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Mechanically stabilized wall (MSW) with geogrids as complement of partially executed anchored wall

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Case Study

Keywords
Mechanically stabilized wall
Reinforced wall
Geogrid
Geosynthetic
Wrap around

Abstract
This article presents the case study of Wall C11 of Lot 1 in the ringroads of Caraguatatuba and São Sebastião job site, whose original design consists of an anchored retaining wall with a concrete face supported on root piles. At the time of its interruption, only a part of the job had been executed. The alternative solution, mainly aimed at speeding up the completion of the job, was the execution of reinforced backfill with geogrids behind the concrete wall, eliminating the need for the remaining anchors. The presence of the bedrock top very close to the face of the retaining wall at some points could compromise the anchorage length required for the geogrids. In the construction phase, tests were carried out to verify the elements already executed, specially, the anchors. During the execution of the reinforced soil and after its completion, the instrumentation followed the displacements in the concrete wall.

1. Introduction

The Tamoios Highway, between the cities of São José dos Campos, on the margins of Presidente Dutra Highway and Caraguatatuba on Rio-Santos Highway, is the main connection between the Paraíba Valley and the northern coast of the state of São Paulo. In 2015, it began to be managed by Concessionária Tamoios. On its arrival in Caraguatatuba, the Tamoios Highway will be connected to the Northern and Southern ringroads, also called the Caraguatatuba and São Sebastião Ringroads, with a total length of about 34 km. The works on the ringroads was halted in 2018 and restarted in October 2021, taken over by the Concessionária Tamoios. Once completed, they will form a modern and safe road complex in the region of Vale do Paraíba and the Northern Coast of São Paulo. When completed, the Tamoios-Ringroads Complex will relieve the flow of tourists travel through the beach region and increase the cargo capacity for the Port of São Sebastião, which only receives road cargo. In general, the original project consisted in embankments with concrete faces reinforced by soil with steel strips known in Brazil as "Terra Armada" system or in anchored walls. With the resumption of the ringroads works and the establishment of very tight deadlines for the conclusion of the new coastal road system, some original design solutions had to be reviewed, to minimize costs and reduce the execution deadlines, in order to meet the construction schedule. It should be noted that this region is located at the base of the Serra do Mar and is subject to heavy rainfall that could impact the construction schedule especially during Spring and Summer.

2. Wall C11 of Lot 1 - original design solution

Wall C11 of Lot 1 is 244.6 m long and has a maximum height of 14.3 m. Initially, it was expected that the backfill would be built in a reinforced soil system. However, when cleaning the vegetation layer of the surface, it was detected that the rocky top was outcropping, for a much greater extension than originally planned and with steeper slopes. Thus, it was necessary to change the solution from reinforced soil to an anchored wall, because the global stability did not reach the minimum safety factor of 1.5 for the long term situation, required by standard for this type of work.

The original design consists of a reinforced concrete-faced wall supported on a line of 31 cm nominal diameter root piles. The horizontal spacing of the piles was designed for a maximum compressive load of 800 kN, resulting in a maximum horizontal spacing of 3 m. For the rock sections, the allowable geotechnical loads were calculated considering the diameter reduction (telescoping) from 31 cm to 23 cm, with a minimum embedment of 5 m in slightly weathered or

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sound rock. According to the geotechnical profile sections, the calculated pile lengths were estimated in the ranging from 11 m and 18 m, starting from the base. The wall consisted at most on four anchor lines per section with working loads of 400 kN, 600 kN or 800 kN and maximum spacing of 3 m, in a total of 289 anchors. At the time of the interruption of the services in 2018, the root piles and the reinforced concrete face were already fully completed, but only about 1/3 of the anchors had been executed, as well as part of the backfill behind the wall. Figure 1 illustrates the front view of the tallest part of the anchored retaining wall. Figure 2 shows the typical cross section of the original design of Wall C11.

3. Restart of construction - alternative solution

This wall was one of the critical structures for the restart of the work, as it corresponds to the only access for the execution of the tunnel ahead, and needed to be completed finish as quickly as possible so that the tunnel excavations could continue without trucks using the local streets. The alternative solution consisted in completing the embankment behind the reinforced concrete wall using the geogrid-reinforced soil technique and a wrapped around face with a lost metallic formwork, eliminating the need to execute most of the missing anchors and working with mixed sections, where the lower part includes the already existing anchors (and eventually a few new ones) and the upper part in geogrid-reinforced soil. One of the main advantages of this alternative solution was the significant reduction in time to finish the whole service, making according to the construction schedule, and with practically no need to interrupt access to the tunnel region.

