Limit equilibrium analysis of gabion walls

Sina Javankhoshdel
Rocscience Inc., Toronto, ON, Canada
Liam Jacob Sy
Department of Civil and Environmental Engineering – University of Waterloo, Waterloo, ON, Canada
Terence Ma, Brigid Cami & Thamer Yacoub
Rocscience Inc., Toronto, ON, Canada

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ABSTRACT
Gabion walls are a form of retaining wall composed of modular steel baskets typically filled with rock. Gabion retaining structures have seen an increase in popularity and use due to their aesthetic properties and structural strength. Very few solutions to modelling gabion walls exist in the literature, lacking especially in limit equilibrium analysis methods. Complications arise in modeling the steel mesh, interactions between baskets, and joint strength of the connected baskets. In this study, different methods are presented to model these types of walls using the limit equilibrium method. The overall stability of these types of walls can be extended to other types of retaining walls. Also, for the first time, the weak layer method is presented in this study, and it can be used to model the joints between gabions if joint failure is of interest.

RÉSUMÉ
Les gabions sont des murs de soutènement composé de paniers en acier modulaires généralement remplis de roche. Les gabions ont connu une popularité et une utilisation croissantes en raison de leurs propriétés esthétiques et de leur résistance structurelle. Très peu de solutions de modélisation des gabions existent dans la littérature, manquant notamment de méthodes d'analyse d'équilibre limite. Des complications surviennent lors de la modélisation du treillis d'acier, des interactions des paniers et de la résistance des joints des paniers connectés. Dans cette étude, différentes méthodes sont présentées pour modéliser ces types de murs à l'aide de la méthode d'équilibre limite et pour la stabilité globale de ces types de murs qui peut être étendue à d'autres types de murs de soutènement. De plus, pour la première fois, la méthode de la couche faible est présentée dans cette étude, et elle peut être utilisée pour modéliser les joints entre gabions si la rupture des joints présente un intérêt.

1 INTRODUCTION

Gabion walls consist of multiple wire-meshed baskets which are joined together to form a retaining wall. The baskets are typically filled with granular material, allowing for drainage of water from the retained soil. The modular nature of this solution makes it an attractive option for practitioners.

As with other retaining walls, a gabion wall needs to be designed to ensure both local stability and the overall stability of the slope is being retained. Local stability of a gabion wall is ensured by checking the factor of safety against failure modes for the wall itself, such as overturning, sliding, and bearing, among others (Peerdawood & Mawlood 2010). Overall stability concerns the sliding of surrounding soil mass either around or through the gabion wall. There are many cases documented in the literature whereby slopes containing gabion walls have failed in the mode of overall stability (Nowatzki & Wrench 1988; Beck & Sharma 2013; Cao et al. 2016; Chikute & Sonar 2019). 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.

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 traditional 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. Then, static equilibrium is solved to determine whether the available shearing capacity in the materials intersected by a slip surface meets the required shearing force required for the mass to remain in static equilibrium. Despite the popularity of LEM, the authors are not aware of any comprehensive solutions available via LEM for modelling the overall slope stability specifically for gabion walls in the literature. Failure through the gabion wall is theoretically possible in at least the following two unique modes: (1) failure through the mesh interface, and (2) failure through the baskets and granular material. Especially in the case of three-dimensional slopes, failure through yielding of the basket meshes on the side flanges of a slip surface has been observed (Nowatzki & Wrench 1988). Corrosion of the mesh is also possible, which reduces the strength of the mesh and can lead to failure (Chikute & Sonar 2019). To account for failure through the mesh interface, this paper proposes a new weak layer method that models the lateral interface between rows of baskets as thin weak layers with equivalent Mohr-Coulomb parameters. To account for failure through the baskets, the authors employ an application of the Grodecki (2017) method for determining homogenized Mohr-Coulomb parameters for the wall material towards LEM. This can be accomplished by using either the proposed cohesion method or mesh methods.

