Experimental analysis of groundwater flow through a landslide slip surface using natural and artificial water chemical tracers

Stephane Binet,1* Hervé Jomard,2 Thomas Lebourg,2 Yves Guglielmi,2 Emmanuel Tric,2 Catherine Bertrand1 and Jacques Mudry1

1 University of Franche-Comté, Geosciences, Besançon, France
2 University of Nice Sophia-Antipolis, Geosciences, Azur, Nice, France

Abstract:
Artificial and natural tracer tests combined with high accurate electronic distancemeter measurements are conducted on a small landslide with a well known slip surface geometry. Outflow yields and chemical contents are monitored for all the experiment duration and they analyzed to estimate the slip surface hydraulic parameters. The main result is that the slip surface acts as a drain for groundwater flows that evacuates interstitial pressures in the slope and brings the sliding mass to be more stable one. Copyright © 2007 John Wiley & Sons, Ltd.

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INTRODUCTION
Rainfall is one landslide triggering factor (Keefer et al., 1987). The water induces movements for two main reasons: (i) infiltration increases water pore pressure on the slip surface and remarkably decreasing shear strengths of the landslide mass (Tsao et al., 2005); (ii) water creates an increase of weight on the slope and destabilizes the mass by loading (Brunsden, 1999). However, during the movement, the slip surface evolution creates a new distribution of fluid pressure that can modify the movement (Cornet et al., 2003) linked with a hydromechanical effect.

Thus, to increase the stability of a landslide mass, drainage wells have been widely used to drain groundwater, but effective drainage needs a good understanding of the slope hydrogeology (Bonzanigo et al., 2001). Water from the entire slope can flow in the sliding mass and can increase the complexity of the hydromechanical coupling, with for example artesian pressure under the instable mass (Jiao and Malone, 2000). At the slope scale, the presence of slip surfaces induces a heterogeneity, where mechanical and hydrogeological properties are modified, that could modify fluid flow (Eberhardt et al., 2005). The slip zone can create an enhanced hydraulic conductivity along fracture zones and/or create a gouge forming a relatively impervious zone which prevents perpendicular flows (Bonzanigo et al., 2001). The hydrogeological context is an important one to discuss the landslide hazard.

In this aim, hydrogeochemical methods, well adapted to moving zones, are developed (Guglielmi et al., 2000). This paper proposes an experimental analysis of in situ hydromechanical monitoring. Groundwater flows are characterized by hydrogeochemical methods. The surface deformation is recorded using a high sensibility geode-
netic network. The main question is about the influence of a slip surface on flow and the possible consequences for slope stability. Thus, a multidisciplinary study is performed coupling geo-electrical survey, natural tracer methods and topometric time measurements to locate the three-dimensional (3D) sliding surface (Lebourg et al., 2005). A water injection about 40 m$^3$ in 5 h is realized through the upper slip surfaces, with artificial and natural tracer measurements. Three objectives are fixed: (i) to estimate the hydraulic gradient with geo-electrical survey and tracer tests, (ii) to quantify the hydraulic properties of the slip surface and matrix with back-calculation from tracer tests, and (iii) to estimate the hydromechanical behaviour of the slip surface having experienced an injection, using topometric measurements during the injection.

DESCRIPTION OF THE SITE
Location
The La Clapière landslide is a large unstable slope, located in the south-eastern French Alps, about 80 km north of Nice city. This landslide, which mobilizes a huge volume ($55 \times 10^6$ m$^3$) of metamorphic bedrock (Follacci, 1999) is developed on the north side of the Tinée valley and affects a mountain that rises to 3000 m, occurring between 1100 and 1800 m of altitude. A large
rupture has been observed since the beginning of the last century. The ‘La Clapière’ slope itself is affected by a lot of tectonic discontinuities. The major fractures are a subvertical N20 intersecting the whole slope far away from the active landslide and limiting several parallels, a few hundred metres wide. The displacements measured by the monitoring system have also a N20 orientation. Thus it can be suggested that the fault plays the role of ‘guide’ localizing landslide deformations and the water drainage (Lebourg et al., 2005). Near the foot of this unstable mass, where the N20 draining faults crop out, a more active superficial landslide occurs in a homogeneous material (Figure 1).

