Vertical Expansion of Residential Land Using Reinforced Earth Walls – Case Study of Cerro Artola

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ABSTRACT: *This paper shows how mechanically reinforced earth walls are used to extend land vertically for housing development in residential highlands, where abrupt orography changes and scarce constructible surfaces limit the use of conventional retaining systems due to cost overruns. Alternatively, reinforced earth walls are conceptualized to adhere into the urbanized environment, providing a flexible, green, and sustainable structure with minimum environmental impact and slight disturbance to the neighborhood. A case study of several reinforced walls stacked up a hillside located in Cerro Artola (Benahavís, Málaga, Spain), merged into the residential development of The Hills in La Quinta Golf and Country Club, is presented. The design of the project started in February 2019, while the construction of the first reinforced wall commenced in September 2019. From there on, subsequent walls were built upwards while villas were being constructed in newly acquired land. The land preparation lasted until May 2020 and, overall, the project accounted for a total extension of 15,600 square meters and a total height of 45 meters. The implementation of the full system resulting from the combination of polyester geogrids, drainage geocomposites, and steel mesh is detailed along with analysis methods, constructive plans, and the project as it was built.*

KEYWORDS: reinforced, wall, expansion, residential, sustainable, geogrid, geosynthetics.

SITE LOCATION: Geo-Database

INTRODUCTION

Reinforced earth walls are retaining structures that mainly result from the combination of geosynthetics with different functions and soil layers to provide a green, flexible, and durable surface (Chou et al., 2020). In contrast with reinforced concrete structures, mechanically stabilized earth walls generate a lower visual impact, can be built using site-specific soils, and raise less safety concerns, often resulting in a more economical and ecological solution due to the limited dependency on foreign materials (Koerner et al., 1998).

The current paper describes the construction procedures followed for The Hills residential development, located in Benahavís (Málaga, Spain), at the hillside of Cerro Artola. This project involved the construction of several reinforced earth walls with wrap-around facing stacked uphill and built to extend the residential land for new housing promotions. The walls formed a total extension of 15,600 square meters and represented a total height of 45 meters. The construction phase lasted a total of 9 months, from September 2019 until May 2020. For simplification purposes, this paper will focus on the walls constructed for The Hills Plot 8, accounting for a maximum reinforced earth height of 8.25 meters and 85º facing.

REINFORCED EARTH WALL

The reinforced mass in mechanically stabilized earth walls with wrap-around facing consists of characterized soil layers separated by high-tenacity polyester geogrids of variable allowable tensile strength, length, and spacing. Additionally, drainage geocomposites serve as the drainage barriers located over the base and back of the reinforced earth, as well as throughout the berms. Steel meshes serve to adequate the facing to the designed slope and ease the installation of each layer.

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Materials

Intergrid polyester geogrids (Figure 1) are flexible geosynthetics made of woven multifilament yarns that provide high tensile resistance at relatively low deformation. To protect the polyester yarns from environmental agents, the geogrid is covered by a polymeric coating. Geogrids with small mesh sizes (Figure 2) are installed over the facing and behind the formwork to avoid the erosion of soil particles at the front and ease the growth of vegetation.

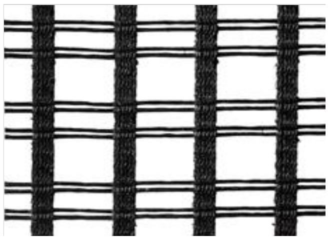

Figure 1. Polyester geogrid.

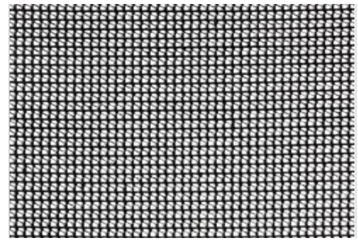

Figure 2. Polyester geogrid with small-sized openings.

Fluid management in reinforced earth structures is an important aspect to consider, and proper caution must be taken to avoid the infiltration and buildup of groundwater within or around the reinforced section. To simplify the installation of the drainage network, the geosynthetic industry provides a large offer of geonets and geocomposite drains customizable to project-specific requirements (e.g. demanding compressive loads, high flow of groundwater, fine-grained soils).

For the current application, Interdrain geocomposites formed by a biplanar high-density polyethylene geonet thermally bonded to nonwoven polypropylene geotextiles on both sides are generally acceptable (Figure 3). However, in some cases where the installation loads or, at the base, when the total height of the reinforced wall exceeds a certain limit, to avoid any crushing of the draining core over the structure's life cycle – and therefore a sudden decrease in the in-plane transmissivity – a more resistant core (e.g., Techdrain triplanar geonet) must be employed (Figure 4). In cases where the structure must be separated from the drainage media by a waterproofing film, geocomposites may also include it in substitution of one of the geotextiles (Figure 5).