2 METHODOLOGY

Very few solutions to modelling gabion walls exist in the literature, lacking especially in limit equilibrium analysis methods. Complications arise in modeling the steel mesh, interactions of the baskets, and joint strength of the connected baskets. Two suggested methods will be covered in his paper using Rocscience's 2D slope stability program *Slide2*. They are described as the (1) cohesion method and the (2) mesh method. Both methods require the friction angle and unit weight of the fill. An additional method using weak layers is also covered.

2.1 Cohesion Method

Based on the additional confining pressure of a membrane shown by Bathurst and Karpurapu and modifications provided by Grodecki, the cohesion of the gabion, c_r, can be determined using Eq. 1 (Bathurst & Karpurapu 1993):

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

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 & Karpurapu 1993).

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

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 & Karparapu 1993), and ε_c is the circumferential strain determined, using Eq. 3.

$$\varepsilon_c = \frac{1-\sqrt{1-\varepsilon_a}}{1-\varepsilon_a} \quad [3]$$

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

2.2 Mesh Method

The gabion mesh can also be represented using a support element. Support elements in LEM are represented by restoring forces applied either in the direction of the slip surface, parallel to the support, or at an intermediate angle. Typically, support elements are assumed to consider three modes of failure: tensile, pullout, and stripping. It is recommended only to consider tensile force since the mesh is joined together and no stripping or pullout occurs. Note that the connection strength must be greater or equal to the tensile strength of the mesh to disregard stripping.

To model the gabion walls, a restoring force can be applied wherever the slip surface intersects the face of a basket. When modeling the mesh, it should simply surround the gabion blocks such as in Figure 1. The material inside the blocks will be assumed to behave based on the properties of the filling.

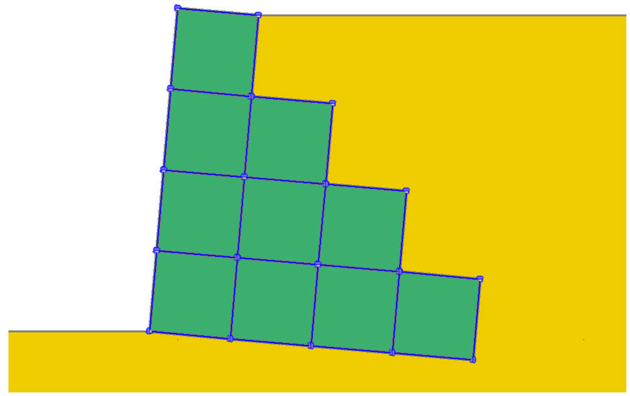

Figure 1. Modelling a mesh of gabion baskets using support elements.

If desired, the inner mesh can be modeled as two separate meshes for additional strength. This can be easily done by creating a new geosynthetic support type like the regular mesh and doubling the specified allowable tensile strength and connection strength by 2. The model should then look like Figure 2.

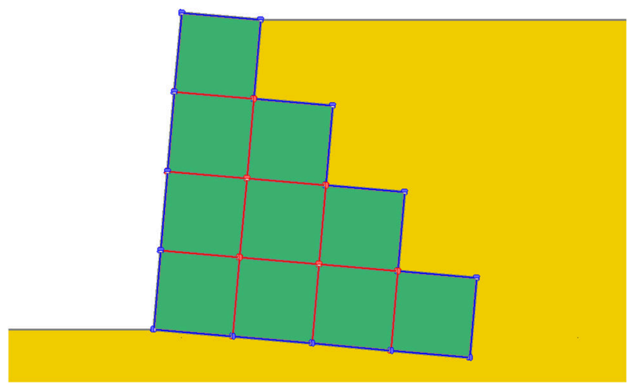

Figure 2. Doubled-up support elements representing two gabion basket faces are shown in red.

2.3 Weak Layer Method

Some slope stability software programs offer a "weak layer" feature, which allows searching of the critical slip surfaces to occur along thin material layers with reduced material strength properties. The joints between gabions and interactions between them can be modeled as weak layers if slipping failure through the joints is of interest. This method can only be used by itself or in conjunction with the cohesion method, as supports from the mesh method will interfere with the weak layer.