**Geometry of the superficial landslide**

The foot of the landslide is a very active area, where a rotational landslide is taking place in fluvioglacial deposits of heterogeneous blocks on top of the gneiss. This zone is structured by north–south faults, which are a local deviation of the N20 fault, driving the landslide evolution (Figure 1). The superficial rupture has been observed since 1997. Since 2000 the movements have

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Figure 1. Geomorphological context of: (1) the La Clapiere slope. Reprinted from *Journal of Hydrology*, 291, Cappa F, Guglielmi Y, Soukatchoff VM, Madry J, Bertrand C and Charmolle A, Hydromechanical modeling of a large moving rock slope inferred from slope levelling coupled to spring long-term hydrochemical monitoring: example of the La Clapiere landslide (Southern Alps, France), 67–90, Copyright (2004), with permission from Elsevier (2) detail of the foot of the slope

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Figure 2. Activity during the years 2004: identification of the slip surface. (A) Location of the slip surface, and displacement, measured with a tacheometer in the (XY) cross-section, (B) geophysical cross-section at $t = 0$. 

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become more continuous. Scarps and trenches, around the rotational landslide, prove a toppling of the sector including a sliding mass in the central part (Figure 1).

Five perennial springs are located in this area which importantly drain deep flow, at the slope scale, from the faults (Guglielmi et al., 2000) and which diverge in the fluvio-glacial deposits which have higher permeability.

Activity

A geodetic network is installed, around the superficial landslide, in order to complete the official network of the Ministry of Equipment, that monitors the overall landslide activity. A total station composed of an electro-optical laser distance-metre and an electro-theodolite (LEICA TDA 5005) measure the position of reflectors located in the moving area (Figure 2A). After corrections of the signal (detailed in the section on Methods), the measurement accuracy is half a centimetre for 1 year of monitoring. The 2003 surface displacements enable to reconstruct the slip surface. The interpretation of spatial repartition of the slip surfaces in the map (Figure 2A) is realized, according to the scarp deepening observations, and surface measured displacements, assumed as parallel to displacements on the slip surface in depth. In Figure 2, the optical target P6, P3 and P4 reveal the same displacement evolution. Indeed the targets are located in the same sliding mass. The P5 and P7 target displacements monitor the upper sliding mass. Between these groups, a discontinuity is necessary to explain the movement heterogeneity and can be interpreted as a slip surface. Three slip surfaces, fitting together, are identified in the area. Out of the sliding mass, the target position evolution (P10 and P8) records an opening of fractures without elevation decrease, interpreted like trench apertures. The horizontal displacement is greater in the upper part (P3, P4) compared to P2, and suggest a growing upward evolution of the landslide from the top of the slope to the bottom, with the upper slip surface cutting over the lower one.

The geo-electrical cross-section (Figure 2C), presents highly resistive superficial zones that correlate exactly with the sliding mass defined with the surface deformation and the geomorphologic structures (Jomard et al., 2007). In the upper part, a fourth slip surface is suggested by geo-electrical measurements.

METHODS

The slip surfaces are well defined and spatially located. The methodology presented in this paper is oriented towards the characterization of the hydrogeological behaviour of these slip surfaces. On this simple object, ground-water interpretations are validated from geo-electrical and tracer data correlation. The landslide movements, during the injection of water in a slip surface, are monitored with a 0.1 mm accuracy and a 15 min frequency.

Figure 3. Natural tracer variability (2003 hydrological cycle)

Protocol of water injection

About 2.2 l s⁻¹ of water are injected (Q inj) in the upper part of the sliding surface (Figure 4) during 5 h. An artificial tracer (fluorescein) is added to the water in the first 15 min of the experiments.

