Manuscript Number: EFA-D-13-00209R1

Title: Morphology and causes of landslides in Portalet area (Spanish Pyrenees): probabilistic analysis by means of numerical modelling

Article Type: Original Research Paper

Keywords: Landslide, geotechnical monitoring, numerical modelling, creep, cracks

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Abstract: The morphology and causes of a big landslide in the Pyrenees (Northeastern Spain), reactivated by the excavation of a parking lot on the base of the landslide area, have been analysed. Through reconnaissance and instrumentation techniques and monitoring the morphology and failure terrain of the area are defined approximately and these results are checked by numerical modelling.

***Research Highlights**

Highlights

- Analysis of morphology and causes of a big landslide in the Pyrenees.
- Excavation of parking on the base of the landslide area studied as probable cause.
- Analysis of landslide with instrumentation techniques and monitoring.
- Monitoring results checked by numerical modelling.

Morphology and causes of landslides inPortalet area (Spanish Pyrenees): probabilistic analysis by means of numerical modelling

Abstract

The morphology and causes of a big landslide in the Pyrenees (Northeastern Spain), reactivated by the excavation of a parkinglot on the base of the landslide area, have been analysed. Through reconnaissance and instrumentation techniques and monitoring the morphology and failure terrain of the area are defined approximately and these results are checked by numerical modelling.

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1 INTRODUCTION

The landslide, as a form of mass movement, is one of the principal processes of hillslope erosion [1]. The temporal distribution of slope movements is determined by the occurrence of triggering factors, such as: rainfall, rapid snowmelt, volcanic eruption, earthquakes and human activity [2].

The susceptibility of a slope to failure is dependent on many factors, including the gradient of the slope, the geotechnical properties of the material involved and the presence of discontinuities. The amount of water entering a slope, which is a function of the vegetation cover, drainage, soil type and rock structure, is also a very important factor indicating the significant linkage between geomorphological hazards and the processes and conditions in the atmosphere and hydrosphere. Human activities can also play an important role in affecting the susceptibility of a slope to failure.

Landslides are always associated with a disturbance of the equilibrium relationship that exists between stress and strength in material resting on a slope. The relationship is determined by factors, such as the height and inclination of the slope and the density, strength cohesion and friction of those materials that form the slope [3]. Instability arises when the shear strength, or maximum resistance of the material comprising the slope to shear stress, is exceeded by a downslope stress. The shear strength depends on internal cohesion, which is independent of the weight of the overlying material. This cohesion is produced by the interlocking of particles that enables the material to rest at an angle and by the internal friction; the resistance of particles to slide across each other, which depends on the weight of the overburden. Both are also highly dependent on material type and state, particularly with regard to the lubrication of internal spaces.

The slope angle is an essential component of slope stability analysis. As the slope angle increases, the shear stress in soil or other unconsolidated material generally increases as well. Gentle slopes are expected to have a low frequency of landslides because of the generally lower shear stresses associated with low gradients [4-7].

Clay soils, the weathering product of rock mass, contribute to landslide occurrence because of their chemical and physical properties.

The properties of clays have been investigated for their effects on landslides because clay presents problems for geotechnical engineers owing to its complex nature. This derives from its plasticity, its low permeability and thus, the time dependency of pore water pressure change and volume change, its structure, chemistry and mineralogy.

It is clear that weathering and agricultural activity alter the nature and topography of the ground surface. Adverse human activities have also contributed to the creation of landslides; these include excavation works, irregular agricultural activity, embankments and in particular, drainage works. Water is one of the most predominant factors that cause landslides, which usually occur during periods of high precipitation. Therefore, in natural slope areas, it is important to construct drainage systems for collecting water, such that movement on the slopes can be reduced.

This paper focuses on the study of an important landslide that occurred in the Portalet area, which is located on the upper part of the Gállego River valley, in the Pyrenees Axial Zone (Sallent de Gállego, Huesca). This is mainly made of Devonian and Carboniferous materials, characterised by intense weathering and high plasticity. Excavation at the foot of the slope, carried out to build a parkinglot area in the summer of 2004, reactivated two existing landslides generating new sliding surfaces that affected the connecting road to France. Measurements of the displacements, performed with conventional and advanced remote monitoring techniques, revealed that the moving mass was still active after constructive solutions were undertaken. A paper published three years ago analysed the same landslide [8]. The objective of that first study, using improved ground based SAR (GB-SAR) technologies, was to retrieve field parameters that could be used in landslide prediction algorithms.In particular, that work was focused on the use of the monitoring data obtained by the continuous GB-SAR measurements of the Portalet landslide to calibrate the proposed model and to predict the displacement of the landslide.

According to previous studies made in the area, it is thought that there exists a double problem of superimposed phenomena, which are:

- "Creep" surface movements; seasonal and probably linked to ice-meltwater processes.
- Deep movement; slower than creep and caused by the landslide of materials, such as colluvium, shales and clays above the rocky substratum.

With the aim of analysing these phenomena, the following work has been undertaken:

- Analysis of results.A morphological characterisation of the landslide according to instrumentation data from many reconnaissance campaigns [8].
- Numerical modelling of the generated landslide by *ALICE*$^{®}$software, to verify the previous morphological characterisation.

2 DESCRIPTION OF THE STUDY AREA

The area under study is situated near El Portalet, at an altitude of 1974 m in the Aragon Pyrenees, in Huesca, which is a mountain border between Spain and France. Figure 1 shows the exact location.

Figure1.- Location of the area under study

Several active landslides affect the Portalet area, which is located in the upper part of the Gállego River valley. These landslides are situated on a southwest-facing hillside of Petrasos Peak, close to the ski resort of Formigal. In this zone, there is a great density of landslides that are reactivated owing to the constant erosive action of the river Gállego[9-11].

The river descends through the valley following a WNW-ESE direction from 2,000 to 1,200 ma.s.l. to theLanuza reservoir (Fig. 1). The climate in this area is characterised by marked seasonality, classified as Mediterranean mountain type with Atlantic and Continental influences (Creus and Gil 2001) [12].

According to the records available from the Sallent de Gállego weather station, the temperature varies from +36 to −21 °C and the average annual precipitation is 1,280 mm/year, which occurs as punctuated intense downpours that can produce 70 to 140 mm per event. A considerable proportion of the precipitation (>30%) corresponds to snowfall that occurs mostly between December and March. The frost and snow coverage, found above 1,500 ma.s.l., may melt rapidly in the late spring causing significant infiltration in a short period of time with the consequent increase in the pore pressure of the slope materials, favouring landslide dynamics [13].

The study area encompasses the magmatic and Paleozoic complex of the axial Pyrenees, affected by the Hercinian folding phase. A geological map (Rios-Aragüés et al. 1987) [14] is shown in Figure2. The centre of the valley is characterised by an outcrop of Devonian slate (12 and 14 in Figure2), whereas in the northern part, this formation is overthrusted by the Carboniferous Limestone formation (21 in Figure2). There is also an outcrop of conglomerate and carboniferous greywacke (23 in Figure2). These materials are usually covered by Quaternary sediments: alluvial or alluvial fan deposits in the valley and colluvial deposits on the slopes that present a significant thickness favoured by the weathering process of highly fissile slate formations with a relatively low rock mass strength. The toe of the scarps is usually covered by talus or rockfall deposits. The study areashows medium-low seismicity (Mulas et al. 2003) [15] and is controlled by two tectonic lineaments, one following the NW-SE direction parallel to the valley and the other following the SW-NE direction.

Figure2.- Portalet landslide area geology

As said previously, in recent years, hillside movements have been registered in the area study. They have been caused by the ice/meltwater action cycle and by excavation works for the construction of a parkinglot in the area. Figure 3 shows the general aspect of the area.

Figure3.- General aspect of the study area

Both factors have caused many creep areas, cracks and flooded areas. (Figure4 and Figure5).

Figure4.- Creep phenomena in the parking-lot area.

