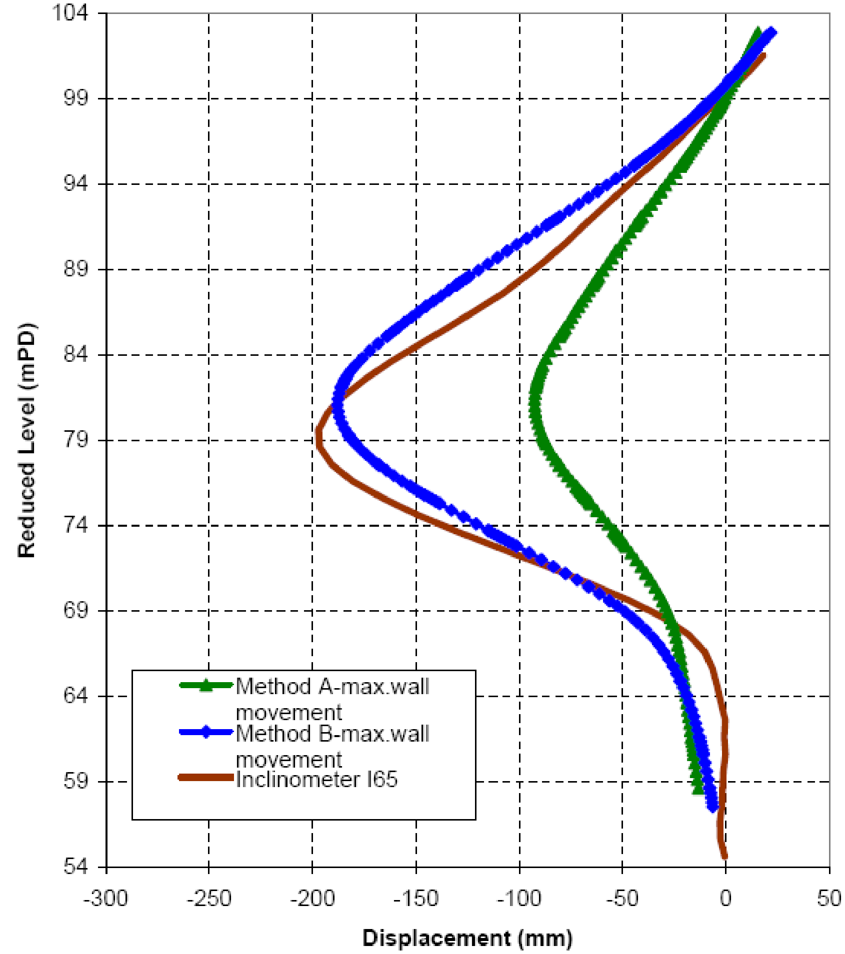
c_u/1.4 doubles bending moment when sensitive





NUMERICAL ANALYSIS RESULTS
COMPARISON OF METHODS A AND B

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Undrained strength in effective stress models

- Reliable computation of undrained strength from effective stress parameters is very difficult.
- EC7 generally requires a higher factor on undrained strength (eg 1.4 on c_u) than on effective stress parameters (eg 1.25 on c', $\tan\phi'$).
- The drafters assumed that effective stress parameters would be used only for drained states.
- The higher factor (eg 1.4) was considered appropriate for characteristic values of c_u based on measurement, which is generally more reliable than values computed from effective stress parameters.
- So it is unreasonable to adopt a lower value for the latter.

Time-dependent analysis

- Beyond EC7!
- Geotechnical category 3

Section 2 Basis of geotechnical design

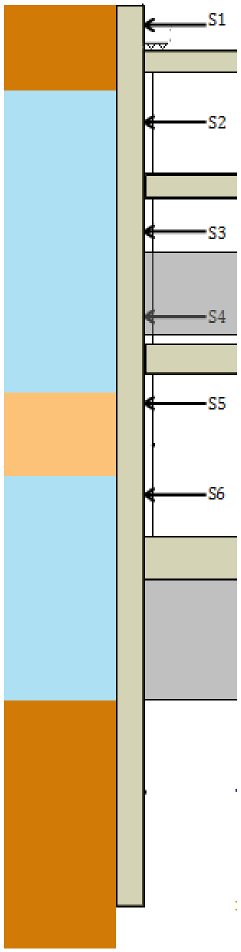
2.1 Design requirements

(12) The procedures of higher categories may be used to justify more economic designs, or if the designer considers them to be appropriate.

