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Mechanically Stabilized Earth Walls Design Using Limit State Criteria

Mayada Abd_Elfattah Mohammed Elhosary, Naseer Mosleh Saleh, Tarek Thabet Abdel-Fattah, Amany Gouda Hassan

Faculty of Engineering At Shoubra , Benha University

ABSTRACT
Limit state design (LSD) has been the basic design method for the Egyptian Code of Concrete Structures Design, and for steel buildings' design code. However, The current issue for the Egyptian's geotechnical design code is still based on the traditional global factor of safety (GFS) design approach. So the geotechnical engineering profession in Egypt is in the process of evaluating LSD for incorporation into the new geotechnical code. The aim of this paper is to calibrate the bearing capacity of mechanically stabilized earth (MSE) walls by using deterministic method.

Key words: limit state design (LSD), Eurocode7, mechanically stabilized earth (MSE) wall, calibration.

Introduction
The present Egyptian geotechnical design code is still depended on the traditional global factor of safety design approach. Introducing LSD in the new geotechnical Egyptian code will provide a harmonized design with other structure design methodologies and geotechnical design in other countries. All design approaches follow the same theoretical backgrounds to evaluate the resistance of the system or to estimate the deformation within the system. Working stress design(WSD) has been used as a basic design approach for many years in civil engineering and recommended for the geotechnical applications in Egypt in 80's as adopted in the first Egyptian Code of Practice for design of foundations. The design philosophy of WSD was shown in the figure 1. The LSD with partial safety factors has been used in Denmark since 1956, and the 1st code of practice was issued there in 1965(D 415 (1965)).

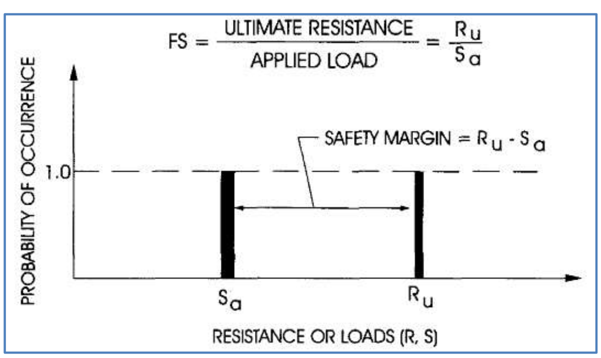

Fig. 1 The definition of WSD (Becker, 1996a)

The historical development of LSD for geotechnical engineering has been check out by many authors (e.g., Meyerhof, 1994; Becker, 1996a; Kulhawy , Phoon 2002 and Tarek, 2011. In 1943,Terzaghi divided the geotechnical problems into stability and elasticity problems. In 1948, Taylor introduced separate factors of safety on the cohesive(c) and frictional components(tan ϕ) of the shear strength parameters of soils to estimate the stability of slopes. For the serviceability limit state design Brinch, 1956 suggested a partial factor of the loads and deformation properties of soils. European countries started developing LSD in the 1960's. The approaches to LSD have developed differently in North America and in Europe. The partial factors are applied directly to the geotechnical strength parameters as shown in figure 2 for the factored strength (European) approach . The resulting factored strength parameters applied in traditional equations/formulas for the direct calculation of factored geotechnical resistance at ULS for design as shown in the following equations.

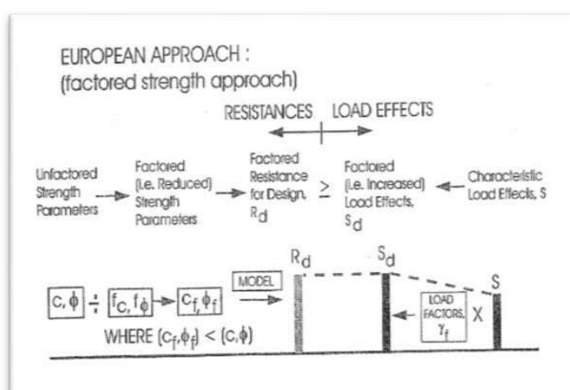

Fig. 2 Factored strength (European) approach (Yasser M .EL-MOSSALLAMY, M.Tawfik, M.A. Zayed(february 2015))

$R_u =$ $f(C_d, \emptyset_d, \ldots\ldots)$……………………………………Eq. 1

$C_d = f_c *$ c…………………………………………………Eq. 2

$\emptyset_d = f_\emptyset *$ $\tan\emptyset$……………………….……….…………......Eq. 3

Where:
C and $\emptyset$ are the characteristic soil shear strength parameters and R_u is the ultimate limit resistance that is a function in design values of cohesion and angle of internal friction, C_d and $\emptyset_d$, respectively. The factors f_c and $f_\emptyset$ are the reduction factors for soil cohesion and soil angle of internal friction, respectively.