Figure5.- Cracks details in the crown zone in one displacements

3 GEOMORPHOLOGICAL CHARACTERISATION OF THE LANDSLIDE ACCORDING TO THE INSTRUMENTATION

From a geomorphological point of view, the studied landslide is of the roto-translational kind with unidirectional movement, which has generated several blocks sliding between each other along pre-existing slip surfaces. Spring water emerges on the slope and infiltrates where it is less steep,creatingsmall depressed pools, which show different terraced and inclined surfaces towards the slope.

The excavation at the foot of the slope, carried out to build a parkinglot area in the summer of 2004, reactivated existing slide surfaces and generating new fissures and cracks. The most important set of cracks is observed halfway up the slope and others are seen on the cut slope benches of the parkinglot construction. The occurrence of this landslide prevented the completion of the digging and part of the removed material was replaced immediately at the landslide's foot in order to arrest the process. As soon as this emergency measure was over, constructive solutions were performed to stabilise the hillside without interfering with the construction of the parkinglot. These solutions involved reprofiling the landslide toe and adding weight and building benches to stabilise the slope. Small retaining walls and drainage were also built where the slip surface outcrops.

In 2009, with the aim of analysing these phenomena, a campaign of on-site testing and the instrumentation of the site wereundertaken:

- Execution of on-site penetration tests with hydraulic cylinders to determine the strength and deformational parameters of the materials of the area.
- Installation of 12 wire extensometers that measure by continuous register, in real time, the approach and separation of two holders fixed to the terrain;they allow an estimation of the magnitude and speed of surface movements.
- Execution of seven boreholes:

    - Three geotechnical boreholes (GB) equipped with inclinometer pipes for periodic reconnaissance with extensometric and inclinometer probes, in order to detect vertical and horizontal movements of the subsoil.

    - Four piezometric boreholes (PzB) implemented with pressure gauges and temperature sensors, to analyse water table variations and the freezing state of the subsoil.

    - Also, two boreholes drilled in 2005 [8], denominated S3 and S4 were taking in account. These boreholes, equipped for the measurement of horizontal movements with an inclinometric probe, had a useful length of 36 m. However, when examined in 2009 to check whether it was possible to use in them the current study, borehole S3 could only be examined to a depth of 14 m and borehole S4 to a depth of 16.5 m.

3.1 PENETRATION TESTS

A penetration test using a hydraulic cylinder [16,17] is an on-site test for analysing the properties of the weathered rock mass. The stress-strain curve of the terrain can be obtained by means of these tests.

Previously, to execute the test, it was necessary to make a trench on the terrain and to place the cylinder inside; such the ends of the cylinder are placed perpendicularly to the walls of the trench, as can be seen in Figure 6.

Figure6- Hydraulic cylinder placed in a trench

Once the cylinder is placed into the trench, pressure is applied and increased gradually. This pressure is transmitted to the terrain, perpendicularly through a cylindrical pin owing to the ball joint. In most tests, the pressure increases until terrain failure occurs.

This type of test allows the stress-strain curve of the terrain to be determined because the failure pressure in each analysed material can be calculated and a residual pressure estimated. It can also be estimated the penetration experimented by the hydraulic cylinder when it is in charge, until the failure terrain is produced.

Thirteen tests were made along seven trenches. Figure 7 shows their location.

Figure7.- Location of the trench for the penetration tests

The first four trenches were excavated in the slope with the objective of analysing the properties of the materials involved in creep surface movements. The remaining trenches were made in one of the slopes of the parkinglot, where the base of the largest depth of slip surface could be located.

Table 1 summarises the trench characteristics, the tested lithologies and the strength and deformational parameters obtained from each test.

Table1.- Characteristics of penetration tests

3.2 BOREHOLES

Figure 8 shows the location of the boreholes and Table 2 shows their characteristics.

Figure8.- Location of the boreholes

Table2.- Summary of the instrumentation of the boreholes

3.3 EXTENSOMETERS

In order to analyse the magnitude and speed of the surface level (creep) terrain movements in July of 2012, 12 wire extensometers were installed in the studied slope.

These extensometers have a uniaxial displacement sensor that is able to collect data of length variation, measured in millimetres, between two holders fixed to the terrain and joined by a steel cable.

These extensometers were installed in four sequences, with lengths of between 40 and 48 m. Figure 9 shows the location of the extensometers and the graphics of the equipment that registered the highest variation in each area.

Figure9.- Instrumented areas and graphics of the equipment that registered the highest variation in each area.

3.4 ANALYSIS AND INTERPRETATION RESULTS

To analyse the results obtained from all the instrumentation installed in 2005 [8], from the new boreholes, tests and instrumentation (2009-2011) and the information collected during the survey of the area (cracks, creep zones), the main landslide that affects the hillside above the parkinglot has been morphologically characterised.

Figure 10 shows a profile in which the boreholes made in different campaigns are represented in violet and their respective displacement curves shown in red (measured with the inclinometric probe).

As can be seen, there is a double displacement at different levels:

- A superficial movement (creep) (discontinuity yellow line, Figure 10), could explain the formation of cracks on the surface of the terrain, the movements registered by the extensometers (especially in those installed in Ex2 and Ex3 trenches) and the failure plane 10 m below surface, obtained from the inclinometric curves of the drilled borehole in 2009 on the base of the displacement (GB4) (see Figure 11).
- A deeper movement caused by the displacement of materials, such as colluvium, shales and clays above the rocky substratum that explains the displacement of the five instrumented boreholes (green discontinuity line, Figure 10).

Figure10.- Representation of the supposed morphology for the displacement.

Figure11.- Inclinometric measurements in GB4 borehole in 2005, next to base of the displacement.

Therefore, the surface of the main failure (deeper) would start at a higher height than borehole PzB1, passing below all the boreholes and below the A-136 road and probably finishing at the same level as the parkinglot.

This estimation is made by taking into account the state of the asphalt (Figure 12) and the state of the walls of the trenches excavated to make on-site tests (Figure 13), which collapsed easily.

Figure12.- Details of the parking-lot

Figure13.- State of one of the excavated trenches for the on-site tests.

4 COMPUTING MODELLING OF THE LANDSLIDE BY *ALICE*$^{®}$ SOFTWARE

Once the morphology of the slip surface is defined according to the installed instrumentation and the observations of the study area, a numerical model of this displacement is developed in order to check whether the collected data of geotechnical properties could reproduce the slip surface with the observed morphology.

ALICE$^{®}$software,which stands for Assessment of Landslides Induced by Climatic Events, was used for the modelling;it is software designed to support landslide hazard mapping [18].

4.1 *ALICE*® SOFTWARE DESCRIPTION

The model is based on a mechanical and geotechnical approach for which the main physical characteristics of the medium are quantified and used by a mathematical model calculating a safety factor [19]. In these models, the spatial variability of the parameters (e.g., mechanical characteristics) has to be known and is handled through GIS software.

The probabilistic approach used in the software allows the consideration of uncertainties by giving probabilistic distributions to some of the model parameters [20].

The software uses the Morgenstern and Price method [21, 22], which is a finite slope stability model based on the equilibrium calculation between slices subdividing the landslide volume. This method is used on regularly spaced topographic 2D profiles, which cover the entire studied area. These profiles are generated automatically by the software using four input raster maps: a Digital Elevation Model (DEM), a slope map, a flow direction map and a flow accumulation map.

Pedological and geological characteristics are taken into account thanks to the altitude maps of the interfaces between each soil layer (Figure14). The highest limit corresponds to the topographic surface (DEM).

Figure14.- Calculating profile generated by *ALICE*® software, showing the topographic surface, the geological model composed of three layers separated by the red lines, sea and water table levels.

Variability and uncertainty of the geotechnical parameters are introduced into the software by means of probabilistic distributions (normal, uniform, triangular or trapezoidal). A distribution is attributed to each soil characteristic (cohesion (c), angle of friction (ϕ) and unit weight (γ)) and for each soil layer.