Figure 3. Biplanar drainage geocomposite.

Figure 4. Triplanar drainage geocomposite.

Figure 5. Biplanar drainage geocomposite w/ waterproofing film.

Additionally, this technology considers the use of a steel wire formwork located at the front of each soil layer. This element consists of 8-mm diameter corrugated steel rebars bended to adapt to the inclination of the wall and achieve a regular form of the facing, as well as a hook to ensure its structural stability during the earth works.

Installation Principles

The recommended procedures to install the reinforced earth wall with wrap-around facing are listed as follows:

1. Remove any protruding elements and regularize the base layer, using fill material when required.
2. Compact the ground layer.
3. Avoid the infiltration of groundwater through the base or the back of the reinforced soil by placing a drainage geocomposite all over the surface. The drainage geocomposite must be designed so that the drainage core does not

collapse due to installation or final static stresses. This collection system must be connected to a network of drainage pipes for the water to exit the soil mass (Figure 6).

4. When considering a steel wire mesh as a lost formwork, place it following the designed frontline and overlap successive elements at about 20 cm. This design considers the use of 8-mm diameter steel wires.
5. Place the reinforcement geogrid of required tensile strength and length as per design. The latter must be extended to account for the vertical rise and the flip side, as well as the anchor. Properly extend the reinforcement layers so that no wrinkles or folds appear. Between successive layers, leave an overlap of 15 cm and ensure the connection with anchor hooks. Overlaps along the longitudinal direction are not allowed, as the reinforcement continuity is not ensured.
6. Install the erosion control geogrid (small-sized grid) on the back of the steel wire mesh (Figure 7). The roll must be wide enough to let the soil sit on the base, cover the vertical rise of each soil layer, and flip over so it connects with the successive layer.
7. Steel metal hooks are used to avoid the opening of the formwork during compaction. These elements connect the base of the formwork to the section of the mesh placed at the front. It is recommended to install them every 80 to 100 cm.
8. Proceed with the earthwork by filling and compacting with the characterized soil up to the prescribed height, which is typically between 50 to 75 cm. Avoid any trafficking of heavy machinery over the geosynthetic layers, as these can be easily displaced. To enhance vegetation growth, it is recommended to pour 20 cm of organic soil over the frontal wedge of the layer. Compaction in this sector should be done using lighter machinery, but always guaranteeing that there are no voids left.
9. Flip the reinforcement and erosion control geogrids so these wrap the soil layer and anchor to it.
10. Reiterate steps 4 through 9 until reaching the top layer.
11. On the top floor, anchor the geogrids to the soil layer using staples and cover them using a topsoil. Additionally, to avoid the direct infiltration of rainwater within the reinforced soil mass, a drainage geocomposite with an impermeable side can be installed over the berms and under the topsoil, leaving the transmissible side facing the azimuth and the impermeable side facing the ground (Figure 8).

