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INFLUENCE OF THE SEISMIC ACTION ON THE STABILITY OF RETAINING CANTILEVER WALLS AND COMPARISON BETWEEN EX-YU REGULATIONS AND EUROCODES

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Abstract

Retaining structures in R. of North Macedonia until recently were only designed according to the concept of global safety factors, with the conventional methods of limit equilibrium. This method was widely used in ex-YU countries until Eurocodes have been published as regulations in the country formal legislation, where there are prescribed different design approaches, with specific partial coefficients for actions, materials, and/or resistances. For the seismic analysis of the walls, “Rulebook on technical norms for design and calculation of engineering structures in seismically active areas” (1987) was used. Currently, the use of both regulations is allowed, but after the expiration of this temporary period, Eurocodes will be the only standards for the design of buildings in our country. In this paper a comparison between the mentioned methods and regulations is made, in terms of the different approaches for the stability verification, as well as the required minimum width of the foundation for satisfying the stability criteria for 5 different heights of the walls, i.e. 3m, 4.5m, 6.0m, 7.5m and 9.0m. As our region is seismically active, special consideration is given to the parameters in seismic analysis procedure. It is shown that in order to satisfy the stability criteria, there is a need to increase the dimensions of the walls in relation to the dimensions obtained by the static analysis. The obtained results show significant differences between the regulations, especially when the seismic action is taken into account.

Keywords:Retaining, Structures, Cantilever, Wall, Eurocode

1. Introduction

With the acceptance of Eurocodes in R. of North Macedonia, as regulation codes for designing the structures, the need for their detailed elaboration has arisen, as well as understanding the differences and similarities with the previous practice and regulation (in the following text – “MKS”).

Eurocodes are divided in 10 parts, depending on the area they relate to. The part that covers the retaining structures is Eurocode 7 - Part 1 (EN 1997:1), entitled "Geotechnical design - Part 1: General rules" [2]. Our country is a seismically active area, so retaining structures are also subject to aseismic design, which is specifically covered in Eurocode 8 entitled "Design of structures for seismic resistance - part 5 (EN 1998:5): Foundations, retaining structures and geotechnical aspects" [3].

As part of this paper, several analyses of a classic cantilever reinforced concrete wall (Fig. 1) with 5 different heights of 3m, 4.5m, 6m, 7.5m and 9m (above ground level), with assumed geomechanical parameters for the backfill and for the subsoil, shown in Table 1, have been performed. The analyses are done with the application of the current regulations - MKS and with the Eurocodes, considering that the approach to control the stability of retaining walls is completely different. The theoretical reviews of the regulations explain the calculation procedures and emphasize the biggest differences between the

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Macedonian regulations, that is, the previous practice of designing retaining walls in relation to the new regulations - the Eurocodes. Also, special attention is given on the effect of seismic action on the retaining structures, in order to perceive and emphasize the differences in the required dimensions to satisfy the stability conditions. After the performed analyses, significantly large differences were obtained according to the different regulations used, as well as a significant increase in dimensions after the performed seismic pseudo-static analyses.

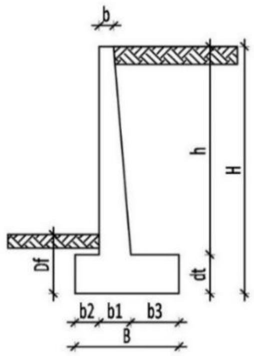

Fig. 1. Schematic view of the analysed wall

Table 1: Assumed geomechanical parameters for the backfill and subsoil

Soil type	γ [kN/m3]	φ [˚]	c [kPa]
Gravel	21	30	0

2. Analysis of retaining walls according to MKS and Eurocode 7 – static conditions

Retaining walls are first analysed according to ex-YU, i.e. macedonian regulations - MKS, and then according to Eurocode - EC 7-1 [2]. The analyses are done using the software GEO-5, Cantilever wall module [4]. In order to make a relevant comparison, the walls are dimensioned with the minimum required dimensions that satisfy all conditions for stability, i.e. with maximum utilization of the section. Since the analysed wall is a cantilever, reinforced concrete section, stability is ensured through the deformation capacity of the wall, while the dimension that contributes the most to stability is the width of the foundation, so only this dimension was analyzed, while all other dimensions are adopted according to the recommendations for preliminary dimensions in the literature, as a ratio of the height of the wall, and are not changed for the different analyses. Also the total height is increased for some minimum embedment. The stability of the walls is controlled for the conditions against overturning, sliding, bearing capacity of the ground, as well as the eccentricity of the resultant force, which is limited to the middle third of the foundation, i.e. to B/6, in order not to cause tension in the foundation under static loads.