The safety factor calculation also requires the landslide type (rotational or translational) and its length. These parameters are defined for the entire studied area.

The water table level is set by determining two piezometric maps: one for the maximal water table level and the other for the minimal. The water table is then generated automatically between these piezometric levels by setting a filling ratio.

On each profile of the studied area, the software calculates the safety factors for several landslide positions (Figure15).

Figure15.- Illustration of the way the software calculates safety factors for several landslide positions (red circles) along a topographic profile. The pink circle represents the landslide position with the highest probability of occurrence along the profile. The graph in the top right-hand corner shows the distribution of calculated safety factors for the pink landslide.

The probability of having the safety factor below one represents the probability of the occurrence of a landslide for a given triggering scenario (i.e., landslide geometry and water table level). The dispersion of the distribution gives the uncertainty of the result.

The calculated probability of occurrence is then attributed to all the pixels of the resulting raster located on the profile and intersecting the landslide geometry. Thus, a pixel receives as many probabilities as landslide positions it is included in. Finally, a map is created, displaying the highest calculated probability of occurrence for each pixel of the studied area.

4.2 LANDSLIDE MODELLING DATA

The two cross sections (see Figure16) built by the Instituto Geologico y Minero de España (IGME) with the results of the on-site tests and instrumentation, are used to determine the geometry at depth of the units comprising the geotechnical model used in the modelling.

Figure16.- Geological crosssections interpreted from geophysical results and drilling core data obtained along two profiles P1 and P2 located on the Portalet landslide.

The topographic profile (DEM) of the study zone changed with time. Figure17 shows the comparison between the two DEMs along profile P1 (see Figure16 for location). The gap between the two DEMs corresponds to the material excavated during the building of the parkinglot.

Figure17.- Comparison between the two DEMs along profile P1

The depth of the boundaries between two geotechnical units for the two profiles have been extrapolated over a strip around 10-m wide, in order to obtain several calculating profiles for the *ALICE*®software (Figure18).

Figure18.- Location of the strip where the depth of interfaces for geotechnical model have been extrapolated from the geological crosssections along profiles P1 and P2. The grey areas display the parkinglot location (light grey) and the location of the road built in 2005 (dark grey).

They have been chosen according to the on-site geotechnical tests done on the Portalet landslide materials and completed with the expertise of the IGME engineers. Normal distributions have been chosen because few tests were available for the study area and the difference between the highest and lowest values is narrow (Table3).

Table3.- Highest and lowest values of mechanical characteristics for each geotechnical unit

According to the available data, the water table level has been modelled with a filling rate of 90% between 1740 m high (stream altitude) and the topographic surface (Figure19).

Figure19.- Portalet landslide crosssection displaying the location of piezometers and inclinometers with water table depth interpolation

4.3 LANDSLIDE MODELLING RESULTS

Next, the process followed in order to determine the morphology and probability of the occurrence of the slip of El Portalet, according to the information reached in successive reconnaissance and control campaigns, is described.

Possible displacements were modelled before and after the end of the parkinglot excavation in 2004.

As the landslides are wide (length greater than 200 m) and because the failure surface is interpreted as lying between the weathered shale and fractured shale, a planar sliding model along this surface has been chosen for the modelling.

Before the parkinglot construction (2004)

The probabilities of occurrence calculated by the software are presented in Figure 20 for both profiles.

Figure 20.- Software results along both profiles P1 and P2 for the stability modelling before 2005. The red line symbolises approximately the landslide extension. Landslide length is 200 and 500 m for P2 and 270 m for P1.

Two landslides with different lengths have been modelled along profile P2. The first one of 500 m takes into account the landslide of the entire mountainside and the second of 200 m accounts for the landslide starting in the middle of the slope. For both cases, no probability of sliding has been calculated. It seems that this part of the mountainside was stable before the construction of the parkinglot.

A landslide of 270 m has been modelled along profile P1. The results give a probability of a landslide of between 0.15 and 0.17. The modelling displays that stability conditions were already weak prior to 2005 for this part of the landslide.

After the parkinglot construction (2007)

The same depth for the geotechnical units have been used for the modelling with the DEM realised in 2007, as for the first modelling. The results are presented in Figure21.

Probabilities of occurrence along profile P1 have almost doubled from 0.15 to near 0.3. Along profile P2, the probabilities of occurrence have dropped from 0 to around 0.2 for both landslide lengths (500 and 200 m). The model computed with the smaller landslide length along P2, shows that it is the downstream part of the slope, where the excavation works have been realised, that presents the highest probability of sliding.

Figure21. – Modelling results for the slope stability of the Portalet landslide after the parkinglot construction (represented as a grey grid). (a) Landslide length of 500m along P2 and 270m along P1; (b) landslide length of 200m along P2 and 270 m along P1.

The computed profiles of Figure 22 show that for a landslide of 270 m in length along P1 and of 200 m in length along P2, the failure surface having the highest probability of occurrence reaches the topographic surface in the middle of the parkinglot. This is also the case for a 500 m length landslide along P2.

Figure 22.- Computing profile of *ALICE*® software along P1 and P2.Notice the geological model of illustration 3.Black hatched parts represent the landslide that has the highest probability of occurrence calculated along the profile. Notice that on both profiles, the failure surface is following the interface between the weathered and fractured shales to reach the surface at the level of the parkinglot.

5 CONCLUSIONS

The modelling results agree with the hypothesis that the excavation undertaken to build the parkinglot influenced the landslide reactivation. However, the low probabilities of occurrence obtained along profile P2 with the DEM built in 2004, shows that even before the parkinglot excavation began, the slope was suitable for landslide activity (even if it looked like it was stable).

The modelling is also consistent with: 1) two imbricated landslides, one of 500 m length and the second of 250 m length, starting at mid-slope and 2) a failure surface located at the interface between the weathered and fractured shale reaching the topographic surface at the level of the parkinglot.

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Morphology and causes of landslides in Portalet area (Spanish Pyrenees): probabilistic analysis by means of numerical modelling