Eurocode 7 depends on the limit state design method set out in EN 1990 –Eurocode: Basis of Structural Design. This design method contains checking that the occurrence of all ULS and serviceability limit states (SLS) during the development of Eurocode 7, it became clear that some countries assume a load and material factor approach to the verification of strength while others selected the load and resistance factor approach to accommodate these differences. Eurocode 7 presented three design approaches in strength verification. Table 1 shows which sets of partial factor is used in each design approach, depending on the type of structure being designed according to (EN 1997-1).

Table 1 partial factors value used in each design approaches according to (EN 1997-1)

1.Partial factors on actions(γ_f) or the effects of actions(γ_E)				
Duration	Condition	Symbol	M1	M2
Permanent	Un favorable favorable	γ_G	1.35 1	1 1
Variable	Unfavorable favorable	γ_Q	1.50	1.30
2- partial factors for soil parameters(γ_M)				
Material property		Symbol	M1	M2
Angle of shear resistance $\tan\acute{\emptyset}$ Effective cohesion Un drained shear strength		$\gamma_{\acute{\emptyset}}$ $\gamma_{\acute{c}}$ γ_{CU}	1 1 1	1.25 1.24 1.4
Un confined compressive strength		γ_{qU}	1	1.4
Weight density		γ_γ	1	1

3- partial resistance factor (γ_R)				
Resistance	Symbol	R1	R2	R3
Bearing capacity Sliding resistance	$\gamma_{R,v}$ $\gamma_{R,h}$	1.0 1.0	1.4 1.1	1.0 1.0

Design Method of Mechanically Stabilized Earth (MSE) Walls
MSE wall are defined as walls formed by using several layers of reinforcement in a soil fill as shown in Figure 3. This paper focused on the bearing capacity of MSE walls.

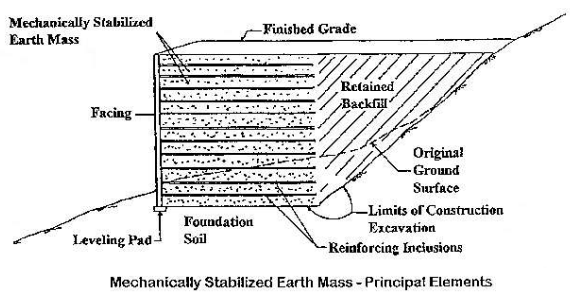

Fig. 3 Schematic cross section of an MSE wall (FHWA-NHI-00-043)

Calibration for ultimate limit state for proposed ECP
Egyptian code may be calibrated using various design approaches such as judgment, fitting with traditional design approaches, reliability theory, or a combination of these approaches. Calibration of the code is the process of determining and specifying numerical values for the partial factors of safety for loads, strength parameters and resistance. These factors can be calibrated using procedure 2 in Euro code which based on a statistical evaluation of experimental data and field observations, which should be executed within the frame work of a probabilistic reliability theory. For both calibration by fitting and reliability theory, the calibration conducted previously by others (Barker, et al., 1991; Paikowsky, et al., 2004)

Calibration by Fitting with WSD
Calibration by fitting can be the most appropriate technique to find out reasonable values of the partial factors. In the calibration-by-fitting technique, the values of partial safety factors of the LSD are checked out to give the same design estimates obtained from WSD. The major advantage of this technique is that it provides a basic link between the new LSD practice and the current practice of WSD. In this type of calibration material partial factor for

cohesion (γ_c) and material partial factor for angle of internal friction (γ_ϕ), are calibrated.

The check for bearing capacity for pure sand:

To calibrate γ_ϕ for drained condition at $C = 0$ pure sand; ULS were derived from a direct-fitting calibrate from WSD for global factor of safety (Fs) =2.5. The values of γ_ϕ were computed using the LSD criterion expressed by the following equation:

$$\gamma_G G + \gamma_Q Q \leq R_d \qquad \text{Eq.4}$$

R_d: is the design resistance.

