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Hydrogeological analyses of the Champlas du Col deep-seated landslide (NW Piemonte, Italy)

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Abstract

Mountainous regions, due to their geomorphological features, are particularly prone to ground instabilities. In recent decades, there has been growing recognition of the role of climatic factors, such as heavy rainfall, in the occurrence and movement patterns of landslides in these areas, which are also vulnerable due to the presence of population centers and infrastructure.

Slow-moving landslides, such as complex-type landslides or Deep Seated Gravitational Slope Deformation (DSGSD), which involve large slope volumes, are highly dependent on seasonal rainfall patterns and snowmelt. The Susa Valley (in the NW of the Piedmont Region, Italy) is a clear example in this context. The displacement rates are influenced by changes in groundwater pressure, which are closely associated with net rainfall and snowmelt process. Therefore, the reconstruction of ground instability scenarios includes the development of a hydrogeological analysis aimed at improving the comprehension of climate impacts on water resources and, consequently, slope movements.

As a first step, the collection of piezometers or monitoring mountain springs data, along with the implementation of suitable statistical analyses, enables the detection of groundwater fluctuations. The influence of these parameters on the increase in displacement trends, recorded by in-situ instruments (e.g., inclinometers), is further investigated by correlating the landslide body displacements with seasonal variations in spring water levels and precipitation inputs. Within this framework, it is useful to define the main infiltration pathways and to identify the conditions responsible for soil saturation that affect slope stability by performing a numerical analysis. In conclusion, the current research makes a significant contribution to the interpretation of ground instability in mountainous regions, emphasizing the role of predisposing factors.

Keywords

Slow-moving landslides, groundwater level, seasonal displacements, numerical modelling, Alps

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1 Introduction

Slope stability analysis is a crucial and challenging geological and geotechnical topic (Chatra et al. 2017) due to the complex geological and hydrogeological processes that drive soil deformation, posing a significant threat to nearby buildings and infrastructure. Particularly in the mountainous context, the role of rainfall and snowmelt contributes significantly to instability mechanisms. Therefore, understanding the relationship between groundwater regimes and landslide displacement in these areas is essential to improve risk assessment and mitigation.

In the case of slow-moving landslides (Cruden and Varnes 1996), phases of rapid acceleration or catastrophic failure may occur due to the specific contribution of several predisposing factors. Generally, positive pore pressure resulting from rising groundwater levels, which are closely linked to net precipitation and snowmelt, is the main mechanism leading to failure in hydrologically induced DSGSD, implying that water content controls the behaviour of slow-moving landslides (Prokešová et al. 2013; Vallet et al. 2016 and Van Asch et al. 2007).

This work aims to analyse the hydromechanical dynamics of the Champlas du Col deep-seated landslide located in the Susa Valley in the Western Alps of Piemonte region (Italy). This landslide is an interesting example of gravitational phenomenon influenced by groundwater variations. The presence of a monitored water spring on the landslide body allows for the detection of changes in the groundwater recharge system through the acquisition of hydrometric data, providing useful insights into the aquifer's behaviour in response to rainfall inputs and the annual snowmelt process.

Given these assumptions, the following analytical steps were carried out: (i) spectral analysis to clarify the effects of groundwater fluctuations on landslide acceleration and (ii) numerical modelling to simulate deformations under specific soil saturation conditions, mainly due to rainfall and snowmelt contributions.

2 Study area

The investigated landslide site is located in the municipality of Sestriere, in the Champlas du Col locality (1768 m a.s.l.), along the SP23R road connecting the Susa and Chisone valleys. The landslide has been classified as complex phenomenon in the Regional Landslide Inventory (Sistema Informativo Frane in Piemonte-SiFraP) and covers an area of 2 km^2, extending from 2080 m a.s.l. down to the Ripa Valley floor at about 1500 m a.s.l (Fig. 1a). The phenomenon is the superficial expression of a larger DSGSD that extends from the top to the bottom of the relief (Narcisi et al. 2024). Surface movements, such as flows and rotational slides, are very active and periodically cause damage the SP23R road.

A complex system with multiple sliding surfaces has been identified due to the presence of highly fractured calcschists with serpentinites (belonging to Cretaceous period), a factor that contributes to the infiltration of meteoric water inputs. The collapse at the scale of the entire slope is dominated by a viscous-plastic deformation component with the development of creep movements distributed over a large part of the rock mass, as a result of which the phenomenon consists of a dominant sliding component along different planes on structural discontinuities (Fioraso et al. 2014).

Upstream of SP23R, movement occurs along horizons of different permeability due to the presence of gravel alternating with silt and sand. These incoherent soils with local glacial deposits, developed during the Last Glacial Maximum, cover the fractured substrate with a thickness of about 100 m. On the other hand, in the lower part of the landslide on the valley floor, the presence of fluvial deposits is more consistent.