(20) Geotechnical Category 3 should include structures or parts of structures, which fall outside the limits of Geotechnical Categories 1 and 2.

(21) Geotechnical Category 3 should normally include alternative provisions and rules to those in this standard.

Eurocode 7 – Good practice in geotechnical design



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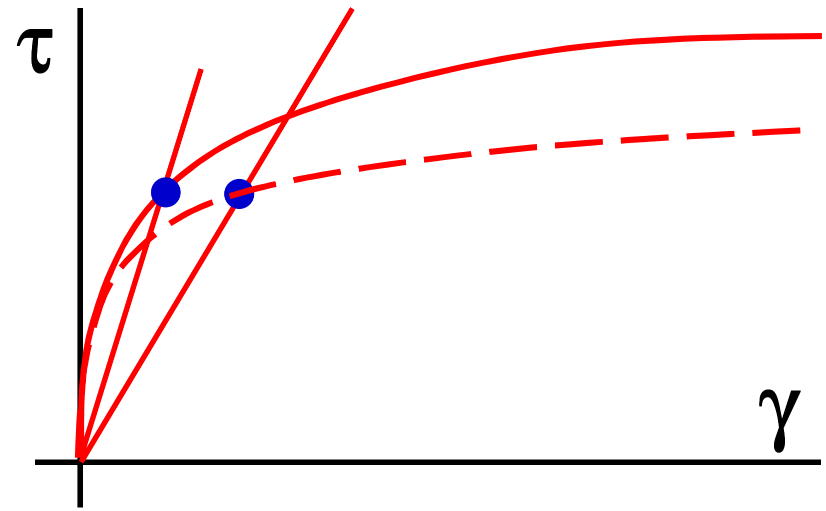
K_o

- In reality, K_0 is not a simple function of soil strength (ϕ').
- So it is not sensible, and not a Eurocode requirement, to factor K_0 or vary it as a function of ϕ'. In situ stresses are taken as a separate parameter – an action.

Soil stiffness

- CIRIA Report C580 recommends that stiffness should be reduced (halved) for ULS analysis. No other publication has a similar requirement.

- The reason for this was that larger strains may be mobilised in ULS analyses – it was not an additional safety margin.



- This reasoning may apply to Strategy 1, but not so clearly to Strategy 2 since, in many cases, most of the displacement has already taken place when the strength is reduced. If the soil is close to failure, stiffness will not be important.

- So reduction of stiffness for ULS analysis is not recommended.

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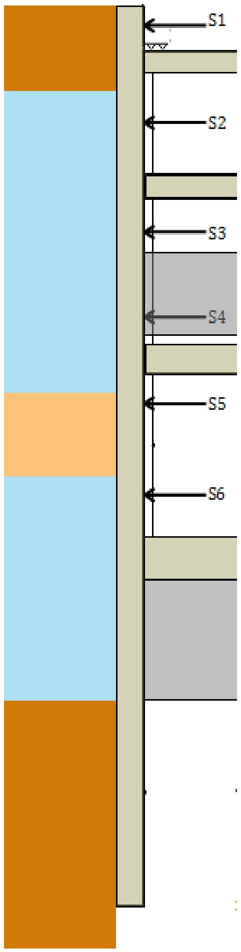

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ULS for staged construction – single propped example

Strategy 1

Compute using factored strength

- Factor material strengths
- Initial state?
- ↓ Excavate to 5m – wall cantilevering
- ↓ Install prop at 4m depth
- ↓ Excavate to 10m

