C. Bertrand, A. Vallet, and J. Mudry

Abstract

Water chemistry is a very fine signal which allows fine location in time and space of the arrival of infiltration water inducing mechanical instability pulses of the landslide. This tool is designed to understand the complex relationship between chemical weathering, hydromechanical changes and weakening/motion of the unstable rock slope. For this purpose, a hydrogeochemical groundwater monitoring has been established since 2010 on the site of Séchilienne (France). Electrical conductivity is representative of the chemical signal generated by the degradation of the massif. The continuous measurement of this parameter is relevant to the site of Séchilienne and can replace chemical monitoring. The benefit of acquiring this data is threefold: real-time measurements, with a short time step, and inexpensive implementation work, enabling to use it as a tool for risk management.

Keywords

Groundwater monitoring • Electrical conductivity • Water chemistry • Risk management

383.1 Introduction

Water chemistry is a very acute signal which allows fine location in time and space of the arrival of infiltration water inducing mechanical instability pulses of the landslide. Chemical measurements have been performed on several unstable slopes. For example, Binet (2006), Binet et al. (2009) showed that the measurement of sulfate concentrations allowed locating in time and space the arrival of infiltration water inducing mechanical instability pulses of the La Clapière landslide (Southern Alps). In this case, the measurement of sulfate concentrations therefore meets the criteria of an observable in a measurement observatory. Nevertheless, there arises the problem of continuous acquisition of this parameter or any other chemical parameter correlated to the mechanisms that control the gravitational movements. Indeed, at present, there is no device that allows a continuous acquisition of chemical parameters, with good selectivity and good resolution. On the other side, it is possible to make indirect measurements, which is that of electrical conductivity of water, easily measured continuously. Indeed, the electrical conductivity is related to mineralization of water, above all major elements. It is necessary to correlate electrical conductivity with the major ion concentrations. If we do not currently have a sufficient chronicle of physical-chemical data at La Clapière (conductivity, temperature, pH and major ion concentrations) this is not the case for Séchilienne (Northern Alps) where all these parameters are monitored continuously for electrical conductivity, and measured with a 4-day time step for chemistry since 2010. In this context, it is proposed to define chemical observables that meet this goal by using chronicles of physical-chemical data in three points of the recharge area. The aim is to better understand the role of chemical weathering of the rock and its effects, and to use this alteration as a marker of unstable slope destabilization.

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383.2 Background and Method

383.2.1 Network Monitoring and Hydrochemical Survey

The selection of the monitoring network is based on a tracer test conducted in 2002 by the University of Franche-Comté. Despite the field constraints (strongly anthropized catchment area to the East of the instability, and lack of active springs on the unstable slope), two points were identified. They seem to better frame the flow mechanisms of the Séchilienne's slope aquifer, which hydrodynamic behavior influences destabilization (Fig. 383.1).

These are Fonafrey spring (FON) and a water outlet issuing from a fissure in the survey gallery (G710) for which instrumentation was implemented (Vallet 2012). The other outlets are monitored periodically, with a three-month sampling rhythm. An autosampler (major cations and anions), a OTT probe (temperature, pressure, conductivity), a weir-gauge (flow) were installed in each of these three points. The measurements are made on short time-steps (4 days for the water sampler, 5–30 min for probes), that can be modified to fit the aquifer recharge conditions. At each field campaign (every 3 months), a sampling of all springs is performed, and water chemistry is analyzed. The measured parameters are temperature, electrical conductivity, pH and major cations and anions. During these campaigns, bicarbonate ions are also analyzed in the laboratory within 48 h after water samples collection. The specific electrical conductivity measurements, carried out on the three points, are used to check the validity of the continuous measurements, and to recalibrate them if needed. The displacement of the unstable slope is also monitored by measurement stations based on different technologies (gauges, radar, infrared, inclinometers and GPS). These stations are located throughout the slope, and data collection is continuous.

