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The restoration of San Pedro cliff at La Alhambra
La restauration de la falaise de San Pedro à La Alhambra

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ABSTRACT
San Pedro cliff is a dihedral 65.5 m high, which has progressed to place itself at 23.8 m from the *Alhambra* wall-palace that is a heritage of the Humankind. A deep research on the Tectonics of the zone, and an insight into the topographic measurements taken during several years, has shown that active normal faults surrounding the cliff have created an extension tectonic regime that loosens the ground and activates the ground falls. One major fault coincides with one of the faces of the dihedral. The factor of safety of the cliff subject to the 100 years period earthquake is 0.73. The preservation solution proposed is a post-tensioned high elastic limit wire mesh and autochthonous vegetation. With this reinforcement, the factor of safety under that earthquake raises to a value around one. In this way, the environmental impact is negligible.

RÉSUMÉ
La falaise de *San Pedro* est un dièdre 65.5 m haut, qui a progressé pour se placer à 23.8 m du mur palais de La Alhambra, qui est un héritage de l'humanité. Une recherche profonde sur la tectonique de la zone, et un aperçu des mesures topographiques prises pendant plusieurs années, a prouvé que les failles normales actives entourant la falaise ont créé un régime tectonique de distension qui a relâché le terrain et activé les effondrements. Une faille principale coïncide avec une des faces du dièdre. Le coefficient de sécurité de la falaise sujet aux de tremblement de terre de période 100 années est 0.73. La solution de conservation proposée est un treillis métallique de limite d'élasticité élevée et une végétation autochtone. Avec ce renfort, le coefficient de sécurité sous ce tremblement de terre augmente à une valeur autour 1. De cette façon, l'impact sur l'environnement est négligeable.

1 INTRODUCTION

The hanging towns, built at the edge of a cliff and subject to frequent slides, hold a significant place within the problems posed by the preservation of historical sites. These landslides have been corrected up to now by expensive and not always efficient means.

An example of this problem is *San Pedro* cliff (Fig. 1), a dihedral 65.5 m high, which has progressed to place itself at a distance of 23.8 m from the *Alhambra* wall-palace, that is a heritage of the Humankind.

The earthfalls have already destroyed an important part of the Christian fence built in1526.

