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A Comparative Analysis between Eurocode 7 and Code of former Yugoslavia for Retaining Wall Design using Reliability Theory

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Abstract— **The design and the analysis of retaining walls are different in different countries depending on the applied rulebooks for geotechnical design. Eurocode7 is the Rulebook which pays a lot of attention to durability, safety and usability of structures and is based on five limit states. The rulebook for the design of geotechnical structures (Official Gazette 1990) which is based on the old regulations of the former Yugoslavia is still in use in the design of geotechnical constructions in B&H. With this paper it is made a comparative analysis of the reliability of the calculation of reinforced –concrete retaining wall according to the EC7 and the old regulations. From the obtained results of reliability of design of capacity and stability, it is clear that EC7 gives a more extensive and more reliable design and it is necessary in B&H to adopt one of the project approaches that it recommends.**

Keywords— **limit states, regulations, analysis of reliability, capacity, stability, project approach.**

I. Introduction

Retaining walls are structures whose fracture can occur in several ways. Since their base load is an influence of the soil, for a well-designed retaining wall it is necessary a geotechnical study. The basic purpose of these structures is to provide stability of roads, buildings, recovery of landslides and others. Depending on the material used, today there are several types of walls, from prefabricated, massive which are usually concrete or stone to classic reinforced concrete such as cantilever, walls with buttresses, anchors and others. Today reinforced concrete walls are widely used in civil engineering due to the high practicality, material consumption and large capacity.

Every country prescribes rulebooks which design these structures. Rulebook of former Yugoslavia (Official Gazette 1990) [1] is still in force in many countries such as Serbia, Macedonia and one part of Bosnia and Herzegovina. Unlike these countries, countries such as Croatia, Slovenia have already introduced some provisions of the Eurocode7 [2] in their standard designs of these structures. Eurocode7 is the Rulebook which is based on the designs of geotechnical structures according to limit states. According to EC 7 we distinguish five limit states, while for the limit states GEO and STR and three project approaches. These project approaches vary according to the used partial safety factors and it is up to every country to choose which project approach it wants to adopt. Unlike EC 7, the Rulebook of the former Yugoslavia the principle of safety factor reduces to the concept of allowable stresses that contain security of fracture.

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In this paper is presented a comparative analysis of the reliability of the design of the reinforced concrete retaining wall according to EC7 and its project approaches and the Rulebook of the former Yugoslavia. Reliability analysis was performed with the help of the software package "Vap" created at the university ETH in Zürich. This software allows us that after we define all limit functions, we enter all the random variables with their distributions and characteristics as the mean and standard deviations and thus determines the probability of fracture for each limit function.

II. Reliability Analysis

In the current deterministic design which proved to be quite accurate is ignored the uncertainty of random variables that may also affect the reduction of reliability. For this reason in this paper is presented a probabilistic approach to the design of these structures which clearly shows how certain variables may affect the possibility of fracture. The methods used for calculating the probability of fracture were FORM method, advanced FORM method (Hasofer Lind) method [3].

Under the term reliability of the structure is meant the ability of the structure that in the appropriate period works without fracture and to provide security and usability. Reliability can be expressed in the function of the probability of the fracture i.e [3] :

$$r = 1 - P_f \tag{1}$$

Where r is the reliability and P_f is the probability of fracture. Fracture occurs in those cases where the load is greater than the resistance of structure or expressed through a joint density distribution follows that the probability of fracture is equal to [4]:

$$P_f = P\left[G(R,S) \le 0\right] = P\left[R - S \le 0\right] = P\left[Z \le 0\right] = \int_D f_{RS}(R,S)\,dR\,dS \tag{2}$$

Where the G(R,S) is a limit function, f_{RS} is a joint density distribution of load and resistance (R is resistance and S is stress-load). Mean and standard deviation are marked as μ and σ.

Since it is sometimes very difficult to define a common density distribution or it is difficult to make a integration, today there are various simplified methods for calculating the probability of fracture, including the Form method, Hasofer-Lind method, SORM method and Monte Carlo method.