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Figure

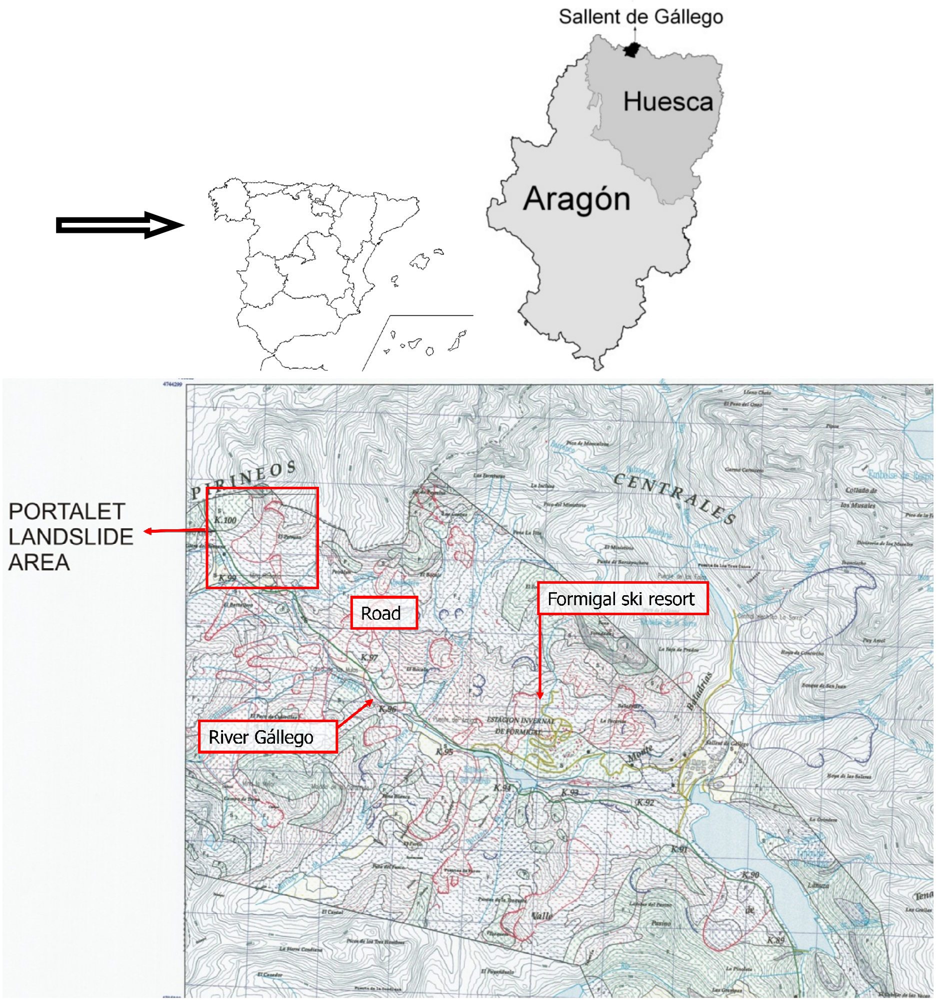


Figure 1.- Location of the area under study

52	Coluvial	Quaternary
23	Greywakes & slates. Culm facies	Carboniferus
22	Black limestones	Carboniferus
21	Black limestones	Upper Devonian-Low Carboniferus
15	Forata limestones	Middle Devonian
14	Slates and sandslones	Middle Devonian
12	Slates	Middle Devonian

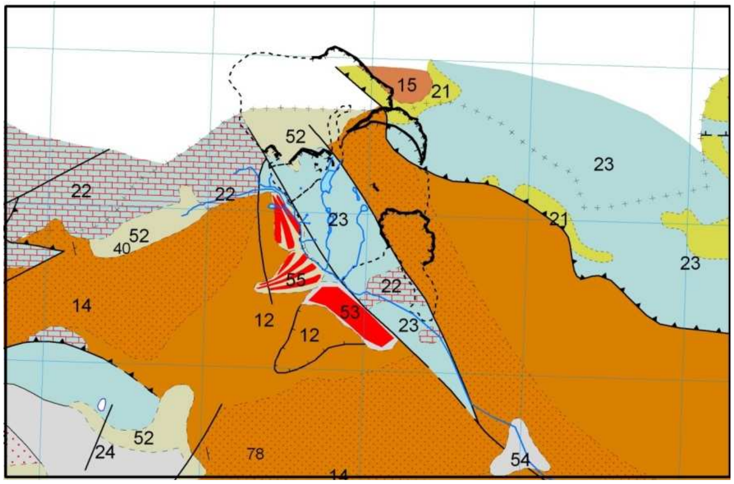


Figure2.- Portalet landslide area geology

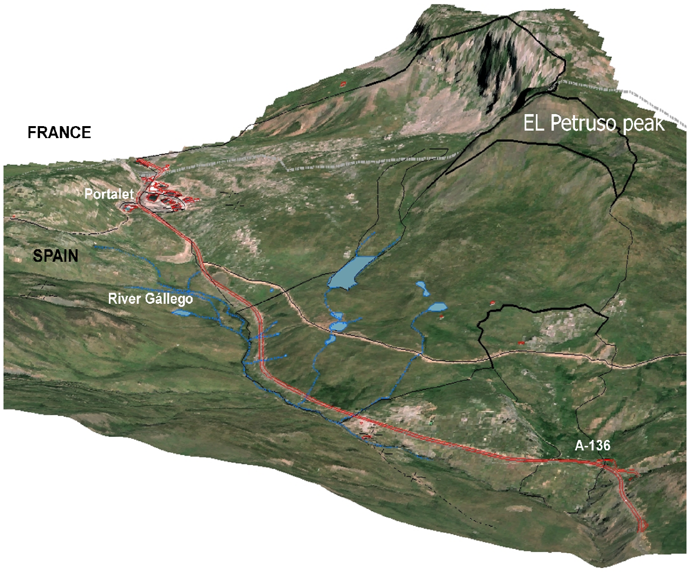


Figure 3.- General aspect of the study area

Figure 4.- Creep phenomena in the parking-lot area.