Time measurements are realized at the spring S15 that drains the zone. Yield, chemical content and fluorescent tracer content are measured every 15 min.

High accurate geodetic monitoring, during water injection

During injection, the tacheometer TDA 5005 records, with a 15 min frequency measurement, the target evolution in the landslide, which aims to observe the reaction induced by the water injection. The data acquisition is similar to the protocol defined by Gunzburger et al. (2005). After the current installation procedure imposed by the constructor (Leica), the position (distance, horizontal and vertical angles) of targets in the moving mass and of reference targets are measured, with four successive iterations.

Data corrections applied to reduce the error range are detailed in Gunzburger et al. (2005). For distance measurements about 150 m, the following corrections are chosen. (i) The internal parameters by conducting both before and after 180° simultaneous rotations of the horizontal and the vertical axes. (ii) External errors are primarily due to the aerial path of the laser beam as its propagation is being influenced by atmospheric conditions which are not homogeneous during the injection. According to the manufacturer’s instructions, the corrected distance D'p is:

\[
D'p = Dp^*(1 + \frac{\alpha}{10^2})
\]

(1)

Where

\[
\alpha = 283.04 - (0.29195p^{-1} + 4.126h^{-1} - 10^4)
\]
and

\[ x = \frac{7.5T}{237.3 + T} + 0.7857 \cdot Dp \]

is the measured distance, \( p \) the air pressure (in mbar), \( T \) the temperature (in °C) and \( h \) the relative air moisture (in %). (iii) The average on four successive measurements decreases the random errors.

**Tracer test**

First, with natural tracing from the 2003 hydrogeological cycle, the natural spatial and temporal variability of the chemical water content is analysed to define the different natural flow way or water type in this slope (Mudry et al., 1994; Binet et al., 2002).

Secondly, water injected has a contrasted water chemical content compared to the chemical content of the spring (Table I). Water rock or soil interactions are possible with injected water. However, no soil is observed in the injected area and no natural nitrates are observed during the experiment, so nitrate breakthrough is the reference. Sulfate and conductivity can increase during underground flow. Both curves will always be compared to nitrate curves to estimate the extent of these reactions.

Thus, injection will induce a dilution at the spring. This dilution enables to estimate the flow velocity within the sliding surface. To determine when a steady state between flow input and output is reached, a chemograph separation is realized. The spring yield \( Q_s \) can be decomposed as follows:

\[ Q_s = Q_n + Q_i \]  

where \( Q_n \) is the yield of natural water from the aquifer and \( Q_i \), the yield (in m\(^3\) s\(^{-1}\)) of injected water arriving to the spring.

Each component has a defined chemical content \( C_n \) for the spring water, \( C_i \) for injected water during the injection, \( C_n \) for aquifer water. The flux of the spring is expressed by Equation (3):

\[ Q_s \cdot C_s = Q_n \cdot C_n + Q_i \cdot C_i \]  

Computing Equations (2) and (3), \( Q_i \) of injected water arriving to the spring can be expressed as Equation (4) (Mudry, 1987; Massei et al., 2003):

\[ Q_i = \frac{Q_s \cdot (C_n - C_i)}{(C_i - C_n)} \]  

Equation (4) will enable to define the time to reach a steady state and the part of water from aquifer (\( Q_n \)) opposed to water from injection outflowing at the spring (\( Q_i \)). During the steady state, the injected yield \( Q_m \) minus the yield of water from injection outflowing at the spring (\( Q_i \)) will provide the yield of injected water that is not drained by the spring (\( Q_m \)).

