

Stabilization of a gabion wall at an electrical substation in Coimbra: Design solutions and monitoring results

André Henriques, Rui Tomásio
JETSj Geotecnia, Lisboa, Portugal, ahenriques@jetsj.com

Rui Carvalho, Ricardo Braga
DST Geotecnia, Braga, Portugal, rui.moreiracarvalho@dstsgps.com

ABSTRACT: This paper presents the analysis, design, and implementation of stabilization measures for a gabion retaining wall located at an electrical substation in Coimbra, Portugal. The wall, approximately 12 m high and founded over sandy fill materials overlying decomposed schist, has exhibited progressive deformation since shortly after construction. Topographic monitoring initiated in 2009 - two years after completion - revealed significant long-term movements. After ten years, average horizontal and vertical displacements reached 30 cm and 22 cm, respectively, while maximum recorded values attained 60 cm (horizontal) and 30 cm (vertical). These displacements led to structural damage to substation buildings, pavements, cable ducts, and other critical infrastructure, motivating the need for a comprehensive geotechnical reassessment and stabilization intervention. The scope of this work includes (i) diagnosis of the failure mechanisms governing wall deformation, (ii) numerical and analytical evaluation of reinforcement alternatives under geotechnical, structural, and operational constraints, and (iii) design and construction of the adopted stabilization system. The proposed reinforcement solution consists of an 800 mm diameter bored pile wall with a depth of 20 m, installed at the gabion wall back side. This wall is braced by a series of buttresses designed to increase the solution stiffness. The buttresses are connected to the bored pile wall by a high stiffness reinforced concrete capping beam, located under the substation pavement in the final construction stage. To mitigate the potential risk of fine material washout caused by water percolation and the subsequent settlement of the substation pavement, the installation of plastic bored piles approximately 4.5 m in depth was also included in the design. The design methodology integrates limit-equilibrium stability analyses, serviceability performance criteria, and construction-stage constraints. Quantitative results from the instrumentation and monitoring program demonstrate the effectiveness of the reinforcement system, with post-construction data indicating a substantial reduction in displacement rates.

KEYWORDS: Gabion wall, Bored pile wall, Buttresses, reinforcement.

1 INTRODUCTION

Gabion walls are widely used as flexible retaining structures in civil engineering works due to their ease of construction, adaptability to differential movements, and favourable environmental footprint. Their performance relies on the combined interaction between the granular fill, wire-mesh confinement, and the surrounding soil mass. Several studies have highlighted the advantages of gabions in terms of permeability and durability when adequately protected (Pereira and Fernandes, 2023). However, despite their inherent deformability, gabion structures may experience significant long-term displacements when founded on compressible or poorly compacted soils, subjected to elevated hydraulic gradients, or when constructed with insufficient toe support or backfill control. Documented problematic behaviours include excessive lateral deformation, internal erosion or washout of fines, degradation of wire-mesh elements, and consequential damage to adjacent infrastructure.

From a sustainability standpoint, gabion solutions are often considered environmentally favourable because they use locally sourced stone, require lower embodied energy compared to reinforced-concrete retaining systems, and promote drainage without the need for extensive pipe networks (Chikute and Sonar, 2021). Nevertheless, ensuring long-term serviceability is essential for meeting governmental sustainability goals, particularly those addressing infrastructure resilience, life-cycle performance, and risk reduction.

2 LOCATION

The Bemposta substation, located in Coimbra, Portugal, is supported by a gabion wall with approximately 12 m high (Figure 1), founded over sandy fill materials overlying decomposed schist. Since its construction in 2007, the wall has exhibited progressive deformations, resulting in damage to the

substation platform, adjacent structures, and underground services.

Topographic monitoring initiated in 2009 revealed horizontal displacements of up to 60 cm and settlements bigger than 30 cm in some areas, with increasing deformation rates recorded in recent years.



Figure 1. Existing gabion wall.

This paper describes the stabilization measures implemented to control the movements of the gabion wall, ensuring long-term efficient serviceability and safety, while minimising interference with adjacent infrastructure and maintaining the operational continuity of the substation.