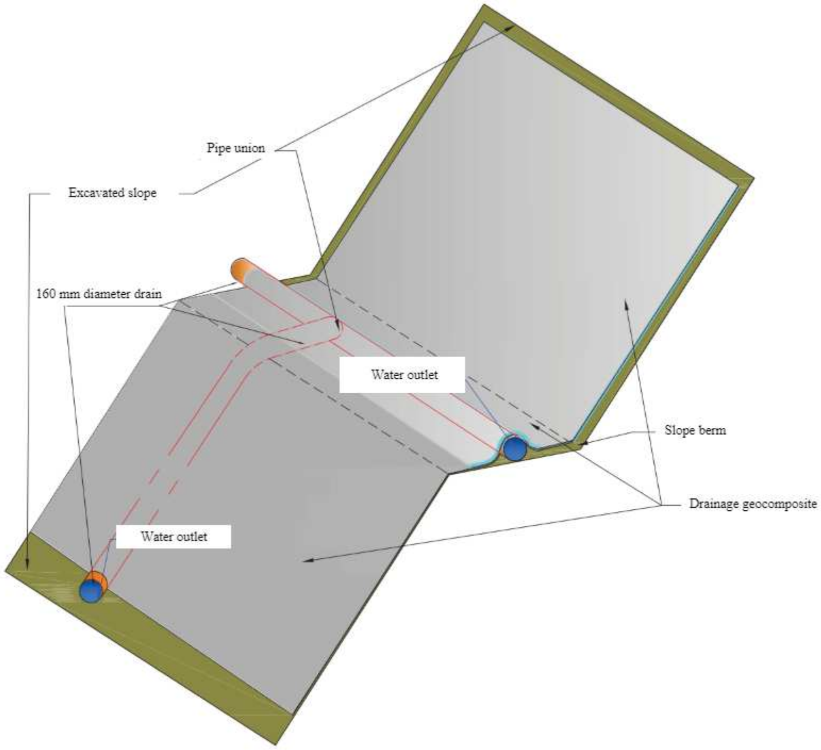

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Figure 6. Drainage over the excavated slope berm (behind the reinforced fill).

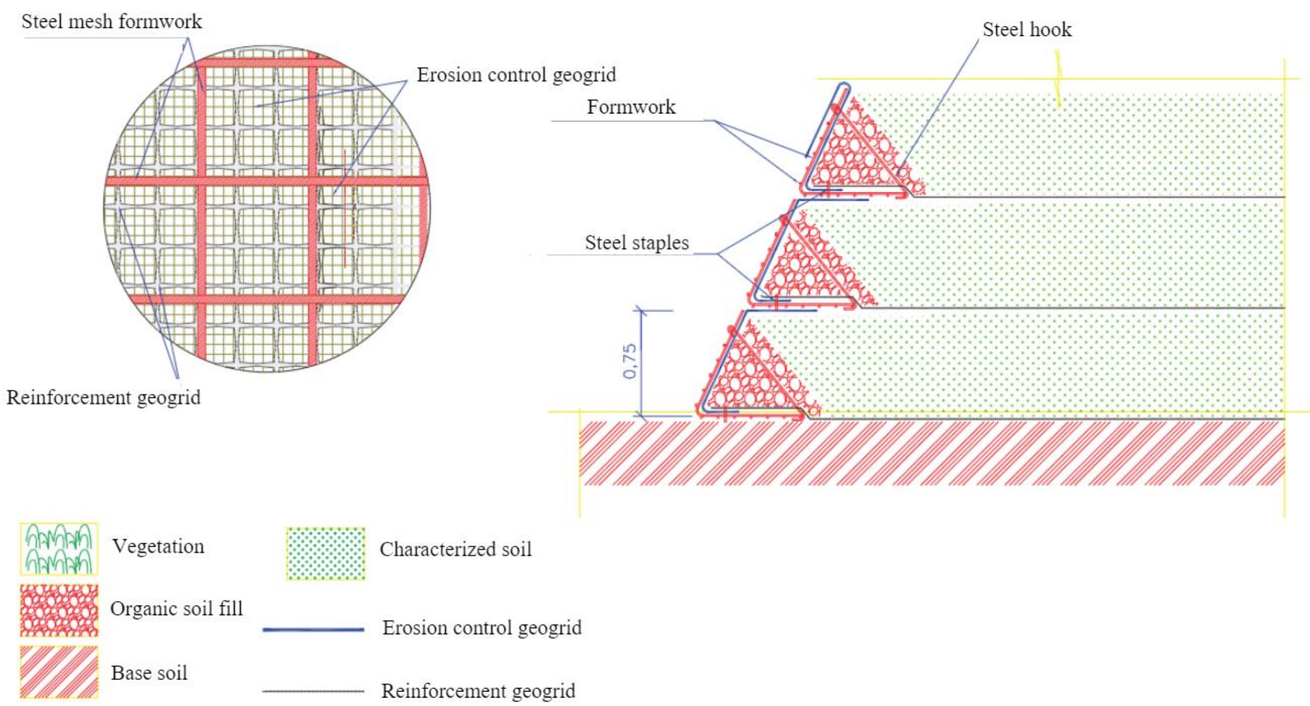

Figure 7. Facing view and cross-section of the reinforced earth wall.