Artificial tracers mark the first water molecules arriving at the spring. The interpretation of the breakthrough curves give information about particular velocity \( (V_p) \)

**Estimations of indirect hydrodynamic parameters**

For the estimation, the media is considered as a multi-permeable equivalent porous media with the Darcy law (Equation (5)) and porosity estimation (Equation (6)).

\[ V_d = K i \]  

where \( V_d \) is Darcy velocity (in m s\(^{-1}\)), \( K \) is Darcy’s hydraulic conductivity (in m s\(^{-1}\)), and \( i \) the hydraulic gradient. By definition: \( V_d = Q/a \) where \( Q \) is the yield (in m\(^3\) s\(^{-1}\)) at the spring and \( a \) the flow section of the spring (in m\(^2\)).

\[ \Phi = \frac{V_d}{V_p} \]  

where \( \Phi \) is the porosity (in %), and \( V_p \) (in m s\(^{-1}\)) the velocity of the artificial tracer determined from the time measurements at the inflection point on the rising limb of the breakout curves.

Darcy law (Equation (5)) and, porosity estimation with Equation (6) from data of the tracer test are used to estimate global parameters of the entire slope (Marsily, 1981; Castany, 1982; Gehlin and Hellstrom, 2003; Nelson et al., 2003). The calculated values give an average trend. In these sub-surface conditions, the slope of the saturated unsaturated limit is considered as the gradient.

Estimation of hydraulic gradient is realized with geological data, according to a strong contrast of electrical resistivities between the saturated/unsaturated limit (Figure 2C). The limit is calibrated with the S15 spring position. The values inferior to 200 ohm m are interpreted like saturated zone and improved with geometric observations.

To validate these methods, data will be compared with hydrogeological work literature data estimated with the tracer method in the same rocks.

**RESULTS**

**Natural spatial variability of the water chemistry**

The space variability of the chemical water content around the superficial landslide is presented in Figure 3. The measurements of magnesium and sulfate (Figure 3) shows presence of two water families, one with low chemical content, for the Tinée river \( (C_i) \) and the spring 20, that correspond to superficial water, one with a high chemical content for the spring draining the landslide \( (C_n) \) that correspond to water from the entire slope (Guglielmi et al., 2000). The time variability of

Table I. Initial content of water before the injection

<table>
<thead>
<tr>
<th>Initial chemical content</th>
<th>Spring ((C_n))</th>
<th>Injected water ((C_i))</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO(_3) (mg l(^{-1}))</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>SO(_4) (mg l(^{-1}))</td>
<td>680</td>
<td>400</td>
</tr>
<tr>
<td>Cond. (µS cm(^{-1}))</td>
<td>1201</td>
<td>378</td>
</tr>
</tbody>
</table>
The variability explanation is the presence of two water types. Between these two clusters, the water of piezometers corresponds to a mixing between these two water types. Thus during flood, the G1 temporary spring is also a mixing between deep and superficial water that proves the connection, during flood, between the deep aquifer and the slip surfaces.

**Outflows after injection**

The injection of artificial tracer had created several new outflows of coloured water in the landslide. Outflows are located on the slip surface, because spatial correlation is perfect between (i) slip surface outcropping and water outflowing and (ii) water sinkhole and counter-scars (Figure 4). The arrival time reveals a quick drainage towards the S15 spring. The water has crossed the landslide in 90 min. Sideways, the flows arrive at the G1 temporal spring 230 min after the injection, displaying a dispersion effect of flows in the slip surface, with a slower velocity of lateral flows.

Around the slip surface a humid area is developing. This zone increases with time to reach 2 m above and below the slip surface. The matrix is not impermeable and a part of the injected water passes in the matrix ($Q_m$). First water arrives from the slip surface, and then the humid area, around the slip surface, increases about 1 m/15 min (Figure 5). The restitution ratio of fluorescent tracer is about 15%, compared to the 60% of restitution ratio for injected water. Like the fluorescent tracer marks the start of the injection, the first litre injected, does not outflow at the spring, but is flowing through the matrix, creating matrix saturation, around the slip surface, and highlighting the relations between the rock matrix and the slip surface. From the 38 m$^3$ injected, 24 m$^3$ outflows through the slip surface. The remaining 14 m$^3$ flows in alluvial deposits, through the matrix. The slip surface drains the water, but a part of the water passes in the matrix. This matrix saturation, around
the slip surface, is observed above the heterogeneity and reveals an interstitial pressure in the landslide with a local water saturation of the material around the heterogeneity.

