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Contribution to the analysis of frequently performed reinforced concrete retaining walls

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Abstract: This paper presents the theoretical basis of dimensioning and an example of the calculation of a retaining wall. The first part provides an insight into the loads acting on retaining structures and the basic design principles according to Eurocode, common to all types of retaining walls. In the practical part of the paper, on the example of a reinforced concrete cantilever retaining wall with a height of 4 m, the calculation procedure for static and seismic actions is presented, using the European standards for geotechnical design, EN 1997-1 and the design of structures for earthquake resistance, EN 1998-5. For the other heights of the retaining walls defined by the task, due to the extensiveness and limited space of the paper, only the calculation results within the analysis of the results are presented. The conclusion of the analysis of the conducted calculation is given at the end of the paper.

Key words: Eurocode, retaining structure, reinforced concrete retaining wall, earth pressure, seismic earth pressure

Prilog analizi često izvođenih armiranobetonskih potpornih zidova

Sažetak: Ovim radom su prikazane teorijske osnove dimenzioniranja i primjer proračuna potpornog zida. U prvom dijelu se daje uvid u opterećenja koja djeluju na potporne konstrukcije te osnovna načela projektiranja prema Eurokodu, zajednička za sve vrste potpornih zidova. U praktičnom djelu rada, na primjeru armiranobetonskog konzolnog potpornog zida visine 4 m, prikazan je postupak proračuna na statička i seizmička djelovanja, primjenom Europskih normi za geotehničko projektiranje, EN 1997-1 i projektiranje konstrukcija otpornih na potres, EN 1998-5. Za ostale visine potpornih zidova definiranih zadatkom, zbog opsežnosti i ograničenog prostora rada, prikazani su samo rezultati proračuna u sklopu analize rezultata. Na kraju rada je dan zaključak analize provedenog proračuna.

Ključne riječi: Eurokod, potporna konstrukcija, armiranobetonski potporni zid, tlak tla, seizmički tlak tla

1. INTRODUCTION

According to Eurocode 7 (EN 1997-1), retaining structures are defined as structures that retain natural soil, earth embankments, rock or backfill and water. A material is considered to be retained if it is kept at a slope steeper than it would eventually adopt if no retaining structure were present. Retaining structures include all types of wall and support systems in which structural elements have forces imposed by the retained material [1].

Reinforced concrete retaining walls are very common and widespread structures in construction, with the purpose of retaining the terrain and taking pressures from the ground. What basically distinguishes them from other retaining structures is that they are founded. The surface of the terrain supported by the wall can be horizontal or at a slope. If the terrain is horizontal, it can be additionally loaded, while slopes are mostly not loaded. They are constructed individually, as linear structures or in combination with several different types of structures that form a cut, side cut or embankment in the natural terrain. They are used in stable and unstable terrains. In stable terrains, they are constructed when it is necessary to protect an excavation at a slope greater than it is allowed by the resistance-deformation properties of the terrain, and a drainage system for rainwater and groundwater is constructed.

This paper focuses on the dimensioning of reinforced concrete retaining walls, structures often used in construction for rehabilitation or prevention of landslides. The principles of dimensioning, common to all types of retaining walls, are reduced to determining the load and its effect on the stability of the retaining wall. The calculation regularly checks the limit state of stability for overturning, sliding, bearing capacity of the foundation soil and the global stability of the retaining wall, specifically within the field of soil mechanics only. It is also necessary to check the effect of internal forces on the resistance of the cross section.

In the practical part of the paper, on the example of a reinforced concrete cantilever retaining wall with a height of 4 m, the calculation results of the structure for static and seismic actions are presented, using the European standards for geotechnical design, EN 1997-1 and the design of structures for earthquake resistance, EN 1998-5. For other heights defined by the task, the calculation results of the retaining wall are presented at the end of the paper as part of the analysis of the results with comments on the calculation.

2. APPLICATION OF EUROCODE 7 WHEN CALCULATING RETAINING STRUCTURES

When designing, it is necessary to prove that the structure will meet all essential requirements for the structure during construction and operation, that is, that none of the possible limit states will be exceeded. Limit states are considered to be those states beyond which the structure no longer meets the requirements stipulated by the design. According to their character, limit states are divided into ultimate limit state and serviceability limit state.

The ultimate limit state is the final state up to which the structure still complies with the loads specified by the design, and the exceeding of which leads to a disruption of the stability of the structure observed as a whole (e.g. overturning or sliding of the retaining wall) or of one of its parts in a critical area/section (e.g. the place where the retaining wall is fixed to the foundation) which results in a failure or excessive deformation that puts people and the structure itself in direct danger.

By exceeding the serviceability limit state, the structure itself is not at risk in terms of bearing capacity, but due to large deformations, displacements, deflections, etc., its use is significantly hindered or it no longer serves its purpose (e.g. damage to the pavement due to inadmissible displacement, occurrence of creep areas, if it is a retaining structure designed to protect a cut in the terrain on which it was constructed, and as a result of exceeding it, traffic is difficult or impossible).

Eurocode 7 [1] emphasizes the use of calculation, while the application of prescribed measures, if not contrary to the standard, can be adjusted through a national annex.

3. STABILITY AND DIMENSIONING OF RETAINING WALLS

When calculating retaining walls, it is necessary to check the particular stability states of the structure related to the field of soil mechanics, i.e. the stability states in interaction with the soil in the space on which or within which the construction project is performed. Stability is checked for overturning, sliding, soil bearing capacity, and global stability check and proof of wall section resistance are performed.

