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► **To cite this version:**

Joshua Ducasse, Catherine Bertrand, Olivier Maillard, Delphine Charpentier, Jean-Pierre Sizun, et al.. HYDROGEOLOGICAL SIMULATIONS OF A DEEP-SEATED LANDSLIDE: IMPLICATIONS FOR HAZARD MITIGATION. XIVth International Symposium on Landslides, Jul 2024, Chambéry (France), France. <hal-04938130>

HAL Id: hal-04938130

<https://hal.science/hal-04938130v1>

Submitted on 10 Feb 2025

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HYDROGEOLOGICAL SIMULATIONS OF A DEEP-SEATED LANDSLIDE: IMPLICATIONS FOR HAZARD MITIGATION

Joshua Ducasse¹, Catherine Bertrand¹, Olivier Maillard¹, Delphine Charpentier¹, Jean-Pierre Sizun¹, Myriam Lajaunie², Joachim Rimpôt³, Céleste Broucke, Jean-Philippe Malet^{3,5}

¹ University of Franche-Comté, CNRS, UMR 6249, Laboratoire Chrono-Environnement, Besançon, France

² Service Hydrographique et Océanographique de la Marine (SHOM), Brest, France

³ Institut Terre et Environnement de Strasbourg (ITES), CNRS UMR 7063, University of Strasbourg, Strasbourg, France

⁴ Institut de Physique du Globe de Paris (IPGP), CNRS UMR 7154, Université Paris Cité, Paris, France

⁵ École et Observatoire des Sciences de la Terre (EOST), CNRS UAR 830, University of Strasbourg, Strasbourg, France

SUMMARY: Following a rockslide triggered in 2018, a slow-moving landslide has been reactivated affecting the Viella municipality (Hautes-Pyrénées, Southwest France). The slope is now sliding inexorably down to the valley; several landslide kinematic sub-units characterized by several ground motion have damaged infrastructures and buildings. In the months following this reactivation, surface velocities of up to one centimeter per day were observed, endangering some buildings and necessitating the implementation of mitigation measures. To assess the water circulation and storage in the slope, a three-dimensional geological model was built as a prerequisite of 3D hydrogeological simulations carried out with GeoModeller. The geological model allows for improving the knowledge of the slope internal structures, the position of the bedrock and of the sliding surfaces. Three-dimensional finite element water flow simulations obtained with the FEFLOW (©DHI) model provide an understanding of the functioning of the landslide aquifer. The integrative approach allows proposing a robust hydrogeological model and the establishment of a piezometric map of the site at equilibrium. In the landslide, the piezometry is between 780m and 970m in elevation, and the direction of the groundwater flow is about 340° North. The hydraulic conductivities determined by the model are between 10^{-4} and 10^{-5} m.s⁻¹ in the shallow sub-surface (colluvium), up to 10^{-7} m.s⁻¹ in depth (Devonian's shales). From the calibrated hydrogeological model, various simulations were carried out in order to estimate the impacts of mitigation works on the water storage and circulation. It further helped to simulate the piezometric response of the slope to an extreme flood event at the toe of the landslide. Model simulations showed that the “sealing” or “waterproofing” of a 650m section in the lower part of the Bayet-Badoueil stream would lower the piezometric height under the village up to a maximum of 30 m and reduce the hydraulic load uphill. A decrease of the water table height of 5 m seems achievable and would be sufficient to significantly reduce the sliding motion with the boundary conditions set (zero flux) in these simulations.

Keywords: Slow-moving landslide, Numerical modelling, Hydrogeological model, Drainage scenario

Introduction

Large landslides have a potentially dramatic socio-economic impact. They are a major threat to human life, buildings, infrastructure and the natural environment in most mountainous and hilly regions of the world (Petley, 2012). The mechanisms controlling their dynamics and their triggering are numerous and complex, which lead to a high degree of uncertainty in



behaviour forecasts both spatially (volume involved, location) and temporally (occurrence, dynamics).

The hydromechanical processes that control the reactivation of large landslides are influenced by the evolution of the terrain deformation in space and time and the water circulation and storage in highly heterogeneous material. In the case of an aquifer located on unstable slopes, it is essential to understand its behaviour in order to propose mitigation solutions such as groundwater drainage.