The unit weight of the filling material should be the same as the gabion fill. As suggested by Grodecki (2017), an interaction coefficient, R, between 0 and 1 can be used to determine the friction angle of the weak layer. For steel mesh, R is typically 0.9 to 0.95 but can be lower in other configurations (Bergado et al. 2003). Therefore, the weak layer friction angle should be set to 90% to 95% of that of the gabion fill. The cohesion can then be assumed to be either zero or calculated using Eq. 4 (Grodecki, 2017).

$$c = f_j / b \quad [4]$$

Where f_j is the tensile strength of the gabion joint in units of force per unit length, and b is the bottom width of the gabion (typically 1.0 m).

If desired, a weak layer through the very bottom of the gabion wall can also be included. The weak layer is the same as gabion joint elements, but cohesion is assumed to be zero. The weak layer should go through the appropriate sections (gabion weak layer between horizontal connections and soil weak layer at the very bottom of the wall). Note that weak layers will not act as desired in the vertical direction. Based on the previous model, the weak layers should look like Figure 3.

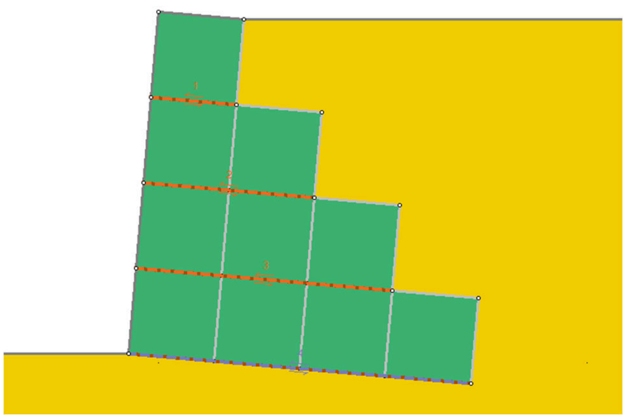

Figure 3. Weak layer method used to model slipping failure between rows of baskets.

The orange weak layers represent the joints of the gabion connections and the purple weak layer at the bottom is the soil and gabion interaction.

3 NUMERICAL EXAMPLE

A numerical example is presented in this section to demonstrate the use of each of the proposed methods towards evaluating the overall slope stability of a gabion wall. It is based on the case study conducted by Cao et al. (2016) on the failure of a gabion wall in Ontario.

The results for this study were obtained using the Slide2 program. A combination of the Cuckoo search method combined with Surface Altering Optimization (Mafi et al. 2020) was employed to determine the critical slip surface in each scenario.

3.1 Cohesion Method

The gabion wall shown in Figure 4 is angled at 9 degrees from the horizontal and consists of 1 m x 1 m x 1 m cube baskets. A road exists at the top of the embankment, whereby an applied gravity load of 12 kPa is assumed. The allowable tensile strength of the mesh is assumed to be 71 kN/m. Taking d = 1.0 m and ε_a = 0.07 gives c_r = 100 kPa from Eq. 1, which will be assumed to be the cohesion in the gabion wall. The material properties of the model are thus given in Table 1.

Table 1. Material properties assumed for the cohesion method

Material	Weight (kN/m^3)	Cohesion (kPa)	Phi (°)
Backfill	21	0	32
Gabion wall	20	100	45
Bottom layer	20	0	30

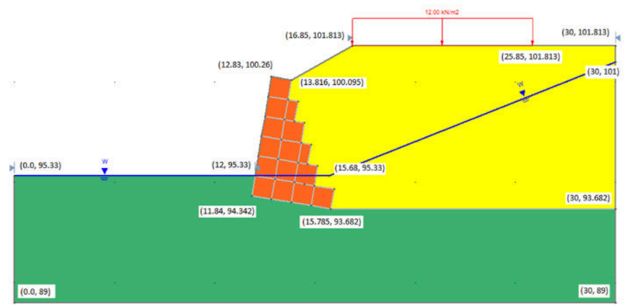

Figure 4. Gabion wall model adopted from Cao et al. (2016), with wall material assumed from the equivalent cohesion method.