The condition for the structure to be in a state of equilibrium is that the safety factor is satisfied for each individual state of equilibrium. The factor of safety is the relationship between the design resistance of the structure or part of the structure and the design effect of action on the structure and must not be less than 1, FS ≥ 1. Otherwise, such a structure is considered unstable.

The stability check is carried out in relation to all the forces acting on the retaining wall, namely [2]:

-active soil pressure (E_a)
-hydrostatic pressure (P_a)
-hydrodynamic pressure (U)
-external, horizontal forces (V)
-additional surface load (concentrated, P, linear, P' and surface, q)
-wall weight (G)
-retention in tension (S)
-passive resistance (E_P)
-friction at the foundation-soil contact (T)

Figure 1 shows the initial geometry when dimensioning the retaining wall according to the above-mentioned forces.

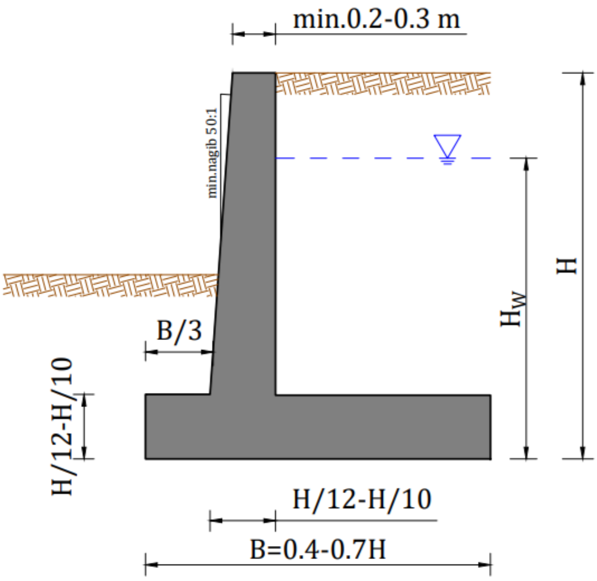

Figure 1. Recommended dimensions of a reinforced concrete retaining wall

The tendency of the horizontal component of the active pressure force (Ea) is to disrupt the degree of equilibrium of the retaining wall by overturning it around the outer edge of the wall foundation (toe) or causing it to slide. This (destabilizing) action is opposed by the force from the structure itself (G). In retaining walls with a heel on the backfill side Figure 2 (T-section wall), the overturning resistance is also opposed by the vertical component of the active pressure force and the weight of the stabilizing backfill mass. In the form of the expression for checking stability against overturning ($E_d \leq R_d$), it is more correct to observe the force E_v as part of one action with a negative sign - the resultant of the active pressure E - than as a separate stabilizing action, that is, on the left, not the right side of the $E_d \leq R_d$ inequation. It is the so-called "single-source principle" from Eurocode 7, according to which the action from the same source (e.g. active pressure with both its components) cannot be observed in the same expression in a way that a part is assumed as an unfavorable action and a part as a favorable action. Namely, both components should be treated either as unfavorable or as favorable actions, and it should be checked which combination is more unfavorable [2]. By its magnitude, the force from the structure has a considerable influence on stability, because it resists overturning and the occurrence of sliding at the same time with its (stabilizing) action. The favorable effect of the G force is most pronounced in massive, gravity retaining walls, but it also plays a significant role in other types of retaining walls (hollow and thin retaining walls) [3].

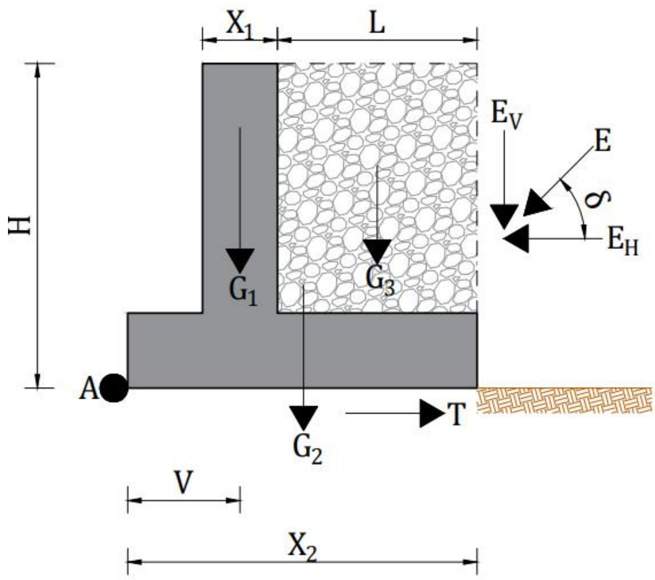

Figure 2. Illustration of forces acting on a reinforced concrete cantilever retaining wall

It should be mentioned that in the process of checking the stability, when determining the total resistance of the wall, it is not desirable to include in the calculation the full amount of the passive resistance force (Ep) that occurs in front of the foundation. Considering that a certain displacement is required to activate the passive resistance, the functionality and usability of the structure are called into question, so it is advisable to include only a part of the force, 1/2 to 2/3 Ep [3]. A regular check of stability of the retaining wall includes four failure mechanisms [4]:

- calculation for overturning
- calculation for sliding
- checking the bearing capacity of soil under the foundation
- checking the global stability of the retaining wall
- checking the stress in the critical section

4. EXAMPLE OF CALCULATION OF A REINFORCED CONCRETE RETAINING WALL

In the practical part of the paper, for a cantilever reinforced concrete retaining wall of comparative heights H=2, 3, 4, 5 and 6 m (the geometry of each wall is shown in Table 1), a static and seismic calculation of stability control for overturning and sliding, proof of bearing capacity of foundation soil and global stability check were performed (in computer geotechnical commercial software "GEO5 - Cantilever wall (demo version)") and calculation of reinforcement was performed by conventional manual calculation.

