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Advantages and limitations of ultimate limit state design methods for braced excavations

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Introduction

Traditionally in the US, braced excavations are designed with a serviceability approach where soil parameters are conservatively estimated and the performed analysis yields the service displacements, moments and forces. Design forces are then calculated by applying a global safety factor that ranges from 1.2 to 1.5.

In Europe, in contrast to the US, an ultimate limit state design approach has been adopted in geotechnical design including the design of braced excavations. In this design philosophy both wall and supports are designed based on an ultimate limit condition. The ultimate design forces are typically determined by reducing the characteristic soil strength parameters or by multiplying the effects of actions and dividing the effects of resistances by various safety factors. At the end, a safety factor of one or greater is required for all structures and other types of safety factors.

In the author's experience the ultimate limit state method works reasonably well for most limit equilibrium methods but can produce very inconsistent results in many cases when numerical analyses are employed. Hence, the advantages and limitations of the ultimate limit state design should be carefully weighted by practitioners and academia in the US before, and if, the ultimate limit state philosophy is incorporated in a legally binding building code.

Eurocode strength reduction methods

EC7 specifies that, when applicable, the following Ultimate Limit States should not be exceeded:

EQU: 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.

STR: Internal failure or excessive deformation of the structure or structural elements, ... in which the strength of structural materials is significant in providing resistance.

GEO: Failure or excessive deformation of the ground, in which the strength of soil or rock is significant in providing resistance.

UPL: Loss of equilibrium of the structure or the ground due to uplift by water pressure (buoyancy) or other vertical actions.

HYD: Hydraulic heave, internal erosion and piping in the ground caused by hydraulic gradients.

In the design of braced excavations, typically the STR, GEO, and HYD checks are of importance. Under all limit states, the designer should verify that:

$$E_d \leq R_d$$

E_d = Design value of the effect of actions (geotech., structural, etc)
R_d = Design value of the resistance to an action.

Partial factors on actions may be applied either to the actions themselves (F_{rep}) or to their effects (E) by applying either one of the following procedures:

$E_d = E\{\gamma_F F_{rep}; X_k/\gamma_M; a_d\}$ (EC7 equation 2.6a)
$E_d = \gamma_E E\{F_{rep}; X_k/\gamma_M; a_d\}$ (EC7 equation 2.6b)

Resistances to actions are determined in a similar manner where partial factors are applied to ground properties (X) or resistances (R) or to both with either one of the following:

$R_d = R\{\gamma_F Frep; X_k/\gamma_M; a_d\}$ (EC7 equation 2.7a)
$R_d = R\{\gamma_F Frep; X_k; a_d\}/\gamma_R$ (EC7 equation 2.7b)
$R_d = R\{\gamma_F Frep; X_k/\gamma_M; a_d\}/\gamma_R$ (EC7 equation 2.7c)

Where:

a_d = Design value of geometrical data
γ_E = Partial factor for the effect of an action
γ_F = Partial factor for an action
γ_m = Partial factor for a soil parameter (material property)
γ_R = Partial factor for a resistance
X_k = Characteristic value of a material property (soil friction, effective cohesion, undrained shear strength, etc).

Eurocode 7 still requires that the serviceability checks for displacement are performed

◊ SLS = Service limit state.
◊ ULS = Ultimate limit state.

Eurocode design approach combinations

Design Approach 1: Combination 1: *A1* "+" *M1* "+" *R1* (DA-1/1)
Combination 2: *A2* "+" *M2* "+" *R1* (DA-1/2)
Design Approach 2: Combination: *A1* "+" *M1* "+" *R2* (DA-2)
Design Approach 3: Combination: (*A1** or *A2*†) "+" *M2* "+" *R3* (DA-3)

*on structural actions, †on geotechnical actions
Where "+" implies: "to be combined with".

Table 1. Partial factors on actions (γ_F) or the effects of actions (γ_E)

Action		Symbol	Set A1	Set A2
Permanent	Unfavorable	γ_G	1.35	1.0
	Favorable		1.0	1.0
Variable	Unfavorable	γ_Q	1.5	1.3
	Favorable		0	0

Table 2. Partial factors for soil parameters (γ_M)

Soil parameter	Symbol	Set M1	Set M2
Angle of shearing resistance (applied to tan φ)	γ_ϕ'	1.0	1.25
Effective cohesion	γ_c'	1.0	1.25
Undrained shear strength	γ_{cu}	1.0	1.4
Unconfined strength	γ_{qu}	1.0	1.4
Weight density	γ_γ	1.0	1.0

Table 3. Partial resistance factors for earth resistance, pre-stressed anchors (γ_R)

Resistance	Symbol	Set R1	Set R2	Set R3	Set R4
Earth resistance	$\gamma_{R;e}$	1.0	1.4	1.0	-
Ground anchors (temporary)	$\gamma_{a;t}$	1.1	1.1	1.0	1.1
Ground anchors (permanent)	$\gamma_{a;p}$	1.1	1.1	1.0	1.1

