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RETAINING WALL - PARAMETRIC STUDY OF THE METHOD OF REINFORCEMENT

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Abstract

The highway section on the D3 highway Hričovské Podhradie – Žilina – Strážov was carried out on the left branch of the highway body on the overpass and on the right branch on the embankment body. The stability of the embankment body was ensured by a geosynthetics reinforced retaining wall. The retaining wall was assembled from reinforced concrete prefabs, on which the uniaxial geogrids were attached. The article presents a numerical analysis of the deformations of this reinforced structure in the profile monitored by geotechnical monitoring. The results of the numerical analysis of the deformations of the retaining wall were confronted with geotechnical monitoring measurements. Geotechnical monitoring measurements confirmed the reality of the numerical model of the retaining wall. Verification of the reality of the numerical model of the retaining wall made it possible to use this model for a parametric study of the influence of the reinforcement method on the deformation of the face of the reinforced retaining wall. In the parametric study, the effects of the change in the horizontal length and vertical spacing of the reinforcement elements, as well as their interaction with the backfill soil on the deformation values of the face of the retaining wall are analyzed.

Keywords:

Retaining wall;
Parametric study;
Uniaxial geogrids;
Geotechnical monitoring;
Interaction.

1 Introduction

The retaining wall reinforced with geogrids is a demanding structure that must be reliable and fulfill its function for a long time. Geogrid reinforced retaining systems are a technical and economical alternative to monolithic concrete gravity or reinforced concrete retaining walls. The reinforced retaining wall with geogrids is widely used in transport construction now. Parameters such as the length of the reinforcing geogrids, their vertical distance, the properties of the backfill material and its interaction with the geogrids affect the reliable functionality of the retaining wall.

Many researchers have studied the reinforcement method of retaining walls using parametric studies. The effect of changes in the stiffness of the reinforcements, changes in the angle of internal friction and cohesion of the backfill and changes in the stiffness of the reinforcements on the deformation of the wall facing was analyzed in [1]. In a parametric study [2] has been introduced to discuss the global factor of safety, maximum horizontal displacement, maximum force of tension of the reinforcement element and the active earth pressure coefficient as a function of the different aspect ratio of the retaining wall (width of the retaining wall / height of the retaining wall), spacing of the reinforcing elements, elastic axial stiffness of the reinforcement elements, soil friction angle and wall height. Parametric analysis of the spacing of the geosynthetic reinforcement, geosynthetic stiffness value, the aspect ratio (*L* / *H*), slope of the retaining wall, the internal friction angle of the backfill and the height of the wall per factor of safety and the maximum horizontal displacement of the retaining wall is in [3]. The impact of spacing of the geogrids, the height of the retaining wall on the horizontal displacement of the wall with respect to its height was evaluated in [4]. Furthermore, the impact of the height of the retaining wall on the maximum tensile force in the geogrids was verified.

The paper presents a numerical analysis of the deformations of the retaining wall in relation to geotechnical monitoring measurements. Verification of the reality of the numerical model of the retaining wall by geotechnical monitoring made it possible to use this model for a parametric study. In this parametric study, the effects of the change in the horizontal length and vertical spacing of the reinforcement elements, as well as their interaction with the backfill, on the deformation values of the face of the retaining wall are analyzed. A panoramic view of the overpass of the left branch of the highway body, behind which is the front of the retaining wall, is shown in Fig. 1.

2 Retaining wall construction

The h D3 Hričovské Podhradie – Žilina – Strážov highway section is carried out in the left branch of the highway body on the overpass and in the right branch on the retaining wall. A panoramic view of the overpass of the left branch of the highway body, behind which is the front of the retaining wall, is shown in Fig. 1.

Fig. 1: Panorama view of the highway body.

The body of the highway was built on a slope according to the project documentation [5, 6]. After cutting for the retaining wall, a foundation block made of reinforced concrete C30/37 was built with a height of 1.2 m and a width of 3.0 m. The foundation block is supported by micropiles. The viewing part of the retaining wall was gabion-facing in one section and concrete-facing blocks in another section. For the numerical analysis, a section with concrete facing blocks was selected. The U-shaped block is mounted on the foundation block for the installation of facing blocks. The retaining wall facing blocks are made of reinforced concrete C30/37 with dimensions of 1.25/0.5/0.25 m. The Tensar RE 560 geogrids are fixed to the facing blocks by a high-efficiency mechanical connection. The length of the geogrids was 4.0 m with a vertical 0.4 m spacing. Crushed stone 0/63 mm was used for the backfill. The Z-shaped prefab made of reinforced concrete C30/45 is mounted on the crown of the retaining wall. The task of the Z-shaped prefab is to transfer the horizontal load from the pavement and the guardrail so that there is no stress on the facing blocks at the head of the retaining wall. A cross section through the reinforced retaining wall structure that forms the right branch of the highway body is shown in Fig. 2, [5]. The installation of reinforcing geogrids on the reverse side of facing blocks is shown in Fig. 3.