According to MKS, the analysis is based on the method with safety coefficients, i.e. the calculation is done by dividing the resistance by the actions on the structure. The ratio between them should be greater than a certain prescribed safety coefficient, which for static conditions is with a value of Fs ≥ 1.50, and for seismic conditions Fs ≥ 1.10. The bearing capacity of the soil, i.e. the permissible bearing capacity is generally obtained by reduction with a safety coefficient of Fs=3.0 in relation to the limit bearing capacity, which is calculated mostly according to the Terzaghi method for the specific type of foundation for adopted geomechanical parameters. However, the permissible stress is also adopted for realistically expected value in practice. The force from active earth pressure is calculated according to the Rankine or Coulomb method.

According to Eurocode 7-1, the analysis is based on the limit state method, where certain partial coefficients are prescribed for the actions (A), for the geomechanical parameters (M) and for the resistance of the structure (R). In EC 7-1, there are 3 possible design approaches for the design of geotechnical structures, labeled as DA-1 (C1 and C2), DA-2 and DA-3, from which each country has the right to choose its national design approach. access. In the Macedonian national annex "MKS_EN_1997_2012_NA_2020" [5], DA-2* approach is adopted, which is actually identical to the DA-2 approach, but instead of the actions, the partial coefficients are applied to the effects of the

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actions, which generally gives identical final results. Also, this approach provides partial coefficients for the reduction of the global resistance of the construction, but does not reduce the soil strength parameters. In a general view, the same can be shown according to Eq. (1):

$$DA\ 2 = A1+M1+R2 \tag{1}$$

(A1): $\gamma_{G,unfav} = 1.35$; $\gamma_{G,fav} = 1.0$; $\gamma_{Q,unfav} = 1.5$; $\gamma_{Q,fav} = 0.0$
(M1): $\gamma_{\varphi'} = 1.0$; $\gamma_{c} = 1.0$; $\gamma_{cu} = 1.0$,
($R2$): $\gamma_{Rh} = 1.1$; $\gamma_{Rv} = 1.4$, $\gamma_{Re} = 1.4$

Detailed explanation of the coefficients and how should be applied, can be found in the appropriate Annexes of the Eurocodes. The force from active earth pressure, same as by MKS, can be calculated according to the Rankine or Coulomb method, but can also be read directly from the graphs given in Annex C of EC 7-1. Moreover, in the national annex, the use of the Coulomb equation is recommended due to the inclusion of more general conditions and the greater conservatism of the Rankine theory. The bearing capacity of the soil is calculated according to the procedure given in Annex D in EC 7-1.
After the performed analyses, in Table 2 are shown the results for all walls, that is, the required foundation width to satisfy the stability conditions according to the two different regulations (MKS and EC-7). For the sake of analogy in the results, a percentage utilization for each condition is shown, rather than showing a safety coefficient. A utilization of 100% corresponds to the prescribed safety coefficient of 1.50 according to MKS. Additionally, Fig. 2 shows the analysed wall with a height of 6m, and the obtained width of the foundation with the different regulations.