In reinforced soils, the inclusion of geogrids as backfill reinforcement element provides an overall redistribution of stresses and strains, allowing the adoption of vertical face structures (walls) or steeper slopes, minimizing the volume of compacted backfill.

The presence of reinforcements in the retaining structure generates a resistant tensile force that acts to balance the embankment mass thrust that tends to surcharge the retaining structure. These reinforcements can consist of geogrids with mechanical properties suitable for this purpose, i.e., high tensile strength and low deformation and should be sized to ensure the stability of the wall immediately after its construction and throughout its life.

The stability of reinforced masses must also be ensured by soil-reinforcement interaction mechanisms, i.e., the anchoring capacity of the geogrid, which is a function of its geometric characteristics and the confining stress to which it is subjected.

The assembly of the system's panels is done simultaneously with the compaction of the backfill layers and the placement of the geogrid layers, with the panels being the very formwork of compaction, which brings a significant gain in terms of time and construction cost. The standard ABNT NBR 16920-1 (ABNT, 2021) specifies the requirements for design and execution of walls and slopes in reinforced continuous earth masses.

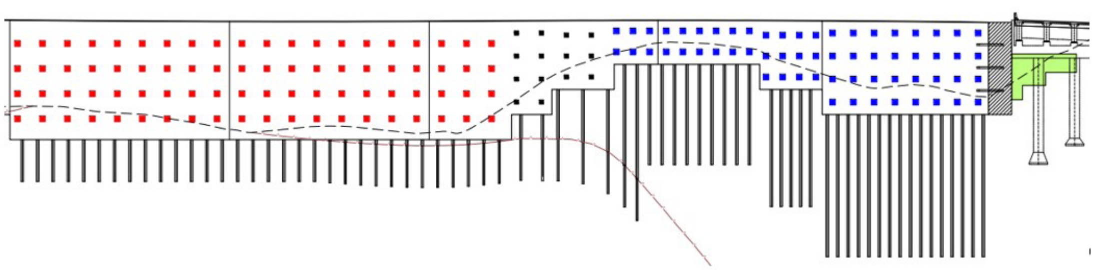


Figure 1. Part of the original design front view.

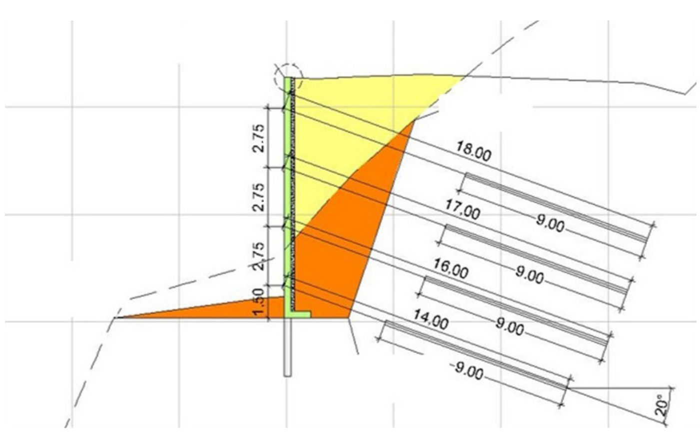


Figure 2. Typical cross section of the original design (units in meters).

One of the difficulties in using reinforced soil was the presence of the rock top very close to the wall face at some points, which could compromise the anchorage length of the geogrids. After a detailed field survey of the rock position, several global stability analyses were performed to verify the suitability of the solution under study using RocScience's Slide v. 6.0 software. In some cases, additional anchors were required.

Figure 3 shows part of the front view of the alternative mixed solution and Figure 4 shows the mixed cross section of the anchored wall and reinforced soil at the section close to pile 1106. Figure 5 presents one of the stability analyses performed.

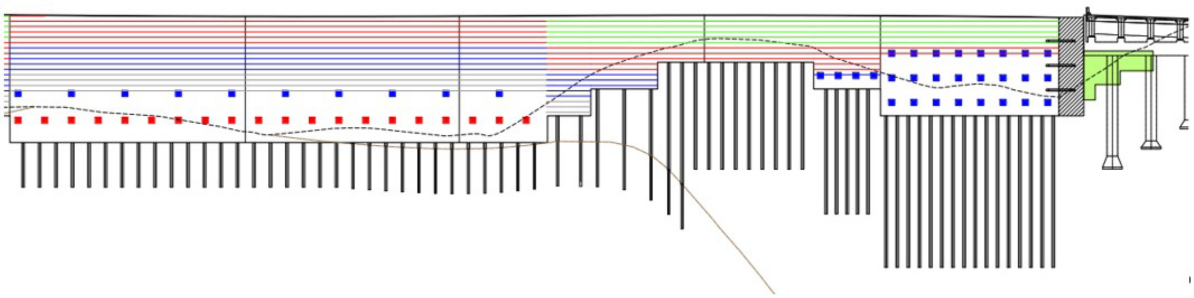


Figure 3. Partial front view of the alternative solution with mixed section (anchors in the lower part and geogrids in the upper part).

