Internal and Global Analysis of a Gabion Wall Using 2D and 3D Limit Equilibrium Analysis: A Comparison of Multiple Methods

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Abstract. Gabion walls are a type of retaining wall made up of steel baskets typically filled with rock. They have gained popularity in recent decades due to their strength and aesthetic. Multiple methods for performing gabion wall internal stability analysis exist in literature. This study will consider two different methods: 1) Maccaferri design method with reference to the French Normative (NF-P 94-281), 2) The cohesion method referring to the ASTM A975-21 for the strength parameters of the gabions. The gabion wall case study used in this paper pertains to a wall in the British Leyland works complex in Longbridge, Birmingham, constructed in 1973. This wall uses polymer-coated gabions to resist acidic backfill and have an appropriate durability. Internal stability of the wall was done using the two methods above. Global stability was then analyzed using both 2D and 3D limit equilibrium analysis. Recommendations are provided regarding the internal stability method.

Keywords: gabion · retaining · wall · slope stability · limit equilibrium

1 Introduction

Gabion walls consist of multiple wire-meshed baskets filled with stones of the proper size and mechanical characteristics, allowing for drainage of water from the retained soil. The individual units are firmly tied together to form a monolithic retaining wall.

Thanks to their inherent properties (monolithic, permeable, flexible, environmental integrated, modular system easy to install), gabion walls have been widely spread in civil works being an attractive option for practitioners. Gabion walls offer a technical, economical, and esthetical alternative to more traditional solutions such as concrete walls and have shown an extraordinary capability of integrating in the natural environment. The gabion units considered in this study are baskets manufactured from double-twisted hexagonal woven steel wire mesh (8×10 mesh type) in compliance with ASTM A975-21. The wire mesh can be coated with an high abrasion resistant polymer to provide gabions an higher durability and consequently a longer design life.

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As with other retaining walls, a gabion wall needs to be designed to ensure both local stability and the overall stability of the slope being retained, and for both ultimate and serviceability limit states. Local stability of a gabion wall is ensured by checking the factor of safety against traditional retaining wall failure modes, such as overturning, sliding, and bearing, among others (Peerdawood and Mawlood 2010). Overall stability concerns the sliding of surrounding soil mass either around (global stability) or through the gabion wall (internal stability).

Although there are many methods and design procedures available for designing a gabion wall to satisfy local stability, there remains little agreement regarding the methodology used to analyze slopes containing gabion walls for overall stability, particularly regarding the internal stability. There are a variety of methods available in the literature which may be used to assess the overall stability of slopes in general. The most popular method for overall slope stability analysis remains the limit equilibrium method (LEM), by which a slope is first partitioned into slices (in 2D) or soil columns (in 3D) above a given slipping surface.

A modelling approach specific for gabion walls was proposed by Javankhoshdel et al. (2022) using LEM to assess the overall slope stability. To account for failure through the baskets, in Javankhoshdel et al. (2022) an application of the Grodecki (2017) method for determining homogenized Mohr-Coulomb parameters for the wall material towards LEM is employed.

In the following, this method is applied to a real case study, to evaluate internal stability of a gabion wall, and compared to a method proposed by Maccaferri.

The method proposed by Maccaferri refers to the French normative "NF-P 94-281" (AFNOR 2014) method and in particular the Appendix E "*Vérification de la stabilité interne des murs cellulaires avec éléments empilés en gabions*" using, as recommended by the normative, homogenized Mohr-Coulomb parameters determined by experiments relating to extreme configurations conducted by the manufacturer.

Some recommendations about the use of the two different methods are provided, especially regarding the serviceability limit state and the durability of the gabion wall, which turn out to be crucial to design a long-lasting solution avoiding excessive deformations in the long-term period.

Finally, the global stability analysis of the case study was conducted by means of 2D and 3D LEM, using, respectively, the Rocscience software's Slide2 and Slide3 (Rocscience 2023a, b).