In WSD, the characteristic resistance can be set as Eq. 5.

$$R_K = FS \sum(G + Q) \qquad \text{Eq.5}$$

$$R_K = X\, R_d \qquad \text{Eq.6}$$

$$R_d = \frac{FS \sum(G + Q)}{X} \qquad \text{Eq.7}$$

$$X = \frac{FS\sum(G+Q)}{(\gamma_G G+\gamma_Q Q)} = \frac{R_K}{R_d} \qquad \text{Eq.8}$$

Bearing capacity equation from Annex D in EC7 for strip footing on pure sand soil:

$$R_K / A' = q' N_{q,K} b_q S_q i_q + 0.50\, \gamma' B' N_{\gamma,K} b_\gamma S_\gamma i_\gamma \qquad \text{Eq.9}$$

$$R_d / A' = q' N_{q,d} b_q S_q i_q + 0.50\, \gamma' B' N_{\gamma,d} b_\gamma S_\gamma i_\gamma \qquad \text{Eq.10}$$

q' : The design effective overburden pressure at the level of the foundation base

N_q, N_γ : The bearing capacity factors

b_q, b_γ Foundation base inclination factors (assumea non − inclined foundation then $b_q = b_\gamma = 1$ for non − inclined foundation)

S_q, S_γ Foundation shape factors (for strip foundation $s_q = s_\gamma = 1$)

i_q, i_γ: Load inclination factors caused by a horizontal load H (assume vertical load $i_q = i_\gamma = 1$)

Take the term of $\gamma' B = G$

$$\frac{R_K}{A'} = N_{q,K}\left(\frac{q'}{\gamma' B'} + \tan\emptyset\right) - \tan\emptyset \qquad \text{Eq. 11}$$

Assume the value of $\frac{q'}{\gamma' B'} = 1$

$$\frac{R_K}{A'} = N_{q,K}(1 + \tan\emptyset_k) - \tan\emptyset_k \qquad \text{Eq. 12}$$

$$\frac{R_d}{A'} = N_{q,d}(1 + \tan\emptyset_d) - \tan\emptyset_d \qquad \text{Eq. 13}$$

By substituting in equation 8

$$X = \frac{R_X}{R_d} = \frac{(Nq(1+\tan\emptyset)-\tan\emptyset)\text{charactaristic}}{(Nq(1+\tan\emptyset)-\tan\emptyset)\text{design}} \qquad \text{Eq. 14}$$

Employing partial factors set in table 1 for loading for design approach 1 and equation 14 in excel can obtaining the value of $\gamma_{\emptyset(avg,bearing)}$ using for proposed Egyptian code . Table 4 shows the results of calibration of bearing in approach 1 combination 1 and 2. Note that the calibration for bearing in design approach EC7(DA3) equal the value for design approach 1 combination 1 EC7(DA1-1), because the two approaches have the same partial factors for action .

Table 2 the results of calibration of bearing check in approach 1

$\gamma_{\phi(avg,bearing)}$ For design approach 1, combination1		$\gamma_{\phi(avg,bearing)}$ For design approach 1, combination2	
ϕ	$\gamma_{\phi avgbearing}$	ϕ	$\gamma_{\phi avgbearing}$
25	1.247	25	1.388
30	1.192	30	1.266
35	1.160	35	1.217

