A jupyter-based computational tool for the geotechnical design of Gabion retaining walls

Keisy D. Morales-Salgado[1], Guilherme J. Cunha-Gomes[2,3] and Jesús D. Villalba-Morales[4]

[1]*Department of Postgraduate Program in Geotechnical Engineering, Federal University of Ouro Preto (UFOP)*
122 Professor Paulo Magalhães Gomes Street – Bauxita, 35400-000, Ouro Preto – MG
keisy.salgado@aluno.ufop.edu.br
[2]*Geotechnical Engineering Graduate Program, Federal University of Ouro Preto*
122 Professor Paulo Magalhães Gomes Street – Bauxita, 35400-000, Ouro Preto – MG
guilhermejcg@ufop.edu.br
[3]*Department of Environmental Engineering, Federal University of Ouro Preto*
122 Professor Paulo Magalhães Gomes Street – Bauxita, 35400-000, Ouro Preto – MG
guilhermejcg@ufop.edu.br
[4]*Department of civil engineering, Pontificia Universidad Javeriana*
7th Avenue No. 40-62, Bogotá, Colombia
Jesus.villalba@javeriana.edu.co

Abstract. Gabion retaining walls are widely used in geotechnical and hydraulic engineering due to their permeability, flexibility, and adaptability to diverse terrains. Despite their broad application, the design of gabion walls remains a challenging, particularly in ensuring structural stability under varying soil and loading conditions. This study proposes a comprehensive methodological approach for the geotechnical design of gabion retaining walls, integrating theoretical analysis and numerical modeling techniques. Gabions are treated as gravity-based structures whose performance depends on parameters such as the weight of the soil unit, the angle of friction, the cohesion, and the geometry of the wall. The proposed design framework includes calculations of active and passive earth pressures, minimum base width, embedment depth, and safety factor evaluation. A Jupyter-based computational tool is developed to simulate the behavior of gabion walls under various soil and loading conditions, incorporating classical geotechnical formulations. Stability is assessed using limit equilibrium methods. The proposed methodology is validated against existing design standards and academic benchmarks to ensure consistency with established geotechnical practices. The results provide a foundation for future developments, including the implementation of computational tools to automate the design process.

Keywords: Gabion walls, Geotechnics, Numerical modeling, Soil interaction, Stability.

1 Introduction

Gabion walls are structures generally made of steel wire mesh filled with rocks, forming walls that can come in various shapes and sizes, such as box, mattress, cylindrical, or sack gabions (J. Oosthoek, 2008). A box-type gabion wall is constructed by vertically stacking each individual unit and joining them with steel wires to provide tensile strength to the entire structure until the specified height is reached (Samayoa et al., 2018). The use of gabions varies depending on the field of engineering, and they can be applied for structural, protective, or even decorative purposes. In geotechnical applications, gabions are essential for controlling soil erosion, reinforcing slopes and embankments, draining saturated soils, and stabilizing retaining structures (Dos Santos, 2018). Common geotechnical uses include stream bank stabilization (Brunet & Shuey, n.d.), embankments for waste disposal sites (Vashi et al., 2012), and gabion mattresses for preventing erosion in channels and earth-retaining structures (Toprak et al., 2016). However, although gabion walls are widely used for these purposes, their design

presents several challenges that can affect their long-term performance.

The design of gabion walls faces several problems that can compromise their effectiveness and durability. These problems arise from both structural factors and site-specific characteristics. Despite the popularity of gabion walls due to their flexibility and ease of construction, they are prone to failures such as excessive deformation, sliding, overturning, and local collapse, especially in applications like slope reinforcement or stream bank stabilization. These failures typically occur when the design or construction is not done properly (Chikute & Sonar, 2019, 2021). A key challenge in their design is ensuring the external stability of the structure, especially in relation to sliding, support, and overturning (Chatpattananan et al., 2021). Additionally, the design process requires an iterative selection of the dimensions of a typical vertical cross-section of the wall, which can be complicated due to changing site and environmental conditions (Peerdawood & Mawlood, 2010).

To address these design challenges, this work presents the development of a computational tool in Jupyter for the geotechnical design of gabion retaining walls. The main objective is to offer an open-source and user-friendly alternative that systematizes the design process in a transparent and adaptable environment, suitable for both academic and professional applications. This paper details the theoretical framework underpinning the tool, describes its implementation and features, and demonstrates its application through a case study. The goal is to highlight the potential of this tool to facilitate sensitivity analyses, improve design reproducibility, and promote the use of digital resources in geotechnical engineering.