Considering the site constraints, soil conditions, and gabion wall geometry, the adopted reinforcement solution consisted of an 800 mm diameter bored pile wall with a depth of 20 m, installed behind the gabion wall and braced by buttresses to stabilize the gabion wall movements.

A Monitoring and Survey Plan was implemented during the works to track the structure's behaviour.

3 GEOLOGICAL AND GEOTECHNICAL SCENARIO

According to the Geological Map of Portugal (scale 1:50,000), the site is located within the Ossa Morena Zone – Porto-Tomar Shear Zone, specifically in the “Série Negra” formation, composed of grey and black schists.

To better understand the site geological scenario a geological and geotechnical site investigation campaign was performed, including 8 boreholes with Standard Penetration Tests (SPT), 2 piezometers and laboratory tests.

The results of this campaign allowed the characterization of the intersected materials in terms of their geomechanical properties and developed geological-geotechnical profiles used at the project stage. The campaign identified the following ground layers, from top to bottom:

- Fill soils (ZG3) – silty deposits with organic matter and decomposed schist fragments, loose to medium dense, with SPT values between 2 and 39 blows and a maximum thickness of about 13m.
- Decomposed schist (ZG2) – grey, locally highly weathered schists, with SPT values between 30 and 40 blows and a thickness of about 5 to 12m.
- Very competent schist (ZG1) – slightly weathered, high-strength rock mass, with SPT values above 60.

Regarding groundwater conditions, the geotechnical investigation recorded a stabilized ground water table at elevations below the gabion wall foundation

The geological-geotechnical profile presented at Figure 2 shows the different ground layers and the existing gabion wall.

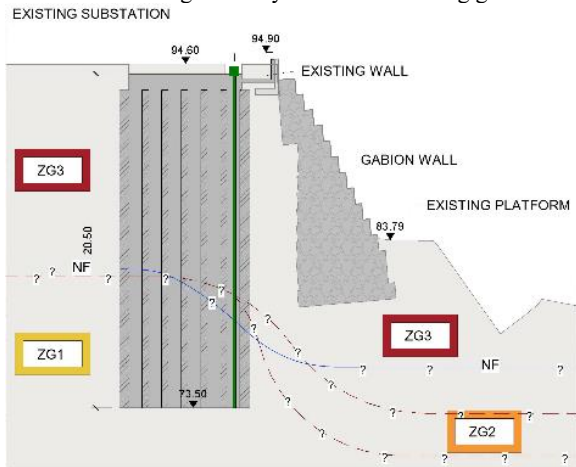


Figure 2. Geological and geotechnical profile, including both the existing gabion wall and the reinforcement solution.

4 EXISTING STRUCTURE AND PATHOLOGIES

According to information provided by the client, the gabion wall was built in 2007. Interpretation of the design drawings, compared with the as-built structure, indicated that the wall cross-section underwent modifications during construction (see Figure 3).

The original wall has an approximate length of 70 m and is topped by a reinforced concrete retaining wall, which was not part of the original design. The height difference between the substation platform and the access path at the wall's toe is about 12 m, with the upper platform at the elevation of 95.00 m and the bottom path at elevation 83.00 m. Boreholes performed to assess the wall's foundation revealed that the gabion structure extends an additional 2–3 m below the existing path platform.

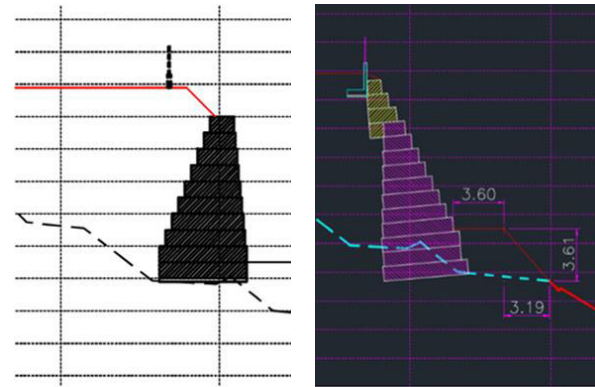


Figure 3. Gabion wall from the original design (left) and gabion wall as executed (expected) (right).

