Piezometric thresholds for triggering landslides along the Normandy coast, France

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ABSTRACT: In Normandy (north-west of France), many coastal landslides occur between Trouville and Honfleur. These are slow-moving and deep-seated coastal landslide characterized by surface displacements of a few centimetres per year (1-10 $cm.yr^{-1}$) but regularly affected by brutal accelerations with several meters of displacements (January 1982, February 1988, March 1995 and March 2001). Because of the presence of economical and physical stakes, the landslide has been progressively monitored since 1985. The first investigations demonstrated qualitatively that the four major accelerations were controlled by the slope hydrology. To improve the knowledge of slope dynamics related to rainfall and groundwater fluctuations, a combination of historical data and field monitoring was necessary. A monitoring system was set up to observe simultaneously triggering factors (28 piezometers, 5 piezometric sensors and one meteorological station) and the very low amplitude surface displacements (twenty-three cemented benchmarks, three permanent GNSS receivers). These investigations highlight the morphostructural control and the seasonality of the landslide kinematic. In a prospective way, the purpose is to define critical piezometric thresholds for landsliding. Thresholds have been identified using long-term continuous single point time series and short, but more spatially distributed, piezometric information. Empirical piezometric thresholds for the landslide triggering have been defined taking into account the antecedent hydro-climatic conditions. Two possible situations have been identified: (1) high accelerations can be associated to a long-lasting rainfall period (several months) with a groundwater water elevation two meters above the annual mean groundwater level observed for the period 1976-2013 (return period of over 6/7 years); and (2) moderate accelerations can be associated to a low intensity rainfall period with limited groundwater rise responsible inducing a moderate (seasonal) kinematic (return period of every years).

1 INTRODUCTION

1.1 Study area

Along the west margin of the sedimentary Paris Basin (north of France), at the edges of the Pays d'Auge plateau (Fig. 1), several active landslides between Trouville and Honfleur occur (Varnes, 1978). These landslides are located on low altitude convexo-concave slopes of the Pays d'Auge Plateau (maximum elevation of 140 m) and present a complex morphology of composite rotational slides. This work focuses on the Cirque des Graves landslide (municipality of Villerville). The Cirque des Graves landslide is the most active and the largest roto-translational landslide of the region with a surface of 47 hectares. As outlined on the Figure 1c, the lithostratigraphic scheme consists of Jurassic sedimentary rocks with superimposed strata of almost 10 m thickness sandstone plunging gently to the South-East (10-20%), marl (25 m thickness) and sand overlayed by chalk material. On the plateau, the chalk can exceed 50 m thickness and is covered with flint clay, slope deposits whose thickness is very variable.
The slope instability started probably during the Holocene period (Flageollet & Helluin, 1987, Lissak et al., 2013) as outlined by the presence of large and high scarps (10-15 m height) before the main acceleration of January 1982 (Fig. 1A). Three other major accelerations (February 1988, March 1995 and March 2001) have been observed and characterized by several meters of displacement creating high scarps by retrogression and large cracks (Fig. 1B). The four accelerations have induced several damages to buildings and traffic infrastructures (Lissak et al., 2011). The resulting topography is representative of successive rotational slides (Fig. 1C) with typical morphological features such as opened fissures, fresh scarps of various sizes, depressions,

counter-slopes and lobes at the toe. Independently of these acceleration events, the landslide is characterized by yearly average surface displacement rates of 5-10 $cm.yr^{-1}$.