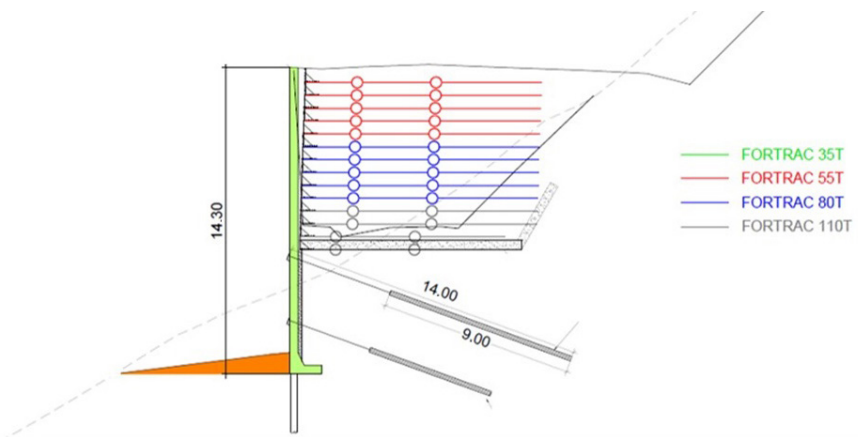


Figure 4. Section with anchors in the lower part and geogrid-reinforced soil in the upper part (units in meters).

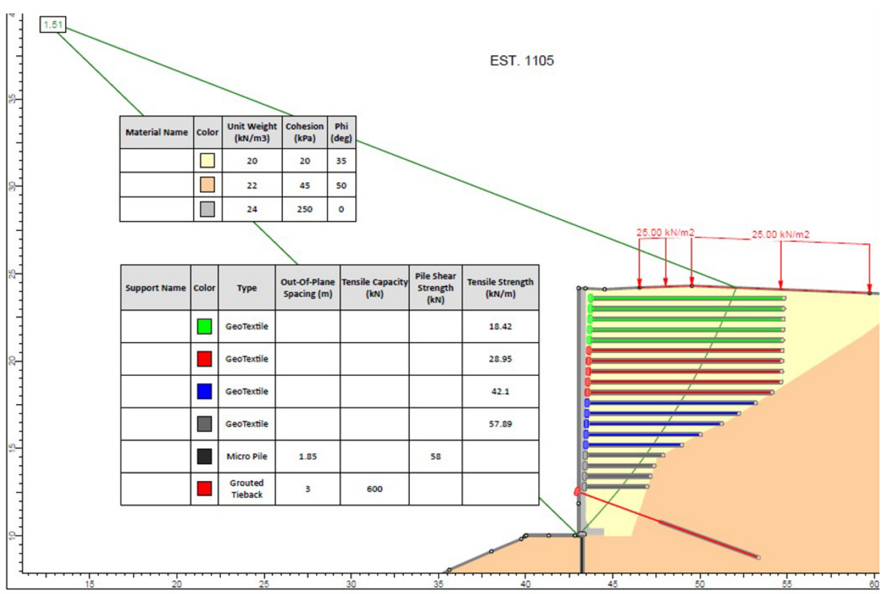


Figure 5. Global stability analysis of a mixed section – section closest to pile 1105.

4. Compacted backfill

For the compacted backfill, stone material produced from crushed material excavated from the site itself was used, with the following composition, based on ABNT NBR 6502 (ABNT, 2022), shown in Table 1 and Figure 6:

According to the characterization tests results provided, the maximum density of the soil reaches 21.7 kN/m^3. From the compaction tests, the optimum moisture is 6.6% corresponding to a density of 19.9 kN/m^3. The strength parameters found in the direct shear test for the soil in a condition close to the optimum water content attain a effective cohesion of 38 kPa and effective friction angle of 39° were obtained (CD test, moisture content of 6.6% and density of 19.9 kN/m^3). Although the shear strength tests of this material have presented higher values, conservative design parameters were adopted with effective cohesion of 20 kPa, effective friction angle of 35° and specific weight of 20 kN/m^3. Figure 7 shows the execution of compacted backfill.

Table 1. Backfill soil composition.