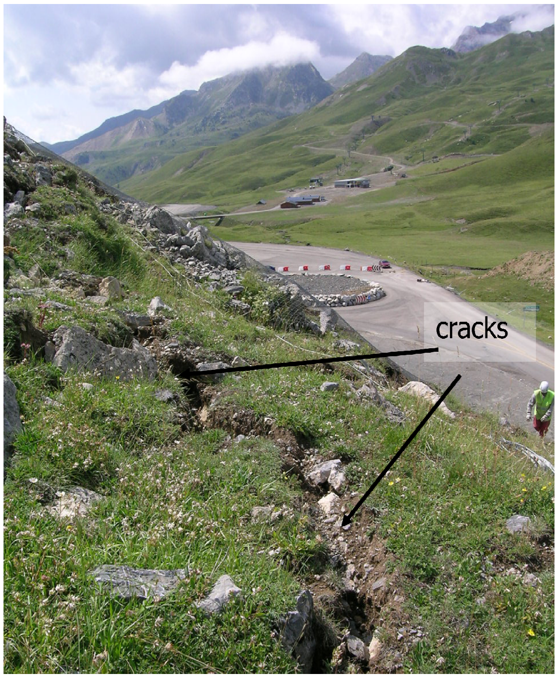


Figure 5.- Cracks details in the crown zone in one displacements

Figure 6- Hydraulic cylinder placed in a trench

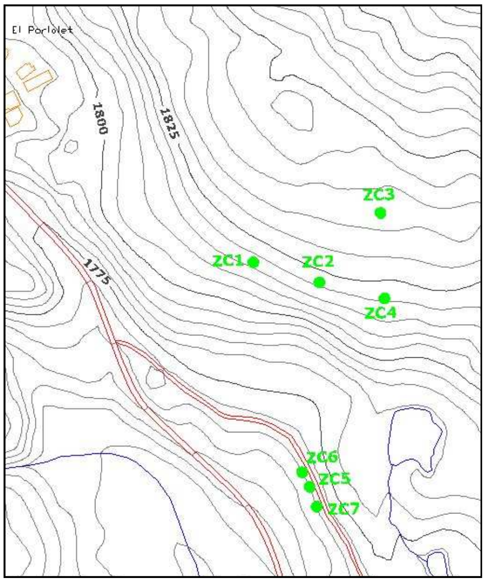


Figure 7.- Location of the trench for the penetration tests

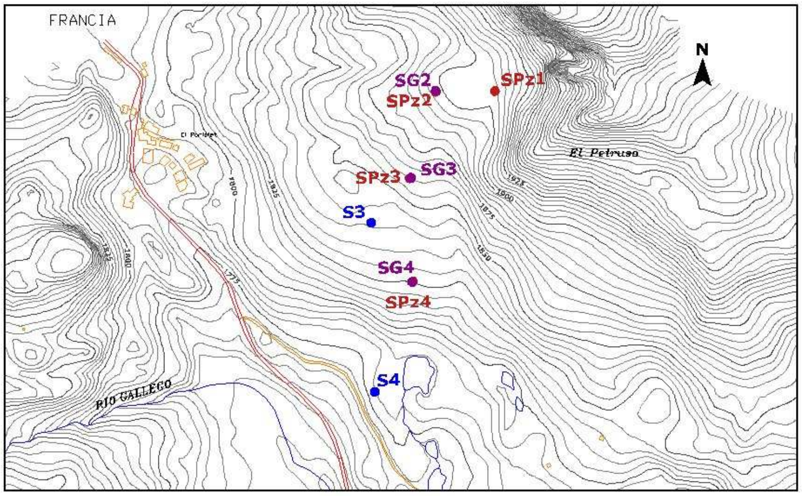


Figure 8.- Location of the boreholes

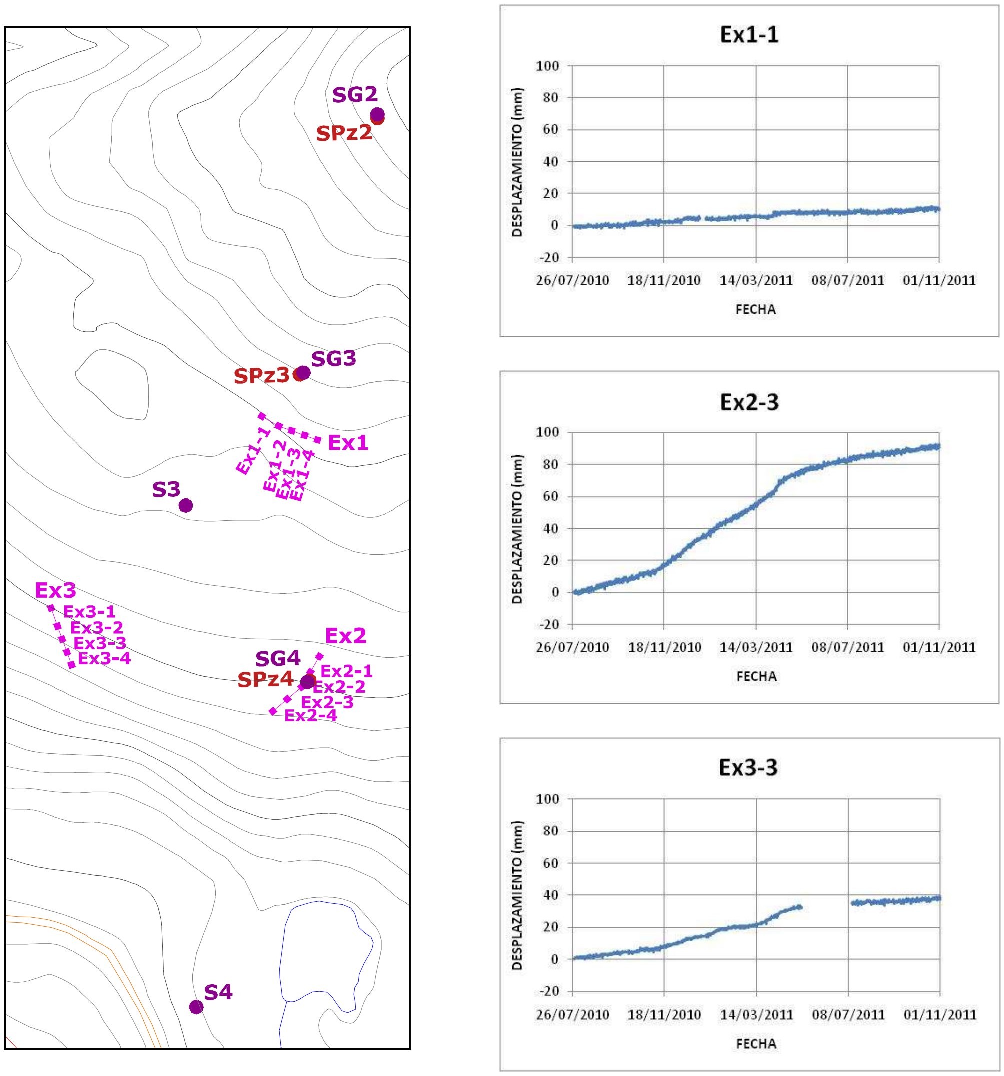


Figure 9.- Instrumented areas and graphics of the equipment that registered the highest variation in each area.

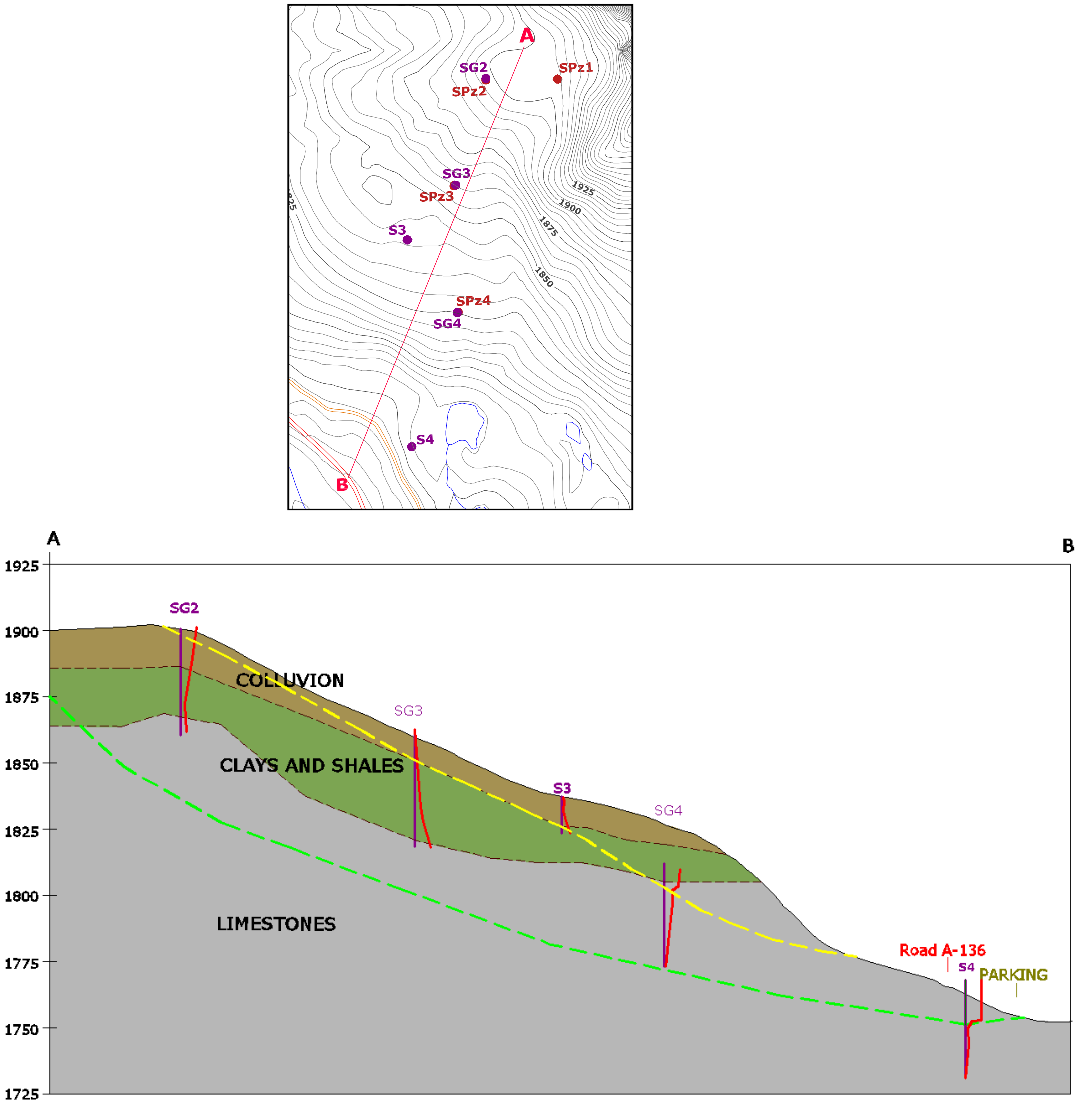


Figure 10.- Representation of the supposed morphology for the displacement.