Spatial and temporal variations of water storage in the subsoil are controlled by the structure, internal geometry and petrophysical properties of the aquifer (Maréchal 1998; Cappa et al. 2004; Bogaard et al. 2007, Vallet et al. 2015a). The main hydrogeological methods to infer these properties are single- and cross-borehole hydraulic tests and tracer tests. These classical methods are not always appropriate and their applications are limited, especially if the groundwater-bearing fracture is not close to the borehole (Ellefsen et al., 2002). Recent studies based on indirect, non-intrusive methods, such as hydro-geophysical methods allow identifying water stocks and variations (Perrone et al. 2014; Gance et al. 2016). These methods can also be used to characterize the geometry of the aquifer and identify preferential flow paths (Kukemilks and Wagner, 2021). However, due to the high heterogeneity of landslide media systems, the hydrogeological behaviour can be very complex, and prone to multiple interpretations and /or conceptualizations. Modelling can be used to test several hydrogeological conceptual models (De Filippis et al., 2017) but also for predicting the hydrogeological system behaviour for several water recharge conditions (Pétronici et al., 2019).

The aim of this work is to develop a numerical hydrogeological model of a landslide aquifer by combining geological and geophysical information. The model supports the test of hypotheses on the aquifer functioning and on inferring the impacts of drainage scenarios on the groundwater levels.

I Study site: the Viella landslide (Hautes-Pyrenees).

The municipality of Viella is located on the Hautes-Pyrénées (65) in the Occitanie region (Southwest France). The Viella landslide has experienced a rare combination of triggering factors, with an extreme flood event (2017) which steepened the lower part of a paleo-landslide, followed some months later by a rockslide (March 2018) that loaded the upper part of the paleo-landslide changing the water circulation in the slope. These factors altered the equilibrium line and the groundwater dynamics modifying the stress regime of the slope. The Viella landslide consists of several nested sliding units of varying surface displacement rates (Fig. 1a). The Bayet stream flows over the landslide and divides it into two lobes. The lithological bedrock outcrops above 1000 m a.s.l. to the south of Viella. It is composed of sandy shale and grey-black clay shale (pelites) with limestone facies from the Devonian. The rockslide of February 2018 consists of shales and pelite screes. The landslide material is composed of glacial moraines on which colluvium and highly weathered screes from the successive dismantling of the overlying reliefs have accumulated. The landslide thickness exceeds 71 m in its central part, close to the center of the village. These formations, with their permeability and porosity, support several aquifers: a) the colluvial aquifer, which is located in the morainic and colluvial formations that form the slopes around the village; b) the scree aquifer is located in the Devonian limestone and shale formations as far as the Couret crest, c) the substratum aquifer of the shales and/or Devonian limestones that form the relief of the mountain of Herrère and, finally, 5) the aquifer of the small valley of Badouiel, located in shale debris from the numerous landslides that have occurred in the area.