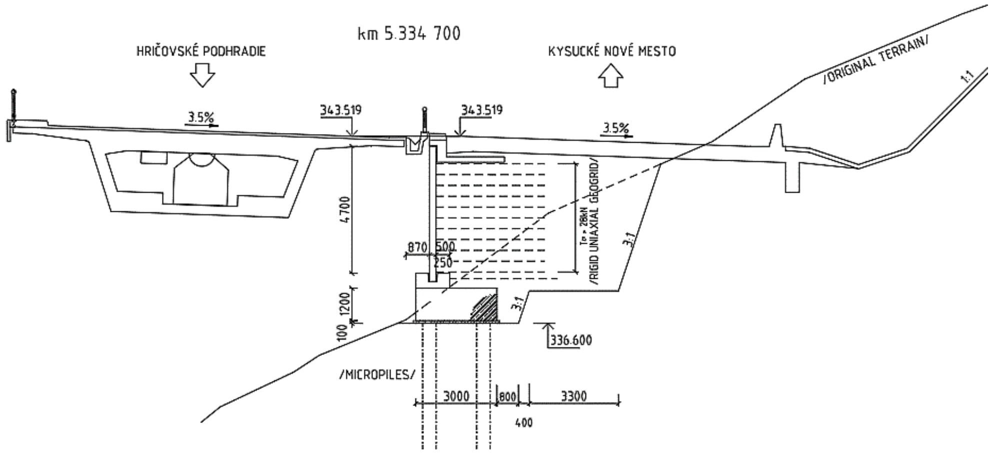

Fig. 2: Cross-section of the reinforced retaining wall [5].

Fig. 3: Installation of reinforcing geogrids on the reverse side of facing blocks.

The subsoil of the retaining wall consists of a deluvial complex and mesozoic bedrock [7]. The layers of the deluvial complex are made of clayey gravel. The thickness of the deluvial complex is variable in the range of 0.7 to 4.6 m. Beneath the deluvial complex is a zone of slightly weathered to weathered tectonically broken sandstones with thin interlayers of claystones. The groundwater level was not detected by survey works in the analyzed profile.

3 Geotechnical monitoring of the retaining wall

Due to the complexity of the geological conditions in some sections of the highway and the resulting technical solutions and measures, it was necessary to monitor the long-term stability of the retaining wall using geotechnical monitoring. Geotechnical monitoring of the retaining wall construction consisted of measuring the deformation of the reinforcing geogrids with extensometers, measuring the pressure of the earth with pressure gauge boxes and measuring the inclination of the retaining wall [8]. The position of the measuring devices in the selected profile of the retaining wall is presented schematically in Fig. 4.

The results of the geotechnical monitoring measurements are shown in Table 1, [9].

Table 1: Geotechnical monitoring measurements.

Date	Extensometers [mm]				Cells for earth pressure [kPa]			Tilt-meter [o]
	Reinforcement level No.							
	2	5	8	11	2	6	10	10
02.08.2007	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10.10.2008	0.1	0.6	1.5	3.1	2.5	0.0	0.0	0.0
25.01.2008	0.2	0.7	1.6	3.2	2.5	2.5	5.0	0.0
11.02.2008	0.2	0.8	1.6	3.2	7.5	2.5	5.0	0.0
21.02.2008	0.2	0.8	1.7	3.3	12.5	0.0	7.5	0.0
29.02.2008	0.2	0.8	1.7	3.3	12.5	0.0	7.5	0.0
26.07.2018	0.2	1.7	2.3	4.6	10.0	32.5	22.5	0.1

Extensometers: + elongation / - contraction, Cells for earth pressure: + pressure / - tension,
Tiltmeter: + tilt from the embankment / - tilt into the embankment.

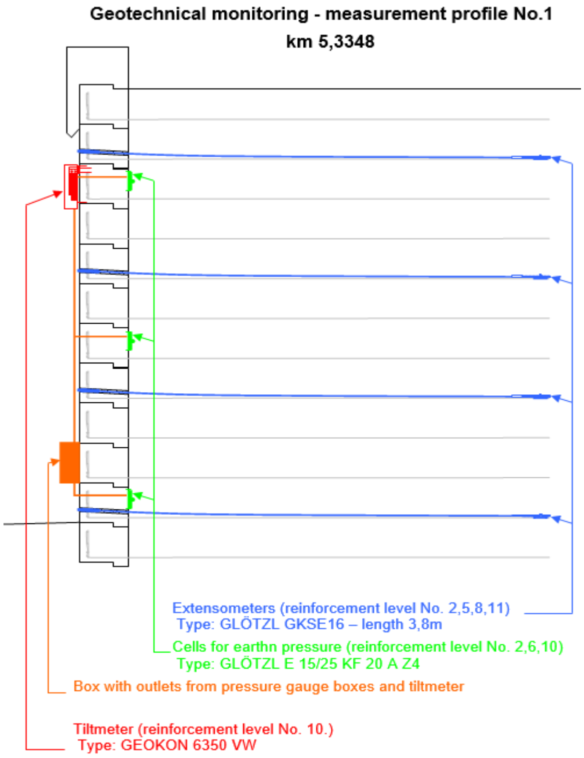

Fig. 4: Location of geotechnical monitoring measurement devices [9].