Table 2: Required foundation width and utilization for static stability, for different wall heights and according to different regulations

Wall height - H [m]	Regulation	Required foundation width - B [m]:	Utilization [%]			
			Overturning	Sliding	Bearing	Eccentricity
3	MKS	1.45	73%	79%	56%	98%
	EC 7 DA-2	1.65	62%	76%	79%	99%
4.5	MKS	2.05	74%	89%	78%	99%
	EC 7 DA-2	2.4	66%	76%	95%	89%
6	MKS	2.65	74%	93%	100%	99%
	EC 7 DA-2	3.2	62%	76%	100%	79%
7.5	MKS	3.6	67%	85%	98%	84%
	EC 7 DA-2	4	66%	78%	100%	88%
9	MKS	4.4	66%	91%	99%	70%
	EC 7 DA-2	4.75	68%	82%	98%	87%

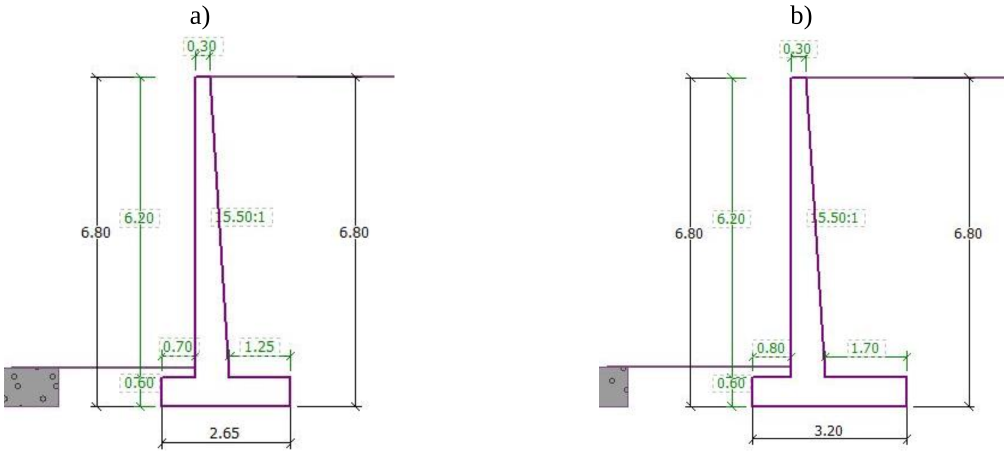

Fig. 2: *Obtained foundation width for the wall H=6.0m according to: a) MKS, b) EC 7-1*

Fig. 3, graphically shows the dependence between the height of the walls and the required width of the foundation to satisfy the stability according to the two analysed procedures - MKS and EC 7 (DA-2).

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The resulting curves are plotted for the five analysed wall heights and can only be used orientationally due to the assumed input parameters.

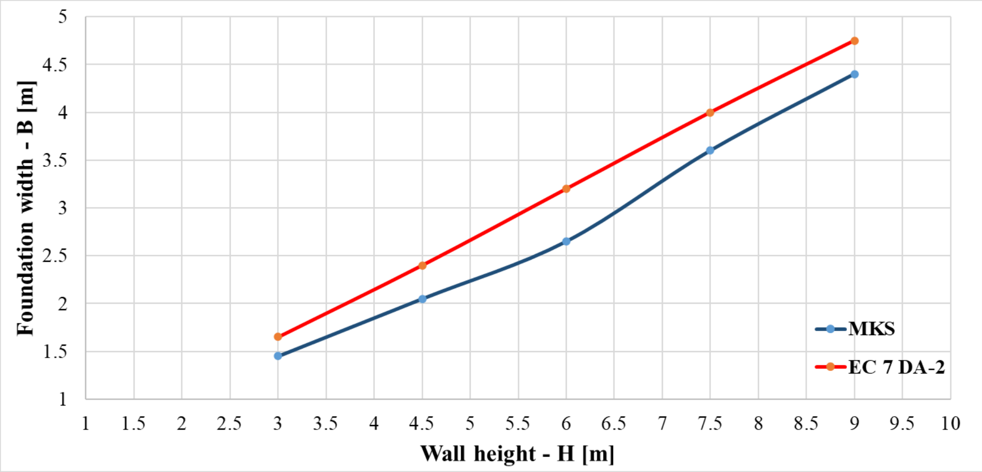

Fig. 3: Dependency: foundation height - width according to MKS and EC-7 (DA-2)

According to the presented results of the performed analyses, it can be concluded that the governing condition that dictates the dimensioning according to both approaches is the bearing capacity of the ground or the allowed eccentricity. It should be noted that the permissible bearing capacity of the soil according to MKS is assumed and it should be taken with a dose of caution, which is also the case for the bearing capacity according to EC 7-1, due to the assumption of all geomechanical parameters. Also, the sliding condition has a relatively high utilization, especially according to MKS, where for some of the walls the utilization is over 90%, so it can be concluded that even for a higher allowable stress on the ground, the dimensions will not change significantly, because the sliding will reach a critical value. On the other hand, overturning is the least utilized and is not relevant for dimensioning. According to the analyses performed for the different heights, it was found that according to EC 7-1 (DA-2), an increase in the width of the foundation of about 10-20% is needed in relation to the width calculated according to the MKS.