383.3 Results

383.3.1 Relationship Chemistry-Electrical Conductivity

Electrical conductivity reflects water mineralization. A multiple linear regression was performed to determine the major ions that contribute mostly to the water mineralization, and then to changes in the electrical conductivity. In the case of the G710, electrical conductivity is correlated with SO_4 (0.844), Ca (0.731) and Mg 0.709). Temporal variations in electrical conductivity clearly represent the concentrations of sulfates. The multiple linear regression was performed with the chemical data of the 15-point campaigns, spread over 3 years. The coefficients of determination are significant for sulfate ($R^2 = 0.712$) and to a lesser extent for calcium ($R^2 = 0.534$) and magnesium ($R^2 = 0.503$).

383.3.2 Relationship Chemistry-Precipitations

Figure 383.2 shows sulfate concentrations *versus* time, in G710 and FON waters. In this graph, the effective rainfall is also represented as a function of time. The available soil water storage capacity used for calculating effective rainfall is 105 mm (Vallet et al. 2014).

Sulfate concentrations vary seasonally. Concentrations decrease in the rainy season and increases during the dry season (e.g. April–August 2011). This trend is more pronounced for sulfate concentrations resulting from FON. FON drains rapidly water circulating in fault zones. The medium is very reactive, and chemistry is influenced by dilution (high water period) and water-rock interaction (low water period). The unstable slope in turn is recharged by a large area, although the contribution of remote flows seems minor compared to local infiltration. The G710 drains a rapid

Fig. 383.1 Site map and monitoring network: *green circle* continuous monitoring: *black circle*: ponctual monitoring
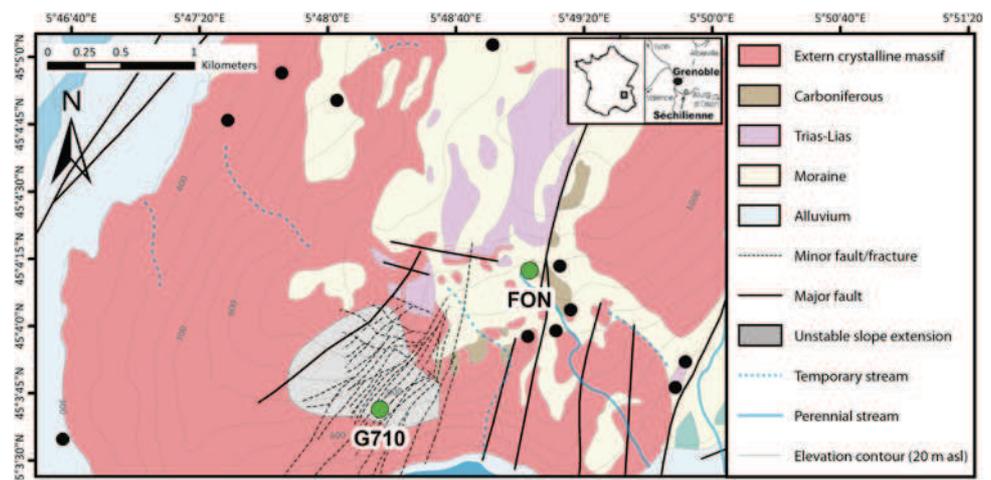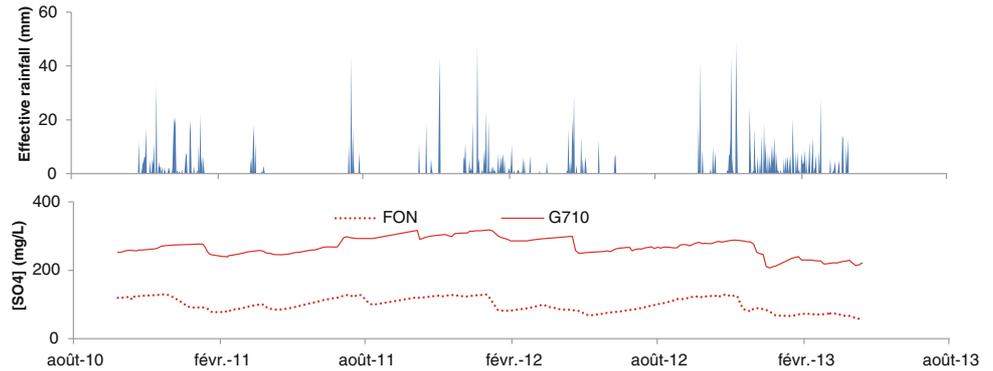
Fig. 383.2 Effective rainfall and seasonal variations in sulfate concentrations (mg/l) from gallery G710 and FON waters

