Pirca stabilization using geogrids in Carabayllo - Peru

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ABSTRACT: Informal housing construction on steep slopes presents high sliding risks. In most cases the population design and construct their own houses without the advice or supervision of professionals. In Carabayllo it is common to see *Pircas* (stacked rock walls) constructed to support different types of buildings, commonly used for housing, which are very vulnerable to seismic loads. The random method of construction of *Pircas* makes it difficult to characterize them; however, a types of *Pircas* have been chosen depending on the slope where they are settled. This work compares numerically four types of solutions to stabilize these *Pircas* taking into account a method used by people in Carabayllo, which are: The first; reinforcement method is covering the *Pirca* with a thin layer of cement mortar; the second is covering the *Pirca* with a geogrid; the third method is covering the *Pirca* with geogrids and 5cm thick sand mortar and the last method uses reinforced *Pirca*-backfill with a geotextile. A comparative table is presented with the safety factors found for each case. This study recommends the best solution, one that presents an acceptable safety factor at the lower cost.

Keywords: Pirca, Carabayllo, rock walls, slope stability, geogrid, pañeteo, sand mortar, reinforced soil

1 INTRODUCTION

Informal housing includes the illegal occupation of settlements, land sales in areas without the basic conditions to live and obtaining land legally based on construction resolutions (UN-Habitat, 2003). Informality brings a high susceptibility to disasters, increased crime and health problems (Smolka and Biderman, 2011). In developing countries, there is no a clear relationship between family income and housing tenure due to self-construction (Arbaiza, 2005).

Carabayllo district shows a significant and sustained population increase during the last 39 years, rising from 28,827 inhabitants in 1972 to 257,325 inhabitants in 2011, according to National Census projections (INEI, 2007). In Carabayllo 30% of the population does not have potable water service or sewage and 9% of children aged between 6 to 9 years are undernourished (Morales, 2007).

The geomorphology of Carabayllo implies that the population is living on hillsides with a high seismic risk due to the steep slopes (up to 40°). The soils are composed of fractured intrusive rocks, backfills and loose blocks (Núñez & Vásquez, 2009).

The Carabayllo human settlements, Eliane Karp, El Manantial and Santa Rosa are located in the El Progreso sector. This sector is part of a ravine that has a main channel with colluvial cones, alluvial deposits and flows into the Chillón river, as shown in Figure 1.

Figure 1. Map of the El Progreso area in Carabayllo district, Lima. Peru.

Pircas are a very common foundation element in Carabayllo. They are characterized by their height, thickness, width and type of rock. However, in the case of occasional or frequent earthquakes we need to study their resistance. They probably do not perform well.

The steep slopes in some areas of Carabayllo can cause landslides, these movements can occur along fault surfaces, free fall erosion or runs (Skempton & Hutchinson, 1969). To estimate the Safety Factor (SF), the limit equilibrium method is used, which estimates the SF as a function of the shear resistance (Bishop, 1960).

The rocks presented in the models of this article are rocks with dry joints; in general the models presented in this article have been analyzed with the Bishop limit equilibrium method with the Slide V.6 program of Rock Science. It will be considered that the *Pirca* is a rigid monolithic solid, although it is not the case, it is used for the smler computational time that implies in relation to the use of discrete elements (Katz et al., 2014). The loads on the structure will be its own weight (P), the external loading pressure (Pl) on one side, and the reaction (R) of the foundation, as shown in Figure 2 (Colas et al., 2008).

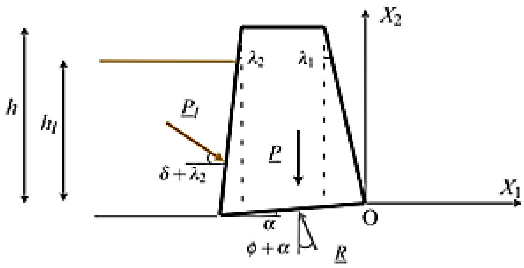


Figure 2. Limit equilibrium analysis for a rock wall with dry joint (Colas, Morel, & Garnier, 2008).

1.1 *Pircas*

Pircas are constituted by burned and irregularly shaped rocks, less than 50cm in size, placed by hand. The stability of the structure is mainly due to the friction between the elements due to the interlocking action between the blocks. *Pircas* are known in the literature as Dry Stone Retaining Walls (DSRW). The lack of a binder allows the accommodation of the pieces and the occurrence of large deformations before collapsing (Vincens et al., 2016).

Previous studies have shown that the discrete element method (DEM) is able to simulate the behavior of DSRW in terms of crack development (Bui et al., 2017) and failure mechanisms (Fukumoto et al., 2014). On the other hand SF can also be evaluated using the technique of Shear Resistance Reduction using finite elements or finite differences, demonstrating that these methods have advantages with respect to limit equilibrium methods (Matsui & San, 1992; Diederichs et al., 2007). Nevertheless; the limit equilibrium method is valid for a first SF estimation.

Pircas are stones piled without any cement and present a high seismic risk danger since during a severe earthquake these would slide (Carrillo, 2012). In Carabayllo many *Pircas* are not adequately built for stabilty (Núñez and Vásquez, 2009). In Figure 3 from left, the overlapping of rocks is observed to form a poorly constructed *Pirca* according to the recommendations of the municipality (right). The *Pirca* must be covered with a layer of cement (MML, 2013). A practical video of construction is shown by Desco (2010), in which it has technical assistance but unfortunately it is rarely used in reality.