Type	Content
Coarse gravel	0%
Medium gravel	5.8%
Fine gravel	26.8%
Coarse sand	23.1%
Medium sand	18.3%
Fine sand	16.1%
Silt	9.5%
Clay	0.4%

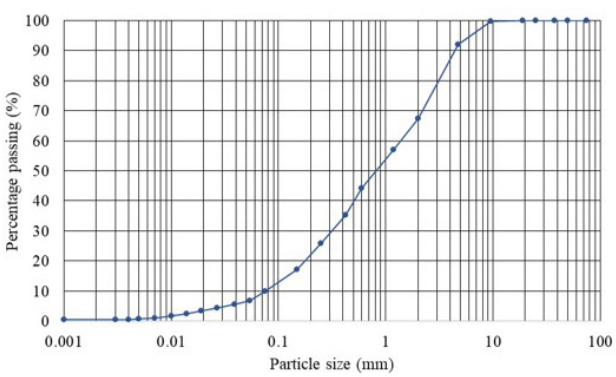


Figure 6. Particle size distribution curve of the material used in the compacted backfill.

Unlike reinforced soil with metallic strips, where the compacted backfill must be basically made of granular material, the geogrid reinforced soil can use soil from the construction site itself, even if it is of finer granulometry, as long as it meets the minimum requirements, according with those recommended by the standard rules.

5. Anchors

When the job activities were halted, Wall 11 had 135 anchors done, nearly 50% of the total number predicted in the original project. It was found that some anchors were without the bearing plate and anchor head and without the driving wedges unprotected tendons, among other mis occurrences.

With the resumption of the work in 2021, the conditions of the installed anchors were initially verified, evaluating if some would not attend the receipt and qualification tests recommended in ABNT NBR 5629 (ABNT, 2018), due to the degradation conditions of structural elements since the construction interruption. As a result, 12 anchors were considered inadequate and discarded.

For the execution of the hybrid solution in part of the anchored wall and geogrid reinforced soil, new stability analyses were performed. Additional 20 new anchors, 13 of 400 kN and 7 of 600 kN had to be included.

In the final design configuration, a total of 150 anchors were defined to compose the system below the geogrid reinforced soil, divided in sections with one row and others with two to three rows of anchors with varying spacing in

Figure 7. Execution of compacted backfill.

each section, being the minimum spacing of 2.5 m and the maximum spacing of 3 m.

Based on Annex D of ABNT NBR 5629 (ABNT, 2018), twelve ties were randomly chosen for receipt test (type A) and three ties were chosen for qualification test with creep measurement (type QF). The remaining tension specimens were tested with type B test, according to Table 2:

In the Type A test, the anchor is tensioned up to 1.75 times its expected working load; in the Type B test, the maximum load is 1.5 times the expected working load. In the QF test, the load of 1.75 times the expected working load is maintained, and the head displacements are measured with two strain gauges, installed diametrically opposite to the tie axis.

Through the conformity tests it was possible to identify some problems in the previously executed anchors:

- Throughout the test, the anchor bulb showed a displacement beyond predicted, requiring the replacement of the anchor.
- During the test, one or two tendons reached failure at loads lower than those foreseen for the end of the test, defining the anchor replacement.
- With the result of the graphs of load mobilization in the anchors, it was verified that the real deformation was not positioned between the range defining maximum and minimum acceptable values according to ABNT NBR 5629 (ABNT, 2018), concluding that they should be substituted.

For the eleven anchors that needed to be replaced, holes were drilled with a concrete extractor 50 cm away from the design point, with a diameter corresponding to 150 mm.

During the beginning of the execution of the reinforced soil behind the wall, a 400 kN tie rod was replaced by a new one.

Table 2. Summary of tested anchors - wall 11 Lot 01.

Expected working load	Test type	Quantities
400 kN	A	5
	B	61
	QF	1
600 kN	A	5
	B	52
	QF	1
80 kN	A	2
	B	22
	QF	1
	Total	150

6. Facing system

The reinforced soil facing was built with a 10V:1H slope, creating a free space behind the concrete wall, so as not to generate horizontal thrusts on the upper part of the wall.

The reinforced soil lost formwork system was composed of non-galvanized steel welded wire mesh, with 6 mm diameter bars spaced every 10 cm, folded in “L”. Each module has a useful height of 60 cm and width of 2.5 m. Its stabilization is done through inclined rods, with seven units per module. In this specific case, the steel mesh is not galvanized and serves only as a formwork or temporary lost form. About 1,170 units of non-galvanized folded metallic template were used. The stability of the reinforced soil facing is achieved by wrapped around of the geogrid, as shown in the detail in Figure 8.