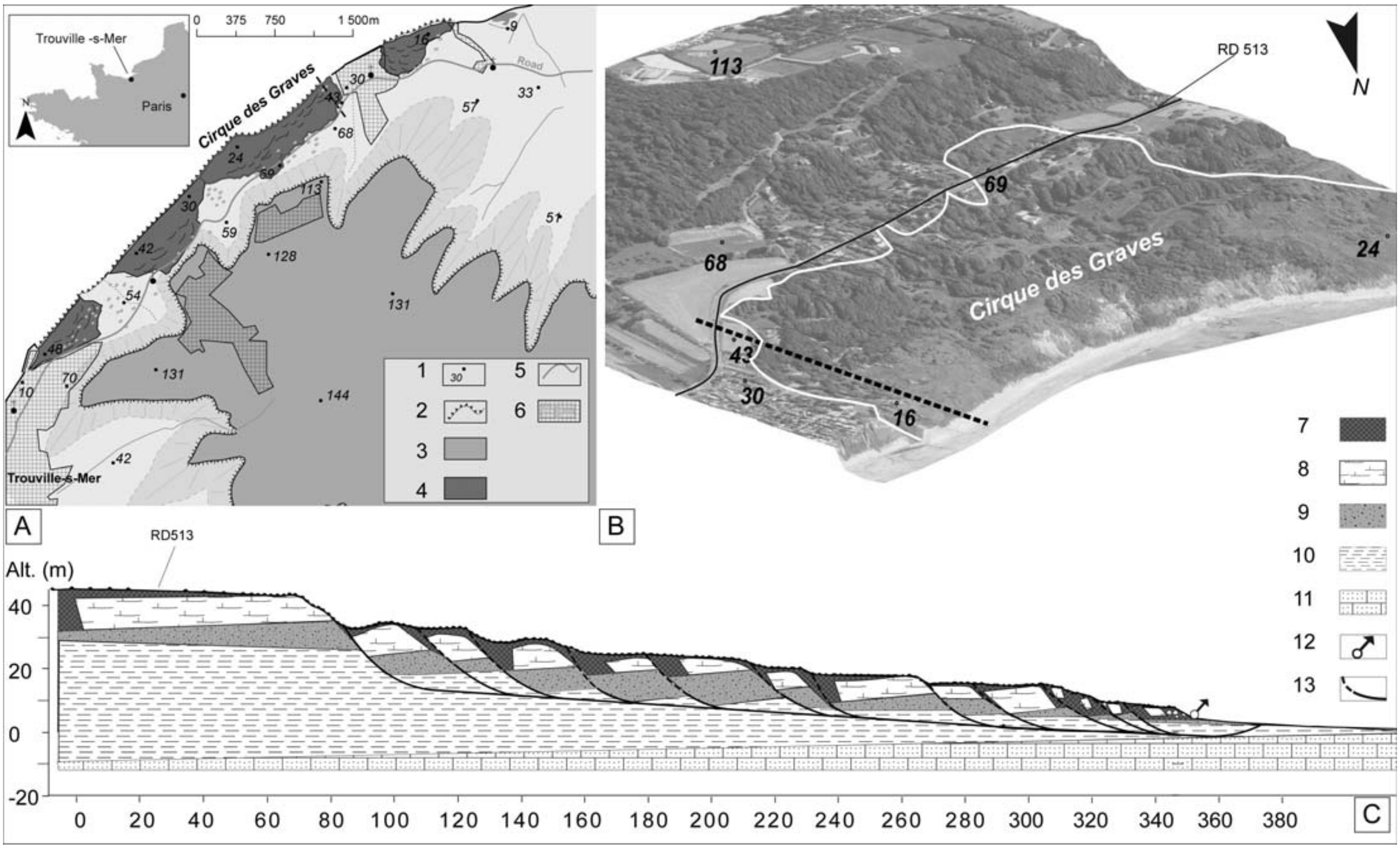

Figure 1. Location and geomorphological setting of the Cirque des Graves landslide. A: Topographic context with location of the active landslide along the coast between Trouville and Honfleur. B: 3D view of the Cirque des Graves landslide in 2006. C: Geological cross-section; 1: Surficial deposit; 2: Coastal slope; 3: Pays d'Auge Plateau; 4: Active coastal landslide; 5: Road D513; 6: Buildings; 7: Surficial deposit; 8: Chalk; 9: Glauconitic sand; 11: Sandstone; 12: Resurgence; 13: Sliding surface.