2 Project Description

The case study analyzed in this work is a gabion wall constructed in 1973 in the British Leyland works complex in Longbridge, Birmingham (UK). A new junction had to be built for an important road infrastructure, therefore a retaining wall was necessary to sustain the main road, the junction roads and the slope retained (Fig. 1). Some design constraints were imposed by the presence of an existing building, the requirement for an easy-to-install solution while reducing the involvement of big machinery during construction. Additionally, the presence of an acidic backfill and the requirement for a draining solution, which avoids the development of overpressures in the ground retained

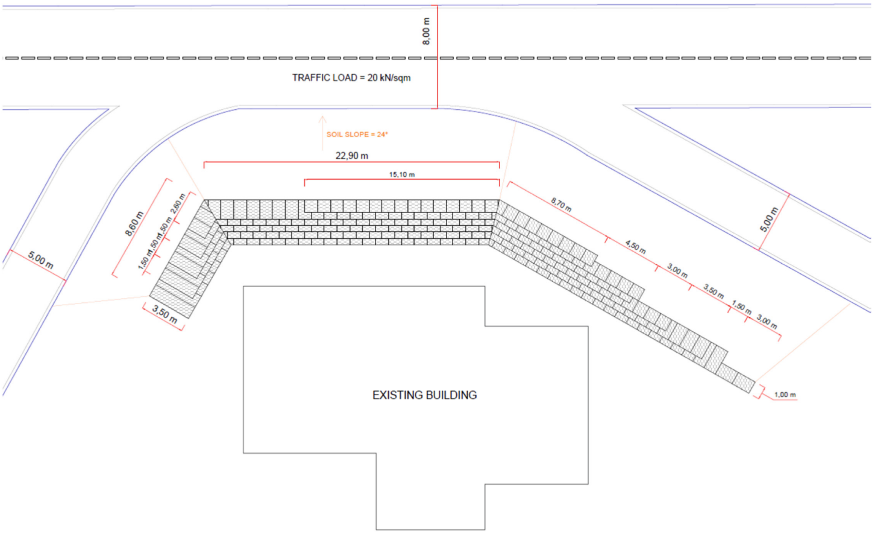

Fig. 1. Plan view of the project

by the wall, led to the choice of a gabion wall. Furthermore, given the wall proximity to the building, the aesthetic of the gabion units was considered.

The wall is built with gabion units manufactured from double-twisted hexagonal woven steel wire mesh, 8 × 10 mesh type, 2.7 mm diameter polymeric coated steel wire. The gabions applied in this solution, as they were produced at the time, are still in compliance with the current ASTM A975-21 standard.

Due to the peculiar geometric constraints of the project, the gabion wall had a unique 3D geometry, which was achievable owing to the modular characteristics of the gabions and the ease with which they can be tailored in corners.

3 Gabion Wall Design

The gabion wall was built with height up to 6 meters (m), to support the slope and the road on top. The characteristics of the foundation and backfill soils can be found in Fig. 2, in which is shown a cross-section of the designed wall.

Gabion walls with stepped front faces are usually preliminary designed, according to recommend practice, considering a base length between 0.5 and 0.7 times the height of the wall. In the case study analyzed a base length of 3.5 m was designed, with step of 0.5 m between each row of gabions.

It is of great importance to provide a geotextile layer at the back of the wall, which will prevent the loss of fine materials from the soil behind the wall while letting the water drain. For the same reason a drainage at the bottom end of the wall back shall be designed.

Gabion baskets can have different sizes and height. In this case study, baskets of 1.0 m height were adopted. Owing to their modular characteristics, different gabion sizes can be used in the same project to achieve the desired shape of the wall. Gabion boxes longer than 1.5 m should be fitted with transverse vertical diaphragm panels at 1.0 m centers to prevent undue distortion and stone migration (BSI 2015).

A typical drawing of gabion units, manufactured with double-twisted hexagonal woven steel wire mesh, is shown in Fig. 3.