2 Theory

This section presents the theoretical framework adopted for the design and analysis of gabion retaining walls. It covers the structural behavior of gabions, earth pressure estimation, and stability criteria used to assess external performance. These principles form the foundation of the computational tool proposed in this study.

2.1 Gabion Walls as Gravity Retaining Structures

Functioning as gravity retaining structures, gabion walls rely on their own mass and geometry to resist lateral earth pressures, classifying them within this category of retaining systems (Das, 2013). These structures—composed of rock-filled steel wire mesh units (J. Oosthoek, 2008) —are widely used in geotechnical, hydraulic, and environmental works to stabilize slopes, retain soil, and facilitate drainage due to their modularity, flexibility, and permeability (Dos Santos, 2018). In contrast to rigid concrete walls, gabions can accommodate minor ground deformations without compromising stability, which is particularly advantageous in erosion-prone or irregular terrain. As with any retaining system, their design must satisfy external and internal stability criteria to prevent failures such as sliding, overturning, or bearing capacity issues (Herrero et al., 2024).

2.2 Earth Pressure Theories Applied to Gabions

One of the most critical steps in the design of retaining structures is the determination of the lateral earth pressure exerted by the soil on the wall (de Almeida, 2010). This pressure depends on the mechanical properties of the retained soil—such as unit weight, internal friction angle, and cohesion—as well as on the wall and backfill geometry (Das, 2013). The design process typically begins with the selection of dimensions for a representative vertical cross-section and progresses iteratively until all stability criteria are satisfied (Peerdawood & Mawlood, 2010).

In this context, the Rankine theory is commonly used to estimate active and passive earth pressures. It assumes planar failure surfaces, no wall friction, and a homogeneous, isotropic backfill. The theory also allows consideration of surcharge loads at the surface, which can be modeled as uniform vertical pressures acting on the backfill. When the backfill surface is inclined, the inclination angle must be accounted for, as it affects the magnitude and distribution of earth pressures. Furthermore, if a water table is present, hydrostatic pressure must be added to the effective stress profile, influencing both active and passive resistance.

These theoretical considerations are essential for evaluating the forces acting on gravity-type retaining walls such as gabions and form the basis for subsequent stability analysis.

2.3 External Stability of Gabion Walls

An essential aspect of gabion wall design is ensuring external stability with respect to sliding, bearing capacity, and overturning (Chatpattananan et al., 2021). These verifications aim to confirm that the wall's self-weight and resistance mechanisms are sufficient to counteract the destabilizing effects of lateral earth pressures.

Overturning occurs when the stabilizing moment provided by the wall's self-weight about the toe is insufficient to resist the overturning moment caused by the active earth pressure. If the resultant of forces falls outside the middle third of the base, excessive rotation or tilting may occur (Das, 2013; de Almeida, 2019).

Sliding takes place when the shear resistance along the wall base, including passive resistance at the toe, is not enough to counterbalance the horizontal component of the active earth pressure. This failure mode is especially critical when the friction angle at the base is low or the foundation soil is weak (de Almeida, 2019; Knappett & Craig, 2012).

Bearing capacity failure occurs when the vertical stresses transmitted by the wall to the foundation soil exceed the soil's allowable bearing capacity, potentially leading to differential settlements or structural collapse (de Almeida, 2019).

These stability checks are fundamental for gravity retaining walls such as gabions and form the basis for determining safe and efficient wall dimensions in varying geotechnical conditions.

2.4 Integration in the Computational Tool

The theoretical concepts discussed are implemented in a structured computational tool for the geotechnical design of gabion retaining walls. The tool uses classical earth pressure theories and limit equilibrium methods to assess external stability. Users input parameters for a typical cross-section, including one or two backfill layers (unit weight, friction angle, cohesion), soil properties, wall and backfill inclinations, surcharge loads, gabion unit weight, and optionally geotextile layers for drainage modeling.

Based on these inputs, the tool calculates active and passive pressures and verifies stability against sliding, overturning, and bearing failure. It outputs the safety factors and a schematic of the wall with applied loads. Though it doesn't perform optimization, it allows quick evaluation of design alternatives, supporting academic and preliminary engineering use. Its Jupyter Notebook environment ensures transparency, reproducibility, and ease of access.

3 Program Implementation

This section describes the development of the computational tool for geotechnical design of gabion retaining walls, covering the programming language and environment, application structure, handled inputs and outputs, and the complete workflow from data entry to results.

3.1 Development Environment and Language

The computational tool developed in this study was implemented in the Python programming language due to its versatility, readability, and wide range of scientific libraries (Bogdanchikov et al., 2013; Srinath, 2017). Python's simplified syntax allows engineers and researchers to express complex concepts intuitively, facilitating the implementation of geotechnical algorithms and design models. In addition to its technical strengths, Python has become one of the most recommended languages for teaching programming in engineering contexts (Bogdanchikov et al., 2013).