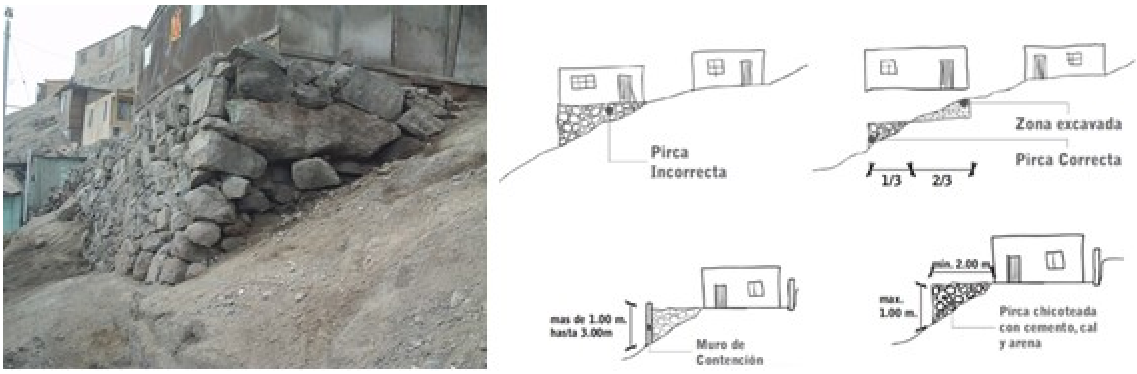


Figure 3. Left, view of a Pirca built incorrectly. Right, recommendations of the Metropolitan Municipality of Lima for the construction of stone walls (MML, 2013).

Studies done in different areas of informal constructions found the foundations of precarious buildings, many of them built without technical help on loose granular soils, uncompacted backfills and on soft soils (De los Ríos, 2006). They represent a risk in case of heavy rains or earthquakes.

1.2 *Limit equilibrium method*

The methods of limit equilibrium for stability analysis of slopes are widely used in projects due to their simplicity. The SF is defined as the quotient between the forces acting on the slope and the resistive forces: $SF = (Resisting\ forces)/(Driving\ forces)$.
The safety factor is used as a function of the shear strength because in most of the geotechnical engineering problems the greatest uncertainties are related to the evaluation of the shear resistance of the soil (Bishop, 1960). It is considered as hypothesis that the soil behaves like a rigid, perfectly plastic material, without considering the stress and strain fields generated by external loads (Skempton, 1977).

1.2.1 *Static analysis*

The slicing method is characterized in that it slices the mass of the upper part of the fault surface. The number of slices depends on the geometry of the slope and the precision required for the analysis. Generally, the equilibrium of moments is considered in relation to the center of the circle for each and every one of the slices. The simplified Bishop method assumes that the lateral forces between slices are horizontal and neglects the shear forces (Suarez, 1998). In this article SF was calculated by the Bishop limit equilibrium method.

Figure 4 shows the profile of the *Pirca*, fill and soil that have been divided into slices, one of them is observed indicating the weight of the slice W_n, P_{n+1} y P_n are the normal left and right forces between slices; In the same way, the shear forces acting on the sides of the segment are T_n y T_{n+1}. N_r and T_r are the normal and tangential force at the base of the slice.

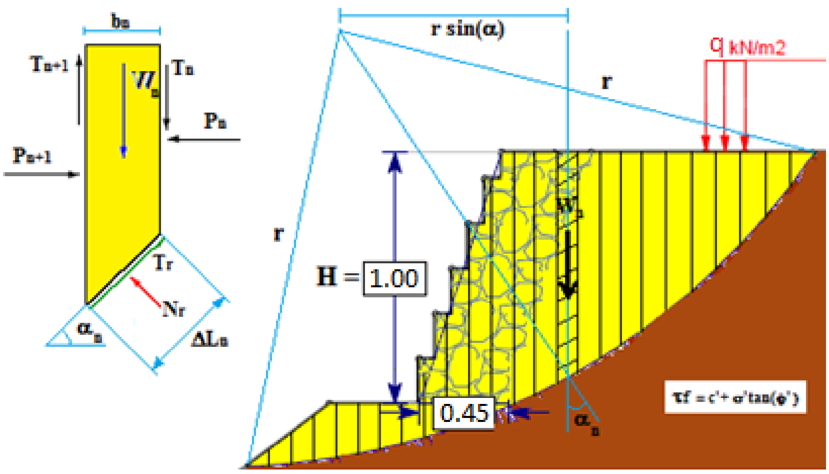


Figure 4. Soil profile, filling and Pirca. Representation of the acting forces in a slice by the Bishop method.

According to the data of Figure 4, the SF by the simplified Bishop method, which does not consider the balance of horizontal forces (P_{n+1}, P_n) and the shear forces (T_{n+1}, T_n) can be neglected for being very small. The SF for circular sliding surfaces can be expressed as follows:

$$FS = \frac{\sum_{n=1}^{n} \left(c'\Delta L_n + \dfrac{W_n \tan \phi'}{\cos \alpha_n \left(1 + \dfrac{\tan \alpha_n \tan \phi'}{FS}\right)} \right)}{\sum_{n=1}^{n} W_n \sin \alpha_n}$$

Where:
c': Cohesion
ϕ': Internal friction angle
ΔL_n: Length of the base of the dowels
W_n: Weight of the dowels
α_n: Angle of inclination of the dowels
n: Number of dowels

It is necessary to perform several iterations to obtain the value of SF until it converges.

1.2.2 *Pseudo-static analysis*

The pseudo-static analysis represent the effects of vibrations in an earthquake, these vibrations are represented by the pseudo-static accelerations that produce horizontal (F_h) and vertical (F_v) inertial forces, these are: $F_h = k_h W$ y $F_v = k_v W$, where k_h and k_v are the horizontal and vertical seismic coefficients and W is the weight of the fault mass.

The earthquakes greatly affect the stability of slopes, therefore the pseudo-static analysis of SF is of importance to take reinforcement measures of *Pircas*, this concept was introduced by Terzaghi, in 1950 who recommended the following values of horizontal seismic coefficient: k_h=0.1 for severe earthquakes, k_h=0.25 for violent destructive earthquakes and k_h=0.5 for catastrophic earthquakes. In all cases the SF must be close to 1 (Terzaghi, 1950). Thus in Figure 4 the seismic forces are applied into each slice, as an inertia force.