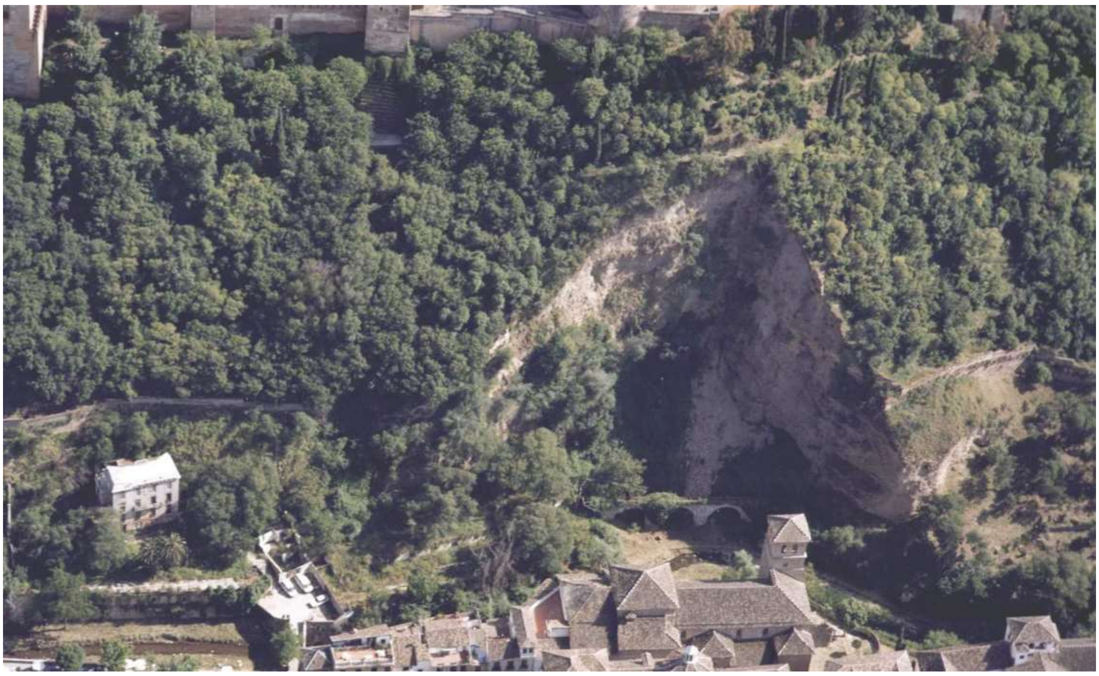

Figure 1. San Pedro cliff below the *Alhambra* walls. River *Darro* and *San Pedro* and *San Pablo* church at the foot.

2 GEOGRAPHY, GEOLOGY AND TECTONICS

The *Alhambra* palace was constructed at the top of a hill. River *Darro* surrounds the northern side of the hill foot (Fig. 2).

San Pedro cliff cuts a series of dense conglomeratic levels that constitute the so-called *Alhambra formation,* of upper Pliocene-lower Pleistocene age, and correspond to alluvial fans originating in Sierra Nevada erosion. At that time, the relief underwent rejuvenation. In later times (medium and upper Pleistocene) a dense fracturing produced the sinking of Grenade depression. The stones are rounded, with an average size of 10 cm. The matrix < 0.08 mm ranges between 13 and 35% and is usually sandy silt, sometimes clayey. There also are layers, 1 m thick, of clayey silt.

Several normal active faults, with strike NW-SE are located in the surroundings of *La Alhambra* (Fig. 2). The right face of the dihedral is a fault of this family (Fig. 2 and 3) with a throw of 7 m. A distending tectonic regime has created these faults.

3 ORIGIN AND EVOLUTION OF SAN PEDRO CLIFF

San Pedro cliff is a consequence of the floods of River *Darro*, the Tectonics, erosion and perhaps the seepage coming from *Alhambra* palace. The fractures produced by the distending tectonic regime have favoured the attack of the slope of the *Alhambra* hill by the River during floods. These floods have created a convex riverbed towards the cliff (Fig. 2).

Under Arab rule there was probably a fence, destroyed by an earthquake in 1431, lined up with the River and a cliff very reduced with respect to the present situation. The news about landslides at the cliff start shortly after 1524 when a fire destroyed the vegetation of the *Alhambra* hill, leaving the ground unprotected. The water spilled from the Alhambra cisterns destroyed an embankment constructed for protecting the foot of the cliff in 1520. The in-depth study of an engraving made in 1564 shows that at that time the wedge was at a horizontal distance of 60 m from the *Alhambra* walls and that the total height of the cliff was 33 m. In 1600 a flood of the River undermines the base of the *Alhambra* hill and leaves the cliff in a situation that starts to look like the present situation.