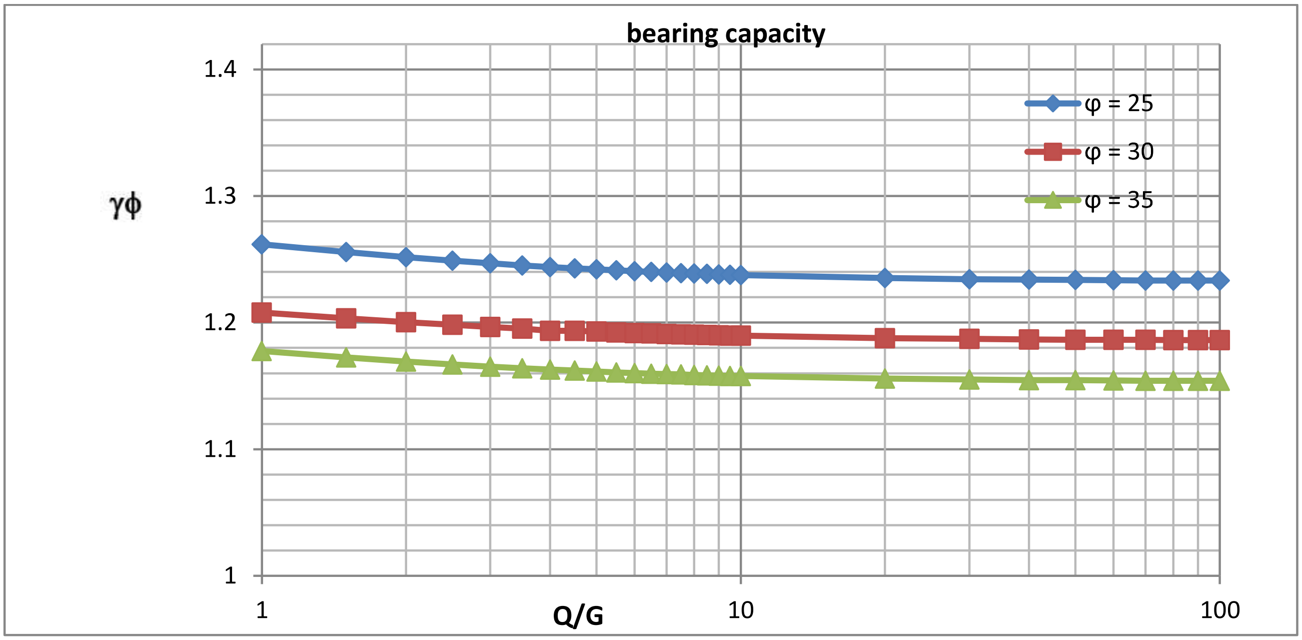

Fig. 4 Typical results for calibration with WSD for bearing capacity EC7 (DA1-1)

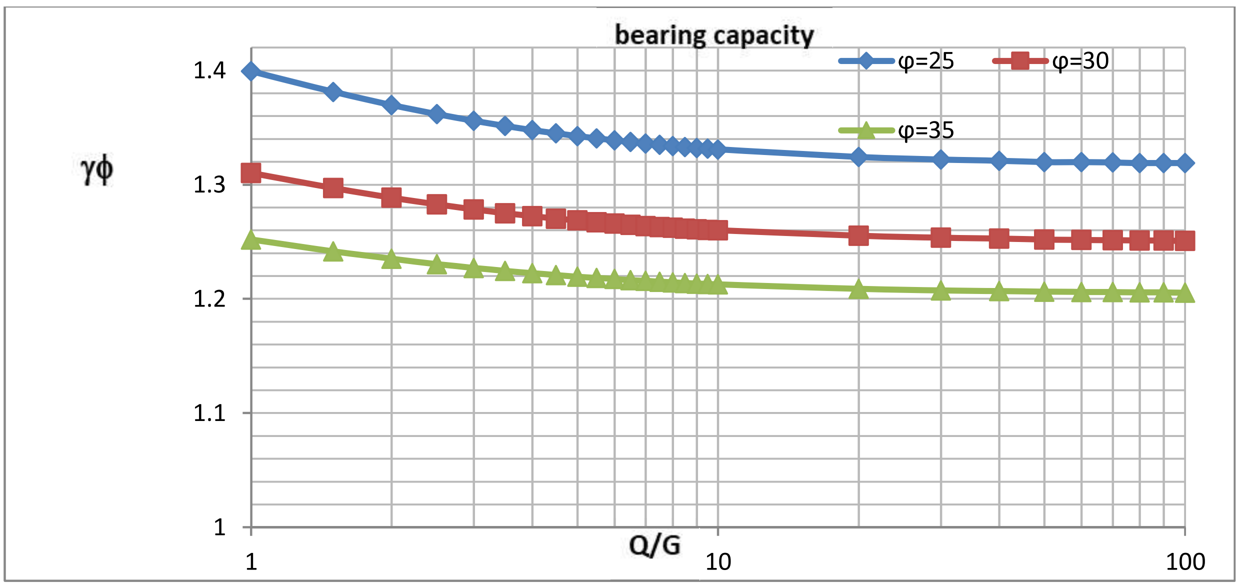

Fig. 5 Results for calibration with WSD for bearing capacity EC7 (DA1-2)

The Comparison between the current Egyptian code, proposed Egyptian code and Euro code bearing capacity check.