The pseudo-static analysis requires the use of appropriate material dynamic strengths. If the SF is under the unity, the slope stability is considered unsafe. Thus, a properly calibrated pseudo-static slope stability procedure requires a compatible selection of the seismic coefficient, material dynamic strengths, and an acceptable SF (Baker et al., 2006); (Bray et al., 2009).

The objectives of this article are: (1) characterize the physical and mechanical properties of *Pircas*, to numerical modeling of the *Pircas* and four reinforcement types (2) calculate the safety factor by the simplified Bishop limit equilibrium method for *Pircas* without reinforcement and four with reinforcement.

2 METHODOLOGY

It is sought that the solution should be suitable for any *Pircas* built in an informal manner that meets the dimensions taken in the model presented. The steps to follow for the analysis of the safety factor are the following:

- ✓ Compilation of field information in the district of Carabayllo to characterize the soil, fill and rock type of the *Pirca* and identification of parameters for stability analysis.
- ✓ Analysis of static and pseudo-static stability of reinforcement methods.
- ✓ Implementation cost estimation.

2.1 *Field data - AAHH El Progreso sector of Carabayllo*

The sector of El Progreso in the Carabayllo district has been impacted by disasters in 1953, 2004 and 2010. A visit was made on May 23, 2017 to the human settlements of: Eliane Karp, El Manantial, Santa Rosa and Alto Perú from *Asentamiento Humano* (AAHH) El Progreso, as can be seen in Figure 5 the areas visited are on hillsides, the foundations of the houses are made on stone walls without any technical supervision, typical of the self-construction predominant in the area.

Figure 5. The human settlements El Manantial (left) and Eliane Karp (right).

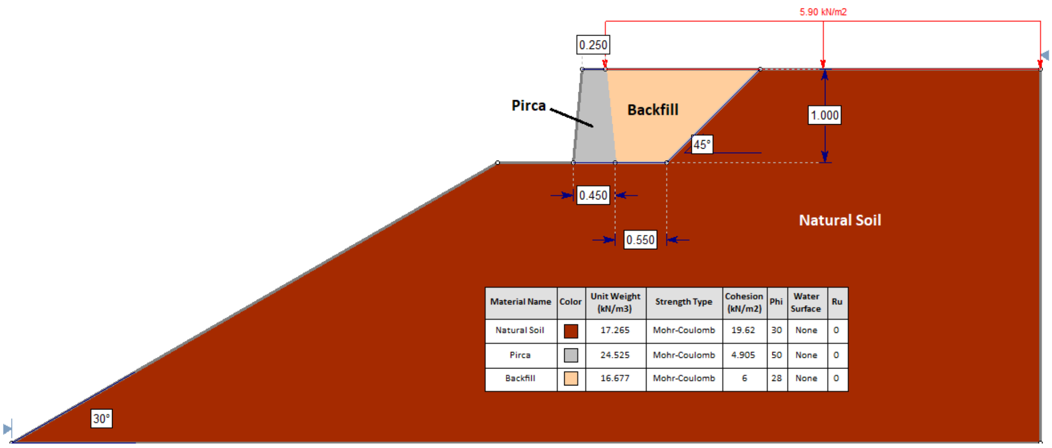
The human settlements visited have steep slopes up to 40°. The soil consists mainly of silty sand and fractured rock from colluvial origin. The rocks used for the *Pirca* construction are: limestone, diorite and andesite. The less durable rocks are the limestones and diorites.

According to the testimony of *pirqueros* (persons having experience of *Pircas* construction), the average *Pircas* present heights between 3 to 4 meters and lengths of 6 to 10 meters. In the city of Lima, specifically in the district of Carabayllo, the use of stone walls has been extensive in hillside areas.

2.1.1 *Field data used in modeling*

For the model, the parameters considered were the worst materials according to the field data provided by the ONG Practical Solutions, the data for this paper was based in the statistical analysis realized by Zanelli et al. (2018). The profile used with dimensions; the angles of the slopes and the parameters of the materials are shown in Figure 6. Cohesion for natural soil is 19.62 kN/m^2; the backfill does not provide greater resistance to the whole, it has 16.677kN/m^3 of density, 6kN/m^2 as a cohesion and 28° of friction angle (phi in the Figure 6).

For the *Pirca* a low cohesion (4.905kN/m^2) is assumed; the laboratory tests indicated that it can be up to 37300kN/m^2 to the rock blocks; however, for the set of rock blocks, a low cohesion is taken. The laboratory test indicated a friction angle between 58.07° and 59.07°, in this case it is considered 50° as a friction angle because there is an interlocking effect due to the irregularities of the blocks that make up the *Pirca*. The water line is not considered because Carabayllo district is a desert area.



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kN/m2)	Phi	Water Surface	Ru
Natural Soil		17.265	Mohr-Coulomb	19.62	30	None	0
Pirca		24.525	Mohr-Coulomb	4.905	50	None	0
Backfill		16.677	Mohr-Coulomb	6	28	None	0

Figure 6. Model profile, it shows density, friction angle and cohesion of Pirca; backfill and natural soil of AAHH El Progreso in Carabayllo District.

To model the natural soil, the backfill, the rock blocks of a *Pirca*; it has been assumed that all the materials are homogeneous. The applied stress over the backfill corresponds to the sum of the dead weight estimated for a wooden one floor dwelling is 4.9 KN/m^2 and an overload due to the transit of people and the weight of non-structural elements (1.0 kN/m) (Norma E0.20, 2006); (Zanelli et al., 2018). For this paper there were considered loads of 1, 2, 3, 4, 5 and 5.9 KN/m^2 to analyze the change of the safety factor.