1.2 Monitoring landslide movements and triggers

To assess and measure the surface displacements, the actual network is composed of 24 cemented benchmarks. Two benchmarks are located on the stable parts of the slope and are used as control point to assess the quality of the measurements (Gili et al., 2000). The benchmarks have been implanted according to the accessibility, the vegetation constraints and the landslide detailed morphology (Lissak et al., 2010, Lissak et al. submitted). Since 2008, the position of the benchmarks has been measured by campaigns of differential GNSS (Gili et al., 2000, Malet et al., 2002a, Squarzoni et al., 2005) with session duration of 17 minutes (X/Y accuracy of 0.7 cm, Z accuracy of 1.3 cm). Since July 2009, high frequency observations are acquired with three permanent GNSS receivers in order to detect very low amplitude displacements (Fig. 2). Each GNSS station consists of a GNSS antenna TRM41249.00 (with random TZGD) and a dual-frequency receiver Trimble NetRS. One GNSS station has been set up on the stable part of the slope (VLRV). Two GPS receivers (VLRH and VLRB) are located on the active part of the landslide, on two subsequent compartments. The acquisition frequency is 30s over 24h sessions. An automatic solution and an internet connection allow a near real time (j + 2 days) data acquisition (Déprez et al., 2011). This network is included into the GPS Data Service of the French Landslide Observatory OMIV. GPS raw data and code phase (Malet et al., 2002a, b) are calculated with the GAMIT / GLOBK software developed by the MIT (Massachusetts Institute of Technology). The automatic daily routine developed by OMIV-EOST Strasbourg takes into account the different tropospheric and ionospheric parameters for a 3D position accuracy of 0.5 cm. The procedure is presented in Déprez et al. (2011).

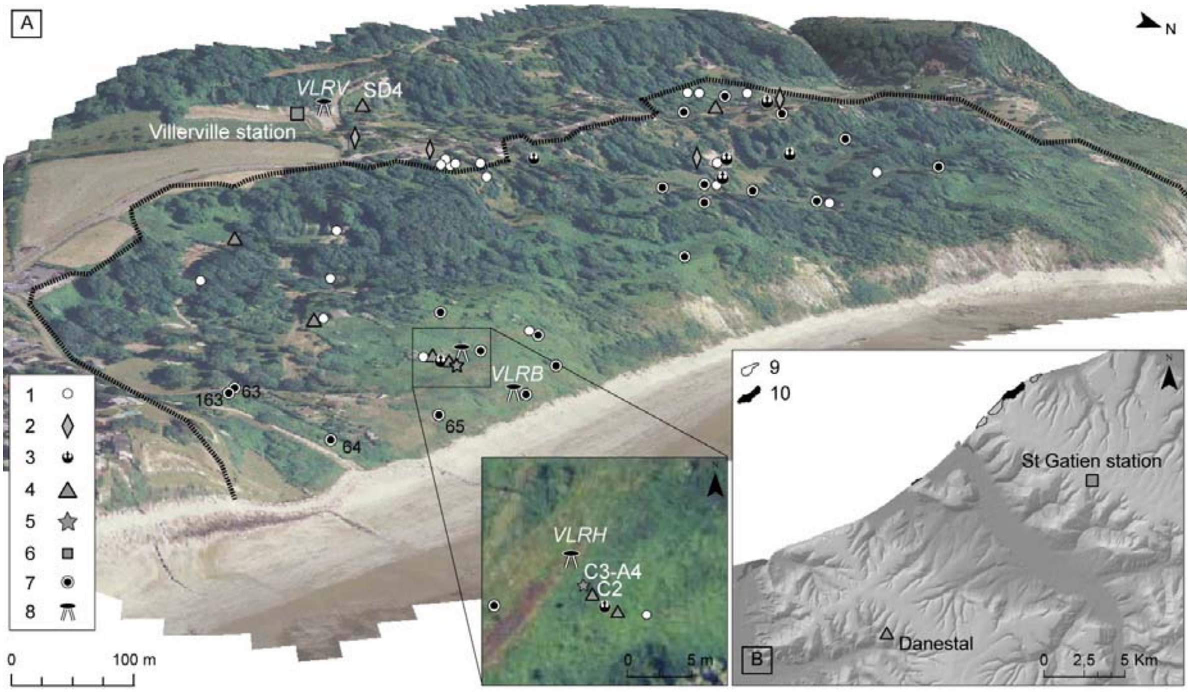

Figure 2. Monitoring network for the Cirque des Graves landslide. A. Cirque des Graves landslide. B: Pays d'Auge Plateau. 1: Piezometer; 2: wells; 3: Inclinometer; 4: Piezometer with permanent sensor; 5: Geobead probe; 6: Meteorological station; 7: Topographic benchmark, 8: Permanent GNSS receivers; 9: Active landslide; 10: Cirque des Graves landslide.

