Monitoring of the Vallcebre landslide, Eastern Pyrenees, Spain

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ABSTRACT: In 1996 and 1997 a monitoring network was set up at the translational slide of Vallcebre. Fourteen boreholes were equipped with piezometers, wire extensometers and inclinometers. Since then groundwater levels changes and wire displacements have been automatically recorded every 20 minutes. Superficial displacements have been periodically measured with differential GPS. The monitoring network has allowed the observation of sudden changes in groundwater levels and landslide displacements taking place in only a few hours. The immediate response of the groundwater levels to the rainfall has evidenced the role of fissures in the infiltration of the water. A correlation has been obtained between horizontal displacements measured with both inclinometer and GPS and the displacements observed with the extensometer wire. This correlation has provided a continuous record of the rate of the horizontal landslide displacement. The latter tend to be constant for steady positions of the water table suggesting the existence of some viscous component in the landslide mechanism.

1. INTRODUCTION

The landslide of Vallcebre is a translational movement located in the Eastern Pyrenees, Spain, 140 km North of Barcelona. It has a stair-shape profile formed by four main morphological units of decreasing thickness towards the landslide toe. Each unit is formed by a gentle slope surface bounded by a scarp of a few tens of meters high. At the foot of each scarp, there exists an extension area that originates a graben. The toe of the landslide reaches the torrent of Vallcebre and overrides the opposite slope. The dimensions of the slide mass are 1300 meter long and 600 m wide. The main direction of the movement is towards the northwest and a secondary direction of movement, towards the Torrent Llarg, is also observed in the upper slide units. Figure 1 shows a geomorphologic sketch of the landslide and the location of the monitored points and boreholes.

2. MONITORING NETWORK

Vallcebre landslide has been monitored since 1987 using conventional surveying and photogrammetry (Gili & Corominas 1992). In 1996, this landslide was included within the frame of NEWTECH project, funded by the European Union, as a test site to check the performance of monitoring equipment, and to carry out water flow simulation and mechanical analysis using numerical codes. Fourteen boreholes were drilled in the landslide in order to identify the materials involved, to assess the landslide geometry, to provide soil samples for laboratory testing and to install monitoring instruments.

The borehole logs allowed a better knowledge of the geological structure of the site. The landslide consists of a set of clayey siltstone and gypsum layers sliding over a thick limestone bed, which outcrops at the landslide edges. The slide material includes from the bottom to the top: a) densely fissured clayey siltstones, 1 to 6 m thick, showing slickensides; b) gypsum lenses, up to 5 meters thick; c) clayey siltstones rich in veins and micronodules of gypsum. The logs have also confirmed the existence of the grabens between the landslide units filled with colluvium.
Half of the boreholes were equipped with both wire extensometers and open piezometers and the rest with inclinometer casings. Wire displacements and position of the groundwater levels were measured automatically every 20 minutes and stored in a data logger. Measurements with inclinometer and differential GPS were made every two or three weeks and at least once in two months, respectively.

2.1 Inclinometric results

The inclinometric profiles indicate that the failure occurs in a thin basal shear zone, with negligible deformation above it (Fig. 2). The shear zone runs along the fissured clayey siltstone layer, close to the contact with the limestone and shows a gentle slope with an average inclination of 10º, similar to that of the ground surface. Inclinometric measurements also showed that the thickness of the slide mass is not constant. The lower slide unit (inclinometers S1, S3 and S8) has a thickness of between 10 and 15 m, whereas the intermediate unit (inclinometer S7) may reach a thickness of at least 34 m in the northern side and between 14 and 19 m in the southern one.

Figure 2. Inclinometric profiles. Numbers in profiles indicate campaign (i.e. number 7 was in 29-Oct-96)
The maximum horizontal displacements obtained from inclinometric measurements are displayed in Figure 2. Inclinometer S7, in the intermediate unit of the landslide, experienced small displacements whereas S1 and S3 were much more active. S1 had a maximum displacement of about 180-mm in only 5 months (campaign number 9 performed in 12-Dec-96). An unusual wet winter in 1997, caused very high rates of displacement at the landslide toe. Consequently, most of the inclinometric casings were lost by the spring of 1997.