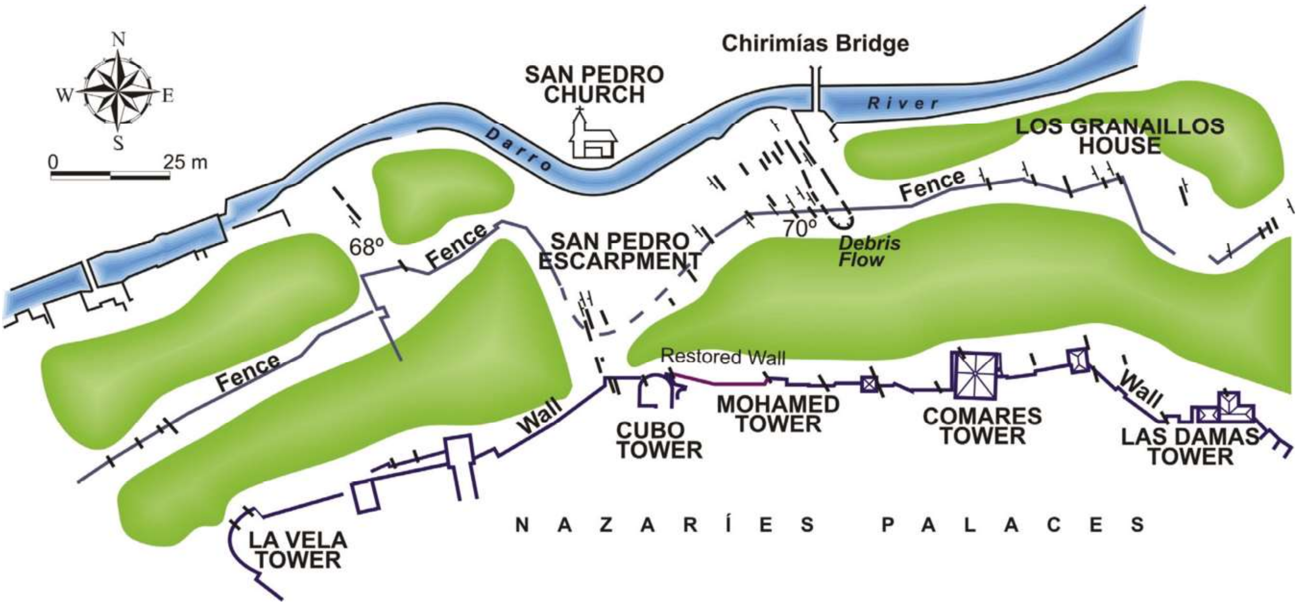

Figure 2. Outline of the site showing the main cracks at *La Alhambra* fence and wall and faults at the hill slope.

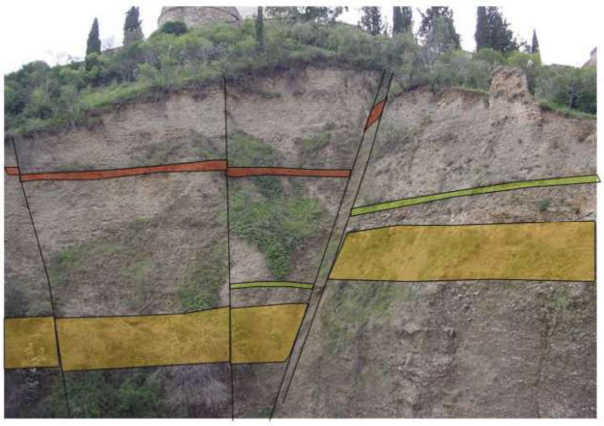

Figure 3. View of the dihedral showing the fault throw.

After this date, there are at least seven well-documented slides. The cited causes are no more the River floods, but the water spilled from the *Alhambra* cisterns, explosions and seepage.

From a comparison of engravings and topographic plans corresponding to different dates it may deduced that the average backward displacement of the wedge might be 8 cm/year.

4 PRESENT SITUATION

At present, a series of active normal faults with throws around 60 cm, cross *San Pedro* cliff. One of these faults, whose strike is N158º, constitutes the western face of the dihedral. The throw of the eastern face is 7 m.

The distending regimen of the Neotectonics produces a reduction of the horizontal stresses in the cliff, which may reach zero value. The joints open in the cliff are now a preferential path for seepage coming from the palace.

The height of the cliff over the River is at present 65.5 m and the horizontal distance of the edge of the dihedral to the wall is at present 23.8 m. The upper steep stretch of the slope has a maximum height and an angle of 67.4º with the horizontal, but this angle is steeper in sections of lesser height.

From 1600, the floods have not been cited as the causes of the slides due to the withdrawal of the cliff from the River produced by the successive earthfalls and the scree located at the foot of the slope. Seepage coming from the palace, loosening of the ground produced by tectonic extensions and erosion may be the present causes for the degradation of the cliff. The ground-falls and the fault displacements have produced the rupture of the Christian fence (Fig. 3).

The average horizontal withdrawal of the edge of the dihedral is 8 cm/year. Although it might take many years to reach the wall, the History shows that the speed of this process is not constant and might be accelerated by an important earthquake, as it will be shown below.