No further factors on strut forces or BMs

Strategy 2

Compute using unfactored parameters

- Initial state
- ↓ Excavate to 5m – wall cantilevering → Could be critical for wall bending moment
- ↓ Install prop at 4m depth
- ↓ Excavate to 10m → Could be critical for wall length, bending moment and prop force

Apply factors on strut forces or BMs

Compute using factored parameters

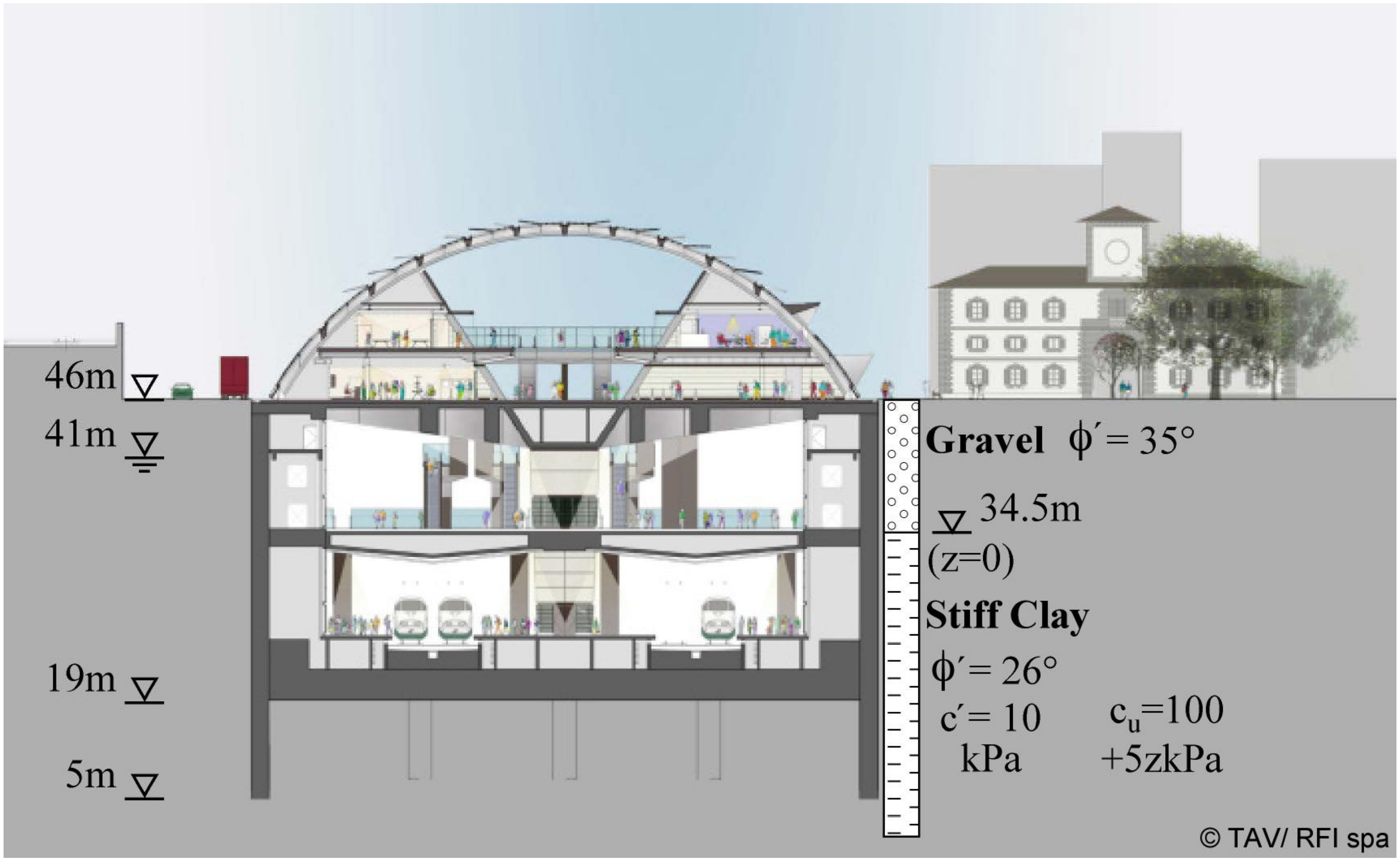
No further factors on strut forces or BMs

Florence Rail Station

- 25m deep, 50m wide,
  550m long
- Mezzanine level prop
- High groundwater level

Simpson, B and Hocombe, T (2010) Implications of modern design codes for earth retaining structures. Proc ER2010, ASCE Earth Retention Conference 3, Seattle, Aug 2010.