Even though the inclinometers have a short life when the landslide is very active, they produce a high quality information on soil displacement profiles, velocities and position of the shear surface.

2.2 GPS measurements

Superficial landslide displacements were also monitored by means of GPS techniques. 30 points were positioned on the landslide surface for periodic control. These points included reference points, fixed points adjacent to the landslide and targets within the landslide mass (i.e. buildings and upper ends of the boreholes). The GPS method used is based on a radiation with Real Time Kinematics GPS. 14 field surveys were carried out with GPS between December 1995 and February 1998.

Figure 3 displays the evolution of superficial displacements at Vallcebre site between July 1996 and February 1998. The GPS data also revealed the variable level of activity of the different parts of the landslide. At the lower slide unit, the horizontal displacements accumulated during the analysed period range between 97 cm, at borehole S1 and 80 cm at borehole S5 (see Figure 1 for the location of boreholes and GPS targets). These displacements are 3 to 7 times higher than those recorded at the intermediate unit. In the latter there are two sectors with different rate of activity. The northern sector moved 24 to 27 cm at the targets G11 and G15, whereas at the southern one the total movement was of 14 to 15 cm (borehole S6 and target G5). Other targets placed on the headscarp of this unit, as the G3, G8 and G16, have remained stable during the same period.

The accuracy of the GPS results is given by the difference of successive positions of the targets located in the Vallcebre limestone, assumed as stable ground (outside of the landslide mass). Measurements at target G17 between December 1995 and February 1998 gave a maximum error of 2.2 cm. This accuracy is of the same order of that provided by conventional surveying (Gili et al., in press). Moreover, the GPS has some advantages with respect to the classical surveying. It allows the coverage of wider areas and does not require direct line of sight between stations. Effectively, in certain procedures it is possible to compute precise baselines being their extreme stations at opposite sides of a hill or a building. The antennas, however, must have good sky visibility, to receive the satellite signals without interference. Ideally, obstacles should not appear 15º above the horizon, otherwise it is difficult to gather accurate readings. This kind of problem usually arises at targets close to the forest, as happened at the borehole S7 in Vallcebre. Unlike
the classical methods, the GPS can work regardless the weather conditions (with rain, mist or fog, strong insolation producing fuzzy collimations, by night), a requirement especially important for angular measurements. Consequently, GPS has many advantages, especially when a long term monitoring of the landslide is performed and displacements are large.

2.3 Groundwater table

Automatic recording of the piezometers provided critical information on the rapid water level variation due to rainfall. Piezometric head was initially assumed constant with depth, and the information obtained from field instrumentation confirms so far that assumption.

The piezometers showed a very fast response to the rainfall (Figs 4-6). This fact suggests that water infiltration is controlled by fissures or macropores rather than by soil porosity. It is also observable that there is a practically simultaneous response of the piezometers. Two basic types of responses to rainfall are observed depending on the location of the piezometers. The piezometers located in tension zones, as the S5, show smaller variations of the groundwater level (ranging between 0.5 to 2 m) and quicker drainage compared to the piezometers placed out of this zone (for example S2, S4 and S11). The latter ones experienced changes of 2 to 5 m and a slower rate of lowering of the groundwater level. We understand that the borehole S5 is located in one of this tension zones. The behaviour of the piezometer S5 is consistent with the presence of a very pervious zone. Consequently, it is assumed that cracks act as a preferential flow path within the landslide body.

Besides the fast response to the rainfall, the piezometers show a defined level below which the groundwater table decreases very slowly. This may be observed during the period between February - April 1997 in which no or negligible rain was recorded in the area.