5 PREVIOUS SOLUTIONS

The danger that implies the progress of the wedge for the Alhambra wall has been foreseen long ago, and from 1520, the following solutions have been proposed and in some cases executed:

a) Embankments or walls at the foot of the cliff provided to protect the cliff against the floods of the River.
b) Banning watering the *Alhambra* forest.
c) To divert the River. One of the proposals considering this possibility implies the excavation of very high cuts and long tunnels.
d) A reinforced earth wall, 9.2 m high, and a double twisted steel wire mesh anchored at the head, in the upper 30 m, to favour the growing of autochthonous vegetation: pendant or climber plants in accordance with the slope.
e) An ecological wall combined with Californian drains, slope sewing, reinforcement micropiles and acrylic treatment of the slope surface to avoid the erosion.
f) Grouting through a series of steel tubes sub parallel to the slope joined to River regulation.

6 CRITICAL REVIEW OF THE PREVIOUS SOLUTIONS

The adopted solution should have a minimum environmental impact, which means minimum intervention, and cost.

a) It is neither necessary nor convenient to construct new embankments (in excess of the scree lying at the foot) or walls at the foot because, as stated above, the problem of the floods is so not important now and in any case should be solved by regulation of the River upstream.
b) If the Alhambra forest is not watered its vegetation would wither.
c) The impact of the River *Darro* diversion would be unacceptable as it is a fundamental component of the urban landscape in one spot as beautiful as the *Carrera del Darro* street. The same argument may be use with respect to the mammoth works that may accompany this proposal.
d) and e) The opening of the double twisted steel wire mesh is too small and the impact from the neighbouring street is not negligible. The impact of reinforced earth or ecological walls is also important because it changes drastically the present scenery. The Californian drains would need pipes to collect the drainage whose impact would not be negligible. The acrylic treatment would demand the removal of the loose portions and the aspect would not be attractive.
f) The grouting of the conglomerate is not guaranteed, as the median coefficient of permeability is 2x 10^{-7} m/s. Rather, it would introduce pressures in planes parallel to the slope that could produce the falling of slabs from the slope.

7 THE USE OF WIRE MESHES IN SLOPE PROTECTION

In recent times, anchored wire meshes have been employed to protect slopes (Geobrugg, 1999; Muñoz and Torres Vila, 2000; Torres Vila, 1999 & 2000). It is an inexpensive process and perhaps the only one possible for high and steep slopes. There are mainly two types:

7.1 Cable nets

They have the following elements:

a) A double twisted pentagonal steel wire mesh with an opening of 8x10/15 mm and a wire somewhat thicker than 2 mm. Its task is to close the space between the cables of the net.
b) A cable net of high strength steel (1770 MPa) with 150 to 300 mm opening and thickness 8 mm. This net applies the pressure to the ground.
c) Steel cables, 16 to 24 mm thick and 2 to 4 m apart, that apply a pressure of 10 to 20 kPa to the cable net, through post-tensioned anchorages at the intersections.
d) Internal and perimeter anchorages post-tensioned at 100 to 500 kN.

This solution would be allowable, but the double twisted steel wire mesh is difficult to integrate with the cliff vegetation.

7.2 High yield stress wire mesh (Fig. 4)

It is a rhomboidal mesh, with yield stress 1770 to 2020 MPa and 3-4 mm wire thickness, lying directly on the slope with opening 65 mm. The pressure on the slope (10 to 30 kPa) is applied by post-tensioned anchorages isolated or reinforced by cables. The anchorages may be GEWI bars 25 to 40 mm thick. Anchored cables 20 to 24 mm thick surround the treated zone.

The 65 mm mesh opening is small enough to avoid erosion of the conglomerate and to provide an acceptable visual impact, especially if the present vegetation is maintained (at least the trees and shrubs) and new autochthonous plants are added.

Figure 4. Tecco mesh reinforced by cables (courtesy of Geobrugg)

It must be taken into account that the street is 40 m apart and *San Pedro* and *San Pablo* church stands in the line of sight (Fig. 1 and 2). Owing to all that this was the solution adopted.

8 STABILITY OF SLOPES

The strength parameters adopted for the conglomerate are:

c = 18-75 kPa Φ = 45-50º

The Geo-Slope program, and Morgenstern and Price method were used in the calculations, with different mesh pressures applied on the slope. The static and dynamic safety factors are included in Table 1.