water flow through fault zones (Vallet 2012; Bertrand et al. 2013). In this area, sulfate concentration can be explained by the groundwater flowing in widely open and transmissive with constant opening and closing of fissures, which modify water-rock interactions. Water chemistry is characterized by a more or less rapid circulation, explaining the seasonal variations and the water-rock interaction with a destructured environment, explaining the increasing concentration trend of chemical elements.

383.3.3   Relationship Chemistry-Degradation of the Massif

If sulfate concentrations measured at FON are influenced by recharge, and the concentrations of the same ion are increasingly influenced by the water-rock interaction in the output point in G710. Then the difference between both signals reflects the influence of rock weathering only.

The displacement signal is correlated to the sulfate signal: each increase in displacement corresponds to an increase in sulfate concentration, which follows a synchronous lowering of both parameters (Fig. 383.3).

During the low activity period of the massif, sulfates decrease with time. During the reactivation of the massif, sulfate concentrations increase, and then decrease again. These sulfate concentration changes are explained by their origin, namely the alteration of pyrite mineral that oxidizes in the atmospheric redox conditions. The oxidation of pyrite

creates a "protective" surface which slows down alteration, resulting in a decrease in sulfate concentrations in water at constant pyrite surface. Upon reactivation of the movement, two phenomena may occur: (i) the movement creates new fissures in the massif, providing new surfaces for pyrite alteration; (ii) the movement creates crushed zones containing oxidized pyrite which shatter into smaller minerals but featuring fresh surfaces to weathering.

383.4   Conductivity as Reliable Observable Data of Unstable Slope

Electrical conductivity measured in the gallery G710 is correlated with calcium, magnesium and sulfate. The temporal variations of these ion concentrations are dependent on two main factors: (i) water circulation in permeable media, that promotes direct infiltration and chemical water–rock interaction; (ii) degradation of the unstable slope. Nevertheless, there arises the problem of continuous acquisition of this parameter, or any other chemical parameter correlated to the mechanisms that control the gravity movements. Indeed, at present, there is no device that allows a continuous acquisition with good selectivity and good resolution of chemical parameters. By against, it is possible to make an indirect measurement, which is that of the electrical conductivity of water, easily measured on a continuous base. Indeed, the electrical conductivity is correlated to major element mineralization. Figure 383.4 shows the temporal