The following geotechnical monitoring was installed on the retaining wall [8, 9]:

- extensometers Glötzl GKSE 16 - length of 3.8 m in the 2nd, 5th, 8th and 11th reinforcement levels;
- cell for earth pressure Glötzl E 15/25 KF 20 AZ4 in the 2nd, 6th and 10th reinforcement levels;
- tiltmeter type Geokon 6350 VW in the 10th reinforcement level.

The right branch of the highway, located on a reinforced earth structure secured by a retaining wall, was built ahead of the left branch located on the flyover and was put into operation in 12/2007.

4 Numerical analysis of the construction of the retaining wall in the selected profile

The numerical analysis of the retaining wall focused on the analysis of its deformations. The profile of the retaining wall analysed numerically was chosen so that its position was as close as possible to the profile monitored by geotechnical monitoring. The reason was the comparison of the results of geotechnical monitoring and numerical analysis. From the position of the profile in which geotechnical monitoring was carried out (km 5.3348) and the position of the numerically analyzed profile of the retaining wall (km 5.3347), it can be concluded that the analyzed profile is identical to the monitored profile.

4.1 Numerical model of the retaining wall

Plaxis 2D was used for the numerical analysis of the retaining wall [10]. The model of the retaining wall created according to the cross section in Fig. 2 is presented in Fig. 5.

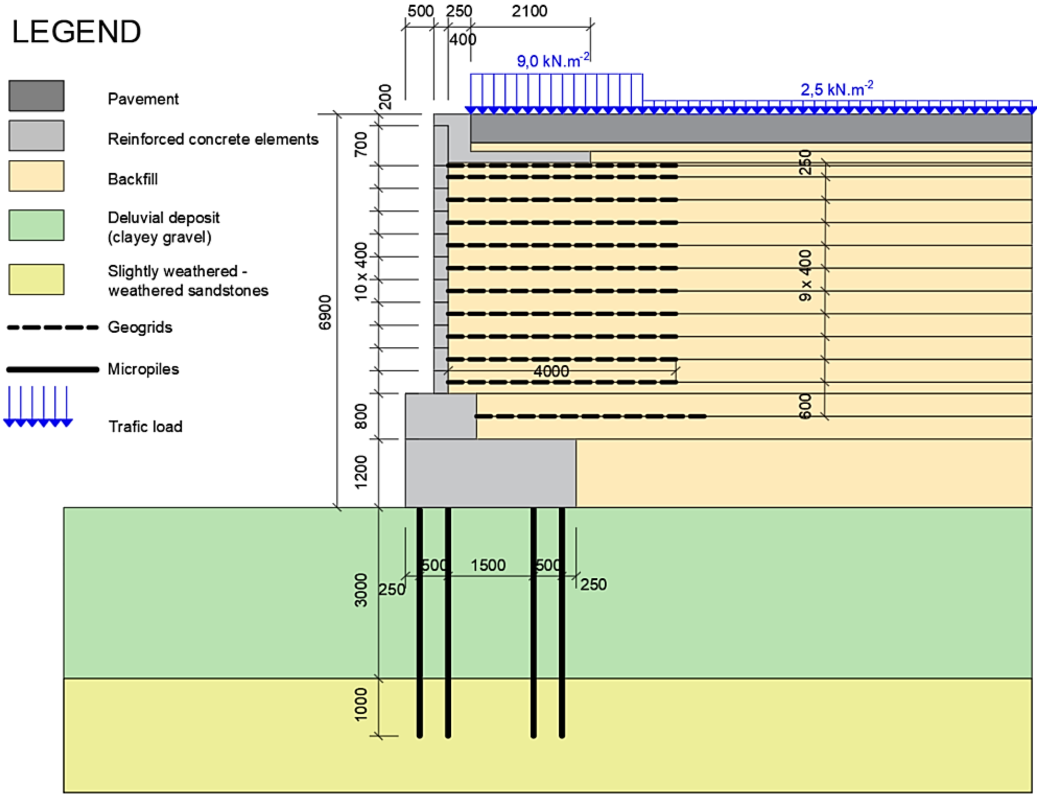

Fig. 5: The retaining wall structure model considered in the numerical model.