**Time variations after injection**

The injected water has a contrasted chemical content compared to water of the slope (Table I) that enables a hydrograph separation. Thus conductivity and sulfate are natural water tracers of the water from the slope and nitrate an injected water tracer. Applying Equation (4) the calculated yields of injected water arriving at the spring \( Q_i \) during this artificial flood enables to estimate participation of both water types at the spring. Figure 6 presents the results for each tracer. The correlation between the three tracers is a proof that the water rock interaction can be neglected with a residence time around 10 h. The first reaction of the S15 spring is a yield increase due to head transfer. At time \( t_1 \) (Figure 6), the injected water reaches the natural saturated zone and creates an increase of yield (pressure transfer). Then at time \( t_2 \), the injected water arrived at the S15 spring, through the slip surface, with a velocity \( (V_p) \) and the percentage between natural water discharge \( (Q_n = 0.22 \text{ l s}^{-1}) \) and injected water discharge \( (Q_{inj} = 2.23 \text{ l s}^{-1}) \) becomes constant. Time \( t_3 \) is the end of the steady state and at \( t_4 \) the slip surface is drained.

The environmental tracers enable to calculate, during the pseudo steady-state defined on Figure 6, that the \( 0.55 \text{ l s}^{-1} \) flowing through the S15 spring \( (Q_s) \) are composed about \( 0.22 \text{ l s}^{-1} \) from the injection \( (Q_i) \), and \( 0.33 \text{ l s}^{-1} \) from the mixing with natural slope water \( (Q_n) \) This pseudo-steady state is useful for hydraulic conductivity and porosity estimation of the slip surface.

During this pseudo steady state, on the \( 2.21 \text{ l s}^{-1} \) injected \( (Q_{inj}) \), \( 0.22 \text{ l s}^{-1} \) flow through the slip surface \( (Q_i) \) and \( 2.01 \text{ l s}^{-1} \) flow in the matrix \( (Q_m) \).

At \( t_5 \), the tracer test breakthrough shows a bimodal response (Figure 7), the water from injection outflowing at the spring \( (Q_i) \) must be decomposed in two flow paths. The first arrivals are the flows in the slip surface \( (Q_{i \text{ slip surface}}) \). The second arrivals are correlated in time with tracer arrival in the piezometer 1 (Figure 4) and can be attributed to flows in the matrix \( (Q_{m}) \), with a part flowing through the alluviums \( (Q_a) \) and the other flowing at the spring \( (Q_{matrix} = Q_{m} - Q_a) \). The fluorescein restitution shows a mix of water from the fracture and from the matrix and enables to estimate flow velocity in the matrix about \( 5 \times 10^{-3} \text{ m s}^{-1} \) and in the slip surface about \( 3 \times 10^{-3} \text{ m s}^{-1} \). The hydrograph (Figure 6) gives an estimation of \( Q_m - Q_i \).

**Estimation of hydraulic parameters**

The obtained results enable to propose a conceptual flow model (Figure 8) with several flow ways of injecting water through the slip surfaces and matrix. Yields, estimated using a natural tracer, are represented in Figure 8B and are used to realize an estimation of hydraulic parameters.

The method used a hydraulic gradient calculation with the geo-electric cross-section. Figure 2C, realized at \( t_3 \) (Figure 6) shows that the 200 Ohm m limit presents a

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Figure 5. Correlation between slip surface and outflows in the cross-section

Figure 6. Hydrograph separation

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Figure 7. Tracer test breakthrough

break when it crosses the slip surface. This observation induces two different hydraulic gradients for flows in the slip surface and in the matrix where the hydraulic gradient is about 32% (±5%) in the sliding mass and about 45% (±5%) in the matrix. During the floods, to connect the slip surface with the slope aquifer, as is observed with the natural tracer (Figure 3), the hydraulic gradient must equal 45% and validate the geo-electric data.