A. Form Method(First Order Reliability Method)

FORM method or the method of the another moment of the first order determines the probability of fracture by knowing the first and second moment of random variables that define the resistance and load and by defining the limit function which is approximated by the first Taylor's order.

$$P_f = P[Z \le 0] = P[(R-S) \le 0] \tag{3}$$

$$\mu_z = \mu_R - \mu_S, \sigma_z^2 = \sigma_R^2 + \sigma_S^2 \tag{4}$$

Previous formulations are valid under the assumption that resistance and load follow a Normal distribution.

$$P_f = \Phi\left(\frac{Z-\mu_z}{\sigma_Z}\right)$$

$$P_f = \Phi\left(-\frac{\mu_z}{\sigma_z}\right) \tag{5}$$

In the previous formulations μ and σ denote the mean value, deviation of random variables R,S and Z while the reference Φ denotes the cumulative standardized normal distribution.

The reliability index β presents a ratio between the mean value and standard deviation of the common standardized function Z. However, this method has its advantages and disadvantages. The main advantage of this method is that it avoids the common integration density distribution and a drawback is that ti is sometimes very difficult for all the random variables to be reduced to a random variable that follows a normal distribution. In some cases it is not suitable for a limit function to be approximated only with the first Taylor's order i.e. higher members of this can not be ignored. For this reason Hasofer and Lind have modified this method and they get an advanced Hasofer-Lind method.

B. Hasofer and Lind Method (Modified Form Method)

Hasofer and Lind have modified Form method so that all the random variables are converted into standardized normal variables with mean value of 0 and standard deviation 1. The essence of this method is that all the random variables are transformed into standardized independent random variables of the normal distribution and that in this new coordinate system we find the shortest distance from the origin point to the defined limit function.

$$R' = \frac{R-\mu_R}{\sigma_R}, S' = \frac{S-\mu_S}{\sigma_S} \tag{6}$$

$$Z = R - S = R'\sigma_R + \mu_R - S'\sigma_S - \mu_S = 0 \tag{7}$$

$$\beta_{HL} = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}}, P_f = \Phi(-\beta_{HL}) \tag{8}$$

Where R' and S' are modified values of R and S with the mean deviation 1 and mean value 0. A point that is least away from the origin point to the limit function is called "design point" and the shortest distance is equal to the value of the reliability index β. In many cases the limit function is not linear and the procedure of determining " design point" i.e. the shortest distance between the limit function and the origin point is determined by an iterative manner in the following way:

$$\beta_{HL} = -\frac{\sum_{i=1}^{n} x'_{di}\left(\frac{\partial G}{\partial x'_{di}}\right)}{\sqrt{\sum_{i=1}^{n}\left(\frac{\partial G}{\partial x'_{di}}\right)^2}} \tag{9}$$

III. Comparation between EC 7 and former Jugoslavian Code

A. Eurocode 7

1) Introduction

The initial prestandard EC7 which was created in 1994 based on the concept of three limit state of load A,B and C which corresponded to the three groups of partial safety factors for actions, material and resistance. Ten years later, this prestandard has been modified and EC 7 (EN 1997-1:2004.) introduces a number of changes. Eurocode 7 is composed of two parts: EN 1997 -1 Geotechnical design – Part 1: General rules and EN 1997-2 Geotechnical design – Part 2: Research and testing of soil [5]. These standards EC 7 many countries in Europe are trying to introduce into their national standards and at the same time adapting it to its already existing standards. According to EC 7 from 2004, we distinguish five limit states and those are [2]:

- EQU – loss of balance of the structure or the soil considered as a rigid body
- STR-fracture or unacceptably large deformation of the structure or its element
- GEO – fracture or unacceptably large deformation of soil
- UPL – loss of balance of the structure or soil due to the effects of the disputed pressure or other vertical action of the tension force
- HYD- hydraulic fracture due to the excessive hydraulic gradient

For the calculation of retaining walls it will be considered limit states GEO and STR for which it is recommended three design approaches. Project approaches differ depending on the used partial safety factors for loads, materials and resistance. Depending on the project approaches EC 7 suggests to the other countries to adopt to his standard whichever they want from the project approaches.