3. Analysis of retaining walls according to MKS and Eurocode 8 – seismic conditions

3.1. Seismic action according to MKS

The seismic analysis of the retaining structures in R. North Macedonia is prescribed in the "Rulebook for technical norms for design and calculation of engineering structures in seismic areas (1987)" [1]. This Rulebook prescribes the technical standards for designing in seismic zones VII, VIII and IX according to the MCS scale (Mercali – Cancani – Sieberg). The seismic calculation is carried out by the method of spectral analysis or dynamic analysis. According to this regulation, the seismic inertial force is calculated taking into account the self-weight of the structure - Eq. (2), as well as a calculation of additional active seismic pressure - Eq. (3):

$$S_{ik}=k_s*\beta_i*\eta_{ik}*\Psi*G_k \tag{2}$$

$$Pa=\frac{3+2tan\beta}{4}*k_s*\ \Psi*\gamma_z*h^2 \tag{3}$$

S_{ik} – seismic inertial force from self-weight
Pa – total seismic ground pressure

The coefficient of seismic intensity k_s is calculated according to Eq. (4):

$$k_s=X_{max}/\mu_p \tag{4}$$

- X_{max} – maximum acceleration of the ground in g's - depends on the seismic zone (Table 3).
- μ_p – prescribed ductility factor of the structure

Table 3: Value of maximum acceleration X_{max} (g) in relation to the seismic zone

Seismic zone (MCS)	X_{max} (g)
VII	0.10
VIII	0.20
IX	0.40

In the accelerations shown in Table 3, although it is not explicitly stated, it is assumed that the amplification of the acceleration that can arise from the local soil conditions is also included, since there is no other coefficient that takes into account this influence. The coefficient μ_p=2.5, according to the Rulebookg, so the coefficient of seismic action k_s for seismic zone – IX is calculated in Eq. (5). The coefficients for which a detailed calculation is not shown in this paper, can be found in the Rulebook cited above. The seismic allowable stress on the ground is predicted with a value 50% greater than the allowable stress for static loads, which is the most common practice in our country.

$$k_s=0.40/2.5=0.16 \tag{5}$$

3.2. Seismic action according to Eurocode 8 – part 5

Eurocode 8, part 5 (EC 8-5) [3] complements Eurocode 7-1 (EC 7-1) [2] and describes the criteria and rules for the seismic resistance of the soil on which the foundation is built, as well as the rules for the design of various foundation structures, retaining structures and soil-structure interaction during an earthquake. For seismic analysis, it is stated that any proven method based on the methods of dynamics of structures and soils and supported by previous experience is acceptable. In this paper, the seismic analyses of the retaining walls is performed with the pseudo-static method, based on the theory of Mononobe (1929) [6] and Okabe (1926) [7]. The total horizontal force, which occurs as a sum of the static loads from the active earth pressure with added action from the seismic action is calculated according to Eq. (6).

$$Ed=0.5*\gamma*(1\pm K_v)*K*H^2+E_{ws}+E_{wd} \tag{6}$$

- γ - specific weight of the soil
- H – height of the wall
- E_{ws} - static water pressure
- E_{wd} - hydrodynamic pressure of water
- K - coefficient of earth pressure (static + dynamic)

