Seasonal and long term analysis of precipitation-displacement relationships on a deep seated unstable slope (Séchilienne, French Alps)

Analyse saisonnière et long terme des relations précipitation-déplacement d’un mouvement de terrain de grande profondeur (Séchilienne, Alpes françaises)

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ABSTRACT: Time series analysis and cross-wavelet analysis are used to characterize the relationship between water input and displacement in the most active zone of the Séchilienne unstable slope. Time series analysis shows a displacement long term trend and seasonal intra-annual variations, respectively independent and synchronous to precipitations. Wavelet analysis has allowed identifying and characterizing the precipitation-detrended displacement relationship which shows that the Séchilienne destabilisation is rather linked to effective rainfall than to raw precipitation (rainfall + snowfall), involving then groundwater process. Seasonal analysis of this relationship was performed, showing that displacement rate follows the behaviour of the hydrological cycle. Finally, trend was analysed and a weakening model approach was developed with an attempt to forecast the next modifications in unstable slope destabilisation behaviour.

1 INTRODUCTION

Pore water pressure, caused by recharge of hydrosystems, is one of the main triggering factors of landslides *(Bogaard et al., 2007)*. However, mechanisms which lead to slope failure of deep seated landslide are complex and involve a wide range of factors (rock mechanical resistance, hydrodynamic behaviour, hydraulic field stress). Therefore, there is no direct causality relationship between precipitation as water input and slope destabilisation rate *(Aleotti and Chowdhury, 1999; Berti et al., 2012)*. In order to understand what is directly caused by precipitation amount and what is inherent to unstable slope damaging, it is necessary to perform long term analysis. Long term analysis allows to give an overview of temporal variations and evolutions and then to identify which of them are independents or not. Taking advantage of long term monitoring of Séchilienne unstable slope (> several years), relationship between precipitation amount and unstable slope destabilisation was characterized thanks to time series and cross-wavelet analysis.

2 MONITORING NETWORK AND DATASET

The Séchilienne site is located on the external part of Belledonne crystalline range in the French Alps, south-east side of Grenoble city in France. The climate is mountainous with mean annual precipitations of 1200 mm. The Séchilienne site is a deep unstable slope on mica-shist bedrock. Precipitations are recorded at Mont Sec weather station (Météo France), including a rain gauge and a snow gauge. It allows estimating total precipitation (rainfall + snowfall), rainfall, snow cover, and snow melt in water equivalent. Groundwater re-charge was computed using a soil water balance method from precipitation, runoff and evapotranspiration (Vallet et al., 2013). Displacement velocities of the Séchilienne unstable slope are monitored by several extensometers since 1990. The A13 extensometer was selected as representative of the Séchilienne most active zone displacement. Daily precipitation, recharge, and displacement time series range from 1st January 1994 to 31 July 2012.