7. Geogrids

Polyester geogrids with nominal or characteristic tensile strengths of 35 kN/m, 55 kN/m, 80 kN/m and 110 kN/m and maximum deflection of 10% at nominal strength were used. These geogrids have an overall reduction factor lower than 1.84 for a design life of 120 years, according to certification issued by the British Board of Agrément (BBA). Approximately 28,000 m^2 of geogrids were used. The Figure 9 shows the tensile strength mobilization curve from the wide band test (CLR curve) and the isochronous curves of the geogrids used on site.

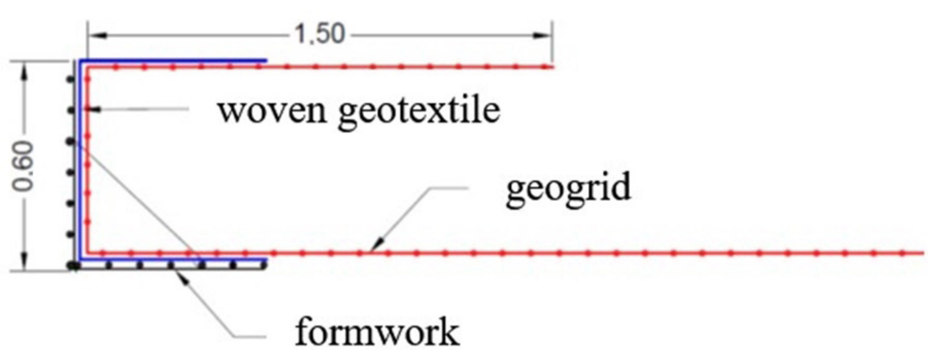


Figure 8. Facing system with non-galvanized metallic formwork and geogrid wrapped around.

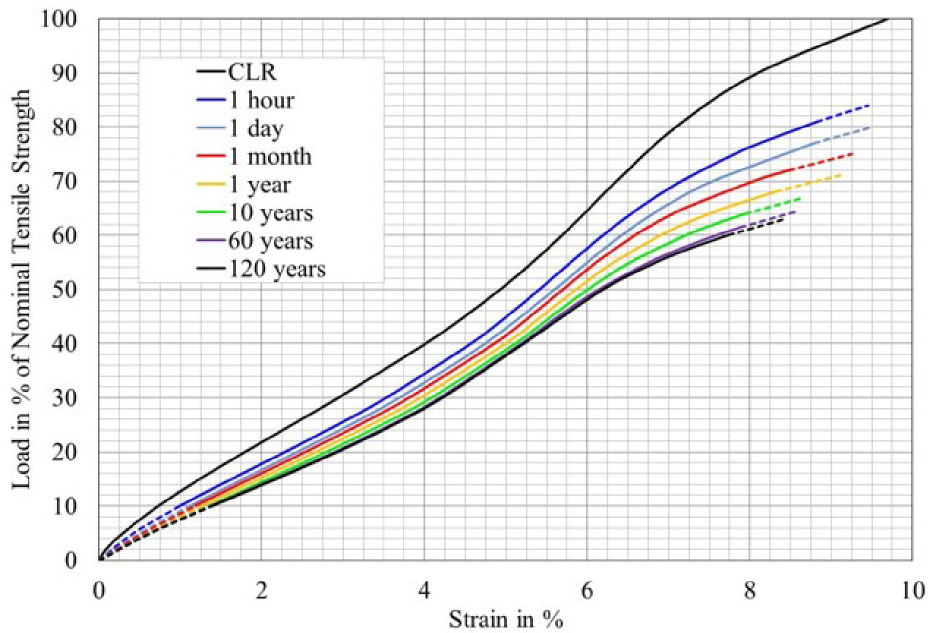


Figure 9. Geogrid tensile strength mobilization (CLR curve) and isochronous curves.

Figure 10. Drainage pipe in the reinforced soil base behind the concrete wall.

8. Drainage system

Due to the large water flow at the site, a robust internal drainage system for the compacted fill was executed, consisting of a gravel bed with a minimum thickness of 40 cm at the contact of the fill with the natural ground and at the base of the wall, associated with drainage pipes. Figure 10 shows the assembly of the drainage pipe in the metallic formwork behind the concrete wall.