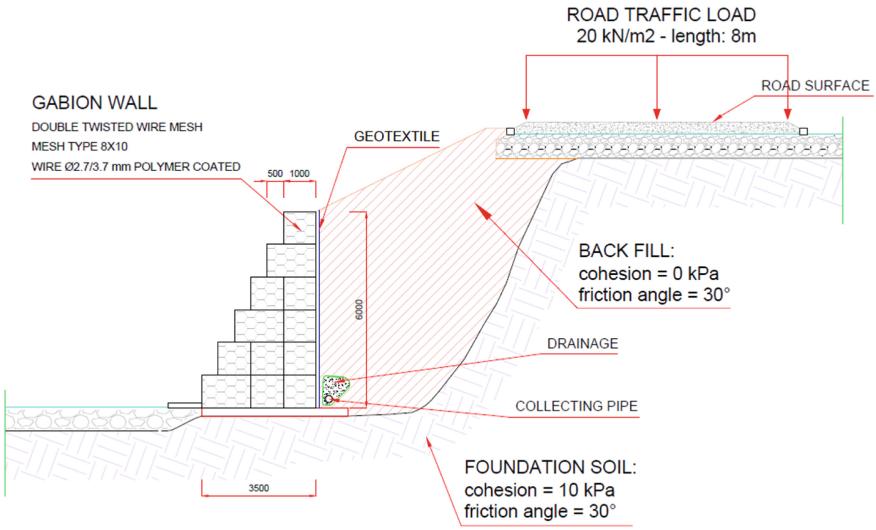

Fig. 2. Gabion wall cross-section (units in millimeters, unless otherwise indicated)

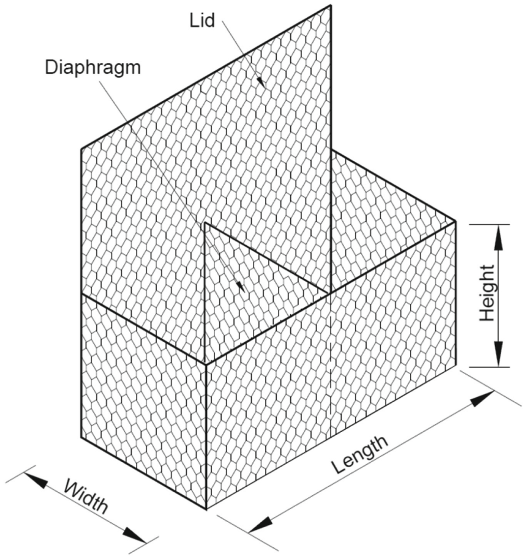

Fig. 3. Typical gabion unit

Due to the presence of an acidic backfill, the gabion structure was manufactured with polymeric-coated wire mesh. The overall diameter including the coating is 3.7 mm, but the steel diameter responsible for resisting the loads is 2.7 mm. The polymeric coating shall provide to the wire mesh, among other characteristics, high abrasion resistance and protection against corrosion as per ASTM A975-21 and shall be proved to be environmental harmless.

The ASTM A975-21 prescribes, for this specific type of gabion, a minimum tensile strength of 42.3 kN/m. The Maccaferri Gabions (8 × 10 mesh type, 2.7mm polymer coated steel wire) can provide higher values, equal to 50.0 kN/m.

The checks regarding the local stability of the gabion wall (sliding, overturning, bearing capacity) are omitted in this study, as they are essentially conducted in the same way as per traditional retaining walls.

4 Internal Stability

In addition to the local stability checks, the internal stability of the retaining wall must be checked. The retaining walls may be subjected to excessive internal stresses caused by the external loading of the thrust and overloads. Thus, this check is made specifically for each type of retaining wall.

In the case of gabion walls, checking the internal stability consists of ensuring that, under the effect of actions applied, the wall will not suffer any degradation threatening its monolithic behavior (AFNOR 2014). The stability checks shall be conducted for each row constituting the retaining structure and performed according to four criteria:

1. Overturning around the downstream point of the row in question.
2. Sliding along a plane formed by the interface with the element located under the row in question.
3. Shear stress acting on the gabions of the considered row.
4. Compressive stress acting on the gabions of the considered row.