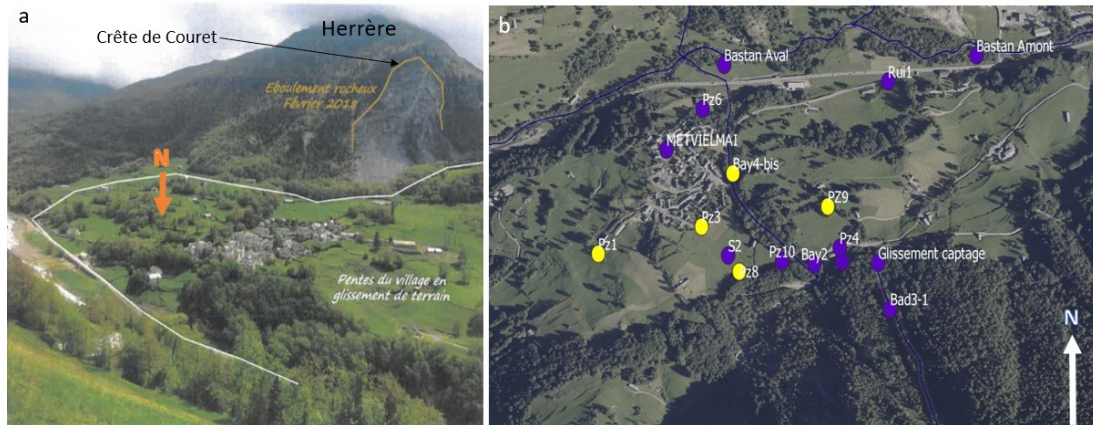


Figure 1: a - View of the Viella landslide (Hautes-Pyrénées); (b) - Location of the hydrogeological sensors, consisting of borehole piezometers with high-frequency groundwater level measurements, electrical conductivity, and water temperature (yellow points), along with the tracing of fluorescein (blue points)

In 2019, the implementation of 16 boreholes of 20 m depth, along with the installation of 7 inclinometers and 9 piezometers, allowed for an investigation of the first 20 m of the moving mass. A network of sensors continuously measuring water level, electrical conductivity, and water temperature (yellow points in fig 1b) was deployed to gather information about the hydrodynamic behavior of the colluvial aquifer and to establish hydraulic connections between surface water (the Bayet/Badouiel streams) and groundwater (the screes aquifer, the colluvial aquifer). Hydrochemistry analyses were conducted at all monitoring points (Fig. 1b) to identify the origin of the water masses. A first hydrogeological conceptual model of the colluvial aquifer was proposed based on the hydrochemistry and hydrodynamic data. Additionally, an artificial tracing was conducted in June 2020 to identify hydraulic connections and the water flow velocities between the surface waters and the groundwater (tracing results showed as blue points in fig 1b). In July 2020, a dense 3D tomography of electrical resistivity and seismic acquisitions were carried out to create several 3D geophysical models in order to image the deep structure of the landslide, from -20m to -120 m (Fig. 2a). This model highlights highly conductive and highly resistant zones within the unstable mass, thereby indicating the presence of several discontinuities and preferential fluid flow pathways (Fig. 2b).

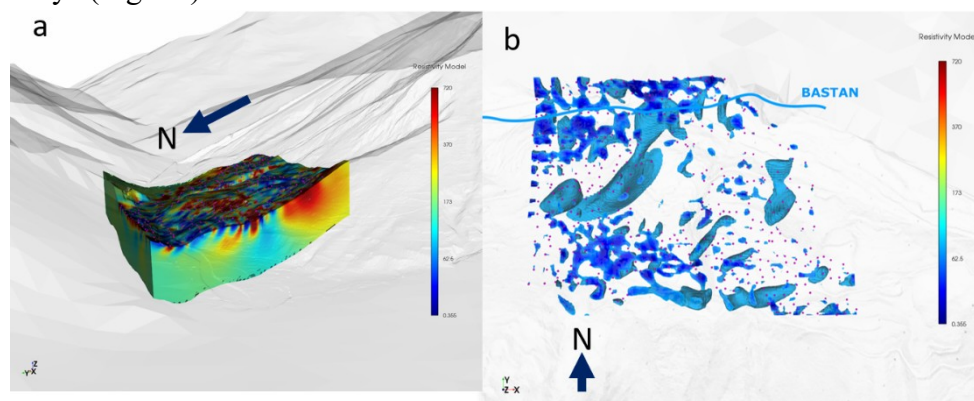


Figure 2: (a) - 3D structure of the landslide with a cube of electrical resistivity values inferred from dense and distributed measurements; (b) - Conductive anomalies seen from above (threshold: resistivity < 120 Ohm.m; small-size anomalies near the surface, large-volume conductive anomalies at depths of 150 to 200 m colluvium).