The calculation with the reinforcement specification and bending schedule is shown in more detail only for the wall height H=4 m, with given dimensions and loads according to Figure 3, while the calculation values for other heights are given in a tabular form (Table 1).

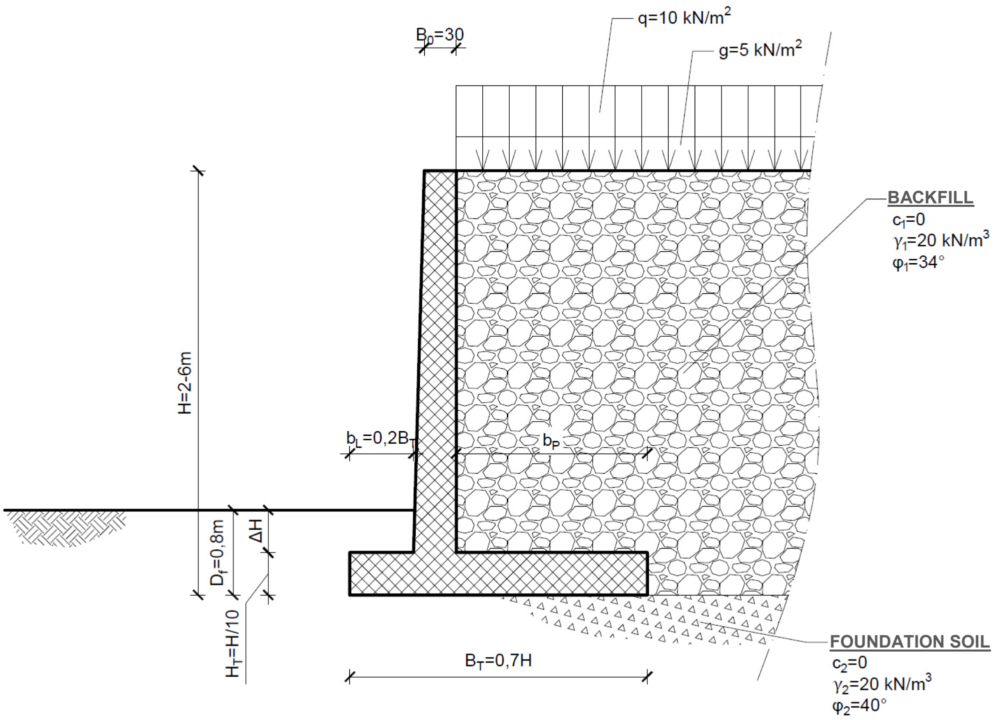

Figure 3. The geometry of the wall and the given load for retaining wall heights H = 2, 3, 4, 5 and 6 m

Table 1. Geometry data for retaining wall heights: H = 2, 3, 4, 5 and 6 m

H [m]	6	5	4	3	2
B_0 [m]	0.30	0.30	0.30	0.30	0.30
B_T=0.7H [m]	4.20	3.50	2.80	2.10	1.40
b_L=0.2B_T [m]	0.80	0.70	0.60	0.40	0.30
H_T=H/10 [m]	0.60	0.50	0.40	0.30	0.30
b_P [m]	2.80	2.30	1.80	1.40	0.80
D_f [m]	0.80	0.80	0.80	0.80	0.80

5. RESULTS AND CALCULATION ANALYSIS

5.1 Ultimate limit states

Table 2 shows the calculation results for the given retaining wall heights H=2, 3, 4, 5 and 6 m. The calculation results are related to the control of stability limit states for overturning, sliding and soil bearing capacity, and to the verification of global stability. The calculation was carried out for a static and seismic combination of actions, according to Eurocode 7 (EN 1997-1) and Eurocode 8 (EN 1998-5) with the application of the expression for the total calculation force (static + dynamic component) acting on the structure under seismic loading according to the procedure developed by Mononobe and Okabe. The ultimate limit states and the calculation approach were conducted according to Eurocode 7 [5].

In addition to the control of the limit states, the usability degree of the bearing capacity of the foundation soil was calculated for each of the limit states, as well as for global stability, which is derived from the stability conditions for overturning, sliding and soil bearing capacity:

Table 2. Recapitulation of the calculation of ultimate limit states for comparative heights of the retaining wall

check	***6 m***		***6 m***	***5 m***	***4 m***	***3 m***	***2 m***
STATIC ACTION							
Overturning	Overturning moment [kNm]	M_p=	371.71	228.46	127.23	60.88	22.31
	Moment of resistance to overturning [kNm]	M_o=	1089.1	634.85	328.49	143.32	44.29
	Safety factor	F_{sp}=	2.93	2.78	2.58	2.35	1.99
	Usability degree	U=	34.10%	36.00%	38.70%	42.50%	50.40%
Sliding	Active horizontal force [kN]	H_a=	166.63	121.05	82.6	51.27	27.06
	Horizontal resistance force [kN]	H_o=	295.46	206.25	132.98	79.61	36.55
	Safety factor	F_{sk}=	1.77	1.7	1.61	1.55	1.35
	Usability degree	U=	56.40%	58.70%	62.10%	64.40%	74.00%
Bearing capacity	Maximum stress [kN/m^2]	σ=	175.18	151.85	128.37	113.75	86.18
	Bearing capacity of foundation soil [kN/m^2]	q_{rd}=	424.04	370.25	315	276.32	208.12
	Usability degree	U=	41.30%	41.00%	40.80%	41.20%	41.40%
Global bearing capacity	Sliding moment [kNm]	M_k=	175.18	151.85	128.37	113.75	86.18
	Moment of resistance to sliding [kNm]	M_o=	424.04	370.25	315	276.32	208.12
	Safety factor	F_{sm}=	41.30%	41.00%	40.80%	41.20%	41.40%
	Usability degree	U=	56.80%	57.10%	55.40%	53.30%	48.70%
This cantilever wall is:			***satisfactory***	***satisfactory***	***satisfactory***	***satisfactory***	***satisfactory***