15-node triangular elements were used in the model. Concrete elements were modelled as nonporous elements characterized by a linear elastic material model. The subsoil and backfill soils of the reinforced retaining wall were modelled as drained by the Mohr-Coulomb material model. The geogrids were modelled with an elastic material model. The soil parameters used in the numerical model were determined based on the results of the geological survey [7]. The material parameters used in the numerical model are presented in Table 2. The load of traffic was modelled according to load model 1 (LM1) of Eurocode 1: Actions on structures, Part 2: Traffic loads on bridges: 2006, see Table 3. A load of 9.0 kN·m^{-2} was applied to a lane of 3.0 m width, and a load of 2.5 kN·m^{-2} was applied to the remaining area. The construction of the retaining wall and its traffic load was modelled in 34 phases. The construction phases are listed in Table 4.

Table 2: Material parameters used in the numerical model.

Structural elements					
Material type	**Drainage type**	**Material model**	**Unit weight** γ **[kN·m^{-3}]**	**Young's modulus** E **[MPa]**	**Poisson´s ratio** ν **[-]**
Reinforced concrete elements	nonporous	linear elastic	25.0	30 000	0.15
Pavement			24.0	5 000	0.20
Micropiles			25.0	210 000	0.20

Soils							
Soil type	**Drainage type**	**Material model**	**Unit weight** γ **[kN·m^{-3}]**	**Young's modulus** E **[MPa]**	**Poisson´s ratio** ν **[-]**	**Friction angle** φ **[°]**	**Cohesion** c **[kPa]**
Deluvial deposit (clayey gravel)	drained	Mohr - Coulomb	21.0	70	0.30	36.0	1.0
Slightly weathered – weathered sandstones			21.0	1 250	0.20	42.0	1.0
Backfill			20.0	150	0.20	38.0	1.0

Gegrids				
Geogrid type	**Material model**	**Tensile strength** T_{ult} **[kN·m^{-1}]**	**Axial stiffness** EA **[kN·m^{-1}]**	**Interfaces** R_{inter} **[-]**
Tensar RE560	elastic	93.0	1000	0.9

Table 3: Trafic loads on the retaining wall.

Location	Tandem system TS	ULD system
	Axle press Q_{ik} [kN]	**q_{ik} (or q_{rk}) [kN·m^{-2}]**
Lane No. 1	300	9
Lane No. 2	200	2.5
Lane No. 3	100	2.2
Remaining area q_{rk}	0	2.5

Table 4: Phasing of the construction and loading of the retaining wall.

Phase No.	Construction phase
1 - 4	constructing of the foundation constructions
4 - 29	constructing of the reinforced earth structure - 12 reinforcement levels
30	constructing of the final prefab on the crown of the retaining wall
31 - 32	constructing of the backfill under the pavement
33	constructing of the pavement
34	load from traffic

4.2 Comparison of the results of numerical modelling and geotechnical monitoring

The deformed model of the retaining wall is presented in Fig. 6. The isosurfaces of the horizontal deformations of the retaining wall are shown in Fig. 7 and of the vertical deformations are shown in Fig. 8. A comparison of the results of geotechnical monitoring and numerical analysis of the retaining wall is shown in Table 5.

Table 5: Comparison of the results of geotechnical monitoring and numerical analysis.

	Extensometers [mm]				Cells for earth pressure [kPa]		
Geotechnical monitoring	**Reinforcement level No.**						
	2	5	8	11	2	6	10
	0.2	1.7	2.3	4.6	10.0	32.5	22.5
Numerical analysis	**Geogrid extension [mm]**				**Earth pressure [kPa]**		
	3.4	4.1	5.0	5.2	20.9	23.8	13.7