Eurocode case study: High speed rail station, Florence, Italy



- 454m long, 52m wide and 27 to 32m deep
- 1.2 to 1.6m thick diaphragm walls
- Three levels of temporary strutting.

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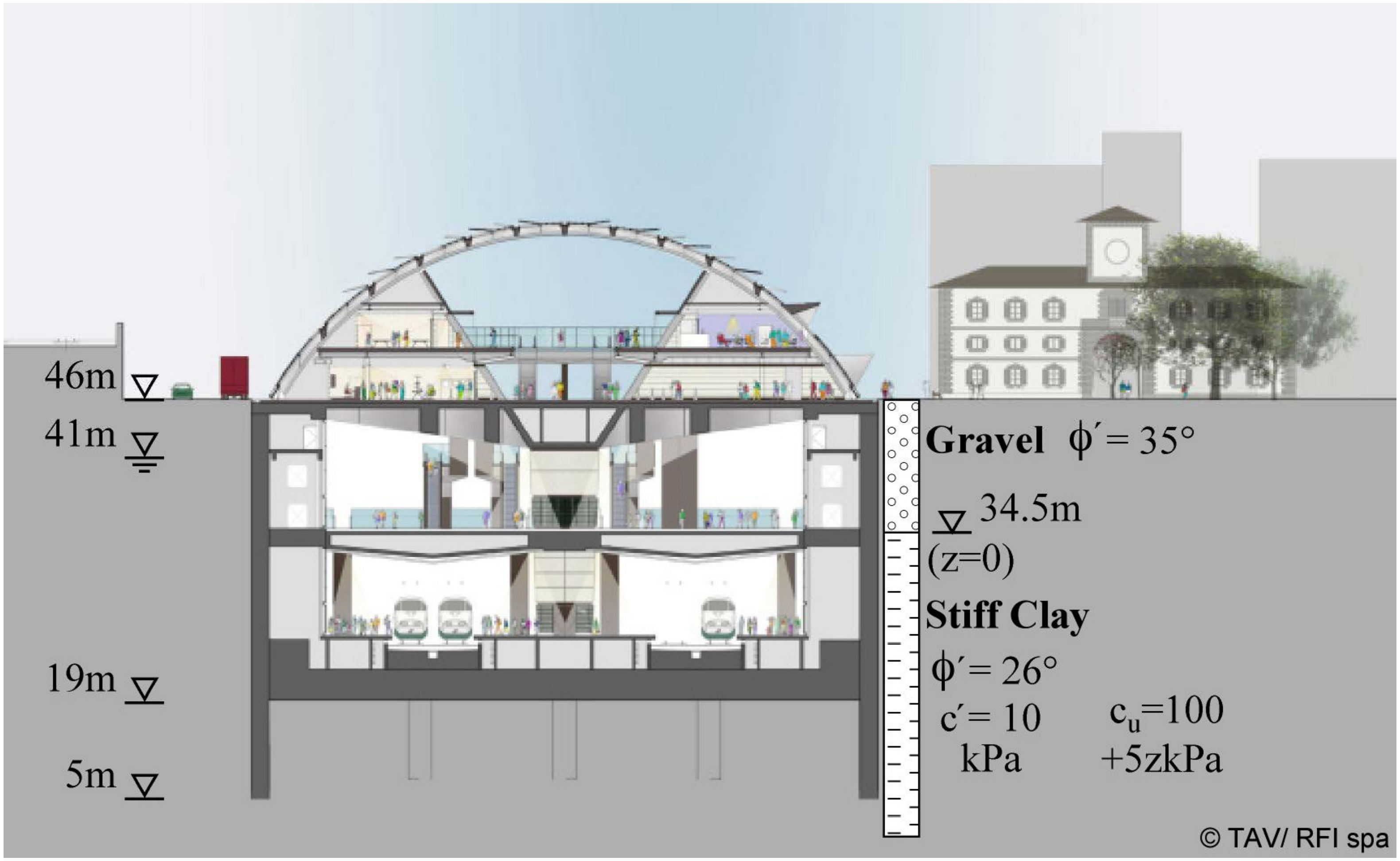
Eurocode case study: High speed rail station, Florence, Italy