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Following Table 1 shows the partial safety factors which recommends EC7 with project approaches for the design of the retaining walls.

TABLE I. SAFETY FACTORS FOR DIFFERENT DESIGN APPROACHS ACCORDING TO EC7

Design Approach		Safety factors							
		γ_G	γ_Q	γ_φ	γ_c	γ_γ	γ_{RV}	γ_{RH}	γ_{RE}
DA1	C1	1.35	1.5	1	1	1	1	1	1
	C2	1	1.3	1.25	1.25	1	1	1	1
DA2		1.35	1.5	1	1	1	1.4	1.1	1.4
DA3		1.35	1.5	1.25	1.25	1	1	1	1

2) Design functions

Basic limit functions of stability for sliding, overturning, and bearing capacity have been shown in the following formulations. It should be noted that these limit functions are defined for design values of load and resistance taking into account partial safety factors according to table 1. This definition of limit functions allows us to compare the reliability of the design of different project approaches for limit states GEO and STR and reliability of calculation of retaining walls according to the Rulebook of former Yugoslavia.

$$G_S = \frac{\mu \sum \gamma_i V_i}{\gamma_R} - \sum \gamma_i H_i \qquad (10)$$

Where μ is the coefficient of friction of the foundation and the soil, $\sum \gamma_i \cdot V_i$ is the sum of vertical forces multiplied by the appropriate partial safety factors which depend on the project approach , γ_R , partial resistance factor for sliding and $\sum \gamma_i \cdot H_i$ is the sum of horizontal forces multiplied by the appropriate partial safety factor.

$$G_O = \frac{\sum \gamma_i M_S}{\gamma_R} - \sum \gamma_i M_P \qquad (11)$$

In the previous equation $\sum \gamma_i \cdot M_S$ is equal to the sum of the moments of the forces that oppose to overturning with the forces that are multiplied by the appropriate safety factors of table 1, partial resistance factor to overturning and $\sum \gamma_i \cdot M_P$ is the sum of moments of factored forces acting on the overturning of the wall.

$$G_{BC} = \frac{(c \cdot N_c \cdot b_c \cdot s_c \cdot i_c + p_o \cdot N_q \cdot b_q \cdot s_q \cdot i_q}{\gamma_R} + \frac{0.5 \cdot b_1 \cdot \gamma_s \cdot N_\gamma \cdot b_\gamma \cdot s_\gamma \cdot i_\gamma)}{\gamma_R} - \left(\frac{\sum \gamma_i N_i}{b_{t1}} \pm \frac{6 \sum \gamma_i M_i}{b_{t1}^2}\right) \qquad (12)$$

The equation of the limit state in which N_c, N_q, N_γ are capacity factors, i_c, i_q, i_γ are factors of incline of the load, b_c, b_q, b_γ are factors of incline of the basic connector s_c, s_q, s_γ are shape factors, b_1 is reduced width of the basic rate for the centric load and $\sum \gamma_i \cdot N$ i $\cdot \sum \gamma_i \cdot M$ are the sum of the normal forces and moments around the center of the basic connecter.

Limit function for the pure bending (bending moment) is defined by the following equation taking into account that the impacts of the normal forces are neglected to increase the bending moment according to [6] [7] [8].

$$G_{BM} = A_a \cdot f_y \cdot \frac{\left(h - 0.5 \cdot \frac{A_a \cdot f_y}{0.85 \cdot b \cdot f_c}\right)}{\gamma_R} - \left(\sum \gamma_G M_G + \sum \gamma_P M_P\right) \qquad (13)$$

The preceding equation defines the limit state of bearing of the retaining wall for bending where A_a is surface reinforcement, f_y, f_c are yield stress of steel and characteristic strength of concrete and $\sum \gamma_G \cdot M_G$ i $\sum \gamma_P \cdot M_P$. are influences of the moment that is causing bending due to permanent and variable loads.