A row is considered stable if none of the four preceding limit states is reached.

For each gabion block level, the overturning and sliding analysis is performed considering the total height of the structure from the top to that level for the active thrust calculation and considering the friction between the blocks as the sliding resistance along the base. The active thrust can be evaluated by means of traditional formulations (ex: Rankine's theory or Coulomb's theory) for simple geometries and boundary conditions; when dealing with more complex conditions, like the case study presented in this work, the application of LEM is recommended.

The maximum shear force acting on each gabion layer can be calculated as the thrust force component parallel to the layer considered. The maximum compressive force on each layer, alternatively, is given by the sum of the normal component of the active thrust and the weight force of the gabions of the upper rows. The relative stresses can be obtained dividing the forces by the arm of their application point.

The maximum shear stress and compressive stress acting on each gabion raw shall then be compared with the allowable gabion pressure and shear.

4.1 Javankhoshdel et al. (2022) / Grodecki (2017) Method

Based on the additional confining pressure of a membrane shown by Bathurst and Karpurapu and modifications provided by Grodecki (2017), an effective value for the cohesive strength through the gabion wall, c_r, can be determined using Eq. 1 (Bathurst and Karpurapu 1993):

$$c_r = \frac{\Delta\sigma_3}{2}\tan\left(45^\circ + \frac{\varphi}{2}\right) \tag{1}$$

where φ is the friction angle of the filling material in the baskets, and $\Delta\sigma_3$ is the increased confining pressure, which can be determined using Eq. 2 (Bathurst and Karpurapu 1993).

$$\Delta\sigma_3 = \frac{2f_t\varepsilon_c}{d\varepsilon_a(1-\varepsilon_a)} \tag{2}$$

where f_t is the tensile strength of the mesh in units of force per unit length, d is the lowest gabion dimension, ε_a is the axial strain at failure assumed to be 0.05 to 0.07 (Bathurst and Karpurapu 1993), and ε_c is the circumferential strain determined, using Eq. 3.

$$\varepsilon_c = \frac{1-\sqrt{1-\varepsilon_a}}{1-\varepsilon_a} \tag{3}$$

This additional cohesion simulates the steel mesh of the gabion wall (Grodecki 2017).

4.2 Maccaferri Method

The method proposed by Maccaferri refers to the French normative NF-P 94-281 (AFNOR 2014) method using, as recommended by the normative, homogenized Mohr-Coulomb parameters determined by experiments conducted by the manufacturer. Maccaferri has conducted extensive test campaigns over the years to determine the most representative resistance values to use for its gabions. Different kinds of test were performed by Maccaferri including compression tests (Fig. 4), direct shear tests, flexibility test and load tests on real-sized retaining walls.

Agostini et al. (1987) studied apparent cohesion concerning the connection between gabion elements. These values depend on the ratio of weight of mesh to the volume of the gabion structure, and it increases as the gabion depth decreases, with gabions filled with diaphragms, and with gabions constructed of heavier mesh.

It is possible to compute the representative apparent cohesion using the empirical expression in Eq. 4.

$$\mathrm{c_g} = 0.03\mathrm{P_u} - 0.05 \tag{4}$$

where $\mathrm{P_u}$ is the weight of the metallic mesh per cubic meter of wall expressed in kg/cm3 and $\mathrm{c_g}$ is expressed in kg/cm^2.

The value of the gabion/stone filling friction angle depends upon different factors: the stone/rocks angularity (φ increases with the angularity), the granulometry (φ increases with the grain non-uniformity) and the density (φ increases with the density) and can be

Fig. 4. Compression test in gabions

conservatively assumed as $\varphi^* = 45°$, in order to account for the effect of the compaction of the gabion fill.