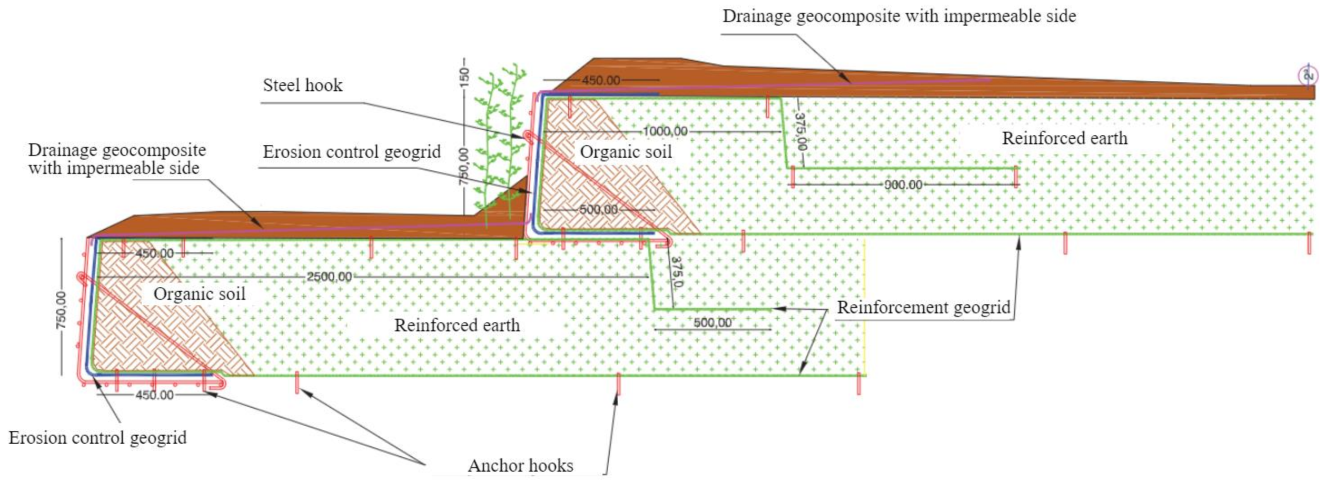

Figure 8. Cross-section of the reinforced earth wall at the berm.

CASE STUDY

In this section, a case study involving the reinforced wall method previously described will be presented. The project is in the municipal region of Benahavís, westbound Marbella village (Málaga, Spain), in particular the residential area of The Hills, located up the hill of Cerro Artola, near La Quinta Golf and Country Club. Figure 9 and Figure 10 show a general view of the project site and the location of The Hills Plot 8, which will be hereby investigated.

Figure 9. Northbound view of The Hills Plot 8 project.

Figure 10. Demarcation of The Hills Plot 8 project.

Site Evaluation

The geotechnical report involved the study over the foundation conditions and recommendations for the design of the reinforced wall. Other details regarding the design and construction of the housing section are not presented in the current paper.

The area under study is located within the Betic Cordilleras, which form, together with the Rif Ranges of North Africa, the most western Mediterranean Alpine orogen. These two mountain ranges, separated in the present in the Neogene basin of Alboran, are located between two Hercynian sockets, the Iberian to the north and the African to the south.

Regionally, there are two important distinguished areas (Figure 11):

- <u>Los Reales Mantle:</u> Composed of a basal lamina of peridotites (lherzolites and harburgites) with a thickness greater than 2 km (Bermeja Mantle), and a sequence inferior metapelitic with a thickness greater than 6 km (Jubrique Mantle and imbrications of Benarrabá).

- <u>Guadaiza Mantle:</u> Presents a lithological sequence constituted by a lower metapelitic formation and an upper carbonate formation, between which there is a gradual stratigraphic transition.