If adequate drainage is designed and a non-cohesive, gravelly material is placed behind the wall, as well as the groundwater table is below the foundation level, then the water pressure forces can be ignored, so that E_{ws} = E_{wd} = 0. The active pressure coefficient (static + dynamic) is calculated according to Eq. (7) or (8):

$$\text{if } \beta \le \varphi'_d - \theta \Rightarrow K = \frac{\sin^2(\Psi+\varphi'_d-\theta)}{\cos\theta \sin^2\Psi \sin(\Psi-\theta-\delta_d)\left[1+\sqrt{\frac{\sin(\varphi'_d+\delta_d)\sin(\varphi'_d-\beta-\theta)}{\sin(\Psi-\theta-\delta_d)\sin(\Psi+\beta)}}\right]^2} \tag{7}$$

$$\text{or if } \beta > \varphi'_d - \theta \Rightarrow K = \frac{\sin^2(\Psi+\varphi-\theta)}{\cos\theta \sin^2\Psi \sin(\Psi-\theta-\delta_d)} \tag{8}$$

- $\varphi'_d=\tan^{-1}(\frac{\tan\varphi'}{\gamma_{\varphi'}})$ – design angle of internal friction
- $\delta'_d=\tan^{-1}(\frac{\tan\delta}{\gamma_{\varphi'}})$ – design angle of friction between soil and structure
- Ψ and β - slope angles on the back of the wall and on the ground behind the wall

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- $\tan\theta = (\frac{k_h}{1 \pm k_v})$ – an angle that depends on the horizontal and vertical seismic coefficients (k_h and k_v) - if the groundwater level is below the wall, which is an assumption in this paper.

The coefficients for the horizontal and vertical seismic action (k_h and k_v) are shown in Eq. (9-11).

$$k_h = \alpha * * \frac{S}{r} \tag{9}$$

$$\alpha = \frac{a_{gR}}{g} * \gamma_I \tag{10}$$

$$k_v = \pm 0.5\ k_h \text{ (if avg/ag > 0.6)} \tag{11}$$

- α - maximum acceleration for a certain category of the structure
- a_{gR}– reference ground acceleration for soil type "A"
- r – coefficient that depends on the permissible movement of the wall - Table 4
- S – soil factor that depends on the type of soil

Table 4: EC8-5 – Values of coefficient „r“

Type of retaining structure	**r**
Free gravity walls that can accept displacement up to dr=300*α*S	2
Free gravity walls that can accept displacement up to dr=200*α*S	1.5
Flexural RC walls, anchored or braced walls, RC walls founded on vertical piles, restrained basement walls and bridge abutments	1.0

The walls are supposed to be located in a zone with reference acceleration a_{gR} =0.25g, according to the seismic zoning map of R. North Macedonia for a return period of 475 years shown in the National Annex for EC 8 - "MKS_EN_1998-1/NA:2020" [8]. In order to make the analyses as much comparable as possible, the acceleration is selected for a region that generally corresponds to the seismic zone IX according to the current seismological map for a return period of 500 and also for 1000 years, which is used according to the above mentioned Rulebook. Type "B" soil is assumed, so the coefficient S=1.20. The coefficient r serves to reduce the input seismic force in relation to the allowed displacements for the different 3 types of structures, shown in Table 4. Although not explicitly shown in EC 8-5, this coefficient represents the ductility of the structure and is analogous to the coefficient q, i.e. the behavior factor for the calculation of seismic forces for high-rise structures. That is concluded because EC 8-5 does not provide another coefficient that takes into account this aspect of the behavior of retaining structures during an earthquake. In Table 4, the retaining structures are divided into 3 types, depending on the flexibility, that is, the displacement that is "acceptable" for the analysed structure, while for more flexible structures, a higher coefficient r is provided, i.e. a greater reduction of the seismic force. Some doubt occurs is the third row of the table, where "flexural RC walls" are located, for which r=1.0, that is, no seismic force reduction is allowed. Moreover, according to the division of retaining structures in EC 7-1, RC cantilever walls belong to gravity walls, which means that they can be placed in the upper 2 categories of this table. At the same time, these 2 categories differ only in the value of the "acceptable" displacement, which depends only on a certain coefficient (200 or 300), multiplied by the acceleration α and the soil coefficient S. In this way, for the analysed location we get acceptable displacement “dr” for the first category from the table of 300*0.25*1.20=90 mm, and for the second category dr=60 mm. The value is given in absolute value, without taking into account the height of the structure, which is the most important factor in determining or limiting the permissible, or acceptable displacement of a structure. What is more, no method is shown by which the displacement of the analysed structure can be calculated or evaluated. According to Fardis M., et al. [9] "the designer should be aware that the magnitude of the seismic action calculated according to EN 1998-5, in the absence of specific studies, leads to a conservative design of the retaining structures. Therefore, the designer should make an individual assessment of the permanent displacements of the wall, in order to select a value for the coefficient r”.