The critical slip surface in this scenario has a Janbu factor of safety of 0.967 and avoids the wall, shown in Figure 5.

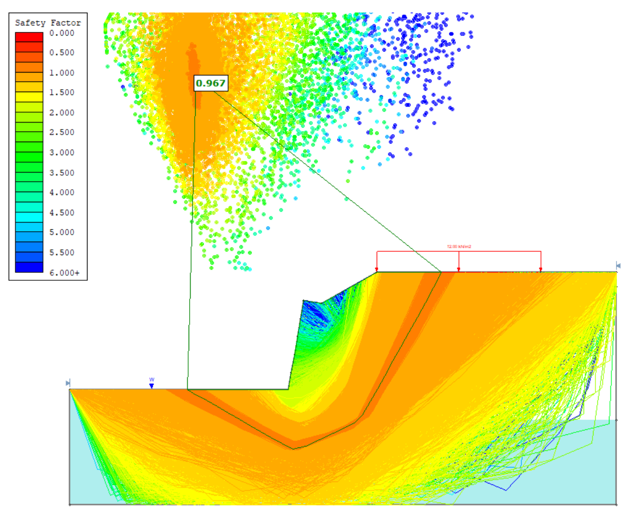

Figure 5. Janbu method factor of safety results using the equivalent cohesion method.

Some of the slip surfaces generated during the search go through the wall and result in high factors of safety indicated in yellow, green, and blue. Note also that very minor slip surface exists at the top embankment above the wall, but it is excluded from the analysis via the use of a minimum slip surface depth filter.

3.2 Mesh Method

For the mesh method, the cohesion of the filling material is assumed to be zero. Support elements with a shear capacity of 20 kN/m were added to the model, shown in Figure 6. Wherever the slip surface intersects a mesh element, a restoring force of 20 kN/m perpendicular to the mesh element is therefore applied on the slipping mass at the location of the intersection. The material properties for this scenario are shown in Table 2, with the gabion wall material set to a cohesion of zero as it is considered separately from the mesh.

Table 2. Material properties assumed for the mesh method

Material	Weight (kN/m^3)	Cohesion (kPa)	Phi (°)
Backfill	21	0	32
Gabion wall	20	0	45
Bottom layer	20	0	30

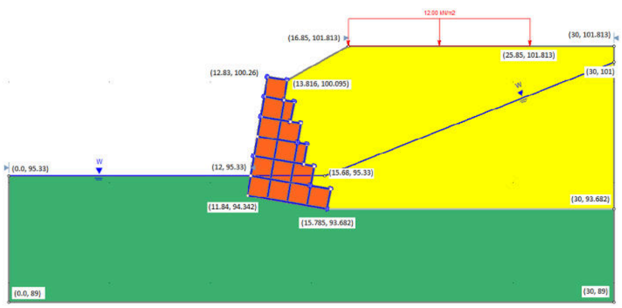

Figure 6. Gabion wall model adopted from Cao et al. (2016) with wall modelled using the mesh method.

The critical slip surface is shown in Figure 7 and is similar to the one from the cohesion method since the slip surface does not intersect the gabion wall.

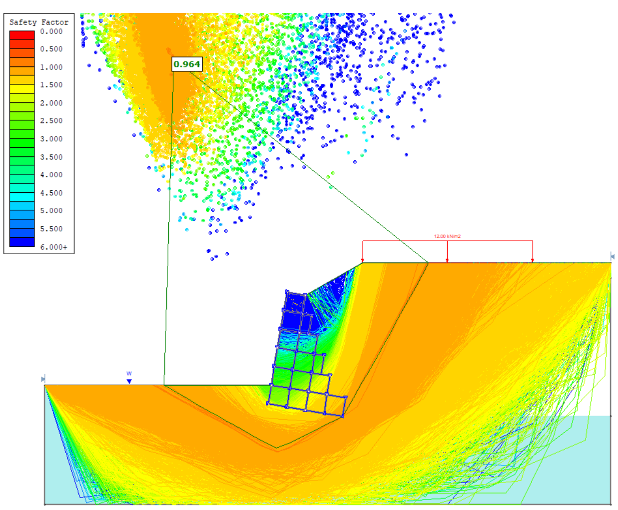

Figure 7. Janbu factor of safety results using the mesh method.