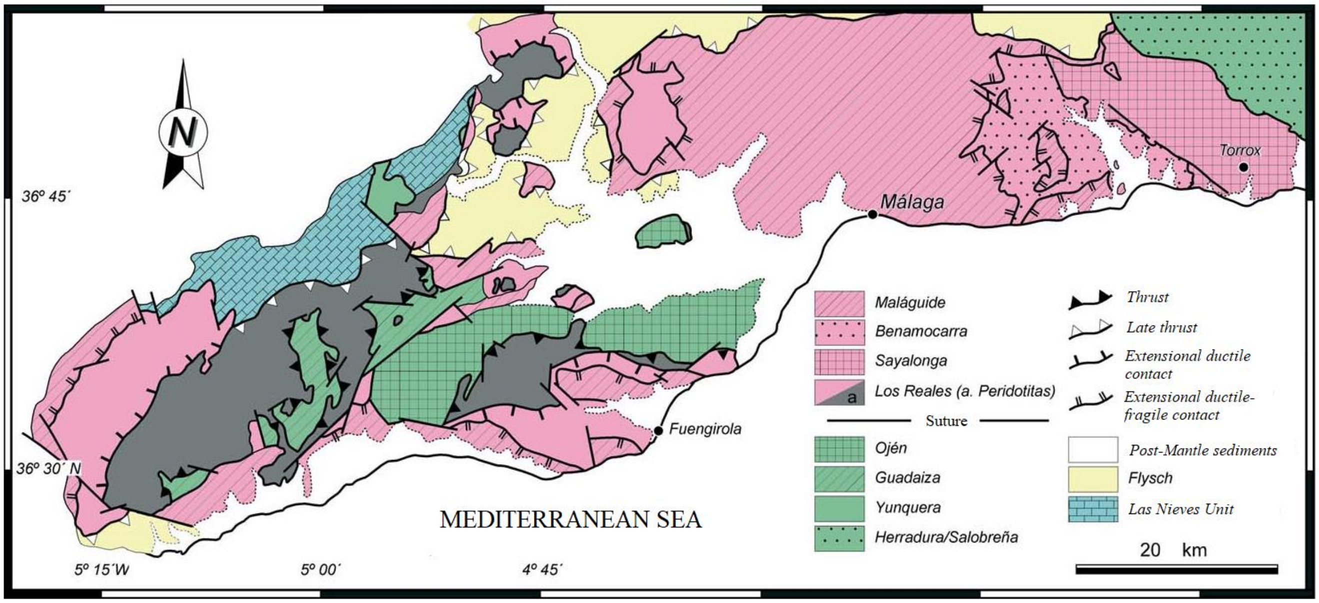

Figure 11. Cartography of the western sector of the Betic Cordilleras (translated from Navarro-Vilá et al., 2007).

In the Southern Hydrographic Basin, there are several aquifers both at the top and coastal sides. The project site is located where the detrital aquifers of earlier formation are found. Although no presence of the phreatic level has been detected on site, it is likely that the water table fluctuates depending on the climatic regime and seasonal changes.

Locally, two mechanical probes were carried out on The Hills Plots 8 and 9 as represented in Figure 12. The extracted samples show that the materials can be divided into three geological units (Figure 13):

- UG.1: Anthropic fill, located from the ground level to 0.50 m below the surface.
- UG.2: Gray phyllites fractured to centimeter fragments, sub-rounded and in sandy matrix, located from 0.50 m to 6 m below the surface.
- UG.3: Fault breccia consistent of fractured angular phyllites of gray tones and crushed with quartzite intercalations, located from 6 m below the surface to the end of the test (20 m).

ID	X	Y	Z
S-08	320708.84	4042545.06	144.75
S-09	320754.38	4042546.40	145.43
UTM 30, S (WGS84)			

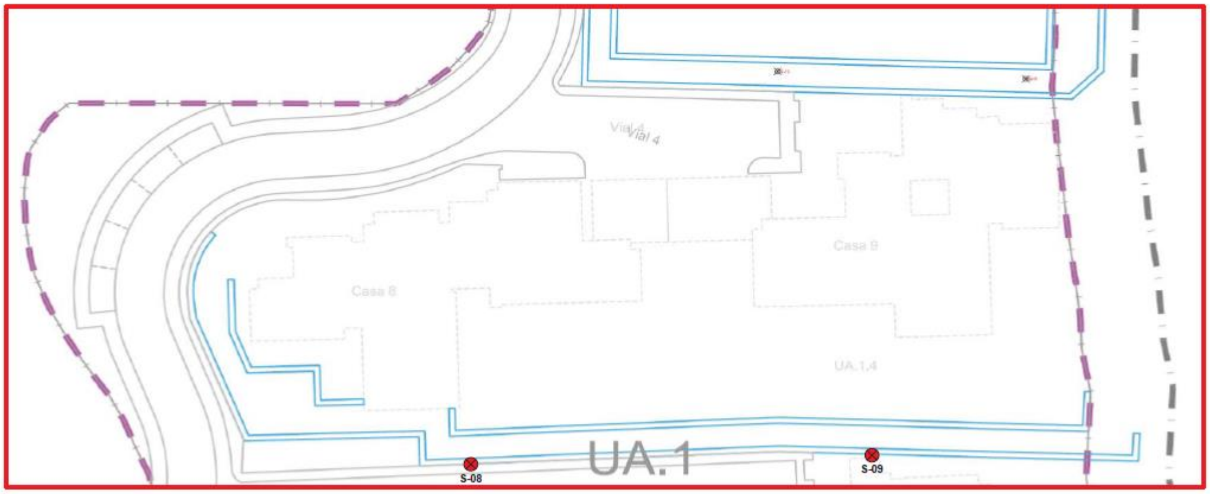

Figure 12. Plan for The Hills Plots 8 and 9.