![Piezometric records at the Vallcebre landslide](image)

Figure 4. Piezometric records at the Vallcebre landslide

2.4 Wire extensometer

Wire extensometers used were specially designed by the authors following an idea of Angeli et al (1988). It consists of a protected steel wire anchored to the limestone (below the slip surface) inside a piezometric pipe. The wire is kept in tension by means of a pulley and a counterweight of which rotation is continuously recorded using a potentiometer. The extensometric wire device has proved to be very useful in recording sudden changes in rates of displacements that can be directly related to the variations of the groundwater table and indirectly, to the rainfall. It is especially convenient when borehole inclinometers have been lost after large displacements.
Interpretation of the displacements of the wire can not be done directly. For landslides in which deformation is confined in a basal shear zone, as in translational slides, the wire displacement can be related analytically to the superficial displacement of the landslide (Corominas et al., in press). This relationship depends on the borehole dimensions and on the landslide geometry (thickness, depth and dip of the shear zone). Horizontal displacements at the landslide surface have been calculated from wire displacements and fit perfectly into the measurement provided by the GPS and the inclinometers (Fig. 5).

![Graph of horizontal displacements](image)

Figure 5. Plot of the horizontal displacements measured with GPS (open circles) and inclinometer (stars) and wire displacement (solid line) at borehole S2. A continuous record of the horizontal displacement Dh (dashed line) has been derived from wire readings Dl by fitting to the observed GPS data.

Readings at the boreholes S2, S5 and S6 started in November 1996. The history of displacement of the wires reflects a quick response to groundwater level changes. The lower slide unit accumulated displacement of the wire of over 700 mm in borehole S2 till March 1998. The period of highest landslide activity correspond to the wet winter of 1997 (between mid January till end of February). In the extensometer S2, were recorded rates of up to 9 mm/day and 50 mm/week during this period. Other extensometers standing on this slide unit, the S5, S9 and S11, exhibited rates lower than these of S2 although they are of the same order of magnitude.

At the borehole S6, placed on the intermediate slide unit, the total accumulated displacement from November 1996 till March 1998 was only 28 mm. The big difference between this displacement and the observed at other borehole S2 may be explained by the minor activity of the intermediate unit.

3. VISCOS EFFECTS

The relationship between the groundwater level and landslide activity is illustrated in Figure 6. There, the rate of horizontal component of the displacement at the surface of the borehole S2 is plotted beside the rainfall record and the changes of the groundwater levels. There exists a perfect synchronism between changes in both records. On the other hand, the rate of superficial displacement tends to be the same for similar positions of the water table. The event of June 1997 is an exception that apparently contradicts this direct relationship. However, this is because the episode of June 1997 was a very short-lasting event. The complete groundwater table rise and withdraw lasted for only 14 hours while the rate of wire displacement is given for a 24-hr span. In this case, the rate of displacement is smaller than expected wire displacement if the groundwater rise had lasted for the whole day.

The relation between the water level and rate of displacement may be easily observed during the dry period of April and May 1997. In this period the groundwater level remained almost constant at about 6 m from the ground surface while the horizontal displacement kept a constant velocity below 1 mm/day. Therefore, a viscous component appears to be important and should be considered in further analyses.

4. CONCLUSIONS

The paper presents some results of the monitoring of the Vallcebre. The continuous record of both the groundwater levels and landslide displacements has allowed to observe some characteristics of the landslide behaviour that otherwise would have been missed.

The morphological units of the slide move at different rates. The fast response of the groundwater levels to the rainfall has evidenced the role of the fissures and macropores in the infiltration into the ground. The range of the groundwater fluctuations may be related to the closeness to such fissures.

Finally, the proportionality between the position of the groundwater levels and the rate of displacement of the landslide is suggestive of the presence of some viscous behaviour.
Figure 6. Above: rainfall record (bars) and groundwater level changes at borehole S2. Below: rate of horizontal component of the superficial displacement at the same borehole calculated from wire measurements.

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6. REFERENCES


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