3 INPUT AND OUTPUT SIGNALS

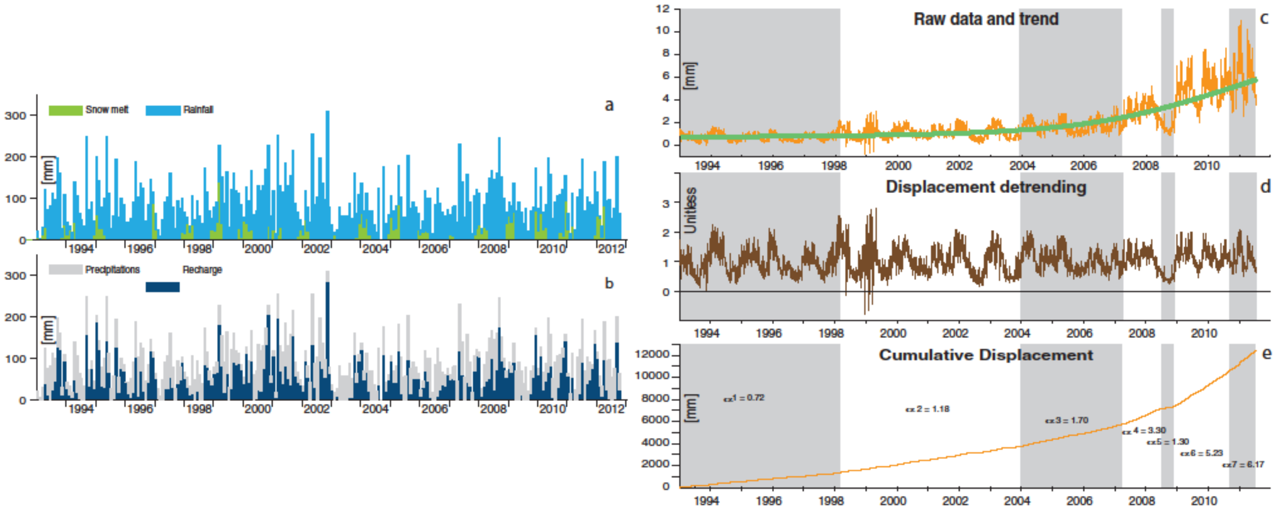


Figure 1: Hydrogeological and displacement daily time series of the Séchilienne unstable rock slope with (a) Precipitation expressed in snow and rainfall, (b) Recharge, (c) Displacement raw data, (d) Displacement detrending, and (e) Cumulative displacement; grey and white colours show periods of similar displacement behaviour

3.1 Input: precipitation data

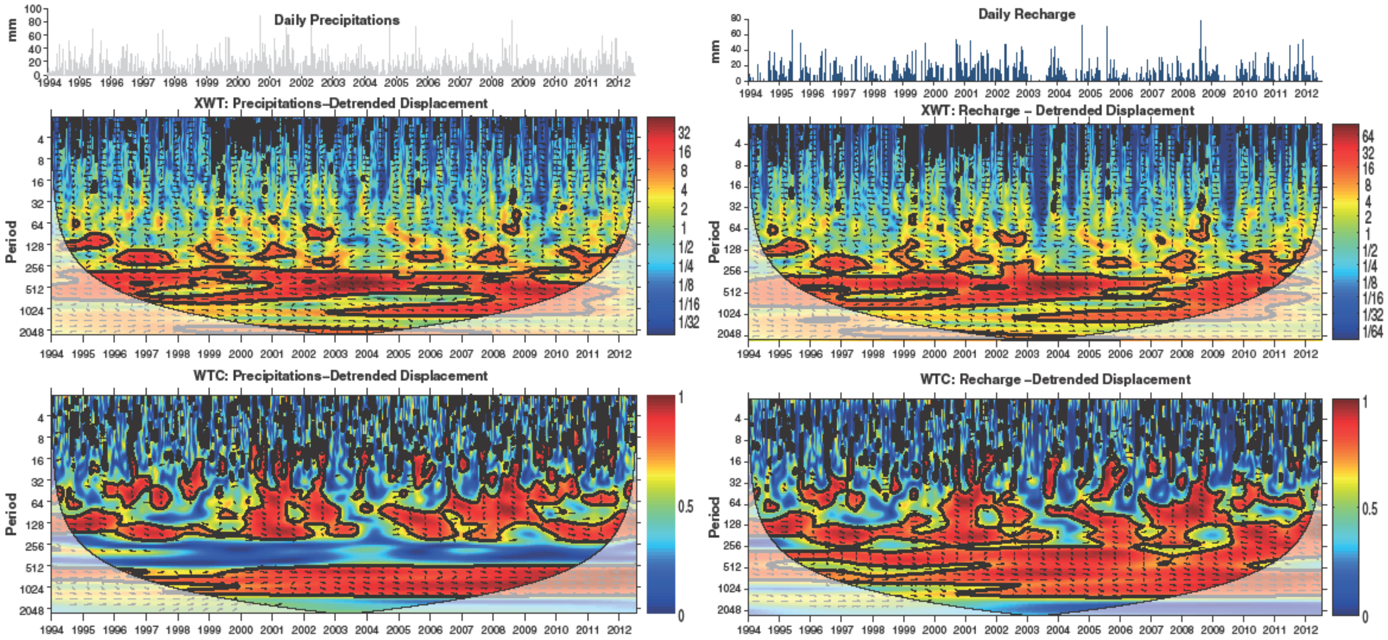
Due to mountainous location, precipitations present two components, rainfall and snow (Figure 1a). Annual snow depth is 8-fold lower than rainfall, and is timely localized (winter). Precipitations show seasonal and annual fluctuations according to the hydrological cycle. As shown in Figure 1b, recharge enhances seasonal contrast (dry summer *vs.* wet winter) because precipitation in summer generated a low aquifer recharge while snowmelt emphasized a high recharge. No trend was identified neither for precipitations nor for recharge data.