Tarek, (2011) pointed that for any combination of partial factor values, one could estimate the corresponding global safety factor as follows:

$$GSF = \frac{design\ load}{characteristic\ load} * \frac{characteristic\ resistance}{design\ resistance}$$

GSF = Total load factor ∗ Total resistance factor

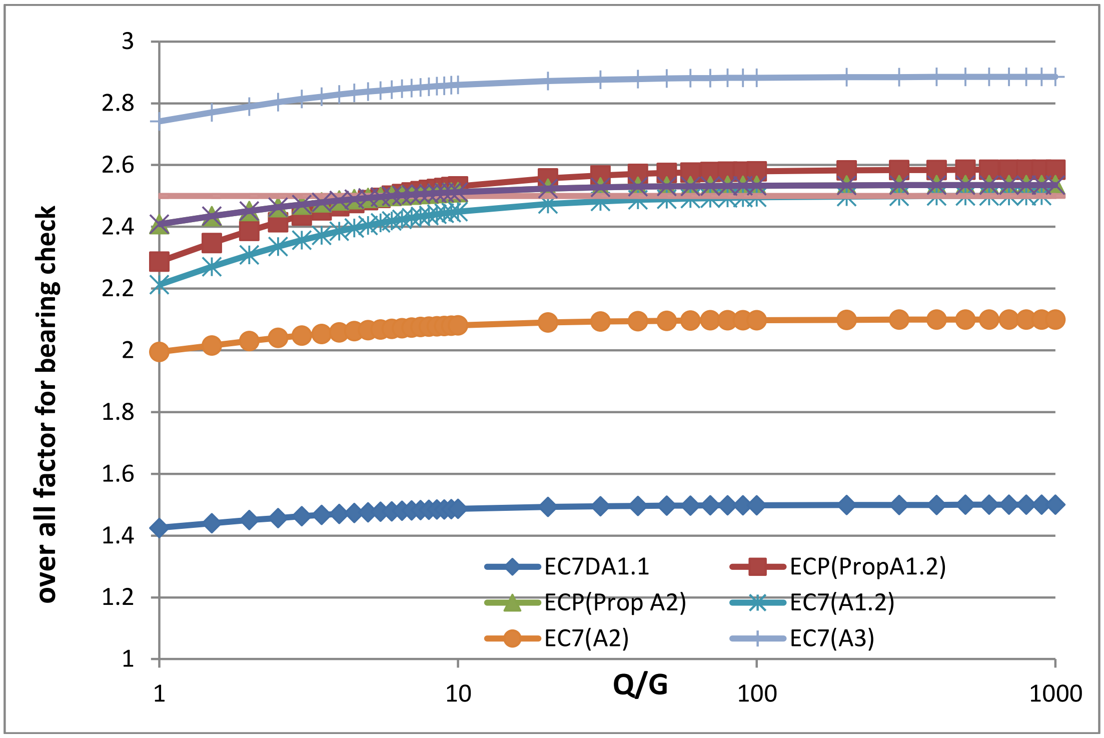

Fig. 6 The Comparison between the current Egyptian code, proposed Egyptian code and Euro code for bearing

Figures 6 cleared that:

- The current Egyptian code offer constant factor of safety for bearing regardless to the value of (Q/G) ratio.
- The suggesed Proposed Egyptian code for MSE walls take the same trend of Eurocode as the overall factor of safety increase with the increasing ratio of (Q/G) till a value of (Q/G =100) then the value of overall factor of safety become constant with the increase of Q/G value.
- The overall factor of safety for design approach(DA1.2) for bearing capacity for MSE walls is the most affinity of Egyptian code because the major partail factors are applied to strength properties.
- The over all factor of safety for design approach3 (DA3) for bearing capacity of MSE walls is the most difference of Egyptian code as the major partail factors are applied to action and material properties.

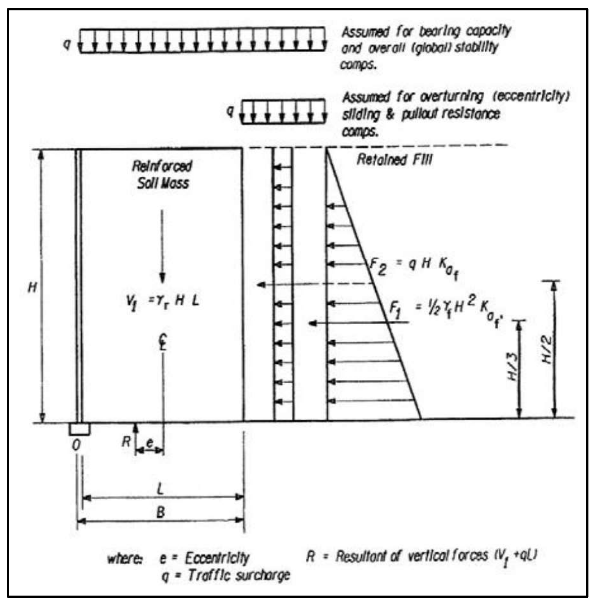

Fig. 7Explanatory form for MSE wall worked example

Manual Analysis OF MSE Walls

The author studied the bearing capacity check for the MSE wall shown in figure 7 for an worked example. The results of the worked example were compared with the Egyptian code, Euro code and proposed Egyptian code.