From the apparent cohesion and friction angle values between gabions it is possible to determine the allowable shear stress:

$$\tau_{adm} = N * \tan\varphi * + c_g \quad (5)$$

where N is the normal force on the respective layer. The allowable compression stress of the gabion can be computed by the empirical relation:

$$\sigma_{adm} = 50 * \gamma_g - 30 \quad (6)$$

where γ_g is the unit weight of the gabion, given in tf/m3.

The limits on the allowable shear stress, suggested by Agostini et al. (1987), are for the purpose of controlling the deformation rather than for safety reasons. Therefore these values do not represent the ultimate limit values but keep in count for the serviceability limit of gabions.

4.3 Results and Discussion

Using the Javankhoshdel et al. (2022) method and considering the Maccaferri Gabions (8 × 10 mesh type, 2.7mm polymer coated steel wire) can be assumed a tensile strength of the mesh equal to 50 kN/m, d = 1.0 m and $\varepsilon_a = 0.07$, which give $c_r = 56.53$ kPa. The results of the Internal stability checks of shear (and compression) strength conducted with the Javankhoshdel et al. (2022) method are shown in Table 1.

Applying the Maccaferri method (Agostini 1987; AFNOR 2014) and considering the gabions employed in the case study the apparent cohesion (c_g) results to be 19.5 kPa. The results of the Internal stability checks of shear (and compression) strength conducted with the Maccaferri method are shown in Table 2.

From the results it is evident that the Maccaferri method is significantly more conservative than the Javankhoshdel et al. (2022) method. This is due to the fact that the

Table 1. Internal Stability checks – Javankhoshdel et al. (2022) method

Layer	τmax [kN/m^2]	τadm [kN/m^2]	**FS_τ**	σmax [kN/m^2]	σadm [kN/m^2]	**FS_σ**
2	4.62	70.16	**15.19**	20.05	–	**–**
3	13.77	94.06	**6.83**	3745	–	**–**
4	30.93	133.48	**4.32**	69.97	–	**–**
5	41.21	178.80	**4.34**	92.22	–	**–**
6	46.34	228.09	**4.92**	102.44	–	**–**

Table 2. Internal Stability checks – Maccaferri method

Layer	τmax [kN/m^2]	τadm [kN/m^2]	**FS_τ**	σmax [kN/m^2]	σadm [kN/m^2]	**FS_σ**
2	4.62	38.98	**8.44**	20.05	553.49	**27.61**
3	13.77	55.25	**4.01**	3745	553.49	**14.78**
4	30.93	74.46	**2.41**	69.97	553.49	**7.91**
5	41.21	89.36	**2.17**	92.22	553.49	**6.00**
6	46.34	101.19	**2.18**	102.44	553.49	**5.40**

Javankhoshdel et al. (2022) method evaluates the ultimate limit state against internal stress in the gabions, while the Maccaferri method sets lower limits to avoid undesired deformations.

When dealing with the internal stability of gabion walls it is of great importance to keep in count for the structure serviceability, which for this specific aspect turns out to be more important than the ultimate limit state analysis.

Therefore, although the gabion wall flexibility is a fundamental characteristic to avoid sudden catastrophic failures, it is crucial to evaluate the serviceability limits of these types of retaining walls. The serviceability limit of a gabion wall is strongly influenced by the durability of the gabion units, and therefore by their capability to keep their resistance characteristics unaltered in the long term. The durability of a gabion depends on many factors: corrosion and environmental effects, installation damage, UV ray's exposure, abrasion, temperature variations and pH effects.

The methodology proposed by Agostini (1987) sets limits for the internal stability of the gabions which turned out to be conservative if compared to more recent tests. Thanks to the continuous improvement in gabions' manufacture and recent research studies to evaluate the membrane effect of the hexagonal doble-twisted wire mesh, a new approach may be proposed.

More recent research and tests conducted on gabions, along with numerical modeling, can potentially lead to a more comprehensive approach to evaluate the serviceability limit state of gabion walls combining the internal stability analysis, conducted for the ultimate limit states, and the durability of the gabion units.