Like the cohesion method, the factor of safety increases gradually as the slip surface intersects higher up the wall. The mesh method in this case appears slightly more conservative because the factor of safety through the wall appears to be slightly higher at any given location of the slip surface.

A sample, non-critical slip surface was queried from the envelope shown and shown in Figure 8 to show the restoring forces generated from the mesh for surfaces intersecting the mesh. Due to the ductile nature of the mesh elements the restoring force was assumed to act in the direction of slippage. However, different assumptions can be made regarding the directions of these forces.

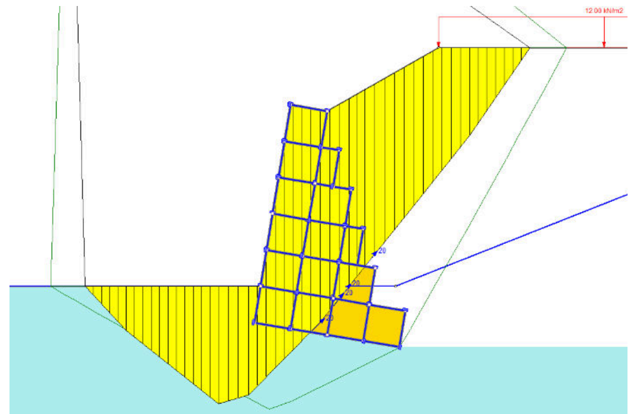

Figure 8. Restoring forces exerted by intersected mesh elements.

3.3 Weak Layer Method

Using the weak layer method, weak layers have been added to the gabion wall in Figure 9 to simulate potential weak joint failure or shear failure through the gabion wall. Note that vertical weak layers would cause the slip surfaces to clip vertically and should be avoided during modelling in general.

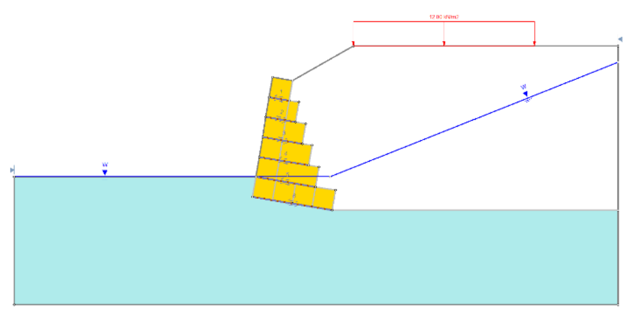

Figure 9. Weak layers added to the gabion wall model.

The properties used in Table 3 were used for the materials in the model.

Table 3. Material properties assumed for the cohesion method

Material	Weight (kN/m^3)	Cohesion (kPa)	Phi (°)
Backfill	21	0	32
Gabion wall	20	100	45
Bottom layer	20	0	30
Weak layer	--	0	15

The weak layer was intentionally made very weak to create a different failure mode for this example. The cohesion and friction angle of the weak layer for this example should typically be higher based on the results of Eq. 3 (e.g. φ = 41.5° with R = 0.9 and Eq. 4 (c = 20 kPa). With these higher values, the weak layers do not govern the critical slip surface, which avoids the wall and is like the ones shown in the previous scenarios.

Nevertheless, scenarios can exist whereby the mesh is assumed to be weaker, the fill material can have a much lower friction angle, and/or the value of the interaction coefficient R is small. Although this failure mode is uncommon, it should nevertheless be considered if the designer suspects there is not much friction between the rows of gabions.