Topographic monitoring of the wall began in 2009, two years after its construction, through the installation of survey targets. Three monitoring campaigns were carried out on April 2009, September 2012, and February 2019. Of the 10 installed targets, only 4 had complete data from all three campaigns (Table 1 and Figure 4). The analysis of the recorded movements showed:

- Horizontal displacement: Targets located at elevation 90.5 m (approximately 60% of the wall height) experienced the largest displacements, about twice that of the other targets, with an average of 60 cm;
- Settlement: Targets at elevation 94.7 m recorded the largest settlements, averaging 30 cm, compared to an average of 22 cm for the remaining targets;
- Plan view distribution: Displacements were greater at central targets (54 cm) than at those near the wall ends (10cm);
- Deformation rate: With some reservations due to incomplete data, the average rate of horizontal displacement and settlement was higher between 2012 and 2019 (1.05 cm/year and 0.16 cm/year, respectively) than between 2009 and 2012 (1.35 cm/year and 0.67 cm/year, respectively). This suggests that observed deformations are mainly associated with long-term consolidation effects.

Table 1. Displacement of the different targets installed in the existing gabion wall.

Target	Displacement (mm)	
	Horizontal	Vertical
1	0,068	-0,184
2	0,413	-0,143
3	0,271	-0,265
4	0,535	-0,175
5	0,083	-0,270

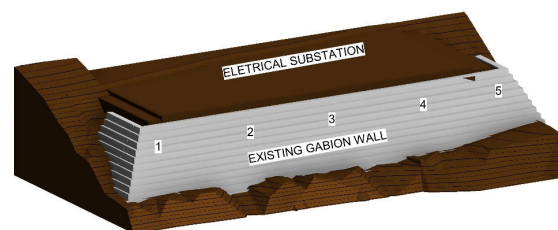


Figure 4. Location of the targets place after the construction of the gabion wall.

These findings are consistent with visual inspection of the wall, which revealed several pathologies such as cracking, misalignment, and local instability at the wall crest (see Figure 5).



Figure 5. Existing pathologies at the substation.

5 ADOPTED SOLUTIONS

The adopted stabilization solution consisted of a bored pile curtain wall with Ø800 mm piles spaced at an average of 1.20 m, executed from the substation working platform at elevation 94.00 m. This wall is braced by buttresses spaced approximately 7.20 m apart, each with a length of about 6.90 m, formed by alternating reinforced and unreinforced (plastic) secant piles, both approximately 20.5 m long.

To increase the overall stiffness, the pile wall and buttresses are connected by a high-stiffness reinforced concrete capping beam, 1.00 m wide and 1.00 m high. This beam will be integrated with the footing and the perimeter wall enclosing the substation (see Figure 6).

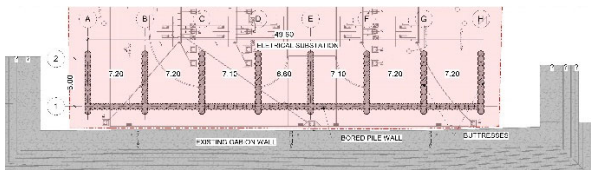


Figure 6. Footprint of the adopted stabilization solution.

Given the potential risk of fine material washout due to water percolation—particularly affecting the upper four meters of the existing gabion wall—and the consequent settlement of the substation pavement, the design also prescribes the installation of plastic piles in front of the wall over a height of approximately 4.5 m, alternating with the reinforced piles (see Figure 7). This arrangement increases the water percolation path length, thereby reducing possible erosion effects, while avoiding a fully impermeable solution (dam effect).

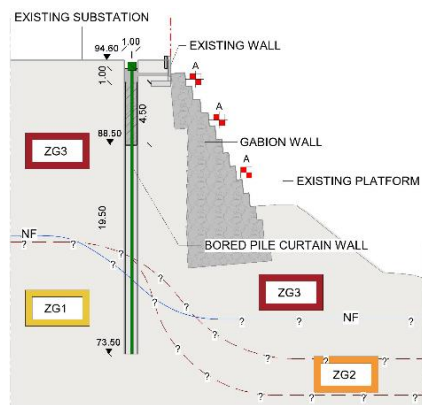


Figure 7. Stabilization solution of the gabion wall.