The hydrological network (Fig. 2) consists of twenty-nine observation points including four wells, seven boreholes equipped with inclinometer tubes and eighteen piezometers whose six equipped with automatic probes (Fig. 2). In addition, to analyse the groundwater behaviour in the stable chalk formation overlaying the landslide, a piezometer, located 15 km away from the study site, has been selected among the regional BRGM groundwater monitoring network (Danestal piezometer). Pore water pressures and soil humidity are also monitored in depth with four multi-parametric probe Geobeads (Peters et al., 2010). Four probes have been set up in the borehole C3 (Fig. 2) at several depths (A1: -1.0 m, A2: -2.0 m, A3: -4.00 m, A 4: -5.80 m) close to the permanent GNSS receiver VLRH, two continuous logging piezometers and one inclinometer. Daily pore water pressure, temperature and inclination data are available using online connexion with the station. The effective rainfall data come from two meteorological stations. One is located on the plateau, 4 km from the landslide (altitude 144 m), at Saint-Gatien; this station from the French Meteorological Survey (Meteo-France). The second station has been set up near the landslide in January 2013 (Fig. 2).

2 PIEZOMETRIC THRESHOLDS AND EARLY WARNING SYSTEM

Only four major accelerations are known. These accelerations occurred during unusually wet periods characterised by a succession of heavy rainfall years (according to the mean annual effective rainfall). According to these events, 4 steps of alert system can be defined (Fig.3). The acceleration of January 1982, considered as the largest acceleration of the landslide, occurred during an excessive hydrological year (July 1981 - June 1982) with particularly abundant winter rainfall amount (Lissak et al., submitted). The consequence of these contributions is an elevation at Danestal of the groundwater level nearly 1.50 m a few weeks before the landslide acceleration, following also a series of six consecutive years of excess rainfall (Fig. 3). The accelerations of 1995 and 2001 occurred after two or three years of hydrological excess, and are associated to a significant rise of the groundwater level caused by this succession of very wet months. The major accelerations are associated to a high groundwater level linked to consecutive years of rainfall excess (Bogaard et al., 2011, Lissak, 2012). The critical groundwater level for landslide stability at Danestal piezometer varies between 9.60 m and 10.35 m in depth. For the acceleration of 1988, 1995 and 2001, the groundwater levels are quite similar, between 10.20 and 10.35 m in depth. As a first approximation, we can consider a critical regional groundwater level threshold close to 10.35 m depth. If this threshold is reached or exceeded, a major acceleration can occur. Moreover, we can observe that, regardless of the groundwater level at the velocity peak, the analysis has focused on the groundwater level at the beginning of the hydrological year (in early winter); in these periods, the groundwater level can rise of 1.48 m to 2.10 m in a few months according to the rainfalls and quickly reach a critical level we can define a pre-alert condition several months before the crisis.