9. Deformation monitoring

The substitution of upper lines of active anchors by passive reinforced soil is supposed to generate more deformation in the upper part of the structure and change the loads in the concrete wall. Throughout the execution of the reinforced soil and after its completion, the concrete wall was instrumented to verify the occurrence of any significant displacements generated by the construction of the reinforced

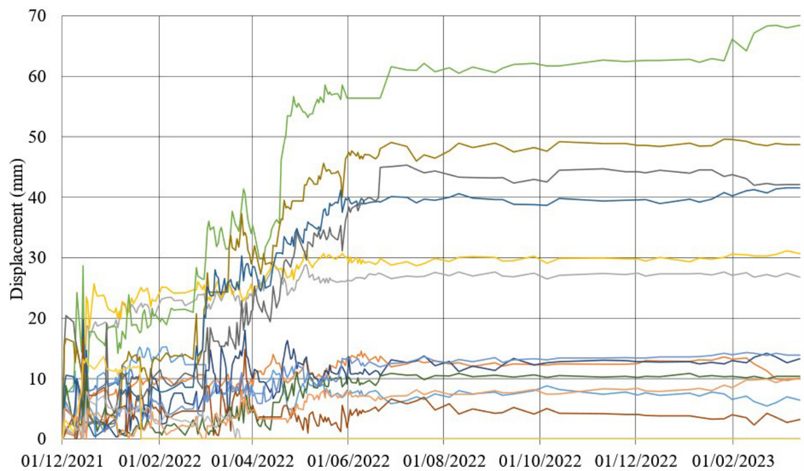


Figure 11. Overview of measured displacements in the concrete wall.

soil, which could indicate inadequate behavior. Thus, a system composed of prisms distributed along the wall was designed, with at least two prisms per section, one at the top and the other at the bottom of the wall. For sections of greater height three prisms were indicated.

The reading schedule was established as follows:

- Daily readings at the beginning of the day for 15 days.
- From day 16 onwards, a weekly reading in the morning until completion of the wall works.
- After completion of the work, monthly readings until release to traffic by the highway.
- After release to traffic, monthly readings for 6 months.
- From the 7th month on, one reading every 3 months for 1 year, then readings every 6 months.

The readings began on 01/12/2021 and the last, before the registers included in the present paper, were observed on 15/03/2023, as shown in Figure 11. During the reinforced backfill and anchors execution, as well as after the liberation for traffic on 15/12/2021, the horizontal displacements presented minimum value of 1.52 cm and maximum of 2.75 cm whereas vertical displacements varied from 0.06 cm to 0.27 cm for the prisms located at the top of the wall. The prisms on the face of the wall presented displacements ranging from 0.02 cm to 0.04 cm. These displacements were within the expected ranges for this type of work. No alteration was observed in the concrete face.

10. Alteration of the walls to the new solution

After the first successful experience with a geogrid-reinforced soil wall, the construction company decided that the retaining walls not yet in place would be redesigned and built with this system. Thus, several designs in the reinforced earth system were changed. Unlike the first site experience, where there was already a previously executed reinforced

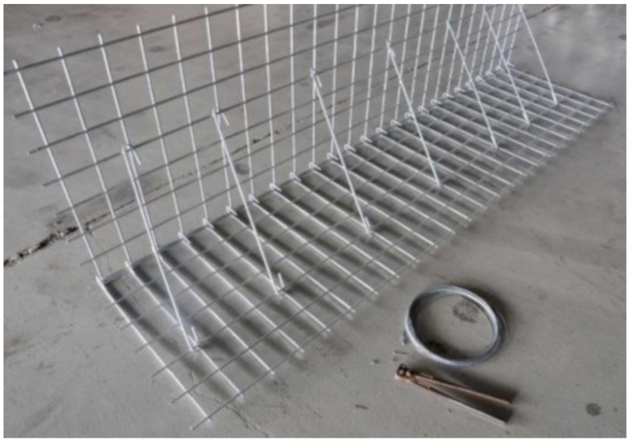
Figure 12. Closed articulated and galvanized formwork.

concrete wall, which led to the adoption of a simple non-galvanized wire mesh form behind this wall, the new retaining walls were designed with an articulated and galvanized mesh face, with stone finishing.

To facilitate the transportation and handling of the wire mesh, the system has an exclusive rod that allows the mesh to be transported folded and installed on site in the final position through manual assembly, as shown in Figures 12 and 13.

In the execution of the system, there is no need for concreting, cutting, or bending of the metallic frames, which are just mounted in the definitive location and locked in place with steel hooks. No formwork or shoring is required.

The panels form modules of 250 cm wide by 60 cm high freeboard on the wall face when assembled. The vertical spacing between geogrids is also modulated by 60 cm by the height of the panels.



Figures 13. Open articulated and galvanized formwork.

Figure 14. Assembling the face modules.

Figure 15. Filling the face modules with small rocks.

Table 3. Main characteristics of the system.