Table 3The properties for an MSE wall

Wall height (H)	2m
The reinforcing fill length (L)	3m
Soil unit weight (γ_s)	19. 63 kN/m^3
Traffic surcharge (q)	11.97 kN/m^2
The retained fill angle	30°
The friction angle	20°
Vertical spacing of strip SV	0.856m

Table 4 the bearing capacity check results for the worked example by ECP, Eurocode7 and proposed Egyptian code.

F.O.S	EPC	A1.1	A1.2	A2	A3	A1.1 Proposed code	A1.2 Proposed code	A2 Proposed code
F.O.S for bearing capacity check	9.27	7.55	3.14	5.6	3.65	4.37	2.43	2.248

LIMIT EQUILIBRIUM NUMERICAL ANALYSIS PROGRAMS

The overall factors of safety for the two manual examples of MSE wall was analyzed using limit equilibrium analysis (slide6). The results of overall factors of safety for MSE wall in the worked example is shown in table 5 for ECP code, Euro code 7and the proposed Egyptian code.

In Slide 6.0 probabilistic analysis, you may assign statistical distributions to almost any input parameters, including material properties, support properties, loads, and water table location. The probability of failure/reliability index is calculated, and provides an objective measure of the risk of failure associated with a slope design as shown in figure 8. Sensitivity analysis allows you to determine the effect of individual variables on the safety factor of the slope.

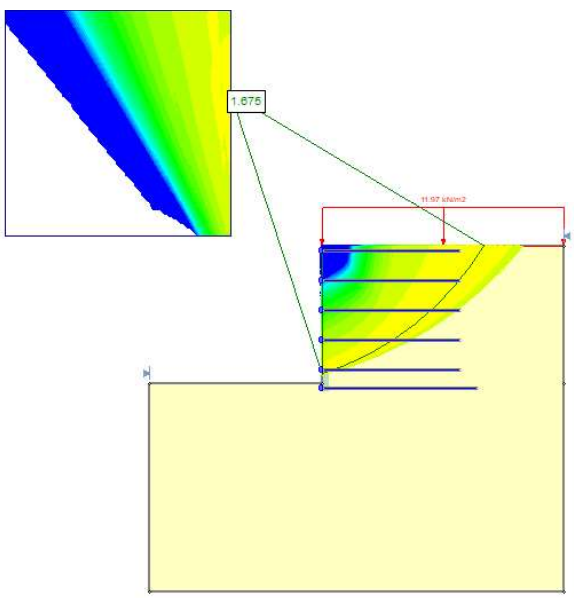

Fig. 8 Critical failure surfaces and the factor of safety for slide 6

Table 5 Results of overall factor of safety for solving the MSE wall (worked example) using Slide 6

ECP	DA 1.1	DA 1.2	DA 2	DA 3	Proposed DA1.1	Proposed DA1.2	Proposed DA2
2.83	2.3	2.04	2.1	2.06	2.2	2.13	1.87

CONCLUSIONS

- All current versions of the structural Egyptian design codes are based on LSD but Geotechnical design code still based on the traditional global safety factora agreements between the design methodologies are an essential requirement for the engineering practice.
- The determination of the characteristic value of the geotechnical parameters is more important, it considered the concept of partial safety factors for geotechnical verifications
- The current Egyptian code offer constant factor of safety applied to ground strengths for bearing capacity regardless to the value of (Q/G) ratio it make it less accurate with other codes.
- The sugessed Proposed Egyptian code for MSE walls offer the overall factor of safety increase with the increasing ratio of (Q/G) for bearing capacity check as Euro code finally it constant.
- The over all factor of safety for design approach1 combination 2 (DA1.2) for bearing capacity check for MSE walls is the most affinity of Egyptian code than combination 1,because the major partial factors are applied to ground strengths, while non-variable actions and resistances are left un factored.
- The over all factor of safety of bearing capacity for design approach3 (DA3) of MSE walls is the most difference of Egyptian code,because the major partail factors are applied to action and material properties.
- The results values for the sugessed proposed Egyptian code are average value between the ECP and Eurocode7 for for bearing capacity check

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