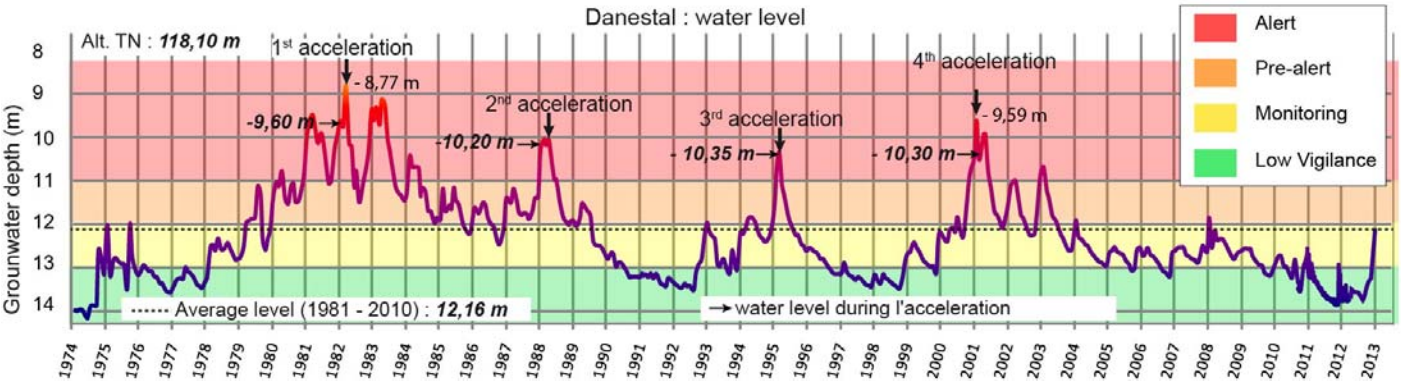

Figure 3. Groundwater level at Danestal since 1974 and critical water level for warning system