3.2 Output: Displacement data

A trend in mean and in variance is observed on the displacement time series (Figure 1c) and was estimated using a polynomial regression fitting of degree 4. Displacement time series was detrended, according to multiplicative methods (Cowpertwait, 2009). The detrended displacement time series shows strong intra-annual seasonal variations with low values in summer *vs.* peaks in winter (Figure 1d). Since 2008, seasonal variations are less marked. On the cumulative displacement curve (Figure 1e), we hypothesis that slope variations (slope = average destabilisation rate) corresponds to a change in the Séchilienne destabilisation behaviour. An iterative segmented linear regression method was performed in Figure 1e to define linear parts which match with periods having similar destabilisation behaviour (alternatively highlighted by grey and white area). Cumulative displacement shows a discontinuous worsening of destabilization rate (succession of stages) in agreement with a decreasing of period extension.

4 METEOROLOGICAL AND DISPLACEMENT RELATIONSHIP: WAVELET ANALYSIS

Wavelet analysis is a powerful tool to investigate non-linear relationships on long hydrogeological time series (Labat et al., 2000): it gives a time-scale representation of the processes and of their relationships. First, cross-wavelet transform (XWT) highlights regions, in time frequency space, where the time series show high common power. Second, wavelet coherence (WTC) highlights regions, where the two time series co-vary (but does not necessarily display high power) (Grinsted et al., 2004). The interpretation of structure for synchronic common high power on XWT and WTC is a causality relationship. Cross-wavelet analysis was performed between precipitation or recharge as input, and detrended displacement as output in order to compare the influence of groundwater processes on displacement (Figure 2). On scalograms, the x- and y-axes represent the time-frequency space, with frequencies expressed as periods in days (high frequencies or low periods at the top of the plot). The z-axis represents the value of the wavelet coefficient with low to high powers in blue to red colors.


Daily Precipitations

Daily Recharge

XWT: Precipitations–Detrended Displacement

XWT: Recharge – Detrended Displacement

WTC: Precipitations–Detrended Displacement

WTC: Recharge –Detrended Displacement

Figure 2: Cross wavelet (XWT) and wavelet coherence (WTC) spectra between precipitation and detrended displacement (left), and between recharge and detrended displacement (right); The thick black outline designates the 5% significance level against red noise and the cone of influence where edge effects might distort the picture is shown as a lighter shade.

Cross-wavelet analysis (XWT) between precipitation and detrended displacement highlighted high frequency structures (< 32 d) related to heavy precipitation events, an irregular monthly component during wet years when seasonal structures are also visible (64-256 d period), a structure on the 1-year band (256-512 d period), and a low frequency structure on the 2 to 3-year (512-1024 d) band from 2003. On the contrary to seasonal and pluri-annual structures, no ssignificant coherence is observed for annual structures although XWT shows high power. Cross-wavelet analysis between recharge and detrended displacement shows identical structures, but in that case, annual structures appears coherent.

The high frequency and monthly structures identified match with punctual higher water amount stress for both signals during wet years. However, the 1-year structure is only identified for recharge as input signal, meaning that annual variations of displacement are related to the part of infiltrated rainwater. Since 2008, monthly to multiannual continuous extended structures are present, showing that the Séchilienne unstable slope becomes permanently sensitive to meteorological input stress. Thus, detrended displacement is better linked to recharge signal compared to total precipitation signal. From this analysis, it appears that the short term component of the detrended displacement results of punctual high precipitation events (for both raw and effective rainfall), whereas long term component is linked to recharge processes.