Using flow velocity in the matrix and in the slip surface and applying Equations (5) and (6), the hydrogeological parameters are estimated with a 45% gradient in the matrix and 33% in the slip area, as presented in Figure 8B. The section of spring flow (a) is 1-2 m² (±0-1 m²) that corresponds to the humid area observed around the spring S15. The results are presented in Table II.

This calculation gives an evolution of hydraulic conductivity about a factor of 50 and a porosity increase about 6%.

HYDRO-MECHANICAL BEHAVIOR OF THE SLIP SURFACE

Implication for methodology

In such a moving zone, local in situ measurements are difficult to perform, because of the durability of boreholes in a moving zone. In the unstable fractured slope, the local hydraulic gradient is not representative of the spring flows, because of the heterogeneity of the hydraulic conductivity fields (Guimera and Carrera, 2000). The geo-electrical method, tested to estimate a range of contingent hydraulic conductivity, gives a spatial evolution of the hydraulic gradient and is coherent with literature data on this type of geo-material ranging between 1 and 6 × 10⁻² m s⁻¹ for the matrix (Guimera and Carrera, 2000; Guglielmi et al., 2005).

Estimation of the hydraulic conductivity of the slip surface

The tracer tests demonstrate the existence of two flow types, one in the slip surface and one in the matrix (Figure 5). The hydraulic conductivity of the slip surface is about 3 × 10⁻⁴ m s⁻¹ (±2 × 10⁻⁴ with head gradient error range) and the matrix hydraulic conductivity is estimated about 1 × 10⁻⁵ m s⁻¹ (±2 × 10⁻⁶). The porosity has increased about 6% with the slip movement. The slip surfaces are drains. The superficial water after a rainfall flows through the moving mass, and is evacuated by the slip surface. After an important flood at the massif scale, the natural water head increases and can connect the slip surface.

The presence of perched water in the slip surface during the flood, observed with the presence of the G1 temporary springs, can be explained by the hydraulic conductivity contrast, with a ratio about 50. The flows are drained by the heterogeneity that creates a saturated zone around the slip surface, including a part of the matrix that is not impermeable.

However, the matrix permeability should be over estimated, because the toppling records with the tachometer
(Figure 2B) out of the sliding mass reveal a decompressed zone by toppling that modifies the matrix hydraulic parameters with creation of drains for flows.

**Implication for stability**

Infiltration, directly in the slip surface does not induce a movement in this case. The optical target do not record a significant (>0.2 mm) movement during the tracer test injection (Figure 7), according to the 38 m³ injected on a 500 m² surface. The draining behaviour of the fractures evacuates water sufficiently fast to avoid a high pressure increase in the landslide.

A local diffuse infiltration in the sliding area can induce an increase of weight by water infiltration in the matrix and can induce movement. At the same time, water in the slip surface can decrease shear parameters. For a superficial landslide, the volume of water infiltrated in the landslide cannot be important, due to the relatively limited surface about 500 m².

The last scenario is an infiltration from the upper moving area. Water can induce under pressure in the slip surface that can reactivate this landslide. In this case, the volume of water is clearly bigger, because this zone drains an important part of the slope from 1100 m to 2700 m (Guglielmi et al., 2002). The anisotropic hydraulic conductivity of the slip surface can confine water and increase pressure under the slope.

All the presented data here insist on the importance of the regional context to make a good risk assessment.

**CONCLUSION**

Even if the slip surface is developing in the same material, it plays a role of discontinuity for groundwater flows, with porosity increasing about 6% and permeability about a ratio 50. During injection, a matrix effect is observed around the slip surface, with a saturation of the matrix. The slip surface drains the flows and diffuses it into the 3D slip surface geometry with a lower velocity.
During a flood, the gradient of the slope aquifer, usually around 45%, increases and is connected with the slip surface that brings water under the landslide. However, the slip surface plays a drain role. It evacuated rapidly the interstitial pressures increase the stability of the slope.

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