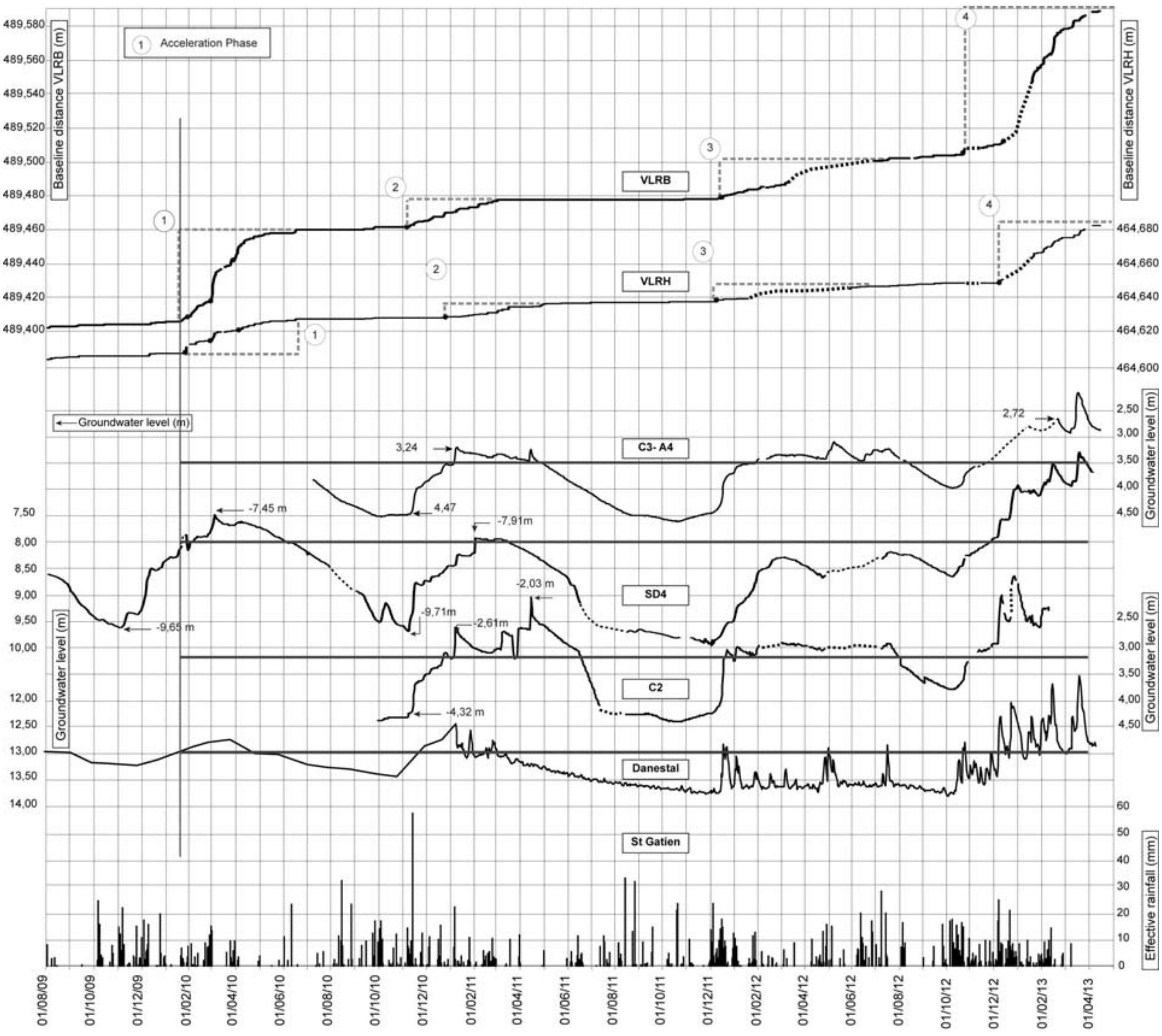

Figure 4. Relations between the displacements (GNSS VLRH and VLRB), piezometric levels (SD4 and C2), pore pressure (A4) recorded at Cirque Graves and daily rainfall of St Gatien station

Out of these acceleration periods, a permanent creeping of several centimeters of displacement per year is observed. The analysis of the evolution of the baseline of the permanent GNSS VLRH and VLRB since August 2009 (Fig. 4) allows to complement this statement. Since 2009 only a few minor accelerations of a few centimetre displacements per year can be analysed. This can be explained by the low groundwater levels measured at Danestal (between -12.5 m and -14.0 m depth) linked to a period of annual effective rainfall amount below or slightly above the mean annual (435 mm at St Gatien). A correlation between the seasonal trends of the groundwater and the landslide velocity is however observed (Fig. 4). The time lag between the groundwater rise and the acceleration beginning ranges between one and four days.

Hydrological thresholds are determined by empirical analysis of rainfall, groundwater fluctuations, and the surface displacements (Fig. 4,5). However, the number of significant events, since the network implementation, is too small to determine critical thresholds based on a statistical approach (van Asch & Buma, 1996, van Asch et al., 1999). To define a local threshold, the time series of piezometers SD4 and C2, and the cell pressure A4 at C3 are used (Fig. 5). Both piezometers have been selected because of their location and their significant seasonal trends. For the first acceleration (20 January 2010 to 13 May 2010), a preliminary threshold, can be defined at the piezometer SD4 (Fig. 4). The landslide displacement rate significantly increases when the groundwater level reaches 8 m in depth at SD4 (Fig. 4). As soon as this level is reached, several small accelerations are recorded in association to the groundwater fluctuations. Finally, the slope stabilizes when the groundwater drops below 8 m in depth. For the piezometer C2 (Fig. 4), close to the GNSS VLRB, the piezometric seasonality is synchronous to the seasonality of the displacements. A piezometric threshold would be 3.10 m depth (Fig.4). For the Geobead probe A4, set up in July 2010, groundwater levels have been estimated from the pore water pressures recorded by the sensor. The piezometric threshold would be at 3.50 m depth. Beyond this value at the beginning of winter, the groundwater level has to be regularly check to initiate the procedure of alert (simultaneously at the local scale and on the Plateau at Danestal piezometer (Fig. 5)).

Analysis of the Danestal piezometer allows defining two significant piezometric thresholds, for respectively, a seasonal acceleration of low amplitude (threshold at -10.3 m in depth) and a large acceleration of high amplitude (threshold at 13 m in depth). Consequently *in-situ* observations suggest that a change of +2.65 m of the groundwater level is necessary to trigger a major acceleration.