II 3D geological modeling

A 3D geological model was constructed by integrating the in-situ geological observations (Fig. 3a), the borehole information, and the 3D electrical resistivity and seismic models. The



data integration and modelling were realized with the 3D GeoModeller software (©BRGM-Intrepid Geophysics). The software enables the interpolation of complex geology using geostatistical methods allowing the creation of a robust 3D geometric model (Fig. 3b) based on a Digital Elevation Model (DEM), as well as stratigraphic and structural information (dip, orientation, interface) and field observations (boreholes, cross-sections)

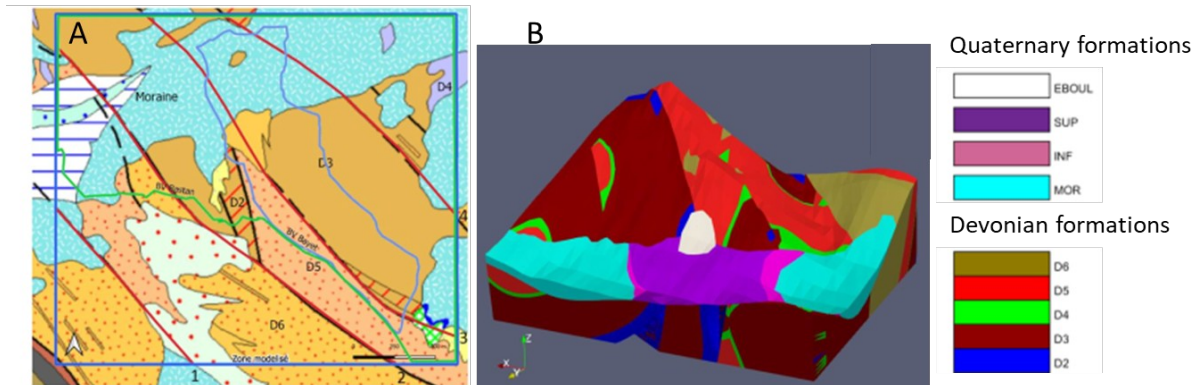


Figure 3 : A - : Location of the material superficial formation on top of the geological map at 1:25.000 scale (©Infoterre -BRGM-) Devonian formations D2 massive limestone (aquifer), D3 Black schist with limestone interlayers (aquifer), D4 detrital calcareous schists (aquifer) D5 black clay pelites((aquitard), D6 Quartzites (aquitard). Quaternary formations: MOR: moraines INF colluvium and scree below the rupture surface SUP: colluvium and scree above the rupture surface, the fracture surface to be represented as the interface between these two units; EBOUL; scree of 2018 landslide. B-: Geological 3D model: Full view of the modeled site.

The geological model provides a 3D reconstruction of the Devonian sedimentary sequence (Fig. 2b). Faults at unconformities cut this sequence. Overlying these formations are the glacial moraines of the Bastan Valley (represented in light blue). The mauve and purple layers are the colluvium and altered scree resulting from ancient landslides that have affected the area. The white mass represents the landslide that occurred in 2018. The volume of moving ground is represented by the purple layer. This area represents a volume of ca. 13 million m³ (13,593,000 m³). The 2018 landslide zone is shown in white. The volume calculated by this model is 201,360 m³.

The model provides a 3D morphological representation of the rupture surface and its location. The simulated rupture surface extends from the 2018 scree to the Bastan, i.e., around 550 m long and 800 m wide. The rupture surface's depth varies from a few meters below the Bayet to a depth of up to 55 m beneath the village before leveling off towards the Bastan River without reaching the moraines at the base of the valley. Structural analysis reveals that rupture interacts with various geological formations within the colluvium.

III 3D hydrogeological modelling

The 3D geological model used a geometric base layer for the hydrogeological modelling carried out with Feeflow (DHI-WASY, 2009). The elevation of the domain ranges from 740 m (western outlet of Bastan) to 1951 m at the summit of Herrère ridge, which forms the northern and southern boundaries of the sector. To the North, an extension has been added beyond the boundaries of the geological model to avoid edge effects in the area. The lateral extent of the study area is bounded by two sub-vertical faults on the east and west sides. The steady-state model for an unconfined aquifer was constructed using a layered destructured approach, with variable-sized mesh volumes and higher resolution within the first 100 m of depth. Resolution is also increased within the geophysical model area to achieve mesh volumes smaller than 10 m³. A final refinement is performed near significant features such as rivers and wells to attain mesh volumes smaller than 1 m³. In this type of model, material



properties are defined for elemental selections. In our approach, we chose to use the geological model to provide the geometry of the elemental selections for formations D2, D3, D4, D5, and to use three threshold values of the electrical resistivity model to define the elemental selections included within the scope of the electrical modeling. The chosen thresholds are - resistivity less than 100 ohm.m⁻¹ - resistivity ranging from 100 to 300 ohm.m⁻¹ - resistivity greater than 300 ohm/m. Finally, the model includes 7 types of materials, with moraine and colluvial formations integrated into the resistivity model discretization.