Example problem

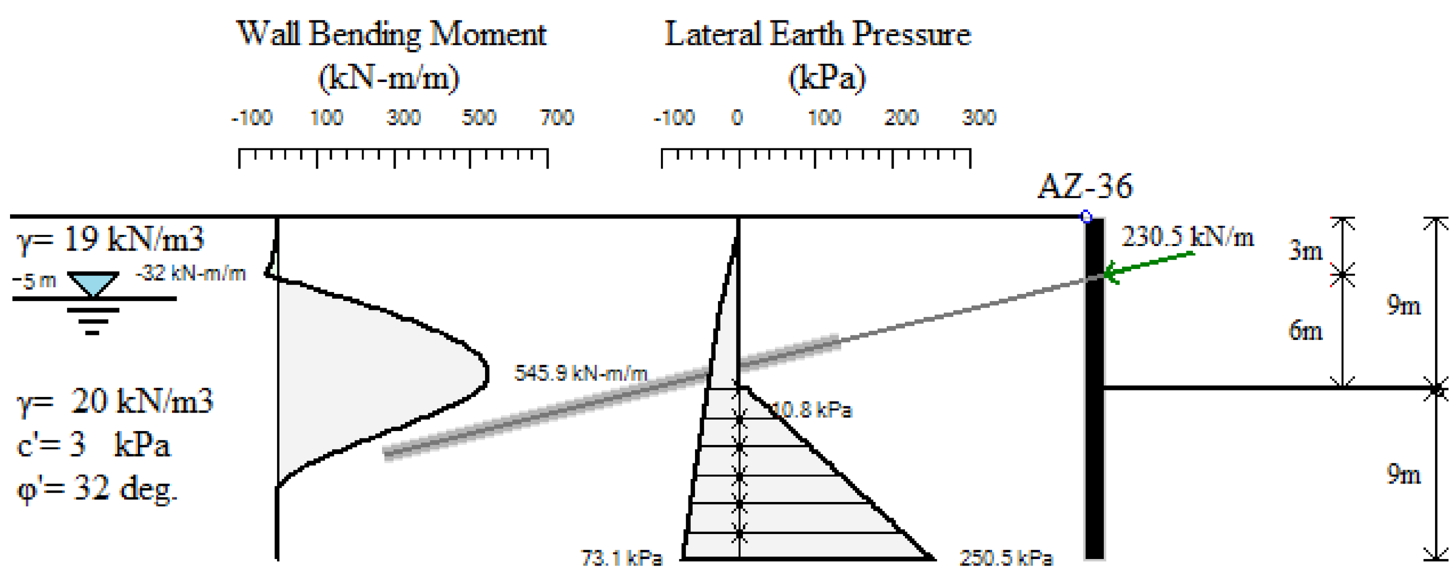

Table 4. Comparison combination methods for braced excavation example with traditional limit equilibrium approach.

Case	M_{MAX} (kN-m/m)	R_{MAX} (kN/m)	*FS* ROT	*FS* HYD	$\sigma'_{A.MAX}$ (kPa)	U_{NET} (kPa)	q_{MAX} (kPa)	$\sigma'_{PASS.MAX}$ (kPa)
SLS	546	230.5	1.787	1.692	73.1	32.7	5.0	250.5
SLSx1.5	819	346.0	1.787	1.692	73.1	32.7	5.0	250.5
DA-1/1	931	354.1	1.324	1.128	98.7	44.2	7.5	250.5
DA-1/2	886	345.6	1.179	1.128	92.1	32.7	5.0	200.5
DA-2 [1]	1478[1]	476.5[1]	0.946	1.128	98.7	44.2	7.5	178.9
DA-3	884	348.5	1.179	1.128	92.1	32.7	7.5	200.5

Notes: 1. Case DA-2 model does not converge

$\sigma'_{A.MAX}$ = Maximum computed unfavorable active earth pressure (including partial factors)
$\sigma'_{PASS.MAX}$ = Maximum computed passive earth resistance pressure (including partial factors)
FS ROT = Wall embedment safety factor against rotation (free earth method)
FS HYD = Hydraulic heave safety factor
M_{MAX} = Maximum computed wall bending moment
R_{MAX} = Maximum computed support reaction at the anchorage direction
U_{NET} = Maximum computed unfavorable net water pressure (including partial factors)
q_{MAX} = Maximum computed unfavorable variable load (including effects of partial factors)

Table 5. Comparison of different combination methods for braced excavation example with beam-on-elastoplastic foundations approach.

Case	δ_{MAX} (cm)	M_{MAX} (kN-m/m)	R_{MAX} (kN/m)	FS Passive Mobilized	FS Wall M vs. SLS	FS Support R vs. SLS	Comments
SLS	6.0	528	263	1.606	1.00	1.00	-
SLSx1.5	6.0	792	394	1.606	1.50	1.50	Same as SLS
DA-1/1	6.0	712	356	1.606	1.35	1.35	Note 1
DA-1/2	12.7	874	365	1.154	1.66	1.39	-
DA-2	9.2	950	408	1.207	1.80	1.55	Note 1
DA-3	12.7	872	368	1.154	1.65	1.40	-

Note: 1. Combination performed by standardizing analysis by $\gamma_G = 1.35$
δ_{MAX} = Maximum horizontal wall displacement

CONCLUSIONS

◊ ULS design procedures offer a unifying perspective on geotechnical design that is lacking in current braced excavation design practice in the United States.
◊ Proper application of ULS methods can be particularly challenging by practitioners, especially when nonlinear effects have to be considered.
◊ ULS analysis requires increased computational and evaluation time cost.
◊ In most cases there is little added value compared to traditional service designs.
◊ ULS methods forces designers to contemplate on the uncertainty of soil behavior.
◊ ULS methods for braced excavation may require more detailed geotechnical investigations.