Most of the monitoring points are concentrated near the Champlas du Col buildings and along the SP23R, due to the recurrent damages observed. Given the heterogeneity of surface deformations, landslide displacements of different magnitude are detected. In particular, on the western sector of the landslide body the movement rates ranging between 2 and 4 cm/year, while on the eastern sector the displacements are more pronounced (around 6-7 cm/year) (Arpa Piemonte 2024a).

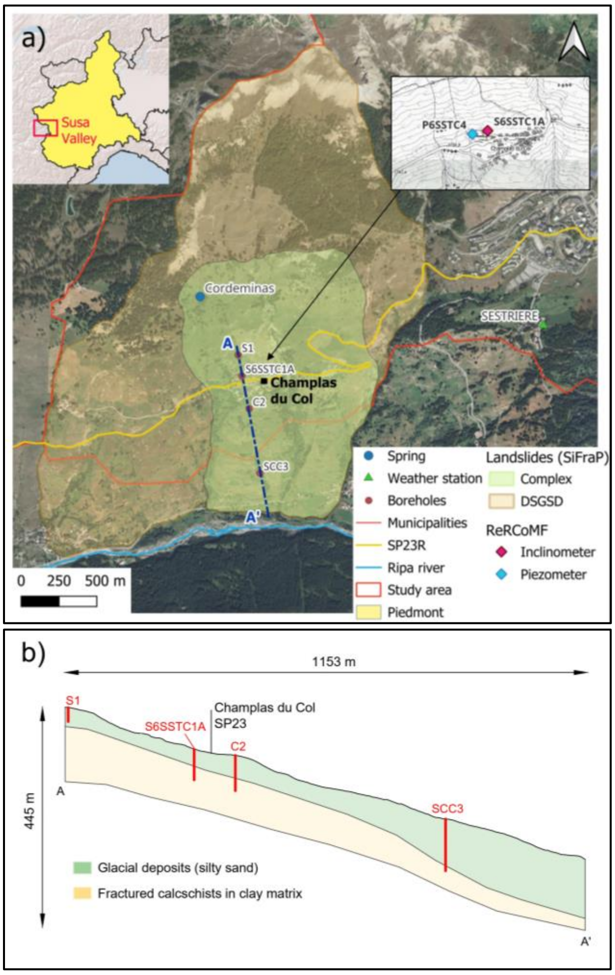

Fig. 1 (a) Location of the Champlas du Col landslide and detail of ReRCoMF monitoring points (b) Cross-section A-A'.

3 Data collection and methodology

The Cordeminas water spring is monitored by the Regional Agency for the Protection of Environment (ARPA Piemonte) in collaboration with the Department of the Environment, Territory and Infrastructures Engineering (DIATI) of the Politecnico di Torino. A multiparameter probe was installed (since 17/10/2020) to measure water level, temperature and electrical conductivity with an hourly time step (Bonomo 2023). The analysed dataset is updated to the last measurement campaign conducted in June 2024.

Spring water levels and precipitation data were considered in order to analyse possible effects on acceleration phases in the landslide deformation trends. Precipitation data were obtained by selecting available weather station from the official ARPA Piemonte regional network. The Sestriere station was chosen because it is close to the investigated site in terms of distance and elevation and it provides continuous time series of rainfall, snow height and temperature since 1996. To ensure consistency between spring and weather datasets, the hourly water level data were transformed into average daily values.

The site has been equipped with landslide monitoring instruments by the ARPA Piemonte through the Regional Landslide Control Network (Rete Regionale Controllo Movimenti Franosi–ReRCoMF). Analogous to the choice of the weather station, only suitable instrument with large and continuous datasets, without any gaps within the previously defined monitoring domain were selected (see Table 1). Therefore, inclinometers without automatic acquisition were excluded, and only fixed probe inclinometers, which provide daily cumulative displacement values from the installation date, were considered. On the other hand, the piezometers measure daily groundwater levels and will be exploited in numerical modelling to analyse water level fluctuations over time and hence their effects on the rate of movement.

Table 1 Landslides monitoring instruments (ReRCoMF)

ID code	Instrument	Date of installation	Daily values
S6SSTC1A	Inclinometer	2013/09	Displacement (mm)
P6SSTC4	Piezometer	2004/09	Groundwater level (m)

3.1 Analysis of spring water levels and inclinometer displacements in the frequency domain

The spectral analysis was carried out to investigate the influence of snowmelt and the consequent rising groundwater level on the increase in the landslide displacement pattern.