The model boundary conditions consist of three components. The first component is a first-order boundary condition, known as the Dirichlet type. It is localized at the model's boundary on both sides of the Bastan, covering an approximately ten-meter-wide area that extends through the entire thickness of the model. The second component is a third-order mixed condition, following the Cauchy type, which combines prescribed hydraulic head and flux. This condition is specifically employed for characterizing rivers. The third component is a no-flow condition is applied by default to the remaining edges of the domain.

The water baseline recharge amounts are estimated using meteorological observations from the Luz-Saint-Sauveur measurement point at 2 km with effective rainfall calculated using the OUDIN method (Oudin et al., 2005) for a 30 mm rainfall event. The parameters (permeability *k* and specific storage *Ss* coefficients) and boundary conditions are initially tuned according to natural conditions

A semi-automatic calibration is performed with PEST (automated software for model calibration and uncertainty calculation for numerical models) using the piezometric data from the 9 piezometers in the sector. It enables a large number of iterations by varying parameter sets to make the model converge. The parameter set calibrated (Fig. 4b) is used to simulate the groundwater regime in a steady state, averaged over one hydrological year.

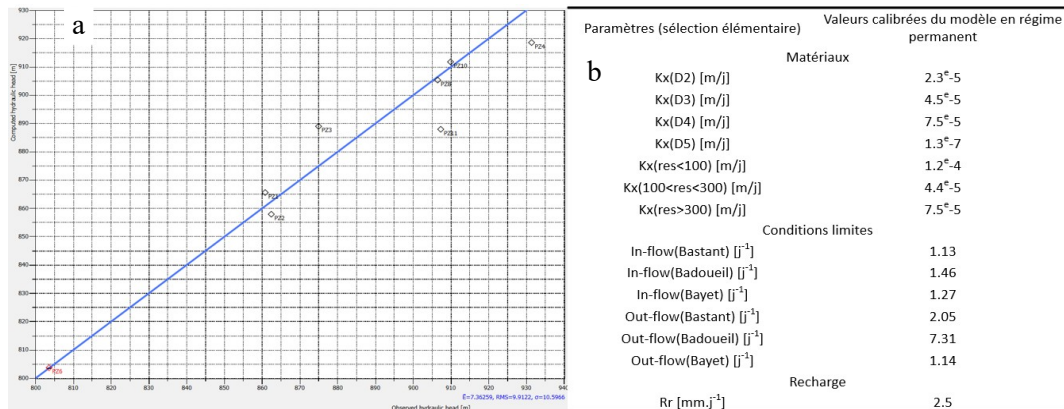


Figure 4: a - Comparison of observed water levels (x-axis) with the water level calculated by the steady-state model (y-axis). b - Optimized parameter values of the steady-state calibrated model.

In the final steady-state model calibration curve (Fig. 4a). The y-axis represents simulated piezometric levels, while the x-axis indicates the observed groundwater table elevation. The blue reference line signifies a perfect match between simulated and observed values.

The optimized hydraulic conductivities determined during calibration are, in both models, on the order of 1e-5 m.s⁻¹ for the Devonian aquifer formations D2, D3, and D4, and 1e-7 m.s⁻¹ for the shale mudstones (D5). The input/output transfer rates of the three rivers have been optimized in the steady-state model without field measurement.

The calibrated model is used to simulate two scenarios:

Scenario #1: Bayet waterproofing simulated in steady-state flow at equilibrium. In this scenario, waterproofing of the Bayet results in a significant reduction in piezometric height at the base of the landslide, of approximately 10 m. Some piezometers, such as PZ1 and PZ2



located to the west of the landslide, record a 10-meter drop in the water level. In the centre of the landslide (PZ10), the potential reduction in the water table height reaches approximately 20 m. Finally, complete waterproofing of the Bayet could lead to a reduction of about 30 m at the piezometer at the foot of the landslide (I8).