The pseudo-static coefficient (k_h) is 0.22, which is for an event of 475 years return period. Groundwater level is not considered because it is a desert area.

2.2 *Reinforcement methods*

The reinforcement methods considered are those used by the residents of Manantial, Santa Rosa y Alto Perú of El Progreso in Carabayllo district. It is important to remark that in the field, the use of some type of reinforcement is rare. In this article four reinforcement types are used. The first reinforcement method is covering the *Pirca* with a thin layer of cement mortar, the second one is covering the *Pirca* with a geogrid, the third method is covering the *Pirca* with a geogrid and sand mortar and the last one is the reinforcement of *Pirca*-backfill with a geotextile.

To give a more secure solution, without modifying the structure of the *Pirca*, the reinforcement can be used by soil nailing that consists of the passive reinforcement of soil or weathered rock by installing closely spaced nails. “This concept of combining passive steel reinforcement and sand mortar has also been applied to the stabilization of rock slopes since the early 1960s” (Lang, 1972), for designing in soil nailing FHWA (2003) is used which is based on limit equilibrium methods. But this method required advanced technology and often is expensive; for this reason it is discarded for use in this article.

2.2.1 *Covering the Pirca with cement mortar*

In general it is called *pañeteo* to cement with water by the local population as shown in the left of Figure 7. The *pañeteo* consists of projecting cement mortar directly on the surface of the *Pirca*, the thickness can be very variable (0.03 cm to 3cm), it depends on the person that constructs the *Pirca*, the time and the economy of people, this method is recommended by the Metropolitan Municipality of Lima (MML, 2013). Another type of reinforcement is used to protect the *Pircas* by a wall of poor concrete and 3/8” steel reinforcement bars as seen in Figure 7. This method is uncommon in the recent construction.

Figure 7. Left, reinforced method with cement mortar called pañeteo by the local inhabitants. Center, wall of poor concrete and 3/8” steel reinforcement bars. Right, 0.01m thick cement mortar represented in the model to cover the Pirca.

In this case, the cement mortar is considered 1 centimeter and 17.972 kN/m^3 of density, 30kN/m^2 of cohesion and 35 degrees to friction angle as shown in right of Figure 7. It is necessary to analyze the SF for this value because it represents the method used in Carabayllo.

2.2.2 *Covering of the Pirca with geogrid*

There does exist papers about the use of geogrid boxes to stabilize rock slopes (Fahimifar et al. 2014) and (Moradi et al. 2018). Usually, the geogrid is not used to cover the rocks of the block used in *Pircas*. Geogrids in Lima are used to cover the cliffs of *Costa Verde* to avoid falling rocks on roads due to the erosion of gravelly soils. For this reason, it was thought that it is possible that geogrids have a degree of stabilization in the *Pircas*.

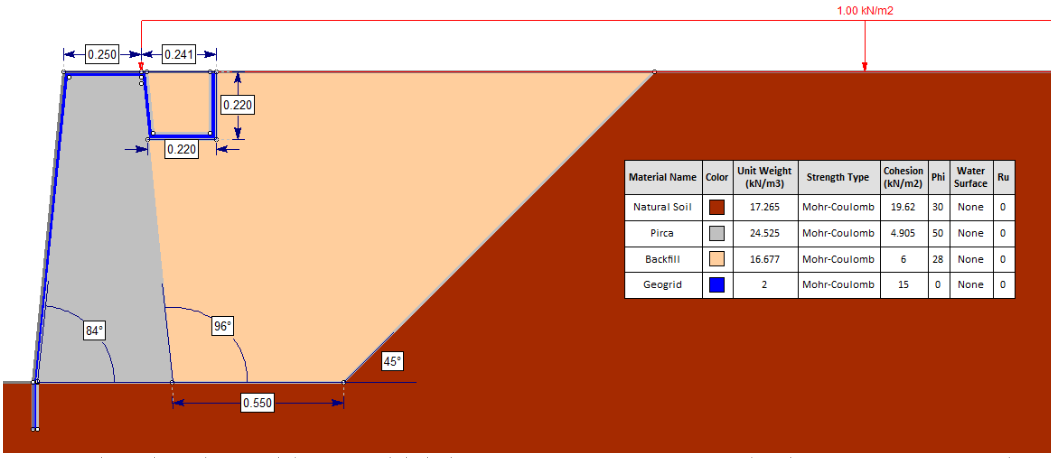
Figure 8. In order to prevent rocks falling on the roads, geogrid was used on the cliffs of the Costa Verde in Lima city (Photo: Andina, 2017).

For SF analysis in the *Pirca* models geogrid GG090 has been used. The Uniaxial geogrid GG090 is woven from polyester coated with PVC, with ultimate tensile strength in the main direction of 90 kN/m and in the secondary direction of 30 kN/m, the density is 2kN/m^3, cohesion is 15kN/m^2 and don't have a friction angle as shown in Figure 9.

Geogrid installation requires an anchoring in 22x22 centimeters fill, these measures can change according to the height of the *Pirca*, as is the case shown in Figure 9 being 1m high, then it follows the facade of the *Pirca* covering its upper part where the anchoring takes place. In this system, the geogrid acts mainly to prevent the small rocks from falling down towards the shelters located below the slope.