- SLS analyzed as if London Clay using the BRICK model.
- Time dependent swelling and consolidation.
- Eurocode 7, DA1, Combinations 1 and 2 analysed using FE and Oasys FREW.

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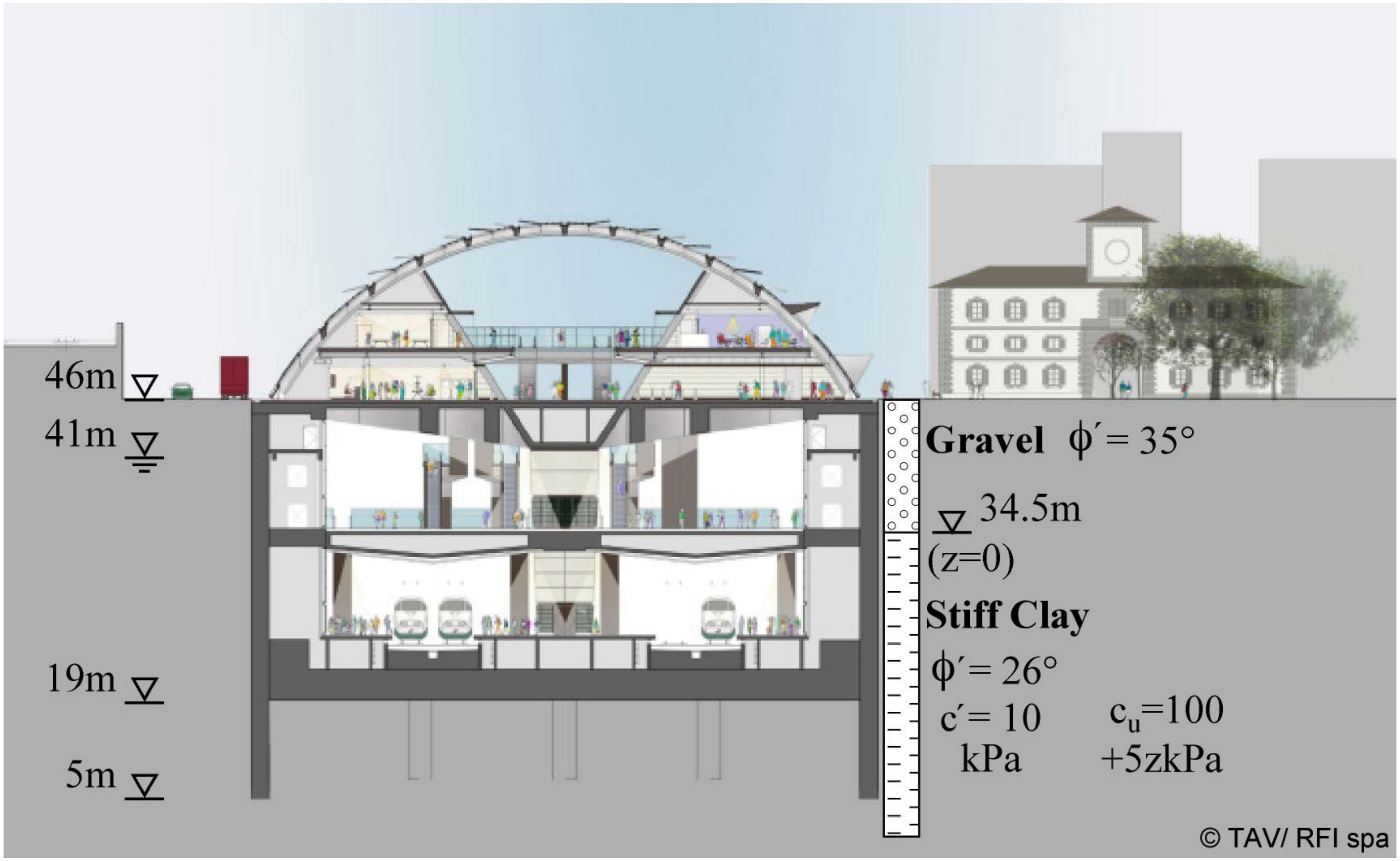
Eurocode case study: High speed rail station, Florence, Italy