Scenario #2: Badoueil waterproofing simulated in steady-state flow at equilibrium. In this scenario, total waterproofing of the Badoueil results in a very significant decrease in piezometric height. All piezometers record a decrease of more than 30 meters, except for PZ6, which also experiences a drop in water level, unlike the previous scenario.

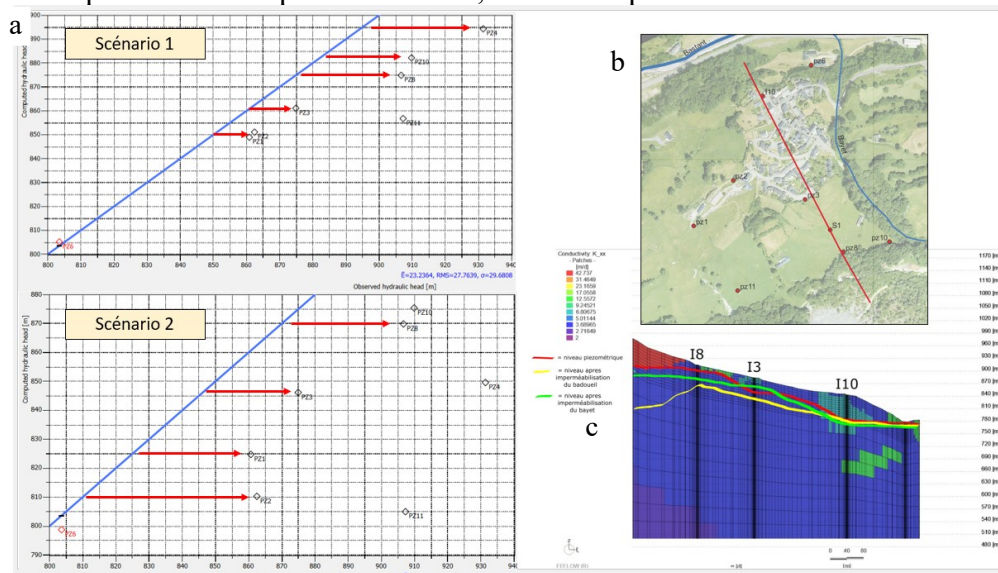


Figure 5: a - Comparison of simulated water levels (y-axis) in scenarios 1 and 2 with the water level calculated by the steady-state model (x-axis). b - Location of the I8-I3-I10 cross-section on orthophotography. c - Representation of the piezometric level in steady-state and in the two scenarios on the I8-I3-I10 cross-section overlying the calibrated hydraulic conductivity of the steady-state model.

It has been possible to test other remedial solutions using pumping systems. In their study, Tacher et al (2005) showed that the displacement intensity of the unstable slope under investigation was significantly reduced by pumping, which was simulated by means of hydrodynamic numerical flow simulations.

Conclusion

The results of this study are promising, and open the door for the using calibrated/validated hydrogeological model to simulate mitigation solutions. However, these models must be based on conceptual hydrogeological model that result from the analysis of multidisciplinary information data (geology, geochemistry, geophysics). They have to be calibrated and validated by means of multi-sensor data (variation of the piezometric level in response to external water inflows, origin of the water masses, and their transit). This approach requires the upstream construction of a 3D geological model, based on complementary geological and geophysical approaches (Loke et al., 2022), which will serve as a mesh for the hydrogeological simulations. Indeed, geometric modelling actively contributes to improving both geological and hydrogeological knowledge by clarifying the relative positions of formations in relation to each other and by highlighting the presence or absence of - potential hydraulic - connections between aquifer levels. The analysis of a large landslide by means of finite element modelling is a very efficient method for studying aspects of natural slope movements (François et al, 2007)

In this study, in order to understand the main causes and mechanisms of the phenomenon and to predict the behaviour of this slope under critical future conditions, it is planned to combine the hydrogeological simulations to a geomechanical model. The numerical simulation of such



problems is particularly convenient for clarifying complex mechanisms governing the movements and slope stability conditions.

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