B. *Former Jugoslavian Code for geotechnic*

The Rulebook on technical norms for the foundation of constructions (Official Gazette 15/1990) was written back in 1965 and it has been applying since 1974 and in 1990 it was partially amended. This Rulebook is still used in some countries of former Yugoslavia. The concept of safety factor in this case comes down to the concept of allowable stresses that contains safety of fracture [1]. Basic limit functions according to this Rulebook are shown in the following formulations. The limit function of stability for sliding is

$$G_S = \frac{tg\phi \cdot \sum V_i + c \cdot b_{t1}}{\sum H_i} - k_s \qquad (14)$$

Where tgφ, c, b_{t1}, k_s=1.5, ΣV_i and ΣH_i in that order are friction coefficient of the foundation with the ground, cohesion, the width of foundation, safety coefficient on sliding according to the Rulebook and the sum of vertical and the sum of horizontal forces of the retaining wall.

$$G_O = \frac{\sum M_S}{\sum M_P} - k_o \qquad (15)$$

In the equation for overturning $\sum M_S$ i $\sum M_P$ represent the sum of moments that oppose and to the sum of moments that cause overturning, while k_o equal to 1.5 is a safety factor on overturning.

$$G_{BC} = (0.5 \cdot \gamma_S \cdot b_1 \cdot N_{\gamma 2} \cdot s_\gamma \cdot i_{\gamma 2} + (c_m + p_o \cdot tg\phi_m) \cdot N_{c2} \cdot s_c \cdot i_{c2} \cdot d_c + p_o) - \left(\frac{\sum N_i}{b_{t1}} \pm \frac{6 \sum M_i}{b_{t1}^2}\right) \qquad (16)$$

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All unknown will be defined in the Table 2. In (16) $i_{c2}, i_{\gamma 2}$ are factors of incline of the load according to [1] , d_c is factor of depth, s_c, s_γ are shape factors equal to [1] and [2]. Design function for pure bending is [9]:

$$G_{BM} = A_a \cdot f_y \cdot \left(h - 0.5 \cdot \frac{A_a \cdot f_y}{0.683 \cdot b \cdot f_c} \right) - (\Sigma \gamma_G M_G + \Sigma \gamma_P M_P) \quad (17)$$

Where γ_G and γ_P are partial safety factor according to [9] and are equal 1.6 and 1.8. All variables in Table 2 are used according to [10], [11] and [12].

TABLE II. DESCRIPTION OF VARIBALES

Variable	Description of variable	Distribution	Mean and standard deviation (μ, σ)
A_a (m^2)	reinforcement surface	Normal	0.0021; 0.0000201
b (m)	width of fundation of 1m	Normal	1; 0.01
b_1 (m)	reduced width of fondation	Normal	4.45; 0.0445
b_{t1} (m)	width of fundation	Normal	5; 0.05
b_{t2} (m)	width of the ground behind the foundation	Normal	2.85; 0.0285
b_{z1} (m)	width on the top of retaining wall	Normal	0.3;0.003
b_{z2} (m)	width on the bottom of retainig wall	Normal	1; 0.01
c (kPa)	cohesion	Normal	5; 1
c_1 (kPa)	cohesion reduced by partial safety factor for resistance [2]	Normal	4; 0.8
c_m (kPa)	cohesion reduced according to [1]	Noraml	2; 0.4
f_c (kN/m^2)	concrete strenght	Log-Normal	30000; 510
f_y (kN/m^2)	steel strenght	Log-Normal	400000; 24000
h (m)	width of wall reduced with protective layer of concrete	Normal	0.95; 0.0095
h_t (m)	thickness of foundation	Normal	0.5; 0.005
h_z (m)	height of retaining wall	Normal	7; 0.007
φ (°)	angle of friction	Normal	28; 2.8
φ_1 (°)	angle of friction reduced by partial safety factor for resistance [2]	Normal	23; 2.3
ϕ_m (°)	angle of friction reduced according to [1]	Normal	19.52; 1.952
N_c	bearing capacity factor [2]	Normal	25.69; 0.2569
N_{c1}	bearing capacity factor [2]	Normal	18.09; 0.1809
N_{c2}	bearing capacity factor [1]	Normal	14.36; 0.1436
N_γ	bearing capacity factor [2]	Normal	14.53; 0.1453
$N_{\gamma 1}$	bearing capacity factor [2]	Normal	6.55, 0.0655
$N_{\gamma 2}$	bearnig capacity factor [1]	Normal	3.24; 0.0324
N_q	bearing capacity factor [2]	Normal	14.66; 0.1466
N_{q1}	bearing capacity factor [2]	Normal	8.69; 0.0869
p(kN/m^2)	uniformly distributed variable load	Log-Normal	15; 0.15
p_0(kN/m^2)	effective stress at the level of the bottom of the fundation	Normal	15.2; 0.152
γ_c(kN/m^2)	unit weight of concrete	Log-Normal	25; 1
γ_s(kN/m^2)	unit weight of soil	Log-Normal	19; 1.14