check	6 m		6 m	5 m	4 m	3 m	2 m
SEISMIC ACTION (CASE A) - seismic force in the horizontal direction							
Overturning	Overturning moment [kNm]	M_p=	551.23	332.45	180.54	84.25	29.22
	Moment of resistance to overturning [kNm]	M_o=	1137.39	662.81	342.81	149.46	46.14
	Safety factor	F_{sp}=	2.06	1.99	1.9	1.77	1.58
	Usability degree	U=	48.50%	50.20%	52.70%	56.40%	63.30%
Sliding	Active horizontal force [kN]	H_a=	228.9	164.26	110.22	67.27	34.23
	Horizontal resistance force [kN]	H_o=	308.62	215.38	138.82	83.06	38.11
	Safety factor	F_{sk}=	1.35	1.31	1.26	1.23	1.11
	Usability degree	U=	74.20%	76.30%	79.40%	81.00%	89.80%
Bearing capacity	Maximum stress [kN/m2]	σ=	246.4	213.1	180.47	160.22	130.48
	Bearing capacity of foundation soil [kN/m2]	q_{rd}=	424.04	370.25	315	276.32	208.12
	Usability degree	U=	58.10%	57.60%	57.30%	58.00%	62.70%
Global bearing capacity	Sliding moment [kNm]	M_k=	5542.06	3413.53	1454.42	756.74	214.72
	Moment of resistance to sliding [kNm]	M_o=	8333.46	5262.05	2366.34	1279.53	400.77
	Safety factor	F_{sm}=	1.5	1.54	1.63	1.69	1.87
	Usability degree	U=	66.50%	64.90%	61.50%	59.10%	53.60%
This cantilever wall is:			***satisfactory***	***satisfactory***	***satisfactory***	***satisfactory***	***satisfactory***

check	6 m		6 m	5 m	4 m	3 m	2 m
SEISMIC ACTION (CASE B) - upward seismic force							
Overturning	Overturning moment [kNm]	M_p=	522.03	315.39	171.69	80.43	28.03
	Moment of resistance to overturning [kNm]	M_o=	1040.8	606.89	314.17	137.17	42.43
	Safety factor	F_{sp}=	1.99	1.92	1.83	1.71	1.51
	Usability degree	U=	50.20%	52.00%	54.60%	58.60%	66.10%
Sliding	Active horizontal force [kN]	H_a=	219.17	157.44	105.79	64.72	33.05
	Horizontal resistance force [kN]	H_o=	282.3	197.12	127.14	76.17	34.99
	Safety factor	F_{sk}=	1.29	1.25	1.2	1.18	1.06
	Usability degree	U=	77.60%	79.90%	83.20%	85.00%	94.40%
Bearing capacity	Maximum stress [kN/m2]	σ=	218.79	189.76	161.71	148.47	128.06
	Bearing capacity of foundation soil [kN/m2]	q_{rd}=	424.04	370.25	315	276.32	208.12
	Usability degree	U=	51.60%	51.30%	51.30%	53.70%	61.50%
Global bearing capacity	Sliding moment [kNm]	M_k=	5199.96	3187.29	1359.2	694.23	200.87
	Moment of resistance to sliding [kNm]	M_o=	7684.05	4824.54	2171.32	1148.21	367.49
	Safety factor	F_{sm}=	1.48	1.51	1.6	1.65	1.83
	Usability degree	U=	67.70%	66.81%	62.60%	60.50%	54.70%
This cantilever wall is:			***satisfactory***	***satisfactory***	***satisfactory***	***satisfactory***	***satisfactory***

From the presented results, it is evident that the geometry of all retaining walls is satisfactory, with the earthquake action having a significant effect on the reduction of the safety factor, especially on the sliding safety factor when the seismic force acts upwards (case B).

The diagrams in the following figures (Figure 4 and Figure 5) show the obtained values of the factor of safety against overturning and sliding, from which it follows that the retaining wall, observed as a rigid body, is more stable with an increase in height, for the case analyzed here when an external load amounting as in the given examples acts behind the wall. In the case when there is no external load behind the wall, with an increase in the wall height, Fs decreases (U increases). However, it should be taken into account that as the wall height increases, the amount of backfill material also increases. Along with other additional loads, the weight of backfill material has an adverse effect on the structure in the form of active pressure, thus causing the maximum bending moment at the part where the vertical cantilever is fixed to the foundation [6]. The greater bending moment requires a larger wall cross-section and larger amount of reinforcement at the point of the critical section. It has been shown in practice that the optimal height of reinforced concrete cantilever retaining walls is up to 7 m, while construction of higher walls has not proven to be particularly safe. The trend of growth in bending moment values in the critical section for geostatic actions depending on the height of the retaining wall is shown in the diagram in Figure 6.