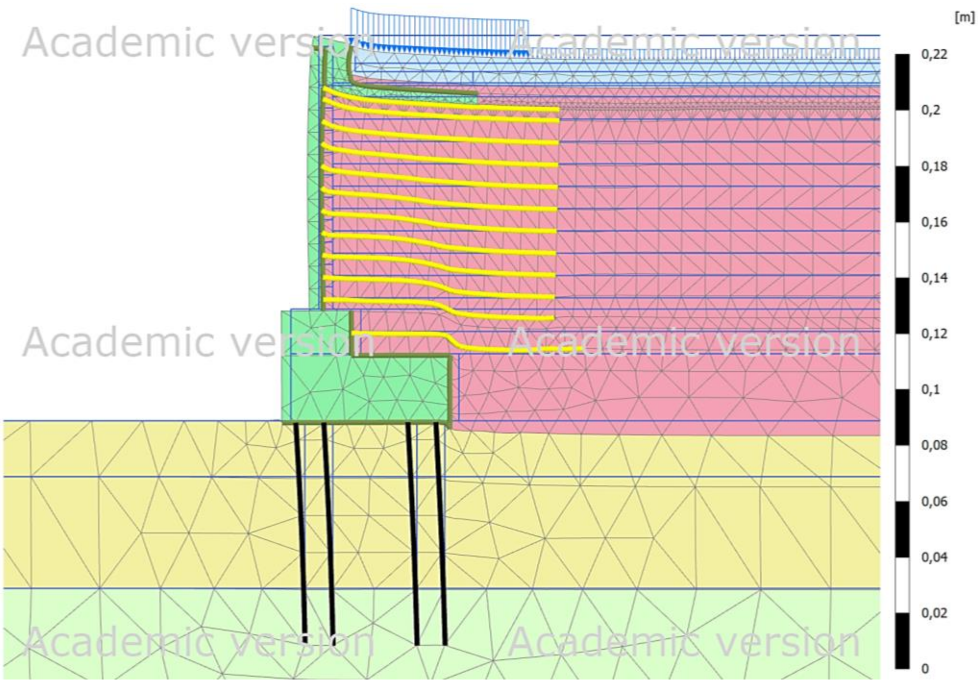

Fig. 6: Deformed model of the retaining wall.

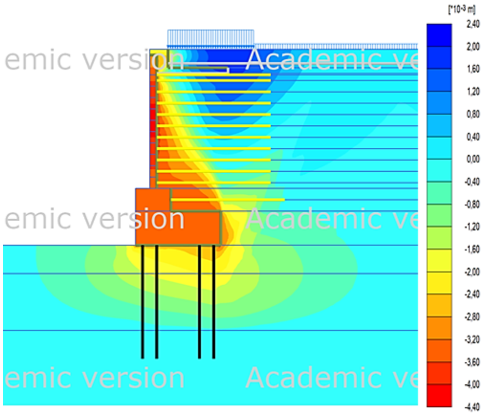

Fig. 7: Horizontal deformations of the retaining wall.

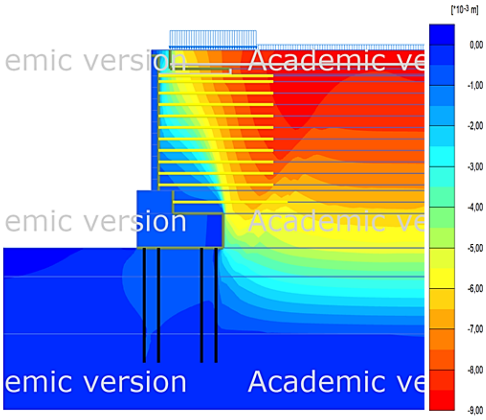

Fig. 8: Vertical deformations of the retaining wall.

The minimum values of the deformations of the geogrids of the retaining wall, as well as the minimum values of the earth pressures acting on the back of the retaining wall resulting from the numerical analysis, were also confirmed by the geotechnical monitoring measurements. The last geotechnical monitoring measurements were carried out 4.5 years ago (June 27, 2018). There is an increase in deformations over time, so it can be expected that the values of the measured deformations at the present time would be closer to the numerically analyzed deformation values, which proves the reality of the numerical model.

4.3 Parametric study of the reinforcement of the retaining wall

The part of the reinforced retaining wall is 4.8 m high. It is reinforced with 12 levels of 4 m long geogrids with a vertical spacing of the geogrids of 0.4 m. This reinforcement of the retaining wall can be characterized as a high degree of reinforcement in relation to its height. This is also indicated by the minimal values of the deformations of the geogrids resulting from the numerical analysis and also confirmed by geotechnical monitoring. For this reason, the numerical model was used for a parametric verification study:

- The effect of the geogrid length on the deformation of the face of the retaining wall;
- The effect of the geogrid spacing on the deformation of the face of the retaining wall;
- The effect of the interaction of geogrids and soil on the deformation of the face of the retaining wall.

The effect of the geogrid length on the deformation of the face of the retaining wall was analyzed in a numerical model by shortening the original geogrid length from 4.0 m to a length of 3.0 m and a length of 2.0 m. The original length of the geogrids was approximately equal to the height of the reinforced part of the retaining wall, and the analyzed shortening represented the length of the geogrids equal to the ratio of 0.75 and 0.50 of the height of the reinforced part of the retaining wall. The retaining wall model considered in the numerical model with a geogrid length of 4.0 m is in Fig. 5, with a geogrid length of 3.0 m is in Fig. 9, and with a geogrid length of 2.0 m is in Fig. 10.

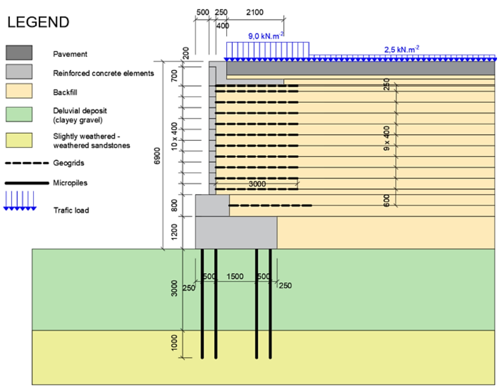

Fig. 9: The retaining wall - geogrid length 3.0 m.