- Eurocode 7 readily used with FE for this large project.
- Geotechnical and structural design readily coordinated.

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Partial factors for DA1 - UKNA

			Design approach 1 Combination 1 A1	M1	R1	Combination 2 A2	M2	R1	Combination 2 - piles & anchors A2	M1 or …	M2	R4 (UKNA)	EC7 values
Actions	Permanent	unfav	1,35										
		fav											
	Variable	unfav	1,5			1,3			1,3				
Soil	tan φ'						1,25				1,25		
	Effective cohesion						1,25				1,25		
	Undrained strength						1,4				1,4		
	Unconfined strength						1,4				1,4		
	Weight density												
Spread footings	Bearing												
	Sliding												
Driven piles	Base											1,7/1.5	1,3
	Shaft (compression)											1.5/1.3	1,3
	Total/combined											1.7/1.5	1,3
	Shaft in tension											2.0/1.7	1.6
Bored piles	Base											2.0/1.7	1,6
	Shaft (compression)											1.6/1.4	1,3
	Total/combined											2.0/1.7	1.5
	Shaft in tension											2.0/1.7	1.6
CFA piles	Base											As	1.45
	Shaft (compression)											for	1.3
	Total/combined											bored	1.4
	Shaft in tension											piles	1.6
Anchors	Temporary											1,1	1,1
	Permanent											1,1	1,1
Retaining walls	Bearing capacity												
	Sliding resistance												
	Earth resistance												
Slopes	Earth resistance												