Item	System
Vertical spacing between geogrids	60 cm
Facing elements	ϕ 8 mm welded mesh screen with 10 cm x 10 cm opening, hot dip galvanized - Larger bar diameter results in less susceptibility to face vandalism
Auxiliary formwork for face assembly	The face elements are self-supporting, requiring no auxiliary formwork for assembly
Maximum diameter of the face stone	20 to 25 cm
Filling the face element with stones	Basically mechanized - System productivity of about 30 m^2 to 50 m^2 of facing area per day depending on the wall geometry
Geogrids for soil reinforcement	Polyester with maximum deformation of 10% PVA with maximum deformation of 5%

PVA: polyvinyl alcohol.

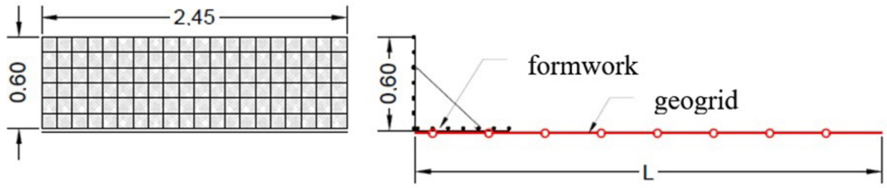


Figure 16. Facing modules and geogrid position.

The structure of the meshes consists of 8 mm diameter bars with 10 cm spacing in both directions on the front vertical panel of the containment, and 6 mm diameter bars with 10 cm spacing in both directions on the horizontal part of the panel that is buried between layers of reinforcement and compacted soil. The 8 mm diameter bar of the front screen presents less risk of damage from vandalism.

The entire wire mesh structure is hot-dip galvanized according to standard ABNT NBR 6323 (ABNT, 2016). Therefore, there is no need to coat the face with geogrid. The geogrid goes under the wire mesh and terminates "topside" at the wall face, as shown in Figure 14. The connection between geogrid and wire mesh is made by the interface friction of the two elements and by the interlocking of the facing stones, as shown in Figures 15 and 16.

Also, for these walls, stone material produced from crushed material excavated from the site itself was used in the compacted backfill. Table 3 presents the main characteristics of the system.

The walls were constructed with geogrids with a nominal or characteristic tensile strength between 55 kN/m and 150 kN/m. The walls were built by the construction company's own teams. The supplier of the reinforced soil system provided a detailed installation manual with photographs and made an engineer available to guide the start of the execution of each wall. In addition, during the entire construction period, its engineers, its consultant, and its representative made regular visits to monitor the work. It is noticeable that there was an evolution of the assembly team over time regarding to the aesthetic quality and productivity.

11. Global warming potential (GWP) comparative assessment

In order to evaluate the performance of the solutions studied in terms of criteria related to sustainability, calculations were developed to estimate the Global Warming Potential (GWP) generated by the consumption of construction materials used in two alternative solutions for the execution of the walls: reinforced soil with geogrids and face in folding galvanized steel mesh and mechanically stabilized soils with face in concrete plates ("Terra Armada" system).

Studies carried out in the last decade, such as the publications by Stucki et al. (2011) and Corney et al. (2010), demonstrate a significant reduction in the environmental impact with the application of geosynthetic solutions in substitution of conventional solutions in civil engineering, especially in terms of greenhouse gas emissions and global warming potential.

For each of the alternatives studied in this case, the consumption of materials used in significant quantities for the composition of the structure was calculated, per square meter of wall face, considering a height of 9 m. Based on the consumption of materials and the reported values of global warming potential in the Environmental Product Declarations (EPDs) made available by suppliers of cement, steel, galvanization and geosynthetics, the total GWP for each m^2 of wall face, in kgCO2-eq., was evaluated. Other materials, such as sand and aggregates, had their GWP values adopted from the ICE Database (2011).

The GWP values collected for the materials are described in Table 4. For this study, the values reported for the "cradle to gate" boundaries were considered, corresponding to the materials production phase. This limitation was adopted due to the availability of data by suppliers, as not all of them have reports covering other phases of the product life cycle. Thus, to enable product comparison, transport to the site and installation work were not considered. Additionally, for simplification purposes, other materials and services, such as transportation and compaction of local soil, were not included in the comparative calculations, as they were taken as approximately equivalent for the two alternatives.

Thus, for each m^2 of wall face for the two alternative systems, it was possible to assign a GWP value related to the materials used for the construction of a wall with a height of up to 9 m.

As can be seen in Table 5, the results obtained show an important reduction in greenhouse gas emissions and global warming potential linked to the materials used in the solution with reinforced soil, compared to the solution with steel strips and concrete face. This difference is mainly due to the reduction in the volumes of concrete used, since cement has a high environmental impact in its production phase. The steel consumed by both solutions, and particularly the galvanizing, also represent a large part of the emissions linked to the systems, followed by the production of geosynthetic reinforcements.