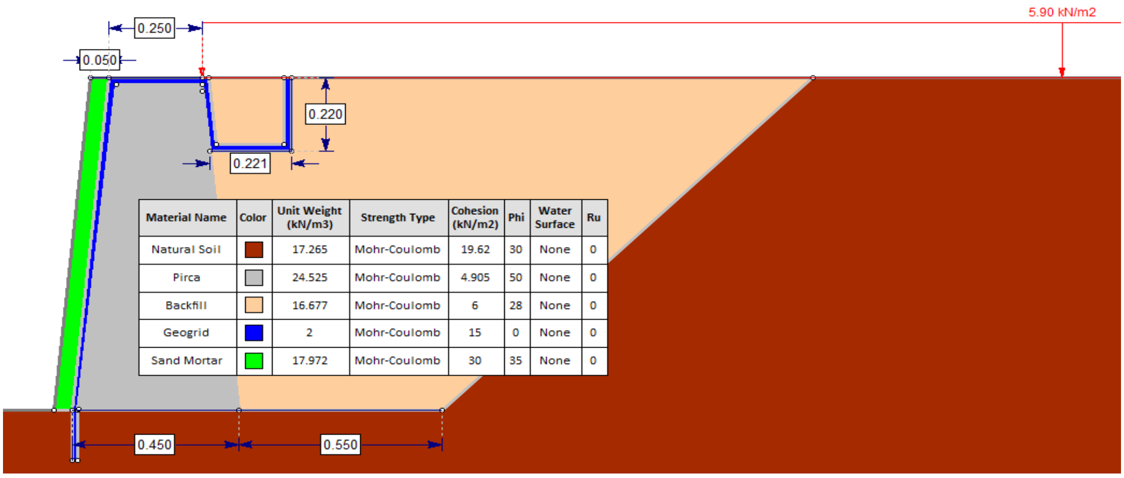
2.2.3 *Covering the Pirca with geogrid and sand mortar*

In El Progreso, some residents use the *pañeteo* that is to add a cement mortar in the facade of the *Pirca* as viewed in the left of Figure 7, this recommendation is given by the Metropolitan Municipality of Lima (MML, 2013). The sand mortar, physically adds a certain cohesion to the rock blocks. The idea is to add cohesion to the *Pirca* to minimize the falling rocks besides the geogrid. In the Figure is considered 5 centimeters thick sand mortar and 17.972kN/m^3 of density, 30kN/m^2 of cohesion and 35 degrees to friction angle.



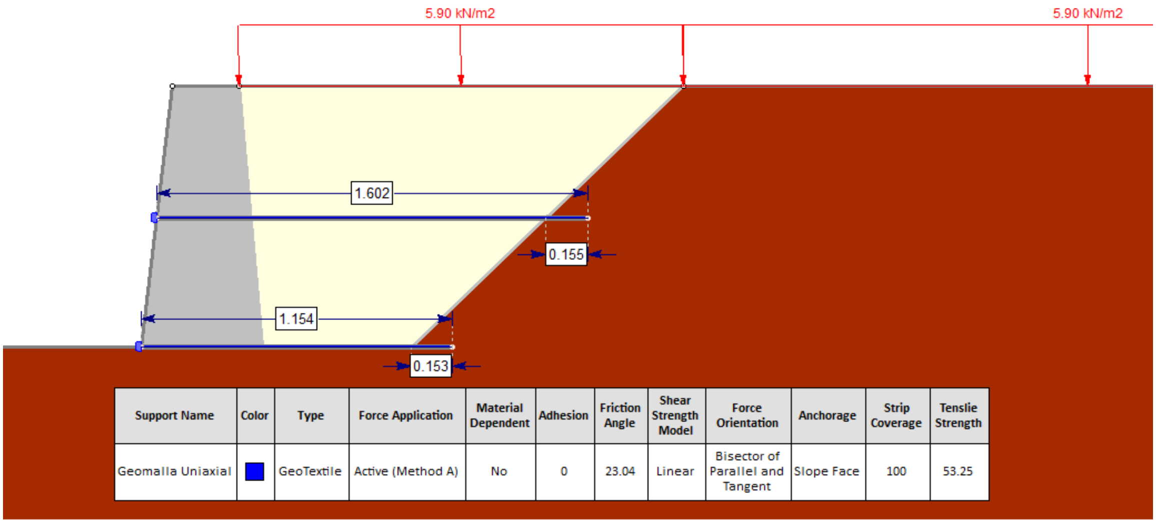
Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kN/m2)	Phi	Water Surface	Ru
Natural Soil		17.265	Mohr-Coulomb	19.62	30	None	0
Pirca		24.525	Mohr-Coulomb	4.905	50	None	0
Backfill		16.677	Mohr-Coulomb	6	28	None	0
Geogrid		2	Mohr-Coulomb	15	0	None	0

Figure 9. Covering the Pirca with Geogrid, it is necessary to use an anchoring 0.22x0.22 centimeters fill.



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kN/m2)	Phi	Water Surface	Ru
Natural Soil		17.265	Mohr-Coulomb	19.62	30	None	0
Pirca		24.525	Mohr-Coulomb	4.905	50	None	0
Backfill		16.677	Mohr-Coulomb	6	28	None	0
Geogrid		2	Mohr-Coulomb	15	0	None	0
Sand Mortar		17.972	Mohr-Coulomb	30	35	None	0

Figure 10. Covering the Pirca with a geogrid and a 5 centimeters sand mortar layer.



Support Name	Color	Type	Force Application	Material Dependent	Adhesion	Friction Angle	Shear Strength Model	Force Orientation	Anchorage	Strip Coverage	Tenslie Strength
Geomalla Uniaxial		GeoTextile	Active (Method A)	No	0	23.04	Linear	Bisector of Parallel and Tangent	Slope Face	100	53.25

Figure 11. Reinforcement of Pirca-backfill with geotextile, an anchorage of 15cm was considered in the natural terrain for greater safety.

The design of retention structures reinforced with geogrids is based on the standards (FHWA, 2001; AASHTO, 2002; NCMA, 2010). The use of geogrids to reinforce soil slopes is quite common (Ziegler, 2017). In general, the stability for high reinforced slope is the function of geometry and mechanical properties of soil, but it is also important to consider the topography of the global system (Liu et al., 2012).

The use of geogrids for slope reinforcement includes the stability analysis in adjacent zone and it is important to consider: geogrid installation, soil particle size, edge distance, all this consideration can improve the slope stability (Mehrjardi et al., 2016). The wall of reinforced *Pirca*-backfill has been designed in layers as seen in Figure , in 2 layers where the geogrid has been placed at 0.5m. The SF is expected to increase considerably, that is with the use of geogrid to assembling the backfill and the *Pirca*.