The retaining wall design is done according to following Fig.1.

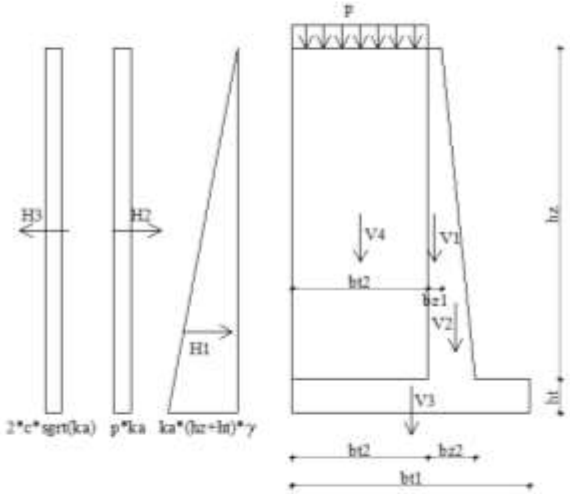

Figure 1. Retaining wall

IV. Reliability results

Reliability analysis of the design situations (design approaches) of the retaining wall according to EC7 for the limit states GEO/STR and the Rulebook on technical standards for the foundation of constructions (Official Gazette 15/1990) is shown in the following Table 3. These results were based on the assumption that there is no correlation between the individual members in the limit functions.

TABLE III. RELIABILITY INDEXES FOR DIFFRENT DESIGN EQUATIONS

Reliability indexes β			Probability of failure
Sliding	EC7 DA1 C1	2.78	$2.74*10^{-3}$
	EC7 DA1 C2	-1.27	$8.97*10^{-1}$
	EC7 DA2	2.19	$1.44*10^{-2}$
	EC7 DA3	-1.65	$9.50*10^{-1}$
	CODE (B&H)	0.418	$3.38*10^{-1}$
Overturning	EC7 DA1 C1	16	$8.09*10^{-58}$
	EC7 DA1 C2	11.8	$2.83*10^{-32}$
	EC7 DA2	10.2	$6.15*10^{-25}$
	EC7 DA3	11.7	$4.34*10^{-32}$
	CODE (B&H)	10.4	$8.74*10^{-26}$
Bearnig capacity	EC7 DA1 C1	20	$2.75*10^{-89}$
	EC7 DA1 C2	8.61	$3.65*10^{-18}$
	EC7 DA2	14	$7.79*10^{-45}$
	EC7 DA3	5.84	$2.61*10^{-9}$
	CODE (B&H)	9.91	$1.88*10^{-23}$
Bending moment	EC7 DA1 C1	1.47	$7.05*10^{-2}$
	EC7 DA1 C2	1.61	$5.41*10^{-2}$
	EC7 DA2	1.47	$7.05*10^{-2}$
	EC7 DA3	-0.102	$5.41*10^{-1}$
	CODE (B&H)	1.2	$1.15*10^{-1}$

The results of the reliability index in the table above show how much reliable is some design situation, given that we have already included in all limit functions their partial safety coefficients. From this it is clear that every reliability index with positive value is favorable while a negative value shows that the retaining wall does not satisfy the given calculation situation. The most critical reliability of the calculation situation is exactly the sliding of the project approach 1 combination 2 and project approach 3 which tells us that these calculation situations are most demanding. Small reliability index is obtained also according to the Rulebook of B&H. Also, the reliability index of bending capacity for the project approach 3 has a negative value. Because each country can adopt any of the project approaches suggested by the EC7 it must be borne in mind that there are large deviations of the obtained results according to various design approaches. The smallest reliability index gives exactly project approach 3 of Eurocode7 which is an indicator that the design of the retaining wall according to this approach will provide the safest project structure. In the following pictures Fig.2, Fig. 3 and Fig.4 is shown how certain factors such as cohesion, the width of the foundation and the external load affects on the increase of the reliability of the corresponding design situation.