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Regarding the design approaches, neither in EC 8-5, nor in the national annex, a design approach is specifically chosen according to which the seismic analysis should be performed. According to Fardis M., et al. [9], due to the fact that the pseudo-static method takes into account design values of the geomechanical parameters, for which partial coeffficients with a value greater than 1.0 are provided only in the design approaches DA-1 C2 and DA-3, it was concluded that these approaches are most compatible with EC 8-5, and will generate the most conservative seismic analysis results. These 2 approaches actually have identical partial coefficients in the absence of structure-generated actions, and give identical final results. Moreover, in EC 7-1, it is stated that in accidental situations, which include seismic loads, all values of partial coefficients for actions should be adopted with a value of 1.0, and all values of partial coefficients for resistances should be determined according to the “specific situation depending on the accidental action", without any further explanation, while the partial coefficients for the geomechanical parameters are not mentioned. Accordingly, using the DA-1 C1 and DA-2 approaches, which prescribe partial coefficients for actions, with reducing them to 1.0 according the statement above, would further reduce the seismicity forces, so that the differences between these approaches would be drastic compared DA-1 C2 and DA-3. This aspect is quite conservative, due to the fact that with these 2 approaches, the same values of partial coefficients are used as in static conditions, i.e. the structure is not allowed to have "lower" safety during an earthquake, as is the case in MKS (safety coefficient $Fs \geq 1.10$ for seismic conditions, in contrast to $Fs \geq 1.50$ for static conditions). According to the mentioned aspects, a reduction coefficient of r=2.0 was adopted for the performed analyses, with which the coefficients k_h and k_v were calculated – Eq. (12) and Eq. (13):

$$k_h = \alpha * \frac{S}{r} = 0.25 * \frac{1.20}{2} = 0.15 \tag{12}$$

$$k_v = \pm 0.5\ k_h = \pm 0.075 \tag{13}$$

The seismic bearing capacity of the ground is given in form of an empirical expression that needs to be satisfied, given in EC 8-5 - annex F.

After the performed analyses, a comparison was made of the dimensions obtained according to EC 8-5 and MKS - zone IX in terms of the required foundation width for all wall heights, summarized in Table 5, as well as in Fig. 5. It can be stated that according to EC 8-5 there is a rather large increase in the dimensions of the wall in relation to MKS, needed to satisfy the stability conditions, mostly the sliding, and also satisfying the expression for the seismic bearing capacity. The results lead to an unexpected and even illogical appearance of the width of the foundation compared to the wall height. The percentage increase is up to 40-60%. Fig. 4 shows the analysed wall with a height of 6m, and the obtained width of the foundation with the different codes.

Table 5: Required foundation width and utilization for seismic stability, for different wall heights and according to different regulations

Wall height - H [m]	Regulation	Foundation width - B [m]:	Utilization [%]		
			Overturning	Sliding	Bearing
3	MKS	1.9	79%	100%	69%
	EC-8-5	2.95	41%	97%	-0.016<0
4.5	MKS	2.65	79%	100%	93%
	EC-8-5	4.2	40%	100%	-0.010<0
6	MKS	3.7	71%	94%	98%
	EC-8-5	5.5	39%	100%	-0.021<0
7.5	MKS	4.7	72%	97%	99%
	EC-8-5	7	40%	100%	-0.006<0
9	MKS	6.05	65%	92%	99%
	EC-8-5	8.5	39%	100%	-0.041<0

Regarding the total force from seismic action, it was also found that according to EC 8-5 a larger force is obtained in relation to MKS, due to the partial coefficients of the materials (reduction of the soil strength parameters), although the coefficient k_h is obtained with a lower value in relation to the MKS. This means that the required reinforcement for the stem and the foundation will also be greater

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compared to MKS, but such dimensioning has not been performed, because it is not a subject of analysis in this paper.