Table 1: Safety factors in static and dynamic slope calculations

Pressure on slope kPa	F			
	Static			Dynamic
	a	b	c	
0	1.13			0.73
10	1..31	1.28	1.31	
15	1.37	1.33	1.38	
20	1.43	1.38	1.44	0.93 (1) 1.00 (2)
25	1.48	1,42	1.50	
30	1.53	1.47	1.42	

(1) c = 32 kPa in upper layer
(2) c = 75 kPa in upper layer

Three layouts of the mesh have been considered:

a) As indicated in Figure 5.
b) Removing the lower part of the mesh.
c) Extending the mesh to the upper part of the scree.

The increase in the static safety factor for mesh pressures larger than 20 kPa is small. Solutions *b* and *c* were rejected because the lower part of the conglomerate needs erosion protection, but not the scree. A calculation acceleration of 0.28 g, corresponding to a life period of 100 years, was used in the dynamic calculations. Figure 5 shows the the critical slip surface under dynamic conditions for a pressure of 20 kPa on the slope. It may be seen that this critical surface penetrates inside the Alhambra wall.

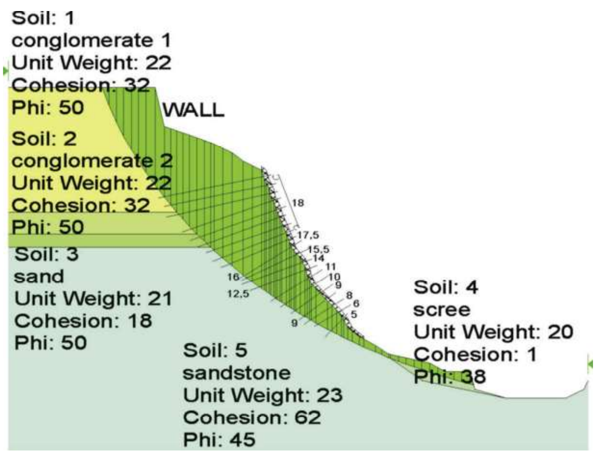

Figure 5. Critical sliding surface under dynamic conditions. The slip line penetrates inside the Alhambra walls.

9 MESH CALCULATION

The mesh, 3 mm thick, has been calculated to support a working pressure of 20 kPa from the slope following the method developed by Torres Vila et al. (2001). The anchors will be placed at distances of 5 m (horizontal) by 2.5 m (vertical). The load per anchor will be 250 kN. Applying a prestress load of 15% (37.5 kN) the maximum displacement perpendicular to the slope will be 73 mm. So as to have a minimum safety factor of 1.67, 40 mm GEWI bars have been selected for the anchors. Assuming a shear resistance of 1 MPa the length of the anchorage zone is 3.1 m. The actual factor of safety of mesh, anchor and anchorage zone is 2.5.

The anchorage zone should be placed behind the sliding surface (Fig. 5). In this way, the upper row of anchors should have 25 m and the eight 19 m. Owing to the difficulty of constructing anchors of these lengths, the tender permits lengths not larger than 18 m, although the bids that will offer larger anchors will be positively considered.

10 CONCLUSIONS

San Pedro cliff is a dihedral, 65.5 m high, which has progressed to place itself at 23.8 m from the *Alhambra* wall-palace that is a heritage of the Humankind. The earthfalls and the displacements of some normal faults have already destroyed an important part of the Christian fence, built in 1526.

A deep research on the Tectonics , and an insight into the topographic measurements taken during several years, has shown that active normal faults surrounding the cliff have created an extension tectonic regime that loosens the ground and activates the earthfalls. One major fault coincides with one of the faces of the dihedral. Erosion is also an important cause of the cliff deterioration. The factor of safety of the cliff subject to the 100 years period earthquake is 0.73. The preservation solution proposed is a high elastic limit wire mesh, prestressed with anchors, and autochthonous vegetation. With this reinforcement, the factor of safety under that earthquake raises to a value around one. In this way, the environmental impact is negligible.

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