The interface was built using the Tkinter library, which is included in Python's standard distribution and enables the development of graphical user interfaces (GUIs) with interactive components. This approach provides a user-friendly environment where geometric and geotechnical parameters can be entered through clearly labeled input fields. The resulting graphical interface is presented in Figure 1, where the input fields for parameters and the control buttons to execute the calculations can be seen. To further enhance user interaction, interactive help icons are placed next to each input field. Hovering over these icons reveals a tooltip explaining the parameter's purpose and its expected range of values, making the data entry process more intuitive.

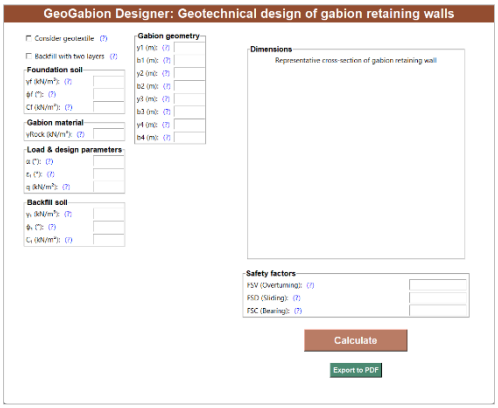


Figure 1. Graphical interface of the developed tool. Input fields for geometric and geotechnical parameters are shown, as well as buttons to perform calculations and export to PDF.

The tool runs locally and integrates seamlessly with the Jupyter Notebook platform, a widely adopted environment for scientific computing and computational reproducibility (Perez et al., n.d.; Rule et al., 2018). Jupyter offers a flexible workspace where numerical results, code, and graphical outputs can coexist, enhancing transparency and facilitating both academic and professional use.

3.2 Structure and Workflow

The program was developed as a standalone Python script integrating all computational routines, input management, graphical output, and report generation. The user-friendly interface, built with Tkinter, organizes inputs into thematic sections: backfill, foundation soil, gabion material, loads, and geometry. Optional checkboxes allow adding groundwater or dual layer backfill configurations to reflect varied site conditions.

After completing the inputs, pressing "Calculate" triggers the computation of active/passive earth pressures using Coulomb's theory and stability checks against overturning, sliding, and bearing failure. These checks are based on limit equilibrium methods and the general bearing capacity equation proposed by Terzaghi. The interface then displays a schematic of the gabion wall, helping users visualize the analyzed geometry.

To ensure proper documentation, the "Export to PDF" button generates a detailed report with all project data, assumptions, formulas, intermediate steps, results, and the wall diagram. This integrated and interactive design streamlines usage and supports fast, transparent geotechnical evaluations.

3.3 User Inputs and Parameters

The tool requires the user to input a comprehensive set of parameters that define the mechanical behavior of the materials involved and the geometry of the gabion wall. These parameters are grouped into six main categories:

Backfill soil: unit weight (γ_1 or γ_2), internal friction angle (ϕ_1 or ϕ_2), and cohesion (C_1 or C_2). The user can opt to define one or two layers, allowing for stratified backfills with distinct properties.

Foundation soil: like the backfill, defined by γ_f, ϕ_f, and C_f, representing the characteristics of the bearing stratum.

Gabion material: unit weight of the rock fill (γ_{Rock}) used inside the gabion cages, which directly influences the wall's self-weight.

Load and design parameters: include the backfill slope angle (α), wall face inclination (ε_1), surface surcharge (q). These values control both geometric layout and loading conditions.

Geometry of the wall: defined by up to four vertical units (y_1 to y_4) and their corresponding base widths (b_1 to b_4), allowing the user to model stepped or variable-height wall sections.

Optional features: checkboxes enable or disable the inclusion of a geotextile and the use of a two-layer backfill system.

This flexible input structure allows the tool to simulate a wide variety of field conditions and design configurations, enhancing its adaptability to practical geotechnical applications.

3.4 Outputs and Visualization

Once the analysis is executed, the tool presents both numerical and graphical results within the interface. The main outputs are the safety factors for overturning (FSV), sliding (FSD), and bearing capacity (FSC), shown in a dedicated results panel that allows users to quickly assess structural performance. Additionally, a schematic cross-section of the wall is generated based on the input geometry, providing visual feedback for validating the wall's shape and layout. To enhance usability and reduce input errors, the interface features automatic checks and real-time messages that notify users of missing or invalid data, calculation issues, or successful operations. A PDF export function compiles the calculated results, formulas, and wall diagram into a report, supporting documentation and reproducibility in line with engineering and academic practices.