5 SEASONAL VARIATION ANALYSIS

Seasonal analysis was performed in order to quantify infra-annual relationships between recharge rate and detrended displacement. Three periods called “Autumn Recharge”, “Winter Recharge”, and “Low Recharge”, were identified from multiannual monthly statistics on temperature, recharge, precipitation, and snow melt time series. Autumn recharge period correspond to high recharge rate by rainfalls in autumn. Winter Recharge period corresponds to high recharge rate by rainfalls as well as snowfalls and melt in winter and at the beginning of the spring, and Low Recharge period correspond to low recharge rate during spring and summer when high evapotranspiration values limit the recharge rate during dry hydrological conditions.

Accumulated Detrended Displacement (ADD) and Accumulated Recharge (AR) were estimated for each period and for each year. The three identified periods do not have the same time extension, so accumulation over a period was normalized to a one month period. Figure 3a presents ADD *vs.* AR and the corresponding linear regression for each period. In addition, boxplots were realized on the entire pluri-annual daily population for each season.

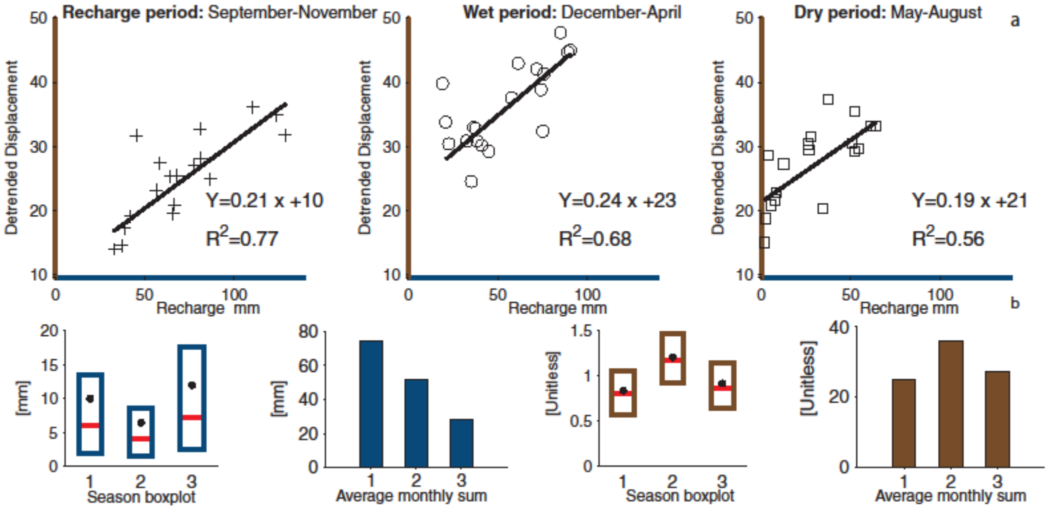


Figure 3: Seasonal analysis results with (a) Accumulated Detrended Displacement vs. Accumulated Recharge for each Recharge periods and associated linear regression, and (b) Boxplot of recharge and detrended displacement based on whole multiannual daily population for the three periods: 1=Autumn Recharge, 2=Winter Recharge, and 3=Low Recharge. Blue and brown colour markers stand for recharge and detrended displacement respectively.

Different slopes and intercepts of the regression lines between AR and ADD showed that the relationships vary according to the period. Slope is considered as an indicator of reactivity/sensitivity of detrended seasonal variation to recharge stress (groundwater transfer velocity). Whereas intercept can be considered as an indicator of the initial hydric conditions (hydrosystem saturation state/pore water pressure background).