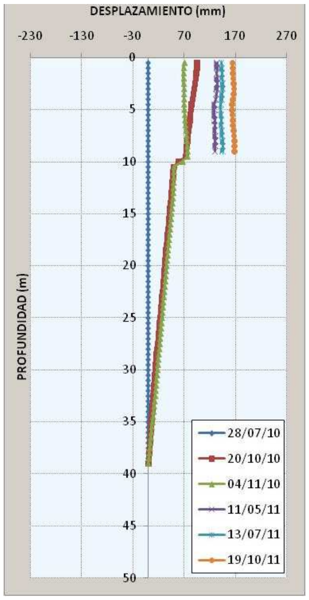


Figure 11.- Inclinometric measurements in GB4 borehole in 2005, next to base of the displacement.

Figure 12.- Details of the parking-lot

Figure 13.- State of one of the excavated trenches for the on-site tests

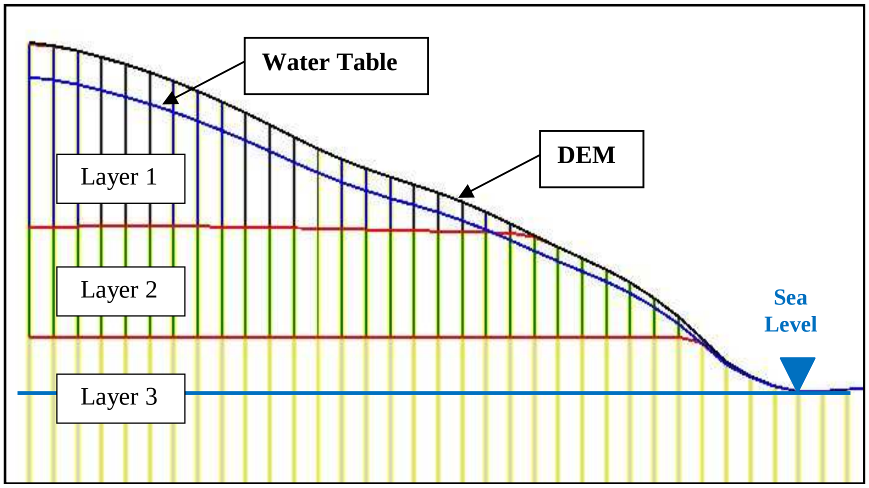


Figure 14.- Calculating profile generated by *ALICE*$^{\circledR}$ software, showing the topographic surface, the geological model composed of three layers separated by the red lines, sea and water table levels.

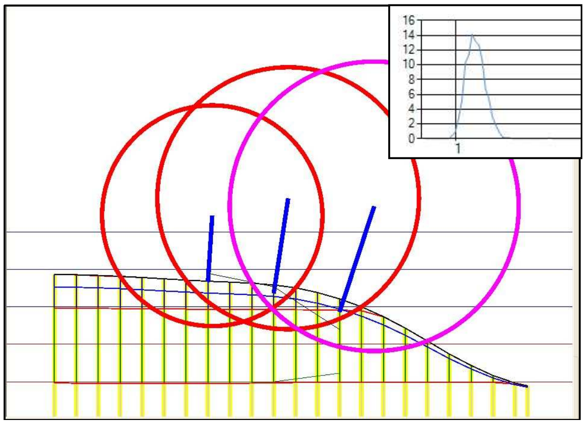


Figure 15.- Illustration of the way the software calculates safety factors for several landslide positions (red circles) along a topographic profile. The pink circle represents the landslide position with the highest probability of

occurrence along the profile. The graph in the top right-hand corner shows the distribution of calculated safety factors for the pink landslide.

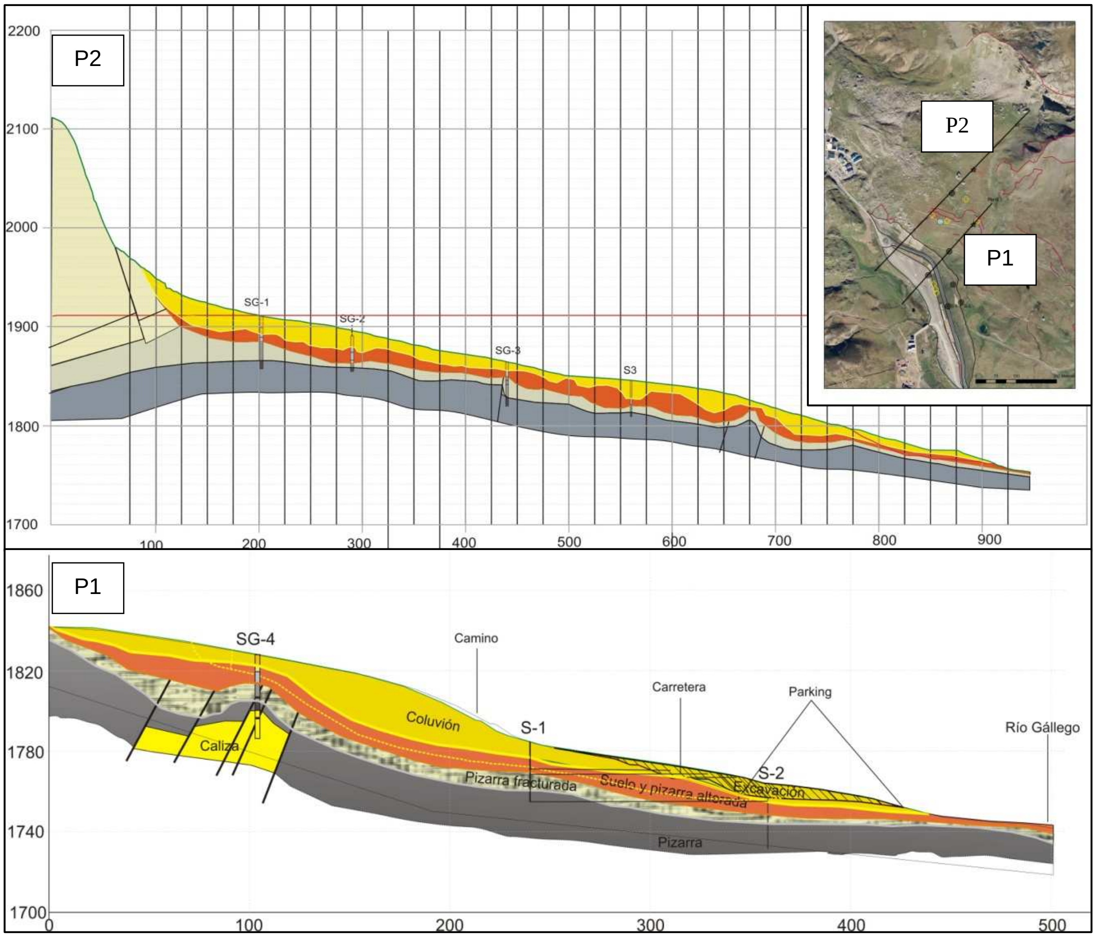


Figure 16.- Geological cross sections interpreted from geophysical results and drilling core data obtained along two profiles P1 and P2 located on the Portalet landslide.