By analysing the Cordeminas water levels, the presence of seasonal components in the groundwater fluctuations was detected in order to understand the possible effects on the variations in the movement trend. For this purpose, a periodogram was evaluated for the groundwater level signal and the displacement variable. The periodogram is an estimate of the power spectral density of a signal and it is mathematically related to the autocorrelation sequence r_{xx} by the discrete-time Fourier transform (Oppenheim and Schafer 1989). This function provides a representation of the spectral components of both parameters in terms of frequency (Fiorillo and Doglioni 2010):

$$\mathrm{Pk}(\omega) = \frac{1}{2\pi} \sum_{m=-\infty}^{+\infty} r_{xx}(m)\, e^{-j\omega m} \tag{1}$$

Where f Physical frequency

f_s Sampling frequency

ω $2\pi f/f_s$

3.2 Numerical modelling

The geological section A-A′ (Fig. 1b) of the landslide was defined using borehole data (Table 2) and geological documents of the area provided by Arpa Piemonte Banca Dati Geotecnica to analyse the stratigraphy and define the soil mechanical properties. The slope layers consist of two main materials: (1) overlying formation (glacial and alluvial deposits) characterised by silty sand with gravel and (2) fractured calcschists in clay matrix.

Table 2 Boreholes along the cross-section A-A’

ID code	Elevation (m a.s.l)	Depth (m)	Groundwater level (m a.s.l.)
S1	1860	33	1840.2
C1	1760	65	1748
C2	1720	75	1710
SCC3	1590	110	1550

A numerical analysis with Plaxis® 2D software (Version 2024.2.0.1144) was performed to model slope stability, identify slope portions along cross section A-A’ affected by high strains, and simulate the landslide movement rate under different conditions. In the model, the Hardening Soil (HS) model (Schanz et al. 1999), an elastoplastic soil constitutive model, was used to describe the behaviour of subsoil layers.

Slope safety was assessed using the ϕ-c reduction technique. In particular, the mechanical information derived from drilling samples was supplemented with literature data and several iterations of modelling to obtain a framework as close to the real case as possible. Vegetation, soil heterogeneity and anisotropy were not considered. A coupled hydromechanical finite element analysis was adopted to simultaneously assess changes in pore water pressure and slope displacements caused by transient infiltration due to rainfall and snowmelt, controlled by the permeability of the two soil layers. The numerical simulation was performed in two main stages: the initial phase and evaluation of the main deformations under the increased groundwater level due to rainfall and snowmelt action, generally observed during spring season. The first step was performed with an initial groundwater level derived from borehole surveys. On the other hand, groundwater level changes over time are provided by the piezometer P6SSTC4. More details about hydraulic boundary conditions are summarized in Table 3.

Table 3 Numerical analysis steps and related boundary conditions

Stage	**Hydraulic boundary conditions**
(1) Initial phase (pre-event)	Constant head at left and right sides Zero flux along the bottom side
(2) Rainfall/snowmelt action	Infiltration rate along the slope surface Time-dependent head at left and right sides Zero flux along the bottom side

4 Main results and discussions

4.1 Cause-effect relationship between groundwater fluctuations and landslide displacement trends

Daily time series of cumulative snow height and incremental displacement recorded by the S6SSTC1A inclinometer are shown in Fig. 2. It is clear that the acceleration phases of the landslide are closely linked to the snowmelt; in particular, winters with heavy snowfall are followed by high displacement rates. Noteworthy are the highest peaks occurred during spring 2018 and 2024, due to the abundant snowfall combined with prolonged rainfall of the previous months (Arpa Piemonte 2024 b and 2024c).

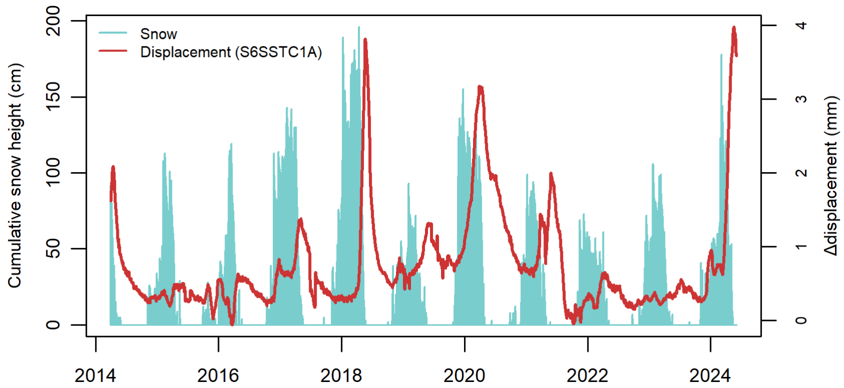

Fig. 2 Daily cumulative snow height and landslide displacement shifts.

The periodogram (Eq. 1) of the spring water levels and the inclinometer displacements further support the comprehension of the snowmelt role in increasing landslide movement rate Fig. 3.