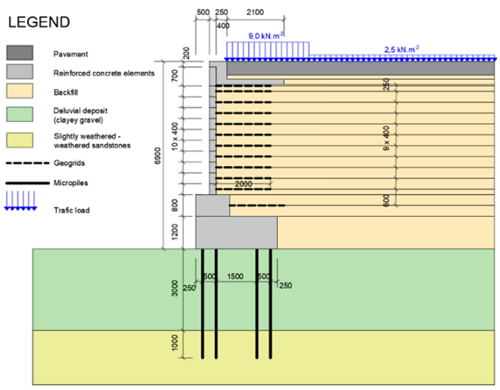

Fig. 10: The retaining wall - geogrid length 2.0 m.

The effect of the vertical spacing of the grogrids on the deformation of the face of the retaining wall was analyzed in a numerical model by increasing the original vertical spacing of the geogrids of 0.4 m to double the distance of 0.8 m and triple the distance of 1.2 m. The retaining wall model considered in the numerical model with a vertical distance of geogrids of 0.4 m is in Fig. 5, with a vertical spacing of geogrids of 0.8 m is in Fig. 11, and with a vertical spacing of geogrids of 1.2 m is in Fig. 12.

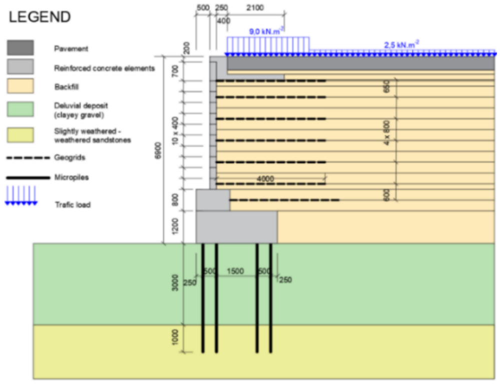

Fig. 11: The retaining wall - geogrid spacing 0.8 m.

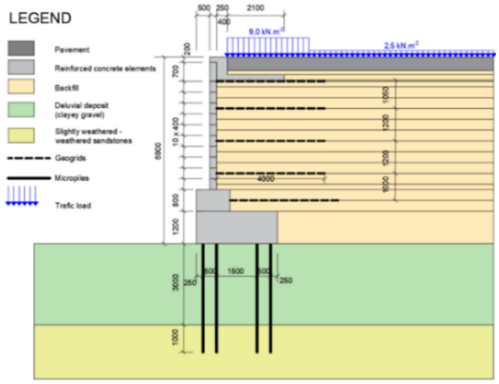

Fig. 12: The retaining wall - geogrid spacing 1.2 m.

The contact property between the geogrids and the soil is given by the R_{inter} parameter [10]. It represents the interaction of geogrids and backfill soil in a reinforced earth structure. The impact of the reduction of shear strength of a soil – geogrid interface on the stability of an embankment is presented in [11]. The authors in [12] state the value of R_{inter} = 0.9 and in [13] state values in the range of R_{inter} = 0.9 - 1.0 for coarse-grained backfill and R_{inter} < 0.9 for fine-grained backfill. The authors in [14, 15] even state values of R_{inter} > 1.0 based on experimental measurements. Numerical analysis in the Plaxis program does not allow the use of R_{inter} > 1.0. Initially, the interaction of geogrids and soil R_{inter} = 0.9 was considered. The effect of the interaction of geogrids and soil on the deformations of the retaining wall face was analyzed in a numerical model by increasing the value of the interaction of geiogrids and soil to R_{inter} = 1.0 and by decreasing the interaction of geogrids and soil to R_{inter} = 0.8.

The results of the parametric study of the numerically analyzed influence of changing retaining wall reinforced are presented in a graphic form. The effect of the length of the geogrids on the deformation of the face of the retaining wall is shown in Fig. 13. The effect of the geogrid spacing on the deformation of the face of the retaining wall is shown in Fig. 14. The effect of the interaction of geogrids and soil on the deformation of the face of the retaining wall is shown in Fig. 15.