3 RESULTS

The results have been based on the safety conditions specified by the Norm E050 (2006) Soils and Foundations of Peru; the safety factor (SF) should be 1.5 for static loads and 1.25 pseudo-static loads. All the simulations presented in this item have been simulated using the Slide program of Rock Science version 6.0.

3.1 *Static analysis*

Considering a 5.9KN/m^2 distributed load on the top of the *Pirca* for the method called *pañeteo*, the static slope stability analysis SF is 1.265 as shown in Figure . In this analysis a 1cm thick cement mortar was considered. For the second case using of geogrid as reinforcement method, especially to avoid falls of rock fragments (see 2.2.2), the SF is 1.294. For both cases the Code is not met, where it is specified that the minimum SF must be 1.5.

In case of using geogrids and 5cm thick sand mortar covering the *Pirca* as a stabilization method under a 5.9KN/m^2 distributed load, the SF is 1.507 as shown in the left side of Figure . Furthermore when the reinforcement method is the *Pirca*- backfill reinforced with geotextile under the same applied load as can be seen in the right side of Figure a SF of 3.594 is obtained. The disadvantage of this last method is that it necessarily would require rebuilding the retaining wall.

In order to comply with the Peruvian Code of soils and foundations the static SF must be greater than 1.5. As seen in Table 1, six different distributed loads including the maximum load of 5.9 KN/m^2 found in the study area of Carabayllo district are used to estimate the static SF. Unfortunately the methods used by most of the people in these areas, the natural *Pircas* and, the 1cm thick cement mortar is not enough to obtain a safety factor that complies with the Code, but complies for very low applied loads.

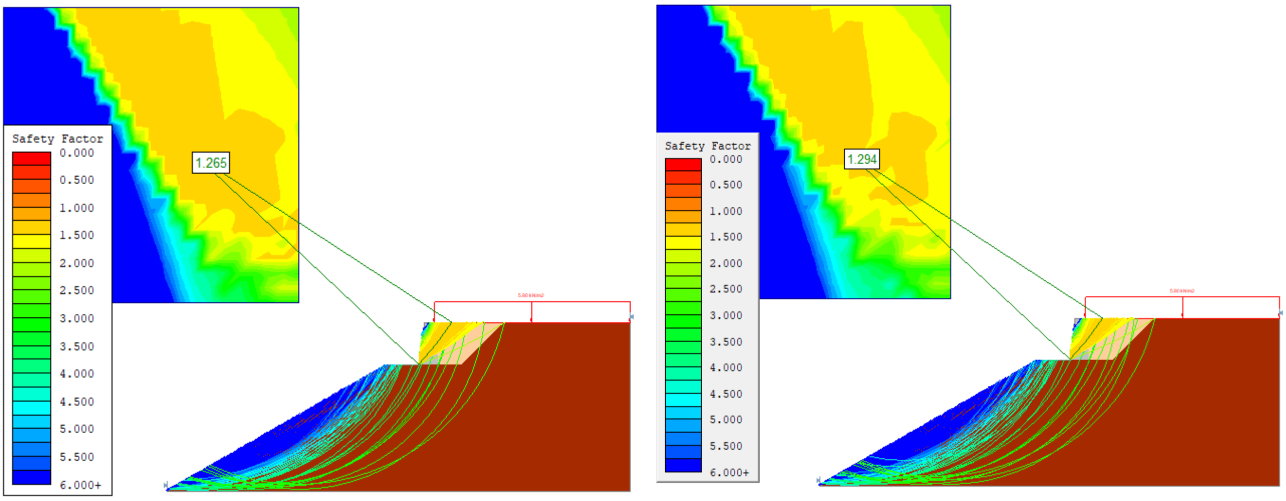


Figure 12. Left, 1.265 of safety factor to 1cm thick cement mortar covering the Pirca. Right, SF 1.294 when the Pirca is covering by geogrid. In both cases the Peruvian norm is not complied with.

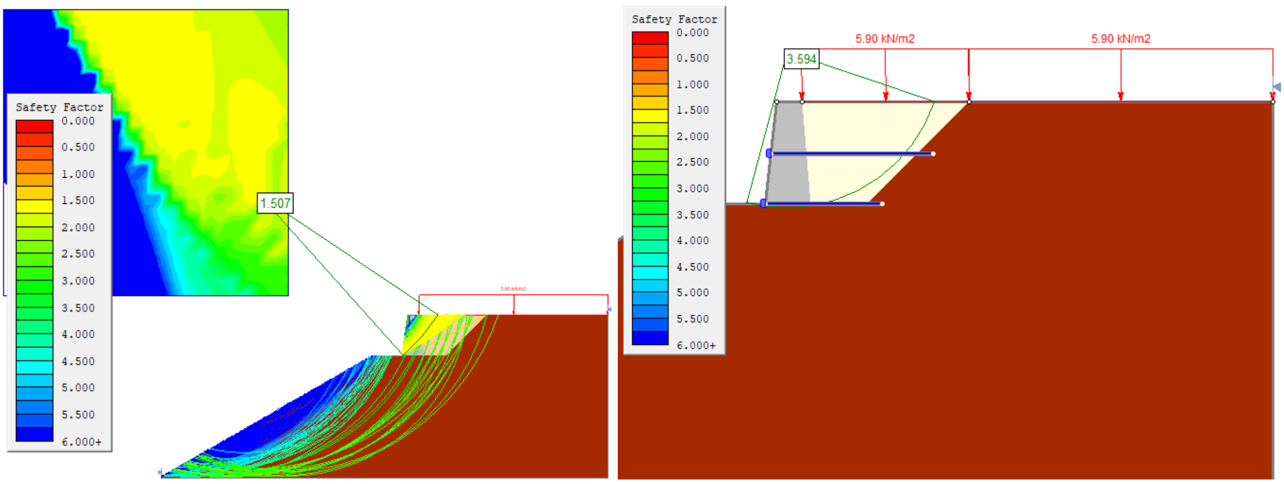


Figure 13. Left, Pirca recovering with a geogrid and 5cm thick sand mortar, the SF is 1.507. Right, Pirca-backfill reinforced with geotextile, the SF is 3.594. Both methods comply with the 1.5 as minimal SF (Norm E050, 2006).