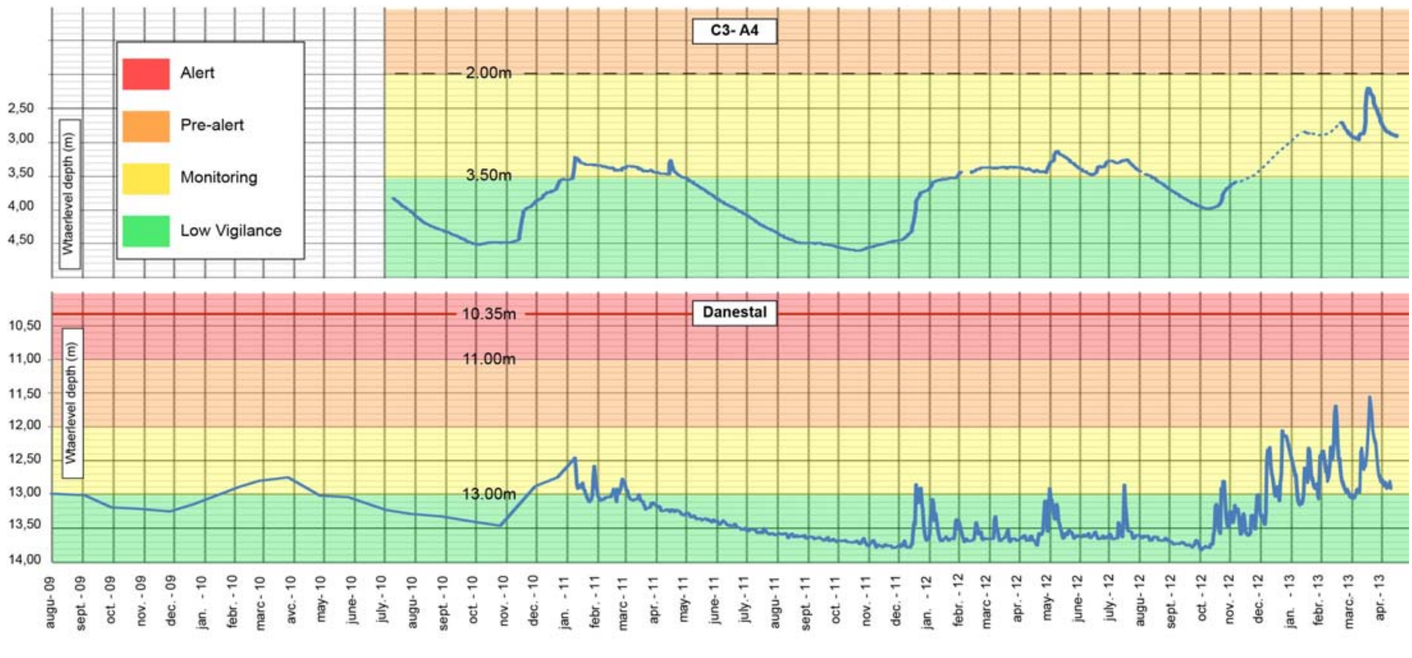

Figure 5. Groundwater levels at Danestal since august 2009 and A4 since august 2010 and critical water level for warning system

3 CONCLUSION

The Cirque des Graves landslide is a typical example of slow-moving and deep-seated landslide developed in a coastal vulnerable area. The landslide dynamic analysis based on historical data and field monitoring highlights the spatial distribution and the temporal variability of the landslide kinematics controlled by slope hydrology. The assessment of the temporal occurrence of the landslide is complex because of irregular crisis occurrence. Statistical methods are generally suggested to investigate the temporal occurrence of landslides. For the moment, only a semi-quantitative approach can be carried out through field surveys. The use of permanent sensors with infra-centimetric accuracy allows to quantify very low movements (mm) which are imperceptible by traditional geodetic measurements. However, the installation at several points of sustainable permanent GNSS receivers with a daily transmission of data is still expensive. It is therefore necessary to implant receivers at strategic points, representative of the whole behavior of the landslide.

The combination of repeated campaigns and permanent monitoring is necessary in this case study in order to: 1) highlight the regressive dynamic of the landslide, 2) evaluate the spatial and temporal heterogeneity of the displacement rates, 3) evaluate the effect of groundwater fluctuations on the velocity pattern, 4) define piezometric threshold for landslide reaction. Two significant piezometric thresholds can be defined in a context of a warning system. A first threshold based on field surveys (short-term/high resolution) for moderate landsliding events recorded since 2009 has been defined at 3.50 m depth in the landslide area. This threshold corresponds to a depth of 13 m of the groundwater level on the plateau. A second threshold based on historical data (long-term/low resolution) of the four major events occurring between 1982 and 2001 has been defined at -10.35 m depth. Thus, by comparing the two thresholds, we can propose a change of groundwater level necessary trigger a major landsliding event of about 2.65 m if the groundwater level is close to 13 m depth. These preliminary results suggest that the effect of rainfall on slope stability is hampered by the prior groundwater levels (several months before a main landsliding event).

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