Fig. 383.3 Difference in the measured sulfate concentrations in G710, and FON (G710-FON: *red curve*). Displacement measured at extensometer A13 (*black curve*)
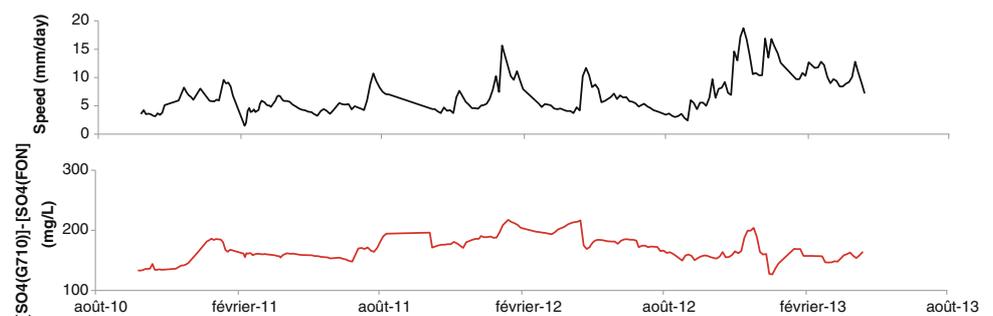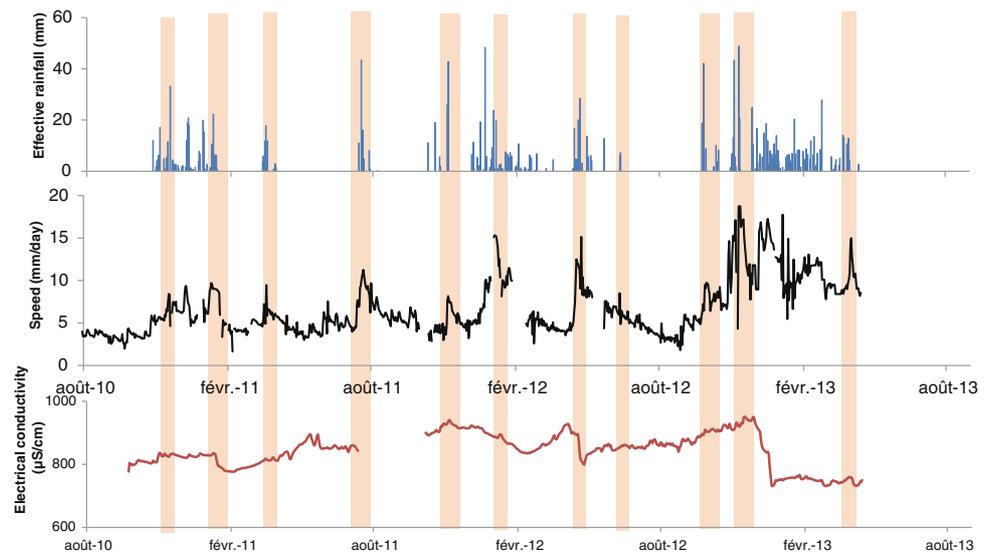
Fig. 383.4 Temporal variations of effective rainfall, electrical conductivity measured in the gallery and displacement measured by extensometer A13

variation of the measured electrical conductivity in gallery G710, and simultaneously the time variation of displacement measured by the extensometer A13. The synchronous effective rainfall, conductivity and displacement peaks are distinguished by the red areas (Fig. 383.4).

The conductivity and displacement curves display the same shape, namely an increase in conductivity during an unstable slope event, and a decrease when the slope is not reactive. The maximum conductivity peaks and maximum displacement peaks are not synchronous, the latter being always subsequent. The lack of electrical conductivity data for the period July–October 2012 cannot enable estimating a reliably delta. The delta between other peaks range between 16 and 25 days during the period September–January 2010–April 2012, and between 4 and 8 days beyond this period. This decrease in delta is due to the fact that from October 2012, the reactivity of the unstable slope accelerated to a climax in December 7, 2012. This behavior results in a sharp increase in the electrical conductivity, reaching a value of 945 μS/cm in November 26, 2012, which is the highest value of the recording from September 2010, with a 11-day shift between both signals.

Thereafter, the conductivity signal stabilizes around an average value of 730 μS/cm, which represents by against the lowest value recorded since monitoring began. This can be explained by the fact that the strong displacement activity in December 2012 has sufficiently damaged the unstable slope to change the hydrodynamic conditions of the environment; it's as if the medium was more interconnected, thus increasing the drainage around the faulted network surrounding the gallery point. Unfortunately we have no flow measurements which could confirm this hypothesis.

383.5 Conclusion

Water chemistry is a very acute signal which allows location in time and space of the arrival of infiltration water inducing mechanical instability pulses of the landslide.

Chemical monitoring implemented in Séchilienne allowed to connect chemical signal, including sulfate concentrations, to deformation. The measured conductivity is mainly explained by sulfate concentration.

Nevertheless, there arises the problem of continuous acquisition of this parameter or any other chemical parameter correlated to the mechanisms that lead gravitational movements. Indeed, at present, there is no device allowing a continuous acquisition of chemical parameters with good resolution.

The electrical conductivity is representative of the chemical signal generated by the degradation of the massif. The continuous acquisition of this parameter is relevant to the site of Séchilienne and can replace chemical monitoring. The benefit of acquiring this data is threefold: (i) real-time measurements, with a short time step; (ii) inexpensive implementation work; (iii) enabling to use it as a tool for risk management.

In the framework of the Unstable Slope Movement Observatory (OMIV), Chrono-Environment pursues acquiring long-term field measurements in the Séchilienne site.

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