4 DESIGN METHODS

To analyze the structural and geotechnical behavior of the retaining and reinforcement system in terms of internal forces and deformations, a finite element analysis was carried out using PLAXIS 3D (see figure 8).

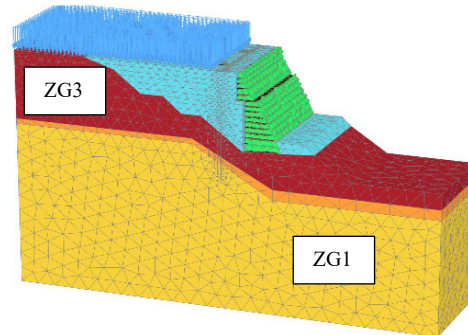


Figure 8. Plaxis 3D model used to evaluate the design solution.

The analysis focused on the most representative section for the behavior of the retaining structure, aiming to assess deformations, stress states, and the slope overall stability, as well as to estimate potential deformation increments in structures adjacent to the gabion wall. Multiple construction stages were simulated, including the original gabion wall construction and the installation of the reinforcement bored pile wall.

The soil behavior was modelled using Linear Elastic, Mohr–Coulomb, and Hardening Soil constitutive models, with deformability and shear strength parameters adopted from the geotechnical investigation. The piles and capping beam were modelled as beam elements. For the bored pile wall, the modelling approach consisted of a cluster assigned with concrete properties, within which dummy pile elements with very low stiffness were inserted to evaluate the forces and deformations on these elements.

The design of the piles was carried out based on the forces obtained from the calculation model, duly factored according to the required load combination and using the provisions of NP EN 1536.

For determining the embedded length of the bored piles wall, two criteria were adopted:

- Control of deformations during the excavation phase, assessed using finite element models;
- Verification of the axial load-bearing capacity by the piles length below the excavation bottom using the Bustamante and Doix method (Bustamante and Doix., 1985).

The modeling limited their maximum strength to ultimate limit states, allowing for the assessment of the maximum global safety factor.

Limit state checks confirmed that the existing gabion wall alone had a factor of safety of 1.16 (Figure 9), while the reinforced solution achieved 1.48 (Figure 10).

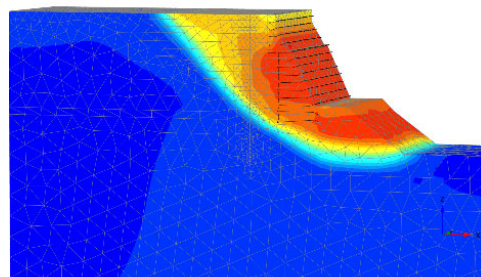


Figure 9. Critical surfaces for the gabion wall solution without reinforcement: safety factor of 1.16.

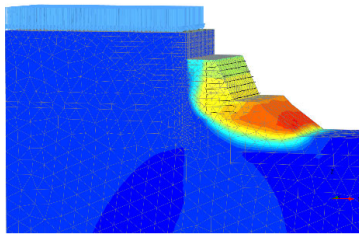


Figure 10. Critical surfaces for the gabion wall solution with the bore pile wall reinforcement solution: safety factor of 1.48.

6 MONITORING AND SURVEY PLAN

The implementation of a Monitoring and Survey Plan, essential for a project of this complexity, was a fundamental tool to validate on time the design assumptions and manage the geotechnical risk. For this project, several monitoring devices were installed, including:

- Topographic targets: to measure planimetric and altimetric displacements (Figure 11);
- Inclinometers: to measure horizontal displacements with depth (Figure 12).

The Monitoring plan and survey defined weekly readings campaigns and established alert and alarm thresholds for each monitored parameter to assess active geotechnical risk during construction.



Figure 11. Monitoring devices installed: topographic targets installed in the reinforced concrete wall.