5 Modelling and Overall Stability Using Slide2 and Slide3

To assess the overall stability of the gabion wall, first a 3D analysis is carried out for the entire wall and then for each side of the wall a 2D analysis is carried out.

Figure 5 shows the 3D model in the Rocscience Slide3 software used in this study.

Multi Modal optimization technique introduced by Li et al. (2020) is used in this model which has the ability to show more than one global minimum factor of safety.

The results of the 3D LEM analysis are shown in Fig. 6. It can be seen in this figure that the 3D LEM analysis provides two minimum FS of 1.34 and 1.44 in two different regions of the middle and the right wall, respectively.

Three separate 2D sections are created in the 3D model to carry out 2D LEM analysis for each portion of the wall. The results of the 2D analysis of the section and the 2D model of the middle section are shown in Fig. 7a and 7b. All three 2D sections give a factor of safety of 1.16.

One might question why the results of the 2D analysis and 3D analysis of this model are so different (about 30%). This is an interesting output for retaining walls which shows the limitations of the 2D analysis. As it can be seen in Fig. 7b, the failure surface in the 2D analysis passes behind the wall. However, in the 3D analysis because of the 3D nature of the model, slip surface intersects the wall on both ends of the slip surface and as a result, some of the columns in the slipping mass adopt the properties of the gabion wall, causing an increase to the FS.