4 Results

To assess the performance and applicability of the developed tool, a representative design scenario was analyzed using the implemented interface. The results include computed safety factors, earth pressures, and the generated wall configuration, allowing verification of the tool's ability to produce technically consistent and interpretable outputs.

4.1 Example Application

To evaluate the functionality and accuracy of the computational tool, a case study was conducted using representative input parameters. The wall consisted of three stacked gabion units with heights of $y_1 = 1.0$ m, $y_2 = 0.7$ m, $y_3 = 0.7$ m, and $y_4 = 0.7$ m, and corresponding base widths of $b_1 = 1.7$ m, $b_2 = 1.4$ m, $b_3 = 1$ m and $b_4 = 0.7$ m.

The backfill soil has a unit weight of 19 kN/m³, an internal friction angle of 28°, and zero cohesion, while the foundation soil shares the same unit weight and cohesion but has a higher internal friction angle of 30°. A uniform surface surcharge of 10 kN/m² is applied. The wall face is inclined at an angle of $\alpha = 10°$ from the vertical, and the backfill surface slopes at 10° with respect to the horizontal.

These parameters represent typical conditions encountered in geotechnical applications such as slope stabilization or erosion control. All inputs were entered through the graphical user interface of the tool, and the analysis was executed by selecting the "Calculate" option.

4.2 Output of the Tool

The developed tool features a graphical user interface (GUI) that allows the user to input design parameters through clearly organized fields. Figure 2. shows the interface before performing the calculation, with all input values filled in for the selected case study.

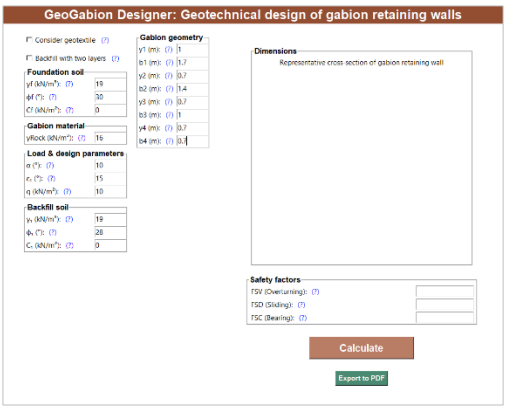


Figure 2. Graphical user interface with input parameters completed. The interface displays the input fields for defining wall geometry, soil properties, and applied loading.

Upon clicking the “Calculate” button, the tool runs the necessary routines to assess the external stability of the gabion wall. Within seconds, it displays the safety factor results for sliding (FSD), overturning (FSV), and bearing capacity (FSC), along with a schematic drawing of the wall geometry based on the provided dimensions. Figure 3. shows the interface after the calculation has been completed, including both the numerical results and the graphical representation of the wall section.

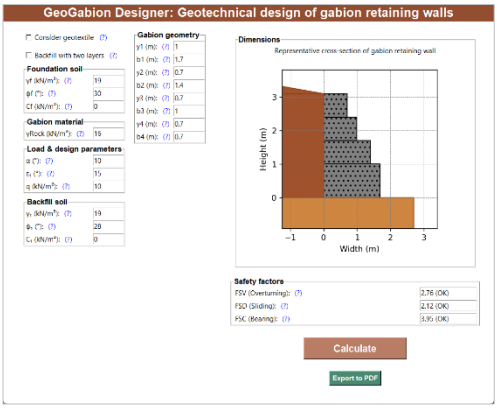


Figure 3. Graphical user interface after calculation. Computed safety factors (FSD, FSV, FSC) are shown, along with an automatically generated schematic of the wall.

In addition to the on-screen visualization, the user can generate an automatic PDF report containing: a summary of the input parameters, the equations used, computed safety factors and a graphical representation of the wall. This functionality enables structured and professional documentation of the design, making it suitable for academic and technical.

The computed safety factors — 2.76 for overturning, 2.12 for sliding, and 3.95 for bearing — all exceed standard minimum values, confirming the external stability of the wall under the specified conditions. These results validate the correct performance of the implemented routines and demonstrate the interface’s reliability for preliminary design tasks.

5 Conclusions

The primary contribution of this work is the development and validation of an open-source computational tool that systematizes and simplifies the preliminary geotechnical design of gabion retaining walls. By integrating essential external stability analyses into a user-friendly graphical interface, the tool provides a transparent and efficient alternative to manual iterative calculations and closed-source commercial software. Its implementation in Python and Jupyter Notebook promotes accessibility, reproducibility, and adaptability, making it a valuable resource for both engineering education and professional practice.