The results of the slip surface search in Figure 10 show that there are multiple possible failure modes through the interfaces of the wall. All possible slipping surfaces with the Janbu method factor of safety below 1.5 are shown in the figure.

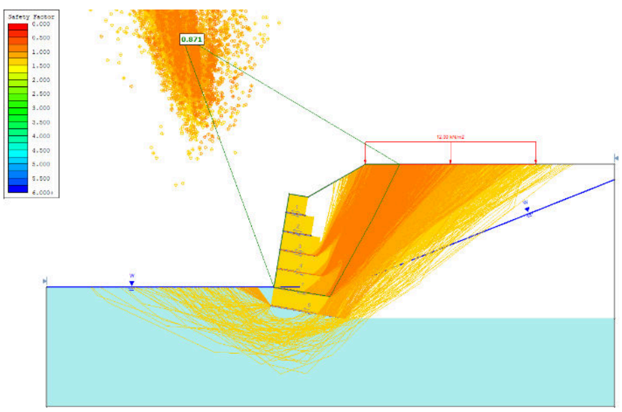

Figure 10. Janbu method factor of safety results using the weak layer method.

The critical failure mode is through the second interface from the bottom, but failures through any of the four bottommost layers are imminent.

4 CONCLUSION

This study has shown demonstrated differing modelling approaches for gabion walls with respect to limit equilibrium. Two methods are presented for modelling the failure of a slope through the gabion wall, and a weak layer method is approached for examining the case whereby a slip surface goes through the interface between adjacent rows of baskets. Although the latter case is shown to be uncommon, it should be considered if the designer suspects there is little friction between the rows of the gabions.

5 REFERENCES

ASTM A975. 2003. *Standard Specification for Double-Twisted Hexagonal Mesh Gabions and Revet Mattresses (Metallic-Coated Steel Wire or Metallic-Coated Steel Wire with Poly(Vinyl Chloride) (PVC) Coating).* ASTM International. West Conshohocken, PA, USA.

Bathurst, R.J. and Karpurapu, R. 1993. Large-Scale Triaxial Testing of Geocell-Reinforced Granular Soils. *Geotechnical Testing Journal,* 296-303.

Beck, W.K. and Sharma, L.M. 2013. Mississippi River Road Gabion Wall/Slope Stabilization. In *Seventh International Conference on Case Histories in Geotechnical Engineering*, Chicago, IL, USA.

Bergado, D.T., Youwai, S., Teerawattanasuk, C. and Visudmedanukul, P. 2003. The Interaction Mechanism and Behaviour of Hexagonal Wire Mesh Reinforced Embankment with Silty Sand Backfill on Soft Clay. *Computers and Geotechnics,* 522-523.

Cao, L., Peaker, S. and Ahmad, S. 2016. A Case Study of Embankment Retaining Wall in Ontario. In *GeoVancouver 2016,* Vancouver, BC, Canada.

Chikute, G.C. and Sonar, I.P. 2019. Failures of Gabion Walls. *International Journal of Innovative Technology and Exploring Engineering*, 8(11): 1384-1390.

Grodecki, M. 2017. Numerical Modelling of Gabion Joints. *Technical Transactions,* 2(2017): 84-88.

Mafi, R., Javankhoshdel, S., Cami, B., Chenari, R.J., and Gandomi, A.H. 2020. Surface altering optimization in slope stability analysis with non-circular failure for random limit equilibrium method. *Georisk Assessment and Management of Risk for Engineered Systems and Geohazards.*

Nowatzki, E.A. and Wrench, B.P. 1988. Geotechnical Investigation into Causes of Failure of a Gabion Retaining Wall. In *Second International Conference on Case Histories in Geotechnical Engineering,* St. Louis, MO, USA.

Peerdawood, C.T. and Mawlood, Y.I. 2010. Analytical Study for Stability of Gabion Walls. *Journal of Pure and Applied Sciences,* 22(5): 21-34.