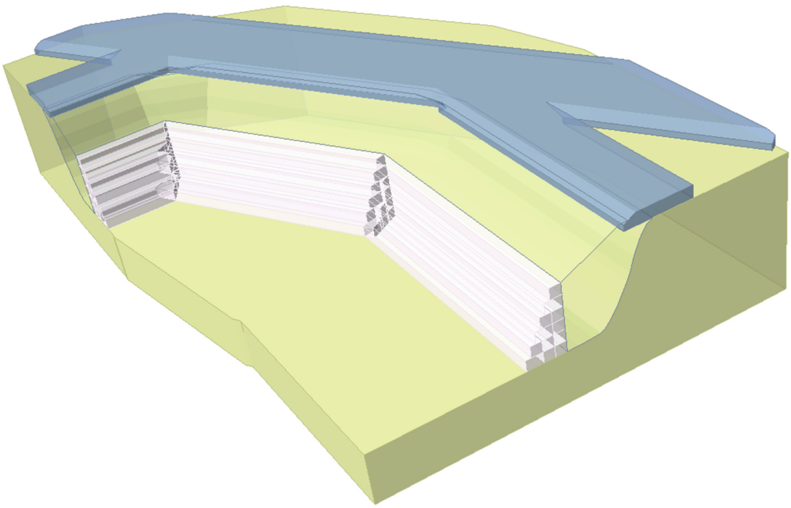

Fig. 5. The 3D model used in this study

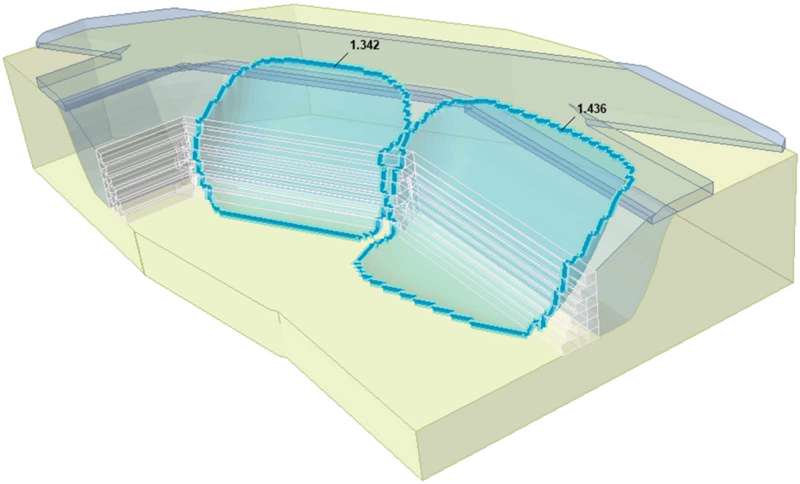

Fig. 6. Results of the 3D LEM analysis

6 Conclusions

The internal and overall stability analysis of a gabion wall has been presented in this study. Owing to the unique 3D geometry and special considerations in the project area, both 2D and 3D analyses were required and accomplished via Slide2 and Slide3. The differences in the analysis results highlight the importance to keep in count for 3D effects, especially when dealing with complex geometries. A comparison between the Javankhoshdel et al. (2022) method and the Maccaferri method (Agostini et al. 1987; AFNOR 2014) was conducted, showing different results for the internal stability analysis results. These differences represent differences in the assumptions between the serviceability and ultimate limit states. As such, it is important to consider the basis for assuming the equivalent cohesion in a gabion wall. More recent research can potentially lead to a more comprehensive method to evaluate the internal stability of gabion walls, combining the ultimate limit states approach and the durability of the gabion units.

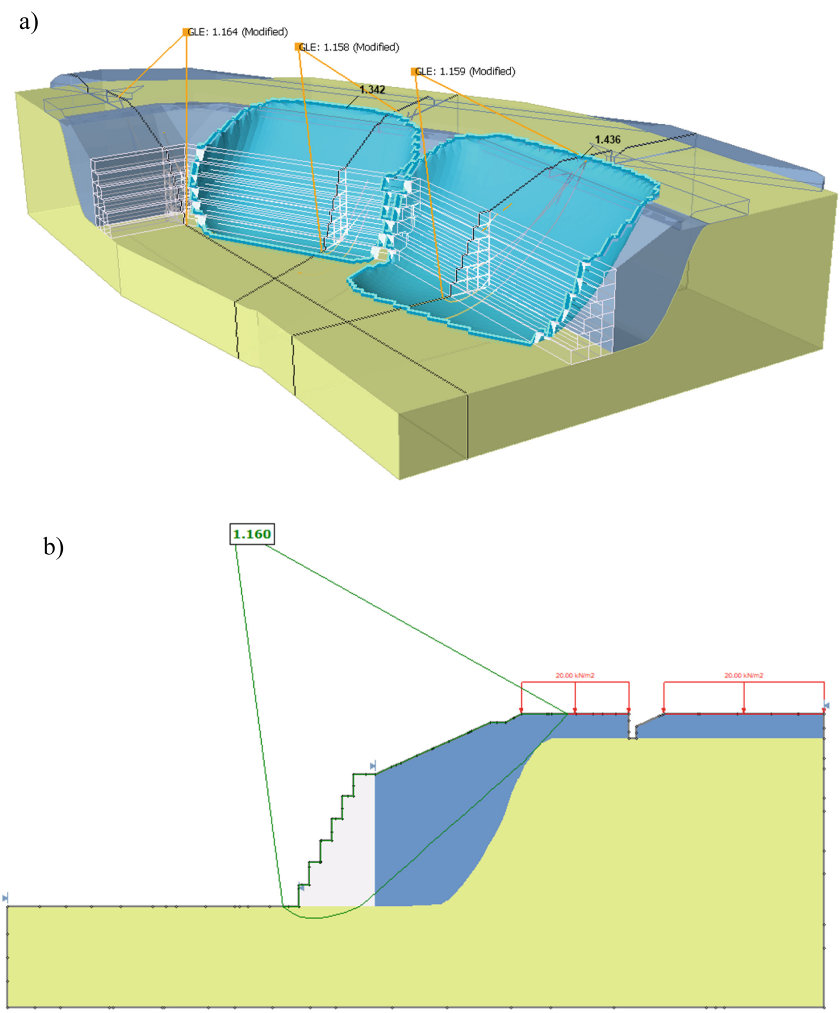

Fig. 7. a) Results of the 2D LEM analysis for three sections on top of the 3D LEM results b) 2D results of the mid-section

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