The Autumn Recharge period is characterized by the highest recharge amount and a moderate average displacement rate (Figure 3b). The slope is relatively high but the intercept presents the lowest value (Figure 3a). Low intercept can be explained by low water levels in the aquifer after the dry season. The Winter Recharge period is characterized by a relatively high recharge, and a high displacement rate (Figure 3b). This period shows the highest slope and intercept (Figure 3A), meaning that transfer velocity is fast in a saturated aquifer. The dry period presents the lowest recharge component and the lowest slope, but an intercept relatively close to that of the wet period (Figure 3). It means that the transfer velocity is slow, whereas the hydrosystem is saturated. This may be explained by a lower recharge rate when evapotranspiration level is high.

6 CONCEPTUAL MODEL

The following interpretations can be established from the results presented above. The displacement trend is independent from precipitation input, and highlights a gradual degradation of rock mechanical properties. This degradation can either take the form of a decreasing of slope rock strength and cohesion, either a modification of hydraulic field stress (permeability and connectivity change) or either both. The Séchilienne destabilisation evolution shows a discontinuous behaviour by successive stages. However, both displacement and meteorological signals show intra-annual seasonal variations following the hydrological cycle.

Seasonal variations of detrended displacement, relatively to the recharge can be explained by the hydrodynamic behaviour of the fractured rock aquifer, to which mica-schist belongs. This type of aquifer presents generally drainage anisotropy, with a double permeability, matrix permeability contained in micro-fractures (stock component/inertia) and macro-fractures (drainage component/reactivity).

Autumn Recharge period follows the summer dry season, and is characterized by high recharge amount and intensity. Hydrosystem saturation state is at its lowest level of the year, so that the major part of infiltration recharges the micro-fracture stock component. The recharge signal is largely buffered by water supply of matrix, which confers a low transfer velocity through the hydrosystem. The Séchilienne destabilisation rate increases over time, and becomes more and more reactive as saturation increase.

Winter Recharge period is characterized by an aquifer drainage functioning. Aquifer saturation state is at its highest level of the year, and most of infiltration is drained by the macro-fracture drainage component which is predominant (micro-fractures are already saturated). The aquifer is more transmissive and less inertial, in relation to infiltration signal. The Séchilienne destabilisation rate is high and reactive to rainwater input, although the recharge signal is diffuse when snow melt occur.

The Low Recharge period is characterized by an aquifer stock functioning. Water stored in micro fractures during previous winter, drain out to supply spring aquifer base flow. Recharge is low, due to high evapotranspiration component, and destabilisation rate decreases with time.