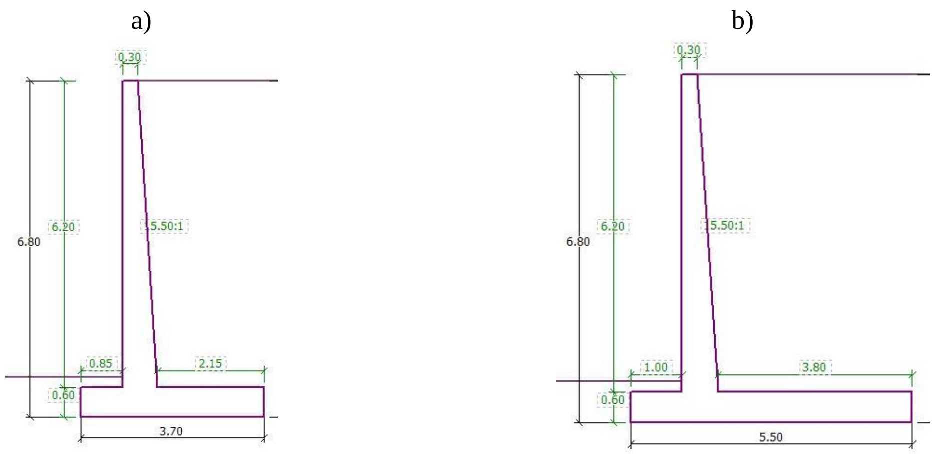

Fig. 4*: Obtained foundation width for a wall H=6.0m according to: a) MKS – Zone IX - MCS, b) EC 8-5, a=0.25g*

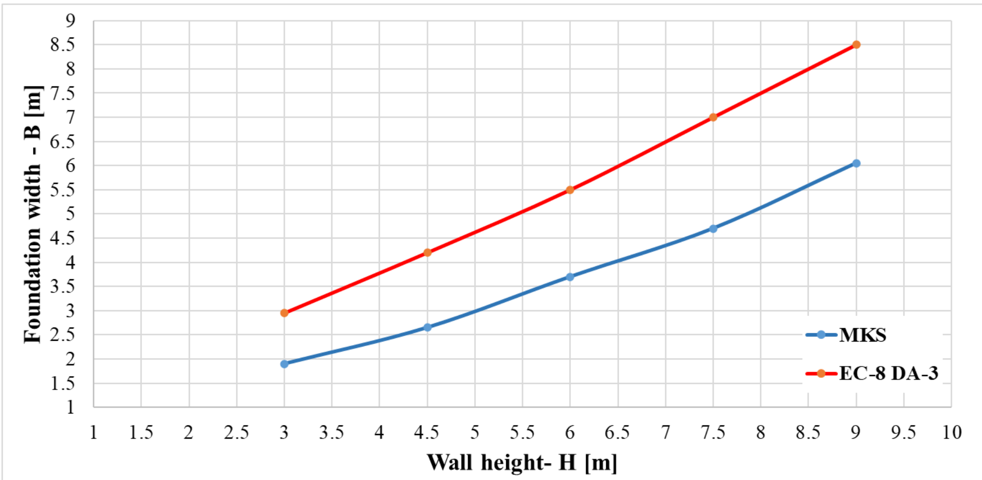

Fig. 5: Dependency: foundation height - width according to MKS and EC-8 (DA-3)

4. Comparative analysis between the static and seismic conditions

According to the results shown, an analysis of the seismic influence can be done for the required dimensions to satisfy the stability of the walls. In addition to the results shown, a seismic calculation was additionally performed for the seismic zone VIII according to MKS, with k_h=0.08, calculated according to Eq. (5), as well as for k_h=0.12 according to EC 8-5 - Eq. (9), as for a region that according to the new seismological map generally corresponds to the zone VIII according to the old seismological map, for the same type of soil (type B). The results are shown in Fig. 6 in form of percentage increase in the width of the foundation for seismic conditions, in relation to the static conditions. It can be concluded that according to MKS, a relatively small increase of up to 9% is needed for zone VIII, and for zone IX the increase is more pronounced, up to 30-40%. According to Eurocode (EC 8-5), approach DA-3, in relation to EC 7-1, DA-2, the increase for k_h=0.12 is about 55-60%, while for k_h=0.15, the increase is even up to 80%. It can be concluded that the seismic effect has a significant role in the dimensioning of the walls, and the seismic analysis should be mandatory for all new retaining structures, especially in seismically active areas.