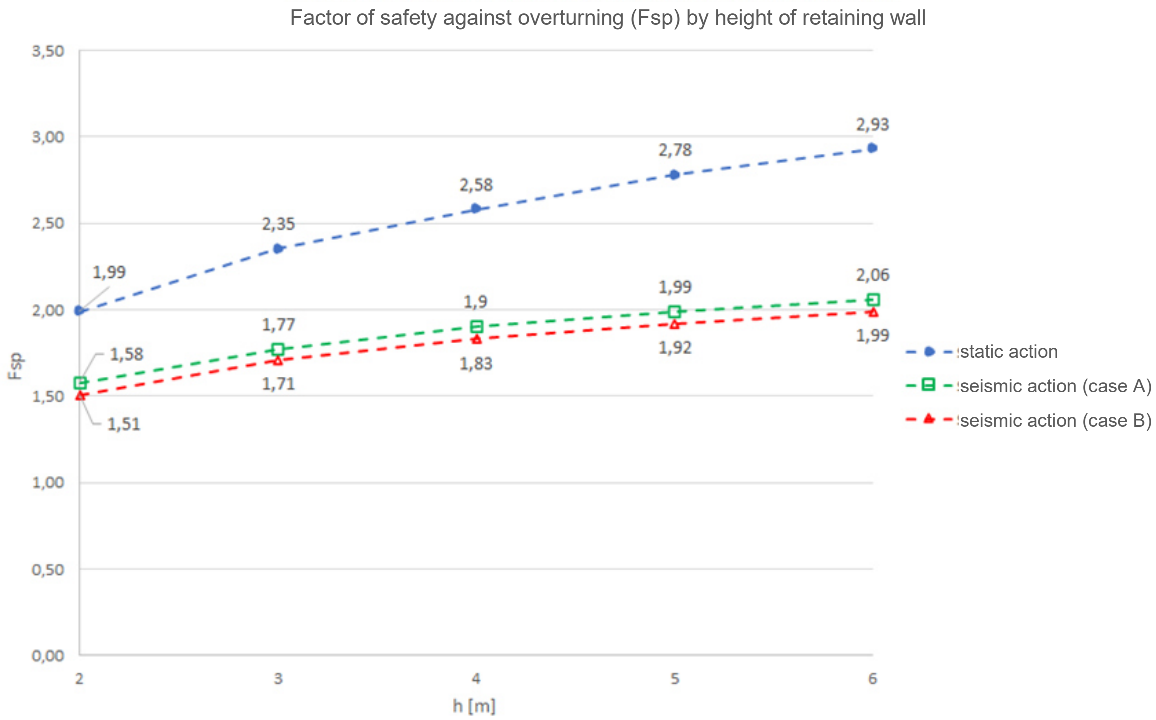

Figure 4. Diagram of the factor of safety against overturning, Fsp for given heights of the retaining wall

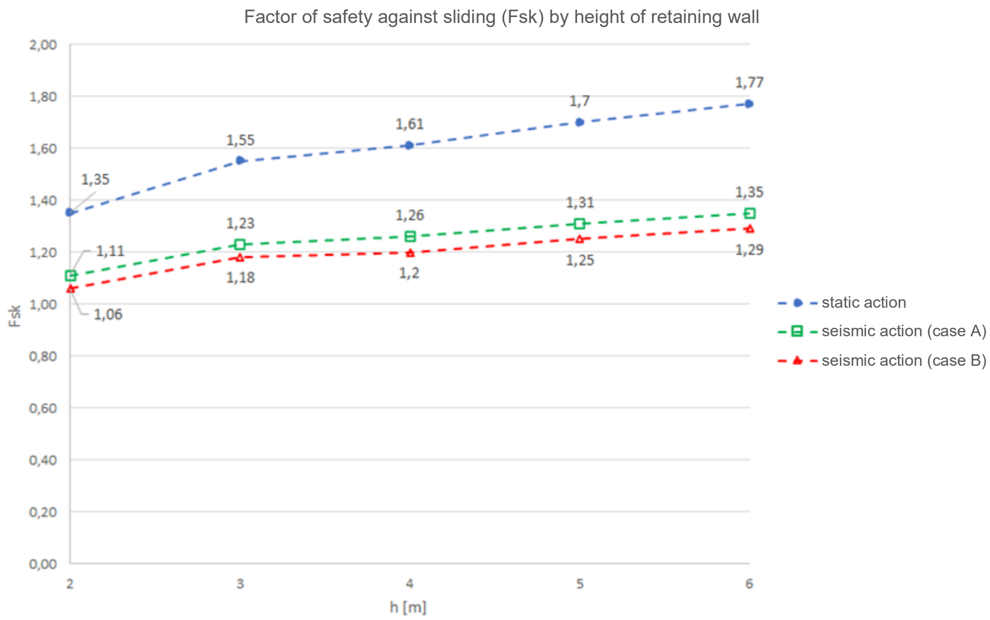

Figure 5. Diagram of the factor of safety against sliding, Fsk for given heights of the retaining wall