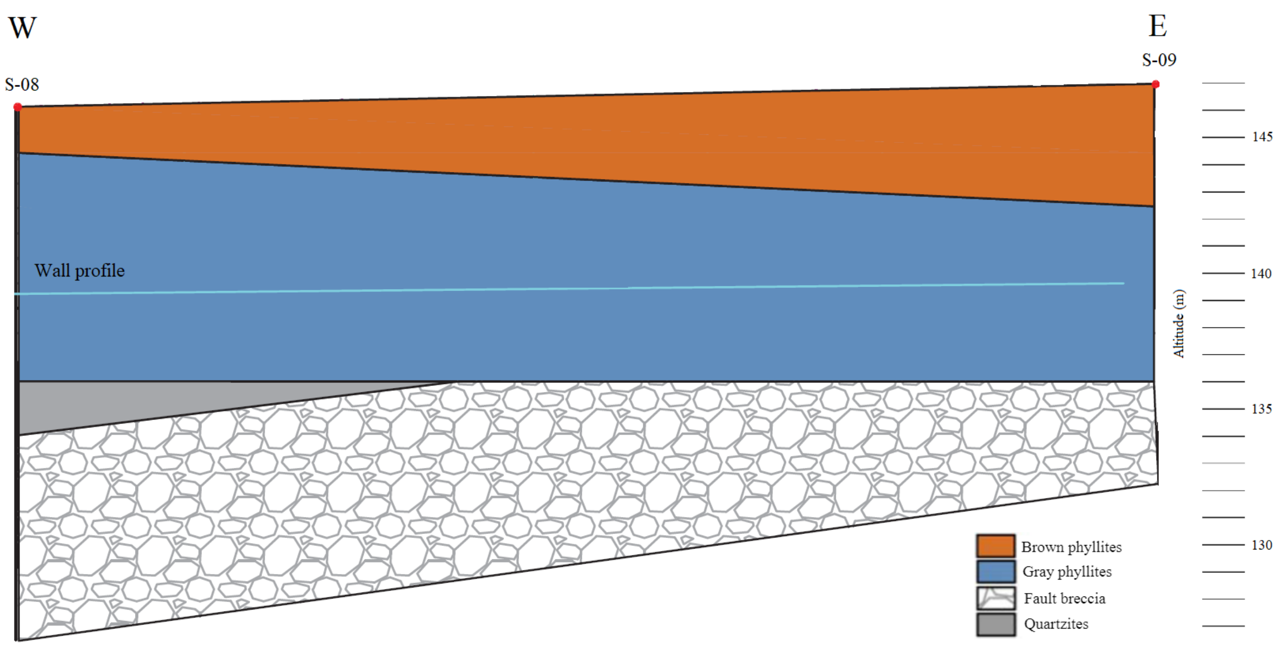

Figure 13. Geological cross-section.

Table 1 represents the total of samples retrieved and physically analyzed, and Table 2 shows the drained parameters for all the discretized geological units. From the geotechnical viewpoint, UG.1 unit represents a low and irregular degree of compaction, and therefore it is not recommended to act as a base soil.

Table 1. Retrieved samples and physical identification.

Sampling		Identification						
		Granulometry			Atterberg limits			
ID	Depth (m)	Gravels > 2 mm (%)	Sands 2 – 0.08 mm (%)	Fines < 0.08 mm (%)	LL (%)	PL (%)	PI (%)	USCS
S-08	2	67.3	17.0	15.7	22.2	17.4	4.8	GC
S-09	1	47.1	35.7	17.2	26	19	6.9	SC

Table 2. Soil parameters.

ID	Unit weight (kN/m^3)	Internal angle of friction (º)	Cohesion (kPa)
UG.1	16	16	0
UG.2	20	30	25
UG.3	20	30	5

Calculation Model

The design of the reinforced wall has been obtained after running stability checks for circular slip failures using the Bishop method, two-part wedge direct sliding using the Spencer method, and global three-part wedge analysis, all modelized with RESSA (Version 3.0; Leshchinsky, 2019), a software developed and commercialized by ADAMA Engineering.

The input values for the characterized soil fraction, extrapolated from the geotechnical report, are represented in Table 3. The parameters for the polyester geogrids were conservatively chosen based on the information available from the manufacturer and can be seen in Table 4.

Table 3. Design parameters for soils.