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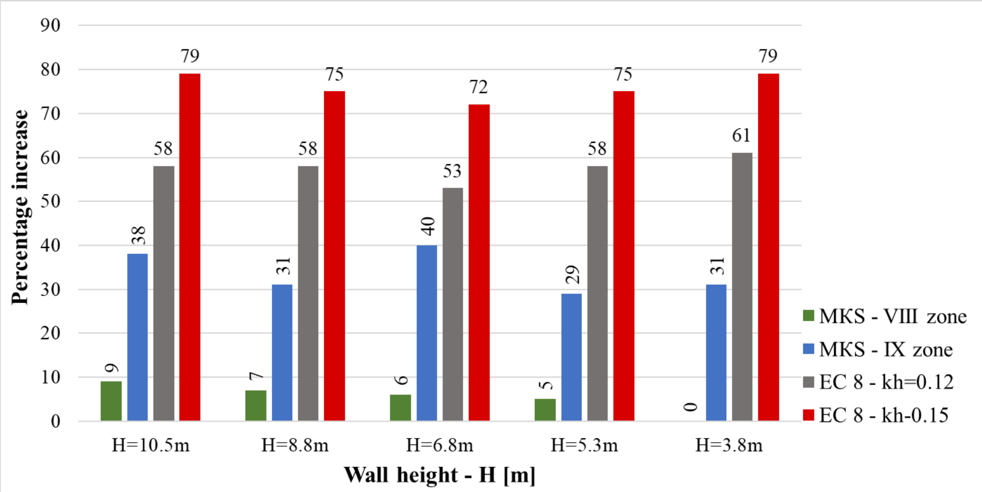

Fig. 3: Percentage increase in dimensions under seismic conditions compared to static conditions

5. Conclusion

According to the results of the performed analyses, the following can be concluded:

- The procedure for the analysis is conceptually different in the analysed regulations, i.e. in MKS it is based on global safety coefficients concept, while in Eurocodes it is based on limit state with application of partial coefficients.
- From the performed static analyses, it was found that according to EC 7-1, with the chosen design approach in the NA – DA2*, an increase in the width of the foundation of about 10-20% is required in relation to the width calculated according to MKS.
- The calculation of the seismic coefficients k_h is very similar between the two regulations, and although the given accelerations for same location are with a different value at first, using maps for different return period, the obtained values are very similar, that is, k_h=0.16 for seismic zone IX (MKS) and k_h=0.15 (EC 8-5). In fact, the theory for calculating the active seismic pressure is identical, which is Mononobe-Okabe theory. The main difference is the different concept for analysis, where with global safety coefficients (MKS) it is prescribed lower coefficient, i.e. it is allowed “less safety" under seismic actions. On the other hand, with EC 8-5 DA-3, there is no difference in the material partial coefficients between static and seismic calculations, so the structure is dimensioned with the same “safety” for both static and seismic condtions, which is the reason for the larger required dimensions, of up to 50-60%.
- The value of the coefficient r is not clearly enough explained in EC 8-5, which leads to uncertainty in adopting its value. It is also not specified which design approach should be used in seismic analysis, neither in the code, nor in the national annex.
- The seismic action has a great influence in the dimensioning, so that significantly larger dimensions are obtained to satisfy the stability of the walls in relation to the static conditions, so the seismic analysis of the retaining walls should be mandatory.
- The current situation of already constructed walls, as well as the design of new retaining structures with the safety coefficients method (ex-YU regulations), does not indicate a need to increase the cross-sections of the walls, because the cases of large and unallowed deformations or damages have not been registered or they are very rare, if the walls were designed and built following all the rules in the regulations.

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