The results obtained from the application example successfully demonstrated the tool's reliability. The calculated safety factors for sliding, overturning, and bearing capacity were validated against established engineering principles, confirming the tool's capacity to produce technically sound and safe designs for preliminary assessments. This validation underscores its practical utility as a decision-making aid in the initial phases of a project, allowing for rapid sensitivity analyses of geometric and geotechnical parameters.

While the current version focuses on external stability, the tool provides a robust foundation for future expansion. The logical next steps include the incorporation of internal stability checks, such as mesh rupture and internal shear analysis, as well as the implementation of optimization algorithms. These enhancements would further extend the tool's capabilities, positioning it as an even more comprehensive solution for gabion wall design.

References

Bogdanchikov, A., Zhaparov, M., & Suliyev, R. (2013). Python to learn programming. Journal of Physics: Conference Series, 423(1). https://doi.org/10.1088/1742-6596/423/1/012027

Brunet, G., & Shuey, R. (n.d.). STREAM BANK STABILIZATION WITH VEGETATED GABIONS.
Chatpattananan, V., Kongsomboon, T., & Ratanavaraha, V. (2021). Designing gabion structures under multi-criteria objectives with goal programming. International Journal of GEOMATE, 20(82), 121–131. https://doi.org/10.21660/2021.82.GX347
Chikute, G. C., & Sonar, I. P. (2019). Failures of gabion walls. International Journal of Innovative Technology and Exploring Engineering, 8(11), 1384–1390. https://doi.org/10.35940/ijitee.J9731.0981119
Chikute, G. C., & Sonar, I. P. (2021). Gabion Wall: Eco-friendly and Cost-Efficient Retaining Wall. Lecture Notes in Civil Engineering, 124 LNCE, 229–249. https://doi.org/10.1007/978-981-33-4590-4_22
Das, B. M. (2013). Fundamentos de ingeniería geotécnica Cuarta edición. http://estudiantesingcivil.blogspot.mx/
de Almeida, P. L. (2010). Obras de Contenção Manual Técnico.
Dos Santos, P. J. (2018). Gabiões e estructuras de arrimo, Análise teórico-numérico-experimental do comportamento mecânico.
Herrero, G. A., Duque, J. H. R., Brito, L. M. dos S., Julio, V. F. de C. F., & Andrade, L. B. (2024). Muro de arrimo e drenagem: uma abordagem prática em engenharia civil. REVISTA DELOS, 17(61), e2566. https://doi.org/10.55905/rdelosv17.n61-038
J. Oosthoek. (2008). The Stability of Synthetic Gabions in Waves Master of Science Thesis on the Application of Synthetic Grids in Mattress Gabion Constructions and the Stability in Waves.
Vashi, J., Desai, A. K., & Solanki, C. H. (2012). Assessment of reinforced embankment on soft soil with PET and PP Geotextile. International Journal of Civil and Structural Engineering, 2(3). https://doi.org/10.6088/ijcser.00202030011
de Almeida, P. L. (2019). Reference Manual.
Peerdawood, C. T., & Mawlood, Y. I. (2010). Analytical Study for Stability of Gabion Walls. In Journal of Pure and Applied Sciences / Salahaddin University-Hawler (Vol. 22, Issue 5).
Perez, F., Granger, B. E., Berkeley, U. C., Poly, C., & Obispo, S. L. (n.d.). AN OPEN SOURCE FRAMEWORK FOR INTERACTIVE, COLLABORATIVE AND REPRODUCIBLE SCIENTIFIC COMPUTING AND EDUCATION.
Rule, A., Tabard, A., & Hollan, J. D. (2018). Exploration and explanation in Computational notebooks. Conference on Human Factors in Computing Systems - Proceedings, 2018-April. https://doi.org/10.1145/3173574.3173606
Samayoa, J., Baraccani, S., Pieraccini, L., & Silvestri, S. (2018). Seismic behavior of one-storey gabion-box walls buildings. Frontiers in Built Environment, 4. https://doi.org/10.3389/fbuil.2018.00007
Srinath, K. R. (2017). Python-The Fastest Growing Programming Language. International Research Journal of Engineering and Technology. www.irjet.net
Toprak, B., Sevim, O., & Kalkan, I. (2016). Gabion Walls And Their Use GABION WALLS AND THEIR USE 1. https://www.researchgate.net/publication/319503581

6 Acknowledgements

The authors would like to thank the Federal University of Ouro Preto (UFOP) in Brazil and the Postgraduate Program in Geotechnical Engineering. We also acknowledge the Geotechnical Nucleus of the School of Mines (NUGEO / UFOP) for their support. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.