Table 1. Safety Factor for static analysis in field conditions and four reinforced methods: 1cm thick cement mortar, Geogrid; 5cm thick sand mortar and Geogrid and Reinforced soil with geogrid.

Load KN/m²	Natural Pirca	1cm thick Cement Mortar	Geogrid	5cm thick Sand Mortar and Geogrid	Reinforced with Geotextile
1	**1,527**	**1,615**	**1,676**	**1,943**	**4,158**
2	1,463	**1,524**	**1,575**	**1,830**	**4,050**
3	1,392	1,445	**1,488**	**1,731**	**3,949**
4	1,325	1,375	1,412	**1,644**	**3,853**
5	1,269	1,316	1,345	**1,568**	**3,713**
5.9	1,221	1,265	1,294	**1,507**	**3,594**

The acceptable methods of reinforcement are a 5cm sand mortar with geogrids and the *Pirca*-backfill reinforced with geotextiles, because these methods comply with the Code for all applied loads. The best method is the one that gives the highest safety factor. However, an economic analysis is necessary, since the study area privileges the low cost.

3.2 *Pseudo-static analysis*

For pseudo-static analysis the same physical and mechanical properties as for the static case was considered (see 2.1.1). A seismic coefficient (k_h) equal to 0.22 was used for the pseudo-static analysis which correspond a 475 years return period event in the study area. For the *pañeteo* method considering 1cm thick cement mortar covering the *Pirca* and a load of 5.9KN/m^2; the obtained SF is 1.039 as shown in Figure . For the geogrid as reinforcement method and the same loads, the obtained SF is 1.073 (Figure , right). For both reinforcement methods, the minimum SF of 1.25, established by the Code is not met.

For the geogrid with 5cm thick sand mortar covering the *Pirca* reinforcement method, the pseudo-static SF is 1.241 as shown in the left of Figure . Finally for the *Pirca* with backfill reinforced with geotextile reinforcement method the SF is 2.696 (see Figure , right).

As in the static analysis, the safety factor for soil, backfill and *Pirca* as it is presented in the study area has been calculated; the results of all loads are presented in Table 2. It is observed that for the first two reinforcement methods, the safety factor of 1.25specified by the E050 Norm for pseudo-static analysis is not met. The reinforcement methods that comply with the code for all the loads are the last two methods that is, the 5cm thick sand mortar with geogrid covering the *Pirca* and the *Pirca*-backill reinforced with geotextile.

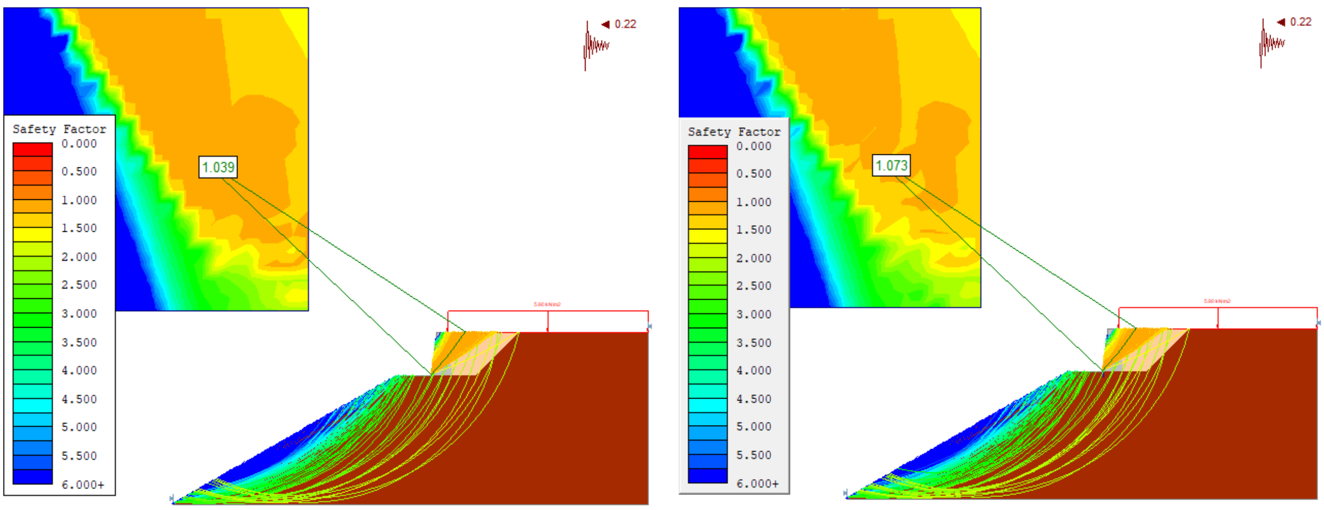


Figure 14. Left, the pseudo-static SF is 1.039 to 1cm thick cement mortar covering the Pirca. Right, SF is 1.073 to geogrid covering the Pirca. The SF of 1.25 is not met Norm E050, 2006).