Soil	Unit weight (kN/m^3)	Internal angle of friction (º)	Cohesion (kPa)
Reinforced soil	20	30	0
Organic soil	20	30	25
Base soil	20	30	5

Table 4. Design parameters for geogrids.

Geogrid (GGR)	Ultimate tensile strength T_{ult} (kN/m)	Reduction factors for 120-year design life			Allowable tensile strength T_{allow} (kN/m)
		Installation RF_{ID}	Durability RF_{CBD}	Creep RF_{CR}	
S35	35	1.20	1.10	1.50	17.68
S55	55	1.20	1.10	1.50	27.78
S80	80	1.20	1.10	1.50	40.40

A parametric study was used to select the geogrids that perform according to the set parameters and boundary conditions. The reinforced wall was divided into four sections:

- Section A: Figure 14
- Section A': Figure 15
- Section B: Figure 16
- Section C: Figure 17

The set of geogrids selected for each section is represented in Table 5. The maximum reinforced mass is 8.25 m high (set-in for 1.5 m below the ground level), with a frontal angle of 85º, and 0.75 m of spacing between reinforcement layers. It must be noted that Section B was designed to fit the swimming pool on the upper end, which also leads to consider a 20 kPa surcharge load.

Based on the recommendations for the area of study, the seismic design considered a 0.07 horizontal peak ground acceleration coefficient (a_b/g). The calculation does not consider water within the reinforced soil, and the minimum factors of safety refer to the most stringent values contemplated in the standards and norms adopted for this design (see British Standard BS 8006, 1995; UNE-EN 1997-1, 2010; MOPU, 1989; Ministerio de Fomento, 2001; Ministerio de Fomento, 2002; Ministerio de Fomento, 2009; and Ministerio de Fomento, 2016).

Table 5. Geogrid distribution per section.

	Section A			Section A'			Section B			Section C		
	GGR	H (m)*	L (m)	GGR	H (m)*	L (m)	GGR	H (m)*	L (m)	GGR	H (m)*	L (m)
	S35			S35	7.40	5						
	S35	6.75	5	S35	6.75	5						
	S35	6.00	5	S35	6.00	5	S35	6.00	5			
	S55	5.25	5	S55	5.25	5	S55	5.25	5			
	S55	4.50	5	S55	4.50	5	S55	4.50	5			
	S55	3.75	5.5	S55	3.75	5.5	S55	3.75	5			
	S80	3.00	7	S80	3.00	7	S80	3.00	7	S80	3.00	5
	S80	2.25	7	S80	2.25	7	S80	2.25	7	S80	2.25	4
	S80	1.50	6	S80	1.50	6	S80	1.50	6	S80	1.50	4
	S80	0.75	6	S80	0.75	6	S80	0.75	6	S80	0.75	5
	S80	0.00	6	S80	0.00	6	S80	0.00	6	S80	0.00	5
	S80	-0.75	5	S80	-0.75	5	S80	-0.75	5	S80	-0.75	5
	S80	-1.50	5			5	S80	-1.50	5	S80	-1.50	5
FS**		1.60			1.56			1.55			2.17	
FS***		1.44			1.36			1.39			1.35	
FS****		1.77			1.73			1.83			2.67	

* H (m) – Height relative to toe.
** FS – Factor of safety for rotational stability analysis under seismic conditions.
*** FS – Factor of safety for translational stability analysis under seismic conditions.
**** FS – Factor of safety for three-part wedge stability analysis under seismic conditions.

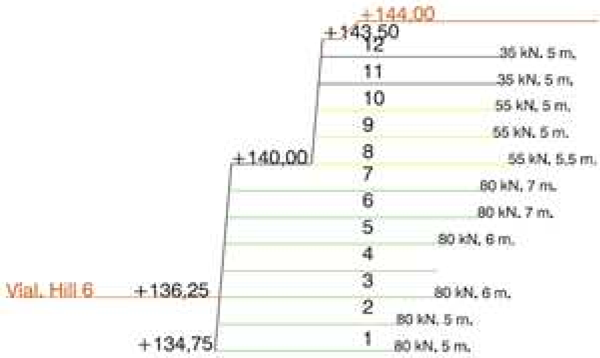

Figure 14. Section A.

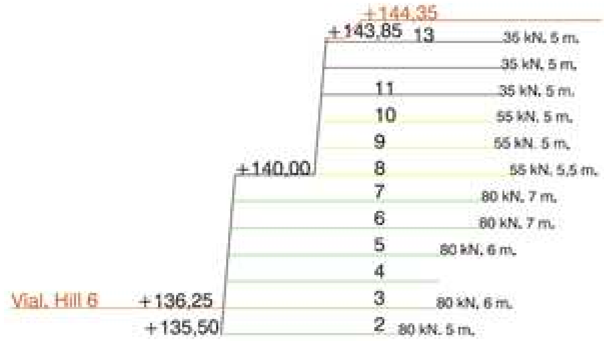

Figure 15. Section A'.