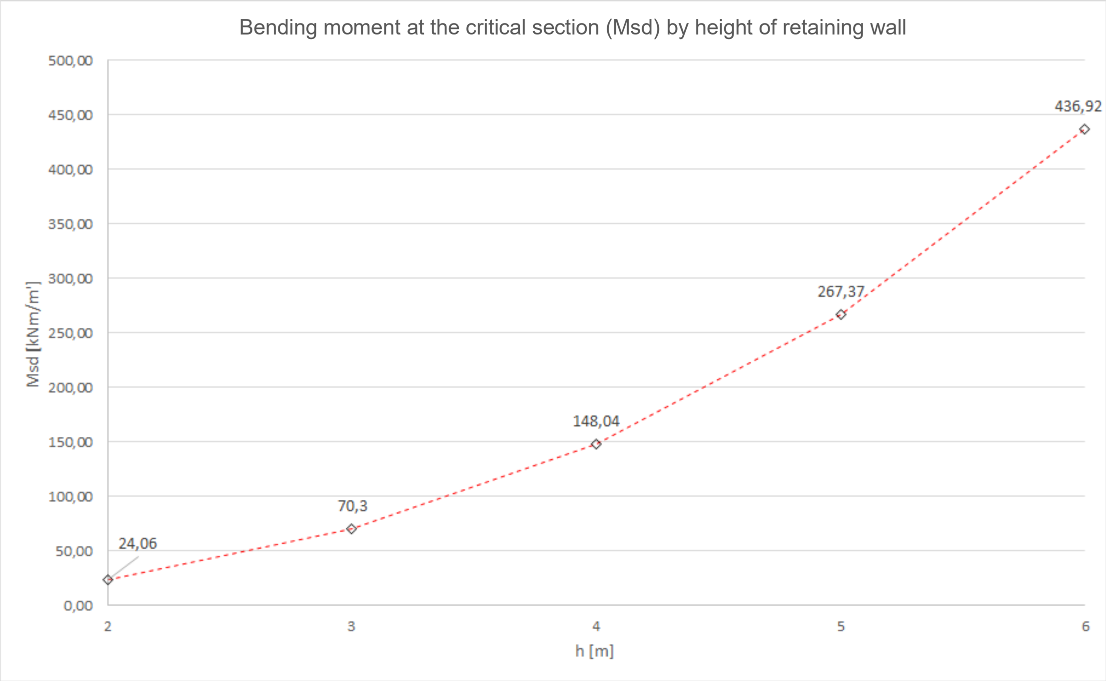

Figure 6. Diagram of the bending moment at the critical section, Msd for given heights of the retaining wall

With regard to the usability degree of the bearing capacity of the foundation soil, as the ratio of the maximum stress to the bearing capacity of the foundation soil [7], almost the same calculation results were obtained, which for static effects are around 40%, while for seismic effects they are greater and are around 60% (Figure 7).

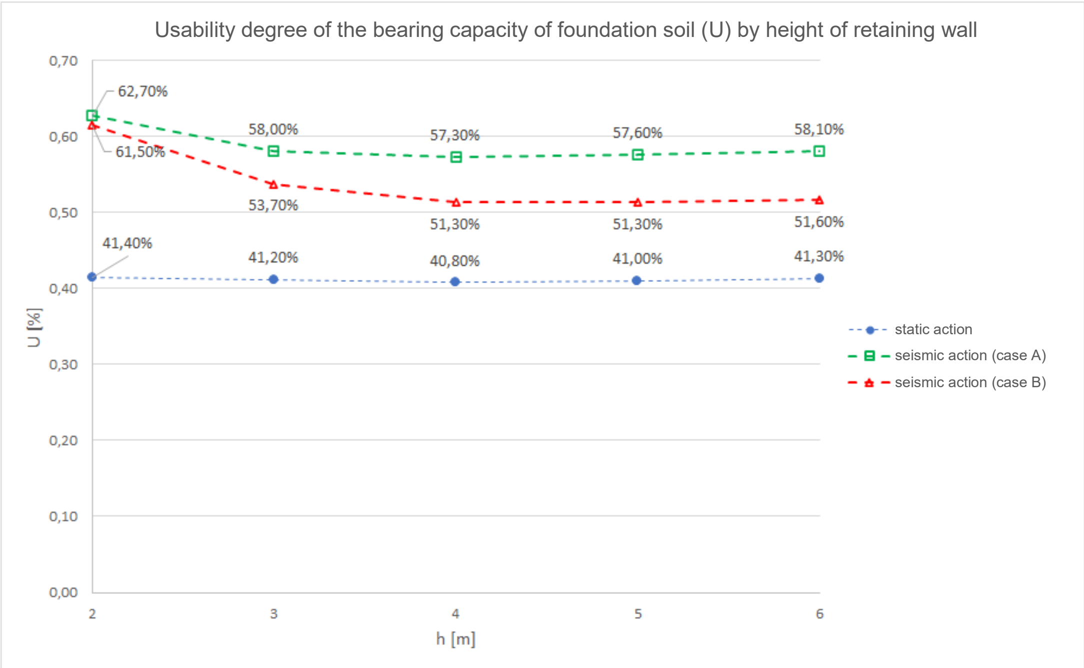

Figure 7. Diagram of the usability degree of the bearing capacity of the foundation soil U, for given heights of the retaining wall

The global stability check was conducted in the computer program "GEO5 - Cantilever wall (demo version)", using the limit equilibrium method, where the Bishop method was used to determine the critical slip surface, or the surface with the minimum safety factor [8], Fm > 1. The calculation results for each individual retaining wall are shown in the diagram in Figure 8.