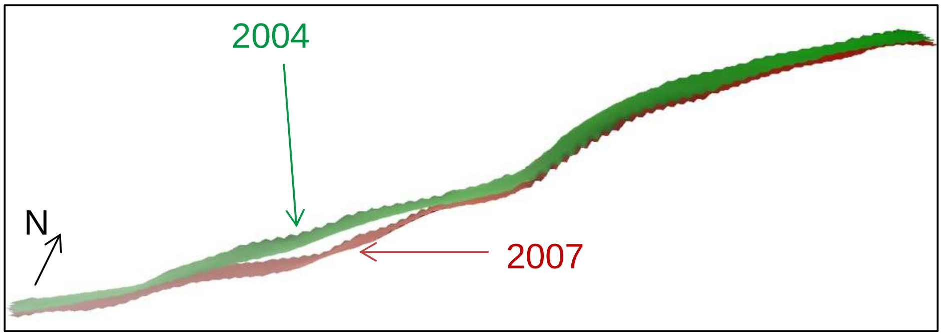


Figure 17.- Comparison between the two DEMs along profile P1

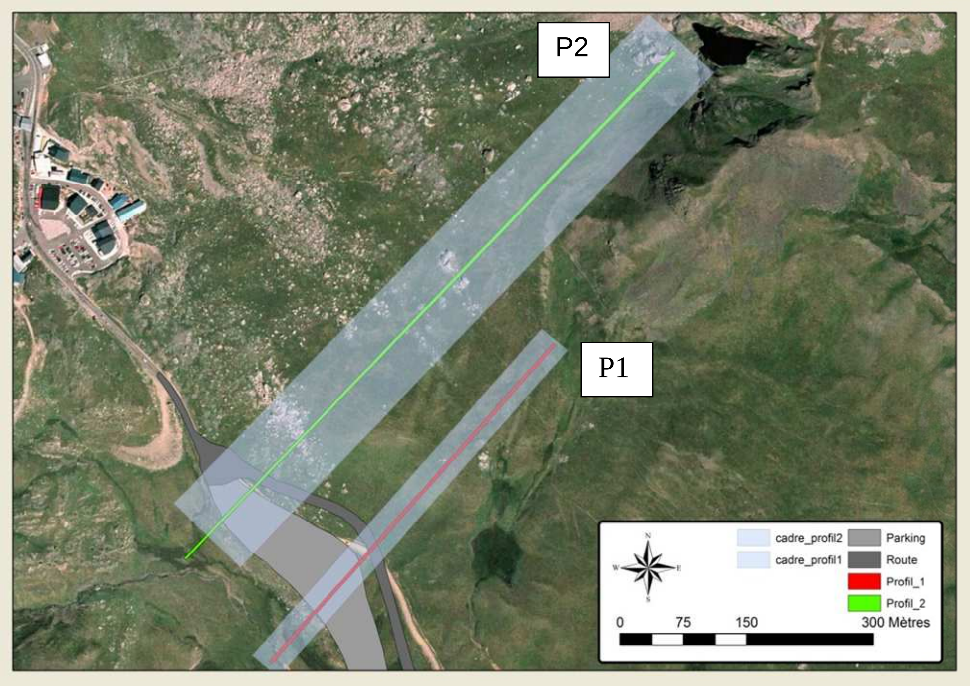


Figure 18.- Location of the strip where the depth of interfaces for geotechnical model have been extrapolated from the geological cross sections along profiles P1 and P2. The grey areas display the parking lot location (light grey) and the location of the road built in 2005 (dark grey).

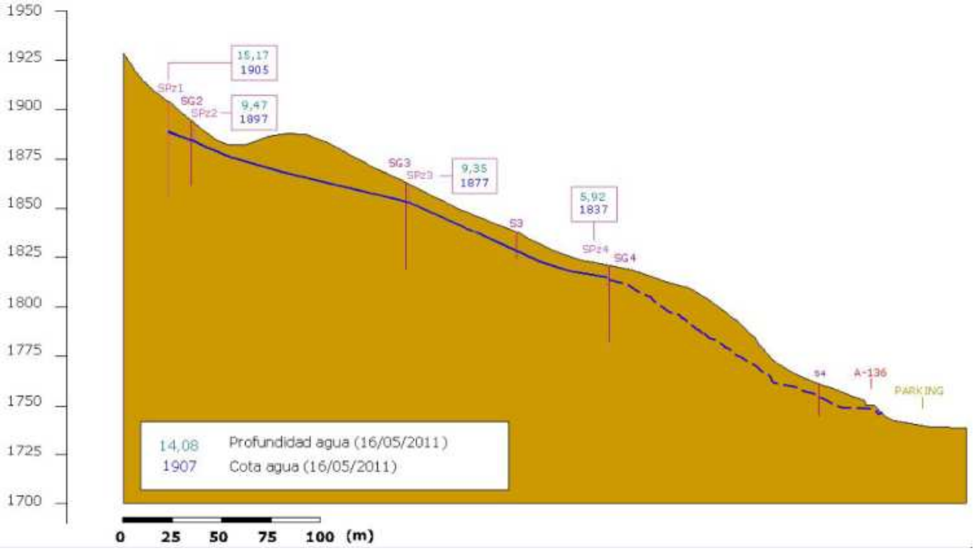


Figure 19.- Portalet landslide cross section displaying the location of piezometers and inclinometers with water table depth interpolation

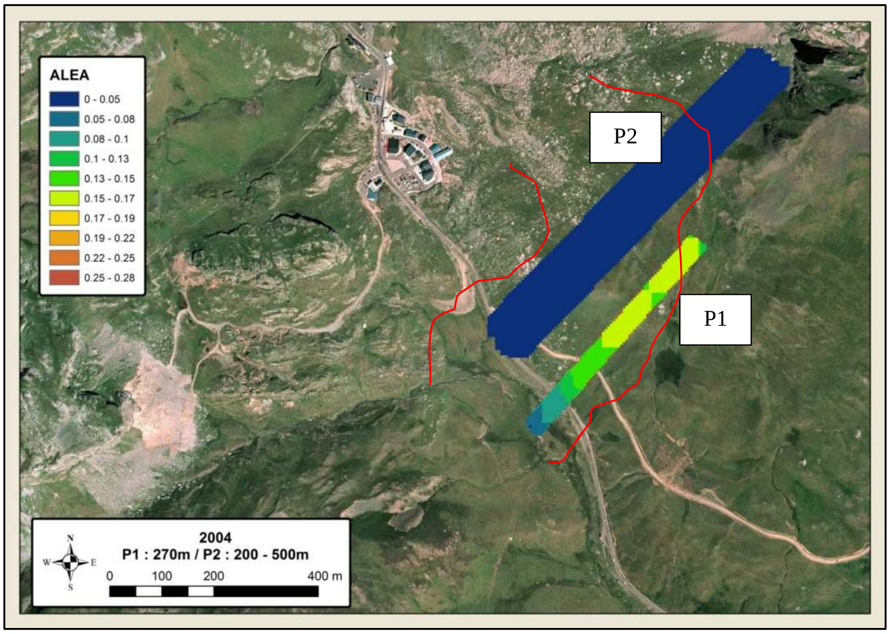


Figure 20.- Software results along both profiles P1 and P2 for the stability modelling before 2005. The red line symbolises approximately the landslide extension. Landslide length is 200 and 500 m for P2 and 270 m for P1.