[green box] indicates partial factor = 1.0

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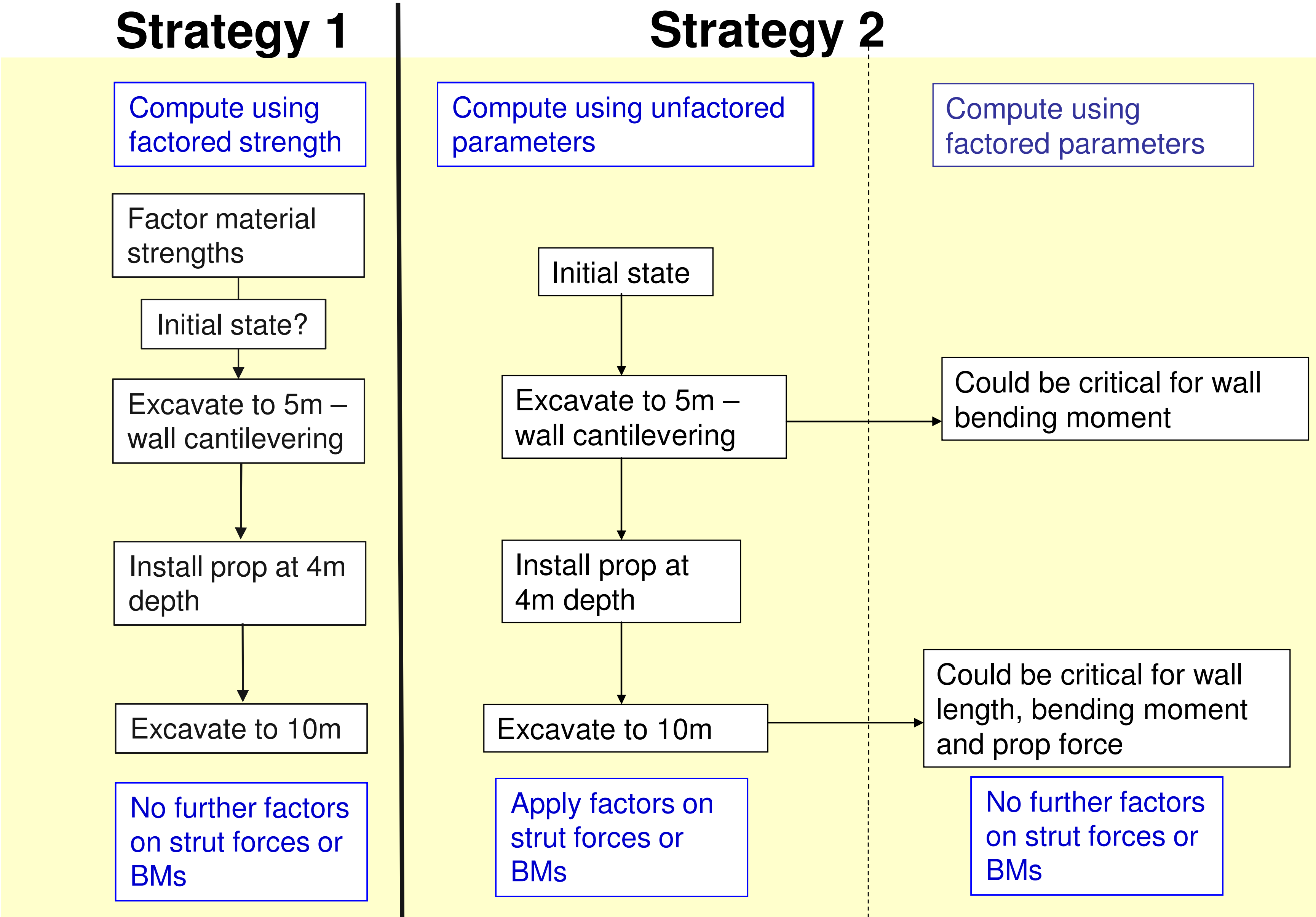
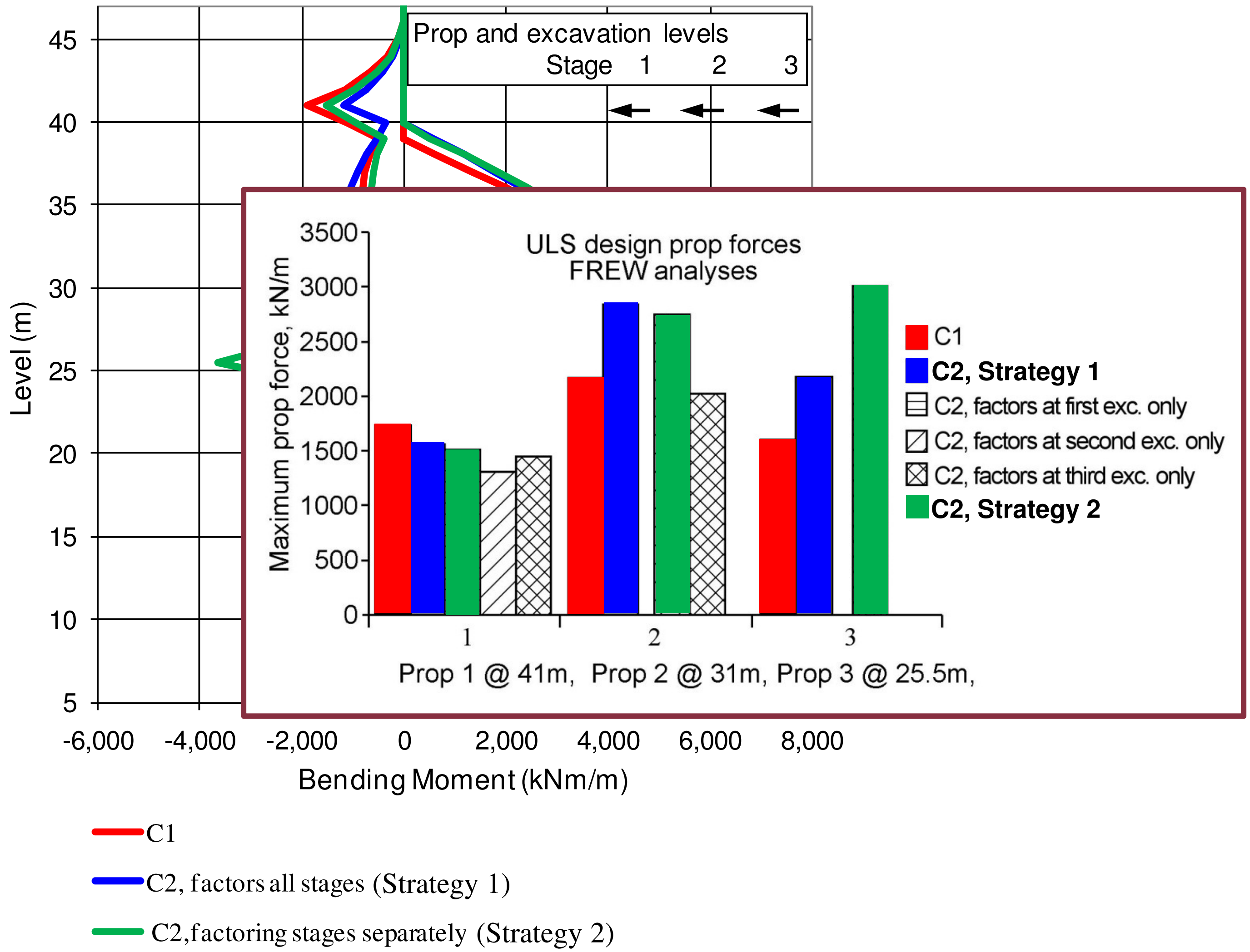
ULS for staged construction – single propped example