7 WEAKENING MODEL APPROACH

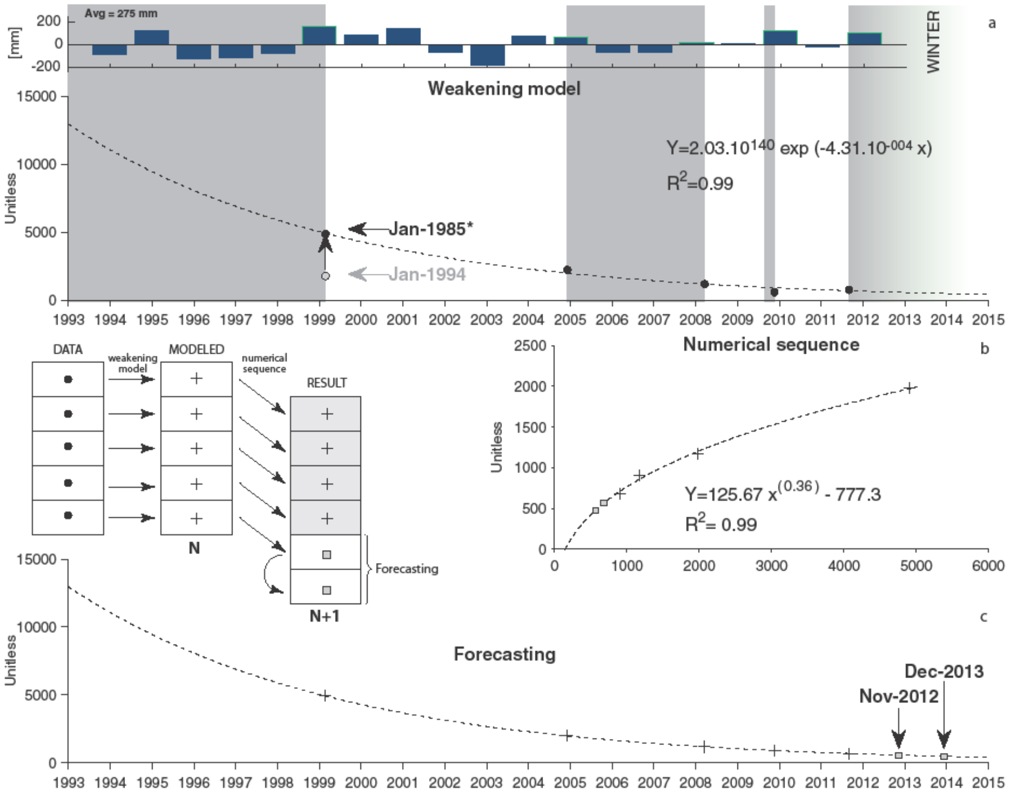


Figure 4: Weakening model and forecasting analysis with (a) accumulated detrended displacement for consistent displacement period vs. time associated with weakening model, (b) accumulated detrended displacement numerical sequence and (c) forecasting of the two next possible dates of destabilisation behaviour change.

The aim of this section is to propose a weakening modelling approach based on the conceptual model build previously. According to precedent analysis, detrended displacement is considered as the landslide response to groundwater hydraulic stress during the hydrological cycle. For each period of consistent behaviour of displacement identified in Figure 1e, detrended displacement was cumulated and was plotted relatively to upper time boundary of the period in Figure 4a. It corresponds to the hydraulic stress amount cumulated by the Séchilienne unstable slope until an irreversible strength/cohesion damage threshold is reached in the rock, sufficient to yield to a significant change in the destabilization behaviour. This require stress amount which will be referred as “destabilisation stress threshold” (DST). Displacement monitoring started about January 1994 which has no hydrogeological/mechanical meaning. In order to estimate the accumulated stress for the first identified period, the date of January 1985 was selected as it corresponds historically to the first modern known date for the unstable slope reactivation (Antoine et al., 1987). Average stress from 1994 to 1999 was extrapolated to estimate the missing data period.

Evolution of DST follows an exponential law, showing that it requires less and less stress amount to increase the destabilization rate (Figure 4a). Furthermore, Figure 4a shows that a change of behaviour generally follows a wet winter. Before 2008, not all the wet winters generate a change of behaviour on the contrary to more recent years. This demonstrates that the Séchilienne unstable slope is more and more sensitive to hydraulic stress. DST time evolution follows a softening/weakening model, which involves that stress is accumulated over a period until a rock weakening threshold inducing a worsening of the destabilisation rate behaviour. Next threshold is lower as well as the precedent, due to decrease of rock tolerance relatively to deformation. These permanent changes occur mainly after a high hydraulic stress period in the form of wet winters (Figure 4a).

An attempt of forecasting the next change of displacement behaviour rate was undertaken. Indeed, DST numerical sequence follows a power law which allows estimating recursively the two next DST values (Figure 4b). The weakening exponential law, established previously, was then used to estimate the date of occurrence of possible change of behaviour matching with the predicted accumulated stress.

The forecasting model assumes a similar and constant recharge background for each period. This model can be used with forecasting rainfall data in order to give indications of future occurrence of behaviour change, which can be linked with a possible rupture threshold.

8 CONCLUSION

Displacement time series can be decomposed into trend and detrended signal. Seasonal variations of detrended displacement are interpreted as the response to groundwater fluctuations (trigger). The Séchilienne unstable slope trend is the result of a degradation of rock mechanical properties. As a consequence, since a few years, the unstable slope becomes more sensitive/reactive to short term events, and seasonal variations are less marked. Evolution in destabilisation behaviour was quantified, and follows a weakening/softening model. A forecasting attempt was undertaken, in order to give indications of the future evolution.

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