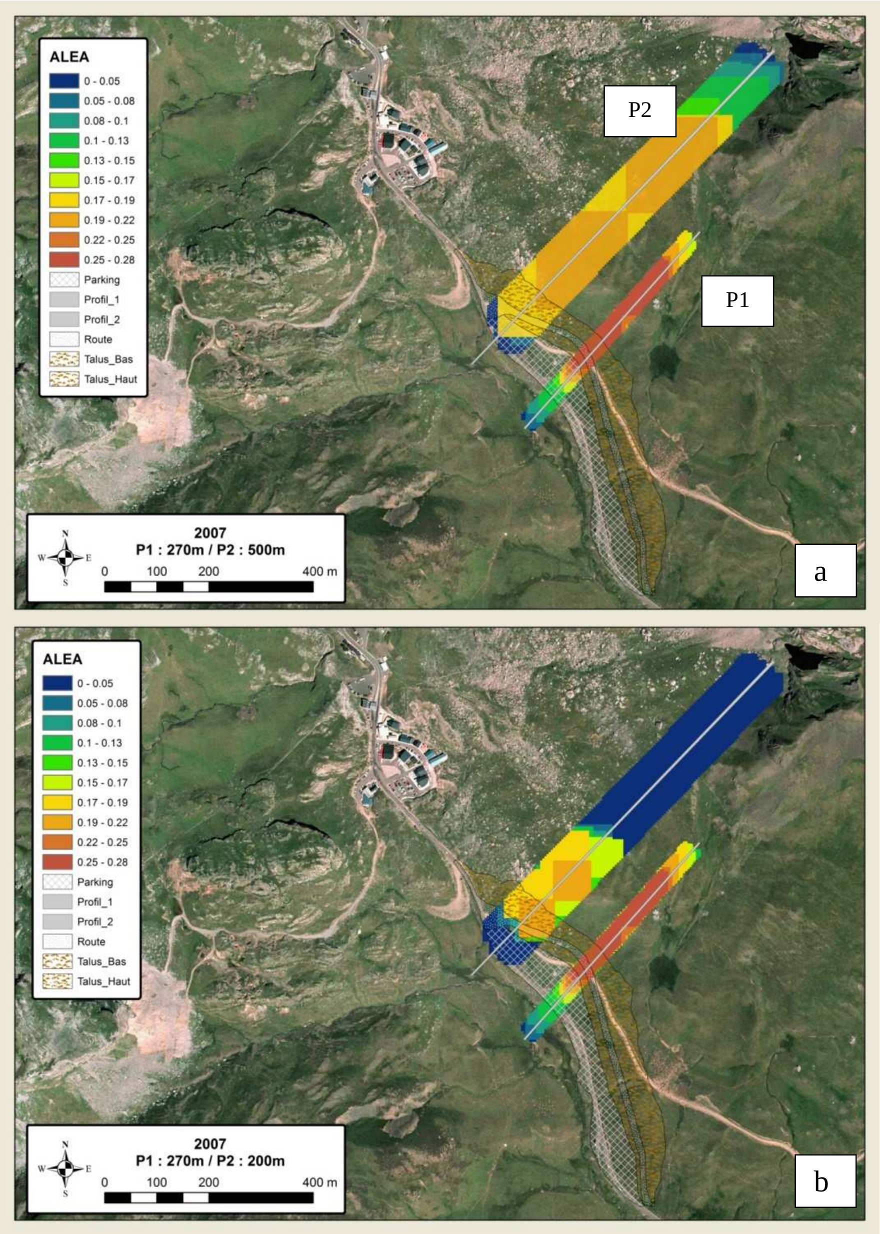
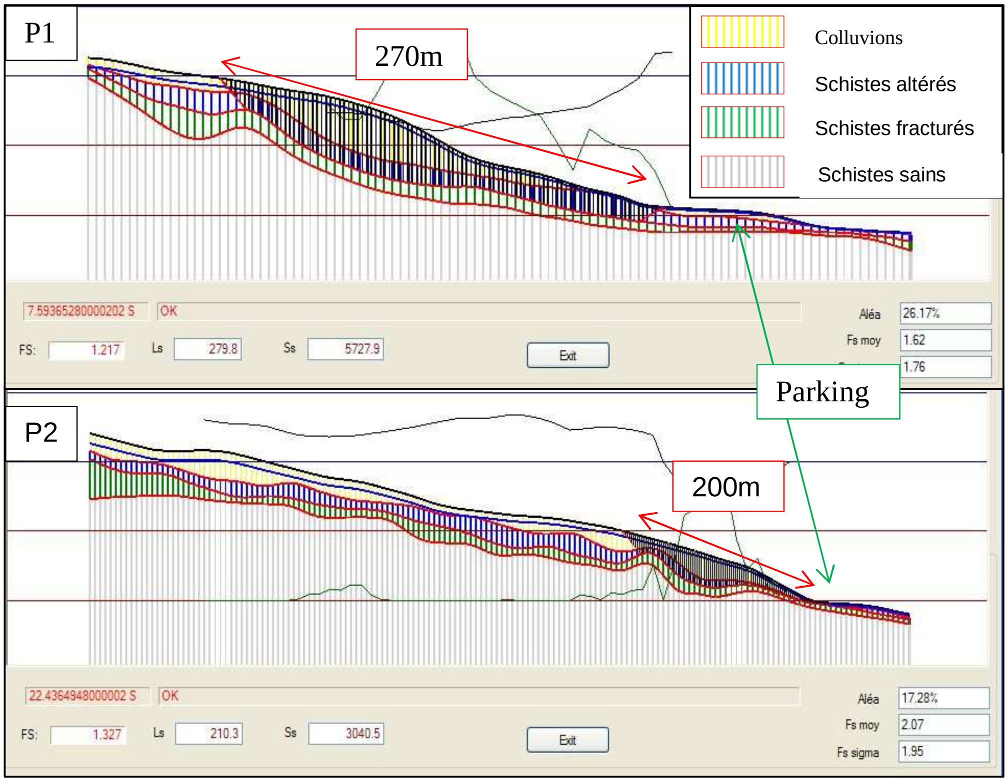


Figure 21. – Modelling results for the slope stability of the Portalet landslide after the parking lot construction (represented as a grey grid). (a) Landslide length of 500m along P2 and 270m along P1; (b) landslide length of 200m along P2 and 270 m along P1.



7.59365280000202 S
OK
FS: 1.217
Ls 279.8
Ss 5727.9
Aléa 26.17%
Fs moy 1.62
1.76

22.4364948000002 S
OK
FS: 1.327
Ls 210.3
Ss 3040.5
Aléa 17.28%
Fs moy 2.07
Fs sigma 1.95

Figure 22.- Computing profile of *ALICE*$^{®}$software along P1 and P2.Notice the geological model of illustration 3.Black hatched parts represent the landslide that has the highest probability of occurrence calculated along the profile. Notice that on both profiles, the failure surface is following the interface between the weathered and fractured shales to reach the surface at the level of the parking lot.

Table

	Material	Trench	Test	Deformational parameters		Strength parameters	
				E (Pa)	**ν**	**c (kPa)**	**Φ (º)**
HILLSIDE	Coluvium (limestone and shale blocks)	ZC1	E1	3,6e5	0,30	5	20
	Weathered shales	ZC2	E1	3,6e5	0,30	5	24
	Weathered shales	ZC3	E1	3,6e5	0,30	6	27
	Shale blocks with clayey matrix	ZC4	E1	2,2e6	0,25	13	24
			E2	6,3e5	0,30	10	22
			E3	2,0e6	0,33	13	22
PARKING-LOT	Clay with shale blocks	ZC5	E1	6,2e6	0,30	27	32
		ZC6	E1	6,2e6	0,30	15	27
		ZC6	E2	6,0e6	0,25	22	45
	Fractured shale	ZC5	E2	1,3e6	0,26	10	26
		ZC5	E3	1,8e6	0,28	10	25
		ZC7	E1	9,0e5	0,30	6	26

Table 1.- Characteristics of penetration tests made

Borehole	Length (m)	Equipment	Object
GB2	36	Inclinometric Pipe	Measure of horizontal movements with inclinometric probe (33 m) Measure of vertical movements with extensometric area (19 m)
GB3	45	Inclinometric Pipe	Measure of horizontal movements with inclinometric probe (44,5m) Measure of vertical movements with extensometric area (21 m)
GB4	40	Inclinometric Pipe	Measure of horizontal movements with inclinometric probe (39 m)
PzB1	53	1 Piezometer and 4 thermometer	Measure of the wáter table and of the temperature in the firsts 10 m.
PzB2	11	1 Piezometer	Measure of the water level
PzB3	13	1 Piezometer	Measure of the water level
PzB4	11	1 Piezometer and 4	Measure of the water table and of the temperature in the first 10 m.
B3	Drilled 36 m/useful 14 m	Inclinometric Pipe	Measure of horizontal movements with inclinometric probe (14 m)
B4	Drilled 36 m/useful 16,5 m	Inclinometric Pipe	Measure of horizontal movements with inclinometric probe (16,5 m)

Table 2.- Summary table of the instrumetation of the boreholes

	Cohesion (kPa)	Friction angle (º)	Unit weight (kN/m^3)
Colluvium	0	17-22	21,3-22,2
Weathered shale	2-5	15-20	16-18
Fractured shale	4-6	16-25	23-27
Shale bedrock	100	20	40

Table 3.- Highest and lowest values of mechanical characteristics for each geotechnical unit