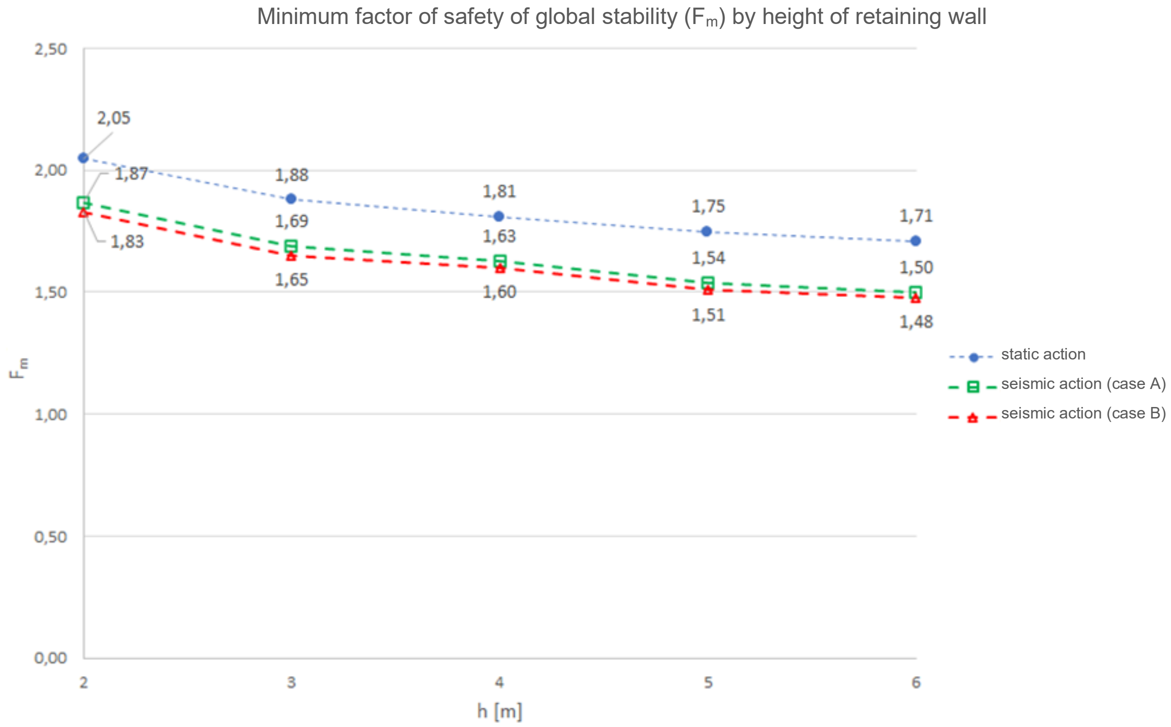

Figure 8. Trend diagram of the minimum factor of safety of global stability, Fm for given heights of the retaining wall

5.2 The amount of reinforcement

Table 3 shows the amount of reinforcement for each individual retaining wall, for wall lengths of 5 m, 1 m, and the amount for 1 m^3 of concrete.

Table 3. Recapitulation of reinforcement for comparative heights of the retaining wall

Retaining wall height:	***6 m***	***5 m***	***4 m***	***3 m***	***2 m***
Reinforcement for wall length L=5 m [kg]	2,183.63	1,353.92	941.83	444.38	269.66
Reinforcement for wall length L=1 m [kg]	436.73	270.78	188.37	88.88	53.93
Reinforcement per 1 m^3 of concrete [kg/m^3]	88.23	76.28	79.15	61.72	51.36