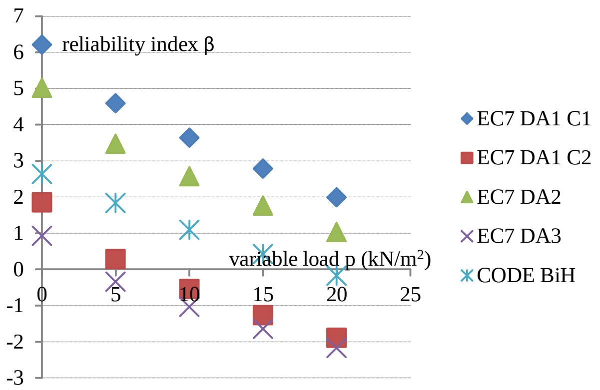

Figure 2. Reliability indexes of sliding in function of uniformly distributed variable loads

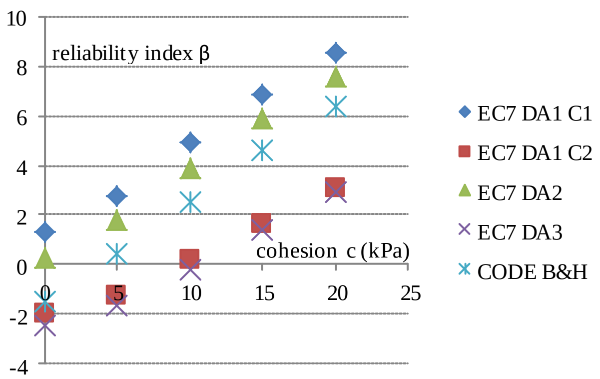

Figure 3. Reliability indexes of sliding in function of cohesion

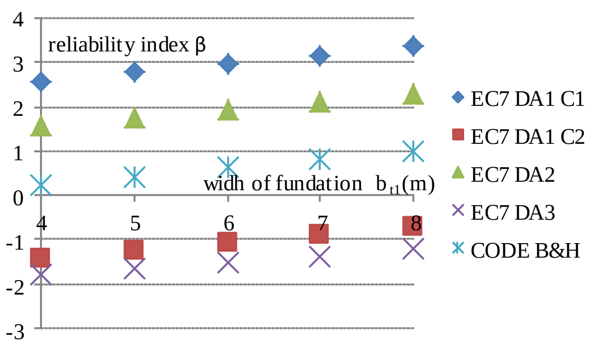

Figure 4. Reliability indexes of sliding in function of with of fundation

V. Conclusion

Based on the data of reliability indices in Table 3 it is clear that the design approach 3 is the most critical case that EC 7 recommends and also using such situation the safest supporting structure is obtained. However, it should be noted that in some cases it is not justified to use this design approach in order to avoid oversized construction. Based on technical standards for the foundation of buildings (Official Gazette 15/1990), which is still in use in B & H reliability indices of this design approach are to be found between design approaches of the EC7. This data tells us that the design under this rule book gives quite reliable construction but it should be modified and take into account all EC7 recommendations. EC7 besides partial safety factor for loads includes the partial safety factor for material and resistance, while the former rule book is based more on allowable stresses that involves unique safety factors.

Fig. 2, Fig. 3, Fig. 4 clearly show how variably uniformly distributed load, cohesion and width of the foundation influence on the sliding. Increasing the external load for only 5 kN/m^2 reliability indices are reduced on average of 30%, while increasing the cohesion for 5 kPa reliability index is increased by around 45%. By increasing the width of the foundations this reliability index rises only an average of 10%, and thus it is clear that cohesion has the greatest impact on the sliding while the width of the foundations least.

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