Figure 12. Monitoring devices installed: inclinometers installed inside the bored pile wall.

As of the current date, no significant deviations from the project estimates have been recorded based on the available readings. The maximum horizontal movements on the targets and inclinometers are approximately 5 mm, below the horizontal displacement estimated at the design phase (see Figure 13).

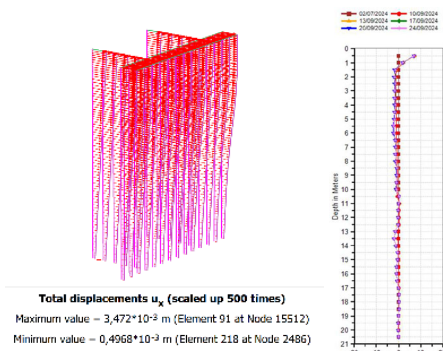


Figure 13. Maximum horizontal displacement estimated for the adopted solution (right) and monitoring results of the inclinometer (right).

7 FINAL REMARKS

This study is constrained by the limited characterization of the initial construction conditions, uncertainties associated with the heterogeneous fill materials, and the fact that monitoring was initiated only after early movements had already occurred.

The adopted reinforcement solution, combining a bored piles wall with secant pile buttresses, proved to be effective and well suited to the geotechnical and operational constraints of the Bemposta electrical substation. Measured displacements remained below design predictions, confirming the adequacy of the design assumptions and the effectiveness of the adopted solution.

While the adopted stabilization system has effectively reduced displacement rates, the long-term performance of the reinforced structure will depend on continuous monitoring and maintenance, especially under variable hydraulic conditions.

Future research should focus additional comparative studies incorporating alternative ground improvement or hybrid reinforcement techniques to contribute to the understanding and optimization of stabilization strategies for aging gabion retaining walls.

Considering the positive outcomes of the established monitoring and survey plan, this case study demonstrates the reinforcement solution, combining a bored pile curtain with secant pile buttresses (see Figure 14), was tailored to the geotechnical conditions and operational constraints of the Bemposta electrical substation

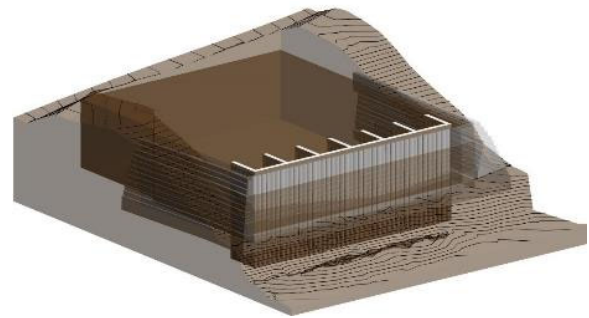


Figure 14. Overall view of the stabilization solution

ACKNOWLEDGEMENTS

The authors express their gratitude to E-Redes for granting permission for the drafting and publication of this article. It is also important to emphasize that the implemented solutions were the result of a team effort developed in collaboration with the geotechnical contractor (DST Geotecnia) and the general contractor (Painhas).

REFERENCES

- Chikute G.C., Sonar I.P., (2021). Gabion Wall: EcoFriendly And Cost-Efficient Retaining Wall. *Advances in Sustainable Construction Materials*, Vol. 124
- Pereira, B., Fernandes, W. (2023). Gabion Walls—A Remedial Measure for Slope Stabilization. In: Muthukkumaran, K., Umashankar, B., Pitchumani, N.K. (eds) *Earth Retaining Structures and Stability Analysis*. IGC 2021. Lecture Notes in Civil Engineering, vol 303. Springer, Singapore
- CT156 LNEC (2016). NP EN 1536 – Execution of special geotechnical works. Bored piles. In portuguese.
- Bustamante, M.; Doix, B. (1985). Une méthode pour le calcul de tirants et des micropieux injectés. *Bulletin de Liaison des Laboratoires des Ponts et Chaussées*, Ministère de L'Équipement, du Logement, des Transports et de la Mer, Paris. 140.