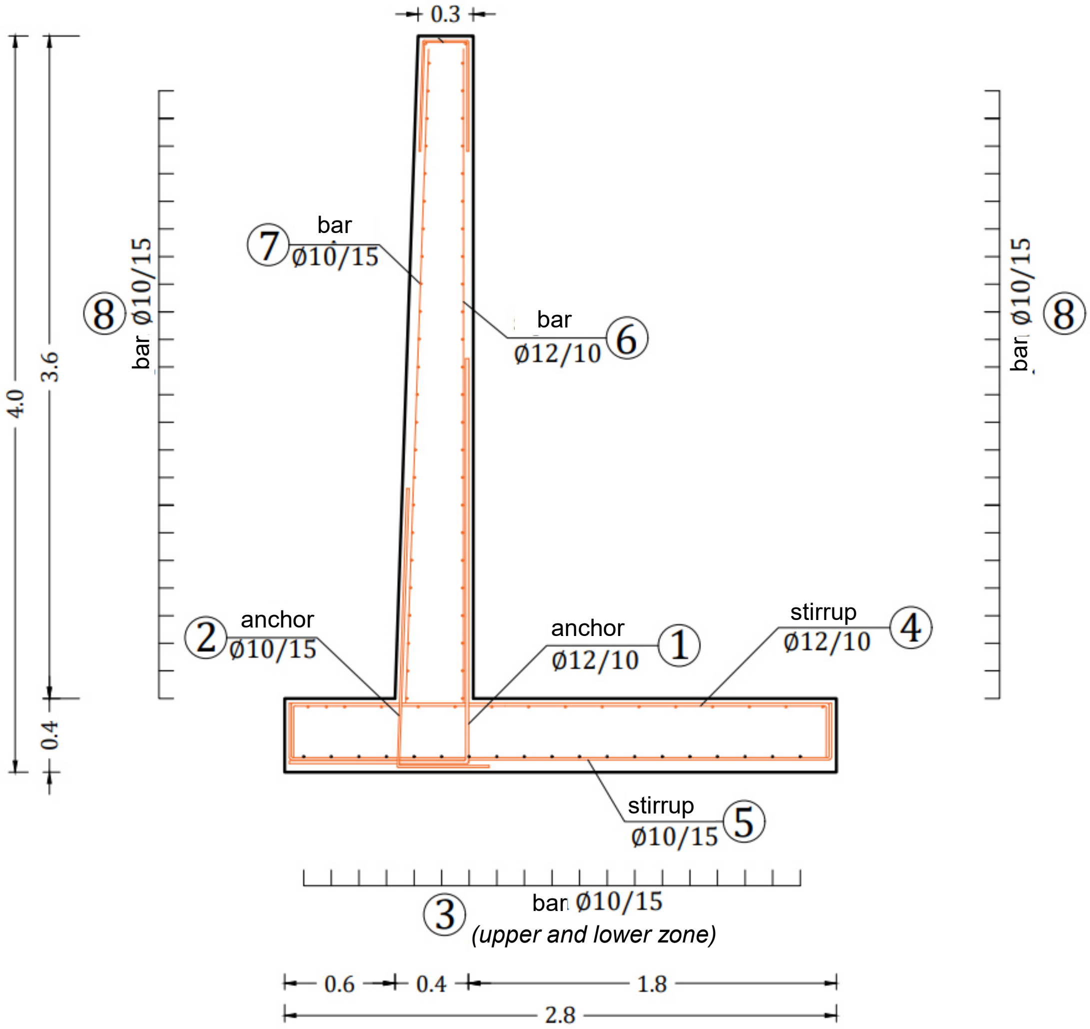

Figure 9. Bending schedule of the reinforced concrete retaining wall with height H = 4 m

The bending schedule of the reinforced concrete retaining wall is made so that the arrangement of the horizontal reinforcement is such as to prevent the occurrence of tensile cracks, therefore the horizontal reinforcement with a larger cross-section of the bars and a smaller spacing between them is in the upper foundation zone, while an arrangement with a smaller cross-section of the bars at a greater spacing is in the lower foundation zone. The arrangement of the vertical reinforcement is such that bars with a larger diameter are placed at a smaller distance in the tensile zone of the vertical wall element, in order to hold the bending moments caused by the soil pressure. On the side where the pressure from soil does not act (left side), reinforcement is made with bars of a smaller diameter, at a larger distance.

The maximum bending moment occurs at the part where the wall is fixed, because this kind of wall can be observed as a vertical cantilever, so in the reinforcement schedule, the fixity part is intersected with vertical and horizontal reinforcement in order to prevent the occurrence of deformations.

RA bars – specification for 5 m' of retaining wall

ozn	shape and measures [cm]	Ø [mm]	lg [m]	n [kom]	lgn [m]
1	90, 220	12	3,10	50	155,00
2	150, 50, 88°	10	2,00	33	66,00
3	500	10	5,00	38	190,00
4	30, 270, 30	12	3,30	50	165,00
5	30, 270, 30	10	3,30	33	108,90
6	355, 18	12	3,73	50	186,50
7	355, 18	10	3,73	33	123,09
8	500	10	5,00	46	230,00
9	30, 26, 26, 30, 30	10	1,42	28	39,76

RA bars – recapitulation for 5 m' of retaining wall

Ø [mm]	lgn [m]	unit weight [kg/m']	weight [kg]
B500 B			
10	757,75	0,634	480,41
12	506,50	0,911	461,42
Total for 5 m' of retaining wall:			**941,83 kg**

Figure 10. Reinforcement specification of the reinforced concrete retaining wall with height H = 4 m

6. CONCLUSION

Due to a number of advantages compared to other types of backfilled retaining structures, reinforced concrete retaining walls are very often used in construction, primarily in rehabilitation and prevention of landslides. In addition to their relatively simple construction, they also proved to be cost-effective in economic terms.

Before the beginning of the design, it is necessary to carry out a preliminary classification of the structure in terms of the scope and complexity of the geotechnical investigation works. This procedure classifies retaining structures into one of three geotechnical categories, with the aim of a more rational and economical approach to the project. The calculation, which is common to all types of retaining walls, proves the stability of the structure in interaction with the soil for the ultimate limit states, or it checks the stability against overturning, sliding, bearing capacity of the foundation soil and the global stability of the retaining wall, as well as proof of resistance of the section to all forces acting on the retaining wall.

In addition to static forces, seismic forces can also act on retaining structures. Their action significantly affects the stability, especially the sliding stability of the structure. Therefore, it is necessary to design them so that they do not sustain significant structural damage during and after the earthquake, and that none of the equilibrium limit states are violated.

Applying a simplified calculation method, using the Mononobe-Okabe expressions for flexible and the defined expression for rigid retaining structures, the dynamic earthquake force is easily converted into a pseudostatic force, and the further calculation procedure is carried out in the same way as with static forces.

Within the calculation section, static and seismic calculations of the reinforced concrete cantilever retaining wall, with heights of 2, 3, 4, 5, and 6 m were conducted using the European standards for geotechnical design, EN 1997-1 and the design of structures for earthquake resistance, EN 1998-5 [9]. From the results of the calculation of ultimate limit states, it was concluded that the given geometry of all retaining walls is satisfactory. From the calculations, it can be concluded that the factor of safety against overturning increases with increasing height, for a height of 2 m it is 1.99, while for the largest height of 6 m it is 2.93. The factor of safety against sliding also increases with increasing height, which indicates that a structure with a height of 6 meters is less prone to sliding than one with a height of 2 meters, so that the factor of safety is 1.35 for a height of 2 meters, while for the maximum height of 6 meters it is 1.77. The above conclusion applies only for the case as in the presented example with the action of the external load behind the wall included.

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