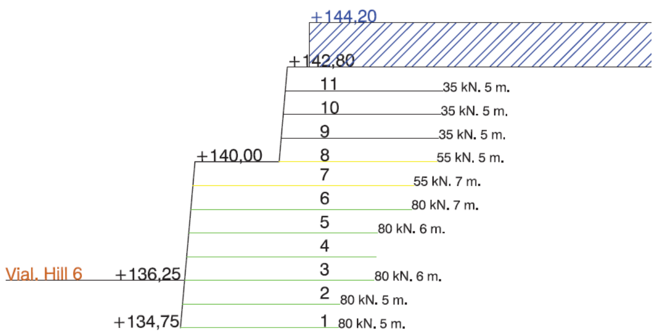

Figure 16. Section B.

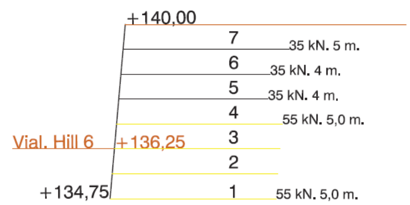

Figure 17. Section C.

Construction Quality Assurance

Before the construction started, it was ensured that the land upon which the structure was going to be settled had the proper leveling and compaction suitable for the requirements per unit area of the structure over time; that is, the sufficient bearing capacity to avoid penetration of structural wedges within the base and differential settlements, which might also cause structural collapse.

For each change in the soil source or its original characteristics, the CQA party defined – using soil classification tests approved by an accredited laboratory – the following parameters to confirm that they agreed the considered calculation variables:

- Internal friction angle.
- Bulk density and dry density.
- Cohesion strength.
- Optimal moisture content for its compaction.

A minimum of 5 Proctor compaction tests must be registered every 0.375 m of compacted soil within the reinforced mass, i.e., half the thickness of each soil layer. This amount may vary depending on the final length of each layer.

Final Remarks

To avoid any affection of the wall stability due to the presence of residential elements, such as the swimming pool previously represented in Figure 16, the premise to be followed is that any subsequent construction over the new platform must avoid the damage of the installed geogrid layers and keep a safe distance of 2.5 m from the wall face.

Following the safest approach, the construction process started at the toe of the hill and proceeded upwards by stacking a series of reinforced walls. A few months into the construction plan, the structure started adhering into the environment with the natural growth of local vegetation, without hydroseeding or other enhancing effects required, as can be seen in Figure 18 and Figure 19. A general view of The Hills project is presented in Figure 20 and Figure 21.

Figure 18. Westbound view.

Figure 19. Westbound view.

Figure 20. Northbound view.

Figure 21. Northbound view.

CONCLUSION

Mechanically reinforced earth walls represent a sustainable solution for the expansion of residential land in regions where the orography is complicated, and the space availability is scarce. Due to their flexible structure and adaptability, reinforced earth walls can be employed in a wide variety of situations with space constraints.

With the increasing concern of communities over the visual impact of structures in the landscape, reinforced walls represent a coherent evolution toward greener solutions that limit the use of imported material. Furthermore, these structures avoid the use of expensive and carbon-intensive materials such as concrete and reinforced steel, minimizing the carbon footprint while maintaining a sustainable use of the available local resources.

Reinforced walls with wrap-around facing combine the functions of reinforcement geogrids of variable tensile strength and length, erosion control geogrids, steel-wire formworks, and drainage geocomposites. Water management is key to avoid groundwater buildup within and around the reinforced land and, therefore, the authors emphasize the importance of using non-collapsible drainage geocomposites that ensure that a minimum flow capacity is achieved over the full structure lifecycle.

The presented case study involved the construction of reinforced earth walls with wrap-around facing for The Hills Plot 8 residential development, situated in Benahavís (Málaga, Spain). Using the methods hereby presented, the project resulted in a total of four sections with a maximum height of 8.50 m and slope angle of 85º, formed by the combination of polyester geogrids of 35 kN/m to 80 kN/m ultimate tensile strength spaced between 0.75 m soil layers of characterized properties, erosion control geogrids, steel wire meshes, and a drainage network of biplanar geocomposites and collection pipes.

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