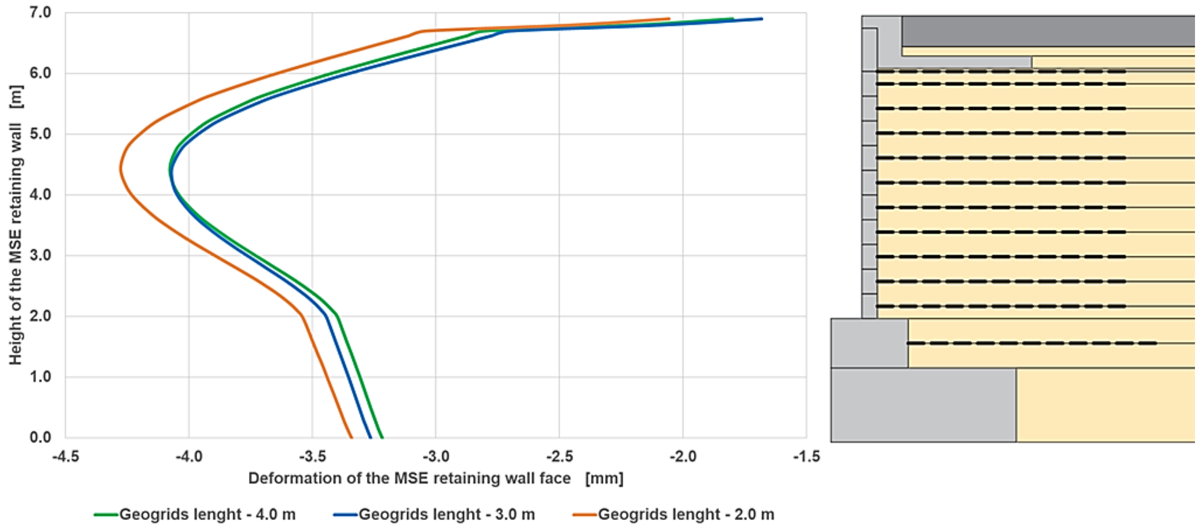

Fig. 13: Effect of the geogrids length on the deformation of the face of the retaining wall.

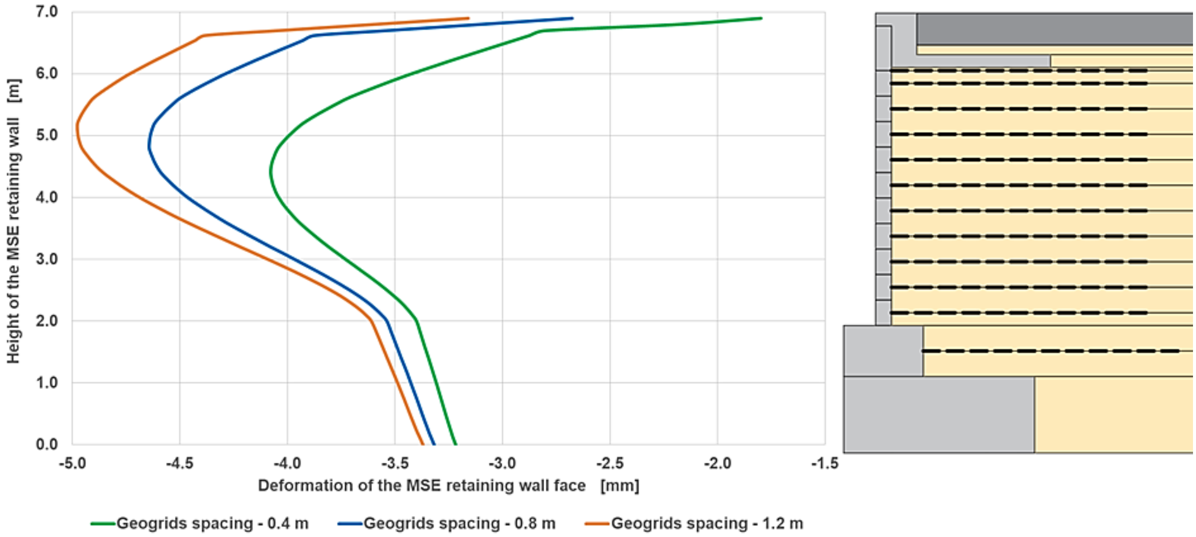

Fig. 14: Effect of the geogrids spacing on the deformation of the face of the retaining wall.