Table 4. GWP referring to the production of materials used in the two alternatives.

Material			GWP*	*Boundary: A1-A3 (production)
Fortrac T Geogrids	Reference: Huesker Synthetic GmbH (2021a)	35T	1.11E+00	$kgCO2eq./m^2$
		55T	1.44E+00	
		80T	1.92E+00	
		110T	2.10E+00	
		150T	2.64E+00	
		200T	3.18E+00	
Concrete	Reference: Votorantim Cimentos S.A. (2023) kgCO2eq/t		3.84E+02 $kgCO2/m^3$	5.76E+02
Steel	Reference: Arcelor Mittal Brasil (2018) kgCO2eq/t		7.86E+02 kgCO2eq/kg	7.86E-01
Galvanizing (A2-A3)	Reference: American Galvanizers Association (2022) kgCO2eq/t		3.30E+02 kgCO2eq/kg	3.30E-01
Aggregate	Reference: ICE Database (2011) kgCO2eq/kg		5.20E-03 $kgCO2eq/m^3$	1.04E+01
Geotextile	Reference: Huesker Synthetic GmbH (2021b) $kgCO2eq/m^2$(780g)		3.59E+00 $kgCO2eq/m^2$ (137g)	6.31E-01
Sand	Reference: ICE Database (2011) kgCO2eq/kg		5.10E-03 $kgCO2eq/m^3$	7.14E+00

*Global Warming Potential.

Table 5. GWP results per m^2 of wall face for the two alternatives.

Reinforced Soil with Geogrids H 9 m				Mechanically stabilized soil with face in concrete plates H 9 m			
Material consumption / m^2 face:			GWP*: [$kgCO2eq./m^2$ face]	Material consumption / m^2 face:			GWP: [$kgCO2eq./m^2$ face]
Sand	0.3	m^3	2.142	Concrete	0.156	m^3	8.96E+01
Fortrac 55T	7.8	m^2	11.23	Sand	0.071	m^3	0.5037984
Fortrac 80T	3.9	m^2	7.49	Aggregate	0.094	m^3	0.98
Basetrac Woven 25	3	m^2	1.89	Steel (galvanized)	5.969	kg	6.66
Aggregate	0.8	m^3	8.32	Steel (not galvanized) 5/16” 8.0 mm	12.77	m	3.97
Quadratum (galvanized steel)	0.7	un.	21.21				
Total [$kgCO2eq./m^2$ face]			52.28	Total [$kgCO2eq./m^2$ face]			101.71

Evidently, these GWP values do not represent the totality of the environmental impact of the construction of the structure, however they provide a good indicator of the potential reduction of the environmental impact that can be obtained when replacing traditional solutions with geosynthetics.

12. Final remarks

The reinforced soil Wall 11 was executed with the construction company’s own personnel, with constant guidance and site visits by the supplier of the metallic template and geosynthetics and the construction company’s consultants. Initially, the period allocated for the conclusion of Wall C11 was 4 months, however, with the project optimizations and interactions between the executor, designer and consultants, the work was concluded in only 2 months. The justifications for this were the close collaboration and agility to define and re-evaluate the solution and execution of the work, with real time flow of continuous new information from the field and project revision by those involved from several companies (construction, designer, consultant, material producer, etc.); the use of crushed granular material for the compacted backfill, allowing fast resumption of earthworks even after a period of heavy rainfall; the adoption of the geogrid reinforced soil technique, which basically consists of an earthwork, allowing very fast raising of the backfill and the possibility of executing the services related to the anchors in parallel with the execution of the backfill in reinforced soil.

In other hand, the comparison between GWP values calculated for mechanically stabilized soil with face in concrete plates from the original solution for the next walls of the job and for the alternative geogrid reinforced wall for a 9 m high section provides a good indicator of the potential reduction of the environmental impact that can be obtained when replacing traditional solutions with geosynthetics. In this case, greenhouse gas emissions resulting from the production of materials are reduced by almost half by using the solution in reinforced soil, indicating an additional benefit of a more sustainable construction, in addition to the already known technical advantages.

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Cristina Francischetto Schmidt: conceptualization, supervision, writing – review & editing. Pedro Paulo Monteiro Soares dos Anjos: conceptualization, data curation, project administration, writing. Ivan Steinmeyer: conceptualization, data curation, writing. Mateus Cardoso Reis Cleto: conceptualization, data curation, writing. Emília Mendonça Andrade: conceptualization, data curation, writing.

Data availability

The datasets generated and analyzed in the course of the current study are available from the corresponding author upon request.

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