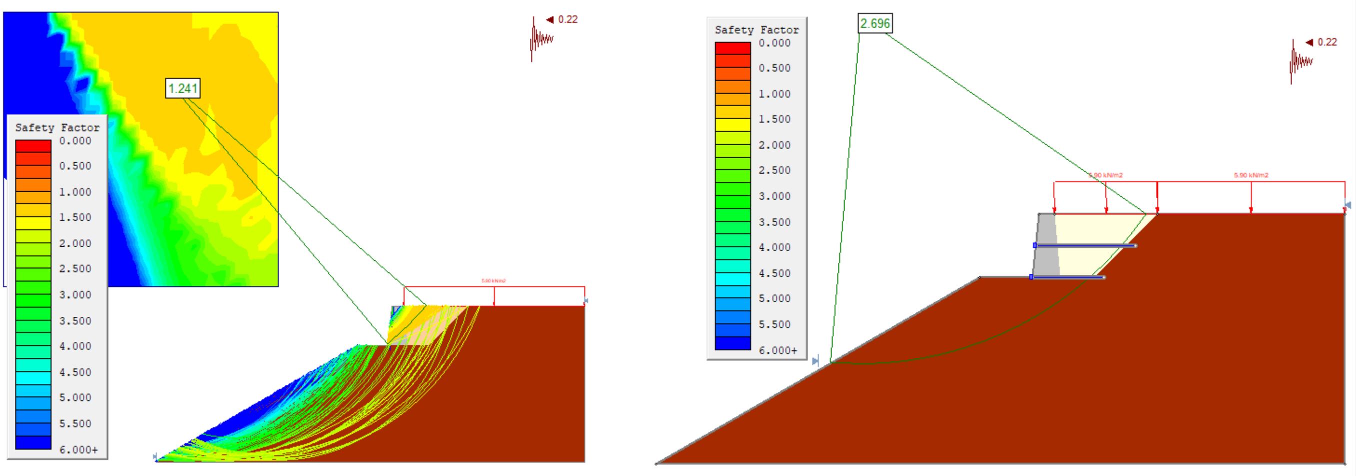


Figure 15. Left, the pseudo-static SF for the Pirca reinforced with geogrid and 5cm thick sand mortar is 1.241. Right, the pseudo-static SF for the Pirca-backfill reinforced with geotextile is 2.696..

Table 2. Safety Factor for pseudo-static analysis with 0.22 of horizontal seismic coefficient in field conditions and four reinforcement methods: 1cm thick cement mortar, Geogrid; 5cm thick sand mortar and Geogrid and backfill reinforced with geogrid.

Load KN/m^2	Natural Pirca	1cm thick Cement Mortar	Geogrid	5cm thick Sand Mortar and Geogrid	Reinforced with Geotextile
1	1,218	**1,273**	**1,332**	**1,526**	**2,92**
2	1,164	1,214	**1,266**	**1,452**	**2,871**
3	0,822	1,163	1,209	**1,389**	**2,823**
4	1,069	1,115	1,157	**1,332**	**2,777**
5	1,030	1,073	1,111	**1,281**	**2,734**
5.9	0,999	1,039	1,073	1,241	**2,696**

The results show the high seismic risk of the *Pircas* in the study area. Therefore for many houses located in El Progreso human settlement: Eliane Karp, El Manantial, Santa Rosa and Alto Perú it is very important and urgent to implement some reinforcement method. In general, the houses are made of wood, with loads around 1 Ton/m^2 approximately. In this sense all simulated reinforcement methods meet the requirement of the Code. The use any of them will depend on the cost. However, for houses made from another type of material is necessary to reinforce the *Pircas*.

3.3 *Cost analysis of reinforcement methods*

The cost of materials of a *Pirca* with the profile shown in the Figure 6, with a length of 6m estimated. It does not include the construction cost. The four reinforcement methods have been analyzed. The first method consists of 1cm of cement morter covering the *Pirca,* and the price of material is USD 28.80, as shown in Table 3. The second method consists of covering the *Pirca* with geogrid and the cost is USD 45.00. Combining the first and the second method, but with 5cm thick sand mortar the cost increases to USD 132.60 and finally the cost of materials for geotextile reinforced *Pirca* and backfill USD 169.90.

Table 3. Price per reinforced method.

Cost of Materials for Reinforcement Methods for a 6m long Pirca	Price USD
1 cm thick cement mortar (*pañeteo*)	28.8
Geogrid	45.0
5cm thick sand mortar and geogrid	132.6
Reinforced *Pirca* and backfill with geotextile	169.9

From the economic and safety point of view, for existing *Pircas* the most effective reinforcement method is covering the *Pirca* with a geogrid and 5cm thick sand mortar; however in case of building new retaining walls, the reinforced *Pirca* and backfill with geotextile method is the recommended one. The other two methods are quite vulnerable and work only for the conditions found in the field, that is, for wooden housing only. Since the installation cost has not been considered, it is expected that the municipalities chose some measure to minimize this cost.

4 CONCLUSIONS

In static conditions, for loads between 1 and 2 Ton/m^2 the method used by the inhabitants of the study area is kept in balance, that is to say the use of the *Pirca* without mortar, with the backfill and the natural soil. In the event of an earthquake, these same conditions do not comply with the E050 Soil and Foundations Code, which recommends a safety factor greater than 1.25. So, it is of utmost importance to use a reinforcement method in order to avoid the houses collapsing in the event of a telluric movement.

The use of the 1cm thick cement mortar as well as the geogrid covering the *Pirca* comply with their function of retaining rock particles falling down affecting the surrounding houses, but it does not give a significant increment to the static or pseudo-static safety factor.

The use of geogrid plus 5cm thick sand mortar increases the static and pseudo-static safety factors, making all simulated loads comply with the E050 Code. Therefore, this method is recommended to be used for reinforcing the existing *Pircas*, since it could be installed just covering the exposed face of the wall.

From all the proposed reinforcement methods, the *Pirca-backfill* reinforced with geotextile is the one that significantly increases the safety factor. However, the use of this method implies necessarily rebuilding the foundation, therefore it cannot be used for existing housing, and only can be applied for new constructions.

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