Florence Station – comparison of bending moments



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Summary – numerical analysis

- FEM analysis of SLS is conventional – nothing new.
- FEM can also be used for ULS
- Design Approach 1 is well suited to this.
- Difficult to distinguish favourable and unfavourable actions from the ground – the "star" approach for these.
- The code requirement is best checked by applying fixed factors to strength – method (a).
- "c- ϕ reduction" might be useful for design refinement – method (b).
- Plastic modelling of the structure would be beneficial.
- When advanced soil models are used, it may be best to switch to Mohr-Coulomb for the ULS check.

Summary – numerical analysis

- Great care is needed in modelling undrained situations using effective stress parameters – requires a good advanced model.
- The full value of γ_{Cu} should be applied for undrained materials.
- Factoring of K_0 and stiffness is not recommended.
- "Strategy 2" – applying factors to stages individually – is recommended.
  - Analyse DA1-1 first, then check critical stages for DA1-2.
  - Computing effort might be reduced if stages for which DA1-2 is critical can be established for a given range of situations.
- EC7 Evolution Group

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8th Lumb Lecture

Eurocode 7 – Good practice in geotechnical design

- Limit state design
- Holistic design – structures and ground
- Practical approach to characteristic values of soil parameters
- ULS and SLS design requirements
- Water pressures
- Ground anchors
- Retaining structures – numerical analysis
- **The future**

The future

- Evolution groups => extensive revisions of most sections
- About to start re-drafting for 2020(?)
- Reorganised into three parts: General, Testing, Specific elements
- Harmonisation – simplifying the Design Approaches
- Consequence classes – variations to partial factors (1.25 → 1.2?)
- Additional sections
    - Reinforced ground
    - Ground improvement
    - Rock mechanics
- Numerical analysis – section or sub-section

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Thanks for listening