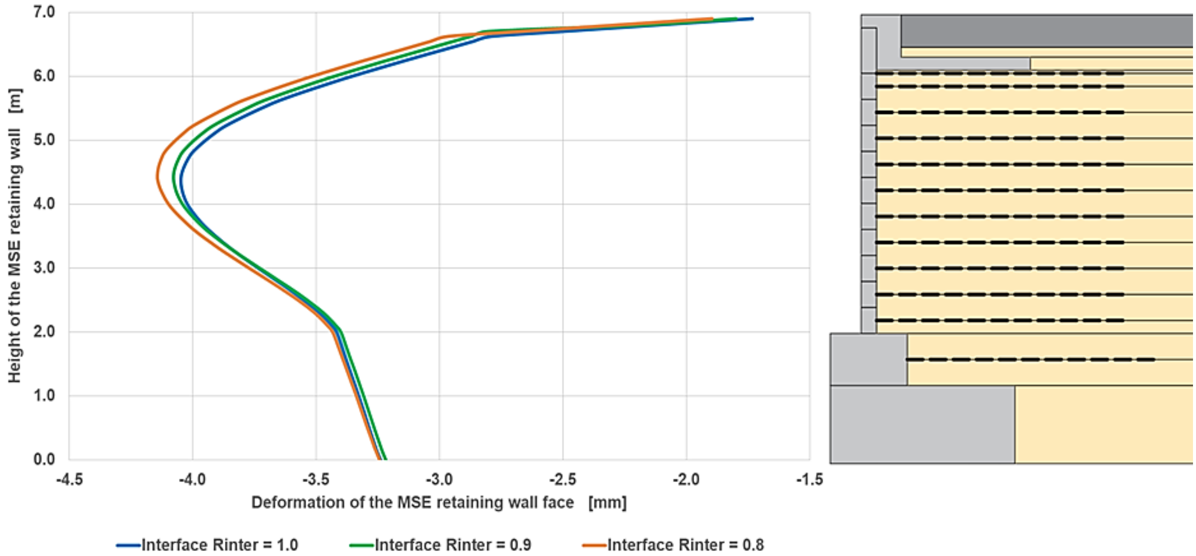

Fig. 15: Effect of the interaction of geogrids - soil on the deformation of the face of the retaining wall.

5 Conclusions

The numerical analysis of the real construction of the reinforced retaining wall with geogrids was focused on the analysis of its deformations. The profile of the numerically analyzed retaining wall was identical to the profile in which the geotechnical monitoring focused on the measurement of the deformation of the reinforcing geogrids, the measurement of earth pressures, and the measurement of the inclination of the retaining wall was carried out. The identical position of the profile of the numerically analyzed retaining wall with the position of the profile monitored by geotechnical monitoring allowed for a mutual comparison of the results of geotechnical monitoring and numerical analysis. This comparison verified the reality of the numerical model of the analyzed retaining wall structure. Small deformations of the geogrids resulting from numerical analysis and confirmed by geotechnical monitoring indicate a high degree of reinforcement of the retaining wall with geogrids. The numerical model of the retaining wall, the reality of which was verified by geotechnical monitoring measurements, was used for a parametric study investigating the effect of the length of the geogrids, the effect of the vertical spacing of the geogrids, and the effect of the interaction of the geogrids and the soil on the deformations of the face of the retaining wall. The following facts resulted from the results of the parametric study:

- The shortening of the geogrids in the 0.75 ratio to the original length, which is approximately equal to the height of the reinforced part of the retaining wall, did not affect the amount of deformation of the face of the retaining wall. The deformation of the face of the retaining wall was approximately identical in the case of the original lengths and the shortened lengths of the geogrids to a ratio of 0.75 to the original lengths.

- The effect of the shortening of the geogrids on the deformation of the face of the retaining wall was manifested when the geogrids were shortened in a ratio of 0.50 to the original length, which is approximately equal to the height of the reinforced part of the retaining wall. In place of the largest deformation of the face of the retaining wall, the deformation increased by 4.9 %.
- The greatest impact on the deformations on the face of the reinforced wall was an increase in the vertical spacing of the geogrids, a reduction in the number of reinforcement levels. The deformation increased by 13.9 % in place of the greatest deformation of the face of the retaining wall by increasing the vertical spacing of the geogrids in a ratio of 2.0 to the original spacing of the geogrids. The deformation increased by 22.0 % in place of the greatest deformation of the face of the retaining wall by increasing the vertical spacing of the geogrids in a ratio of 3.0 to the original spacing of the geogrids.
- A decrease in the value of the parameter R_{inter}, which is considered in the numerical analysis as the interaction between geogrids and soil from the original value of R_{inter} = 0.9 per R_{inter} = 0.8, there was an increase in deformation of 1.6 % in the place of the largest deformation of the face of the retaining wall. With an increase in the value of the R_{inter} parameter from the original R_{inter} = 0.9 per R_{inter} = 1.0, the deformation decreased by 0.7 % in the place of the greatest deformation of the face of the retaining wall.

From the results of a parametric study of a numerically analyzed real structure of a retaining wall the results showed that the greatest effect on its horizontal deformation is the number of reinforcement levels, and the smallest effect is the value of interaction parameter considered between geogrids and soil.

The results of the geotechnical monitoring of a real engineering structure are very valuable, not only from the point of view of the integration of early warning and risk management, but also from the point of view of calibrating the numerical model of the structure. The numerical model calibrated in this way can be used for parametric studies, as is presented in this paper. The last geotechnical monitoring measurements were carried out 4.5 years ago (June 27, 2018). It would be appropriate to continue geotechnical monitoring at regular intervals.

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