A peak at approximately 365 days was detected, indicating the presence of an annual component in the water level signal. This finding suggests a relatively consistent pattern typical of spring discharge across hydrological years. However, additional significant peaks appear in the water level response, recurring at frequency ranging between 0.005 and 0.015. These peaks are attributed to the spring's greater sensitivity to surface runoff and rainfall events. The hydrometric level pattern depends on the position of the spring monitoring. Indeed, Cordeminas spring is embedded in a shallow system, which makes it strongly influenced by rapid flow contributions, characterised by water level peaks following intense rainfall events, which overlap with the base flow component driven by snow accumulation.

At the same time, the displacements spectrum evaluated within the same time window of the Cordeminas spring, also shows a peak at 382 days, suggesting a close dependence of displacement variations on the groundwater recharge system and consequently on the annual snowmelt cycles.

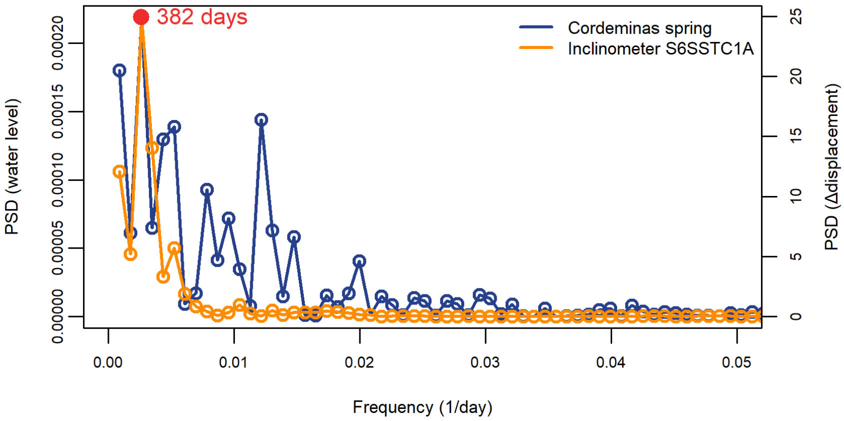

Fig. 3 Power spectral density (PSD) of the water levels (Cordeminas spring) and displacement shifts (inclinometer S6SSTC1A)

4.2 Hydromechanical response of the landslide to rising groundwater levels

For the purpose of the analysis, the scenario occurred in the spring of 2018 was taken as an example, in which the piezometer P6SSTC4 recorded an increase in the groundwater level of approximately 5 m (from -13.07 m on 04/03/2018 to -8.71 m on 10/05/2018), due to the abundant snowfall of the previous winter and also due to the contribution of heavy rainfall in May 2018 (Arpa Piemonte 2024b).

In particular, the numerical analysis was focused on a shorter time window (Fig. 4) to reduce the modelling computation time, but still meaningful for the interpretation of the phenomenon. Therefore, since a significant groundwater level rise of about 3 m occurred in 7 days (17/04/ 2018 to 24/04/2018), the changes in the displacement pattern in the following 30 days were investigated. A constant infiltration rate over time was set in the model, by assuming an average daily rainfall value of 0.05 m/day over 7 days and time-dependent hydraulic head variation.

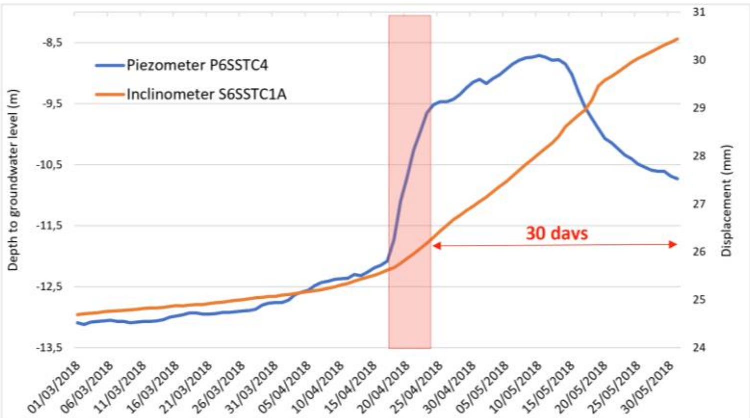

Fig. 4 Scenario of the spring 2018: acceleration of the landslide following the rising groundwater level occurred on 17/04/2018-24/04/2018 (red time window).

Consequently, the displacements in the 30 days following 24/04/2018 with the reached groundwater level were evaluated. As it can be seen in Fig. 5, the main distribution of the obtained displacements along the landslide section is close to the slope surface, where the main sliding planes are assumed to be located. In particular, the resulting increase in displacement evaluated at the mesh node where the inclinometer fixed probe is located coincides with the 3 mm shift recorded by the instrument. The safety factor values obtained from the initial phase and the post-event were compared, the graph in Fig. 6 clearly demonstrates how the rise in groundwater level causes a reduction in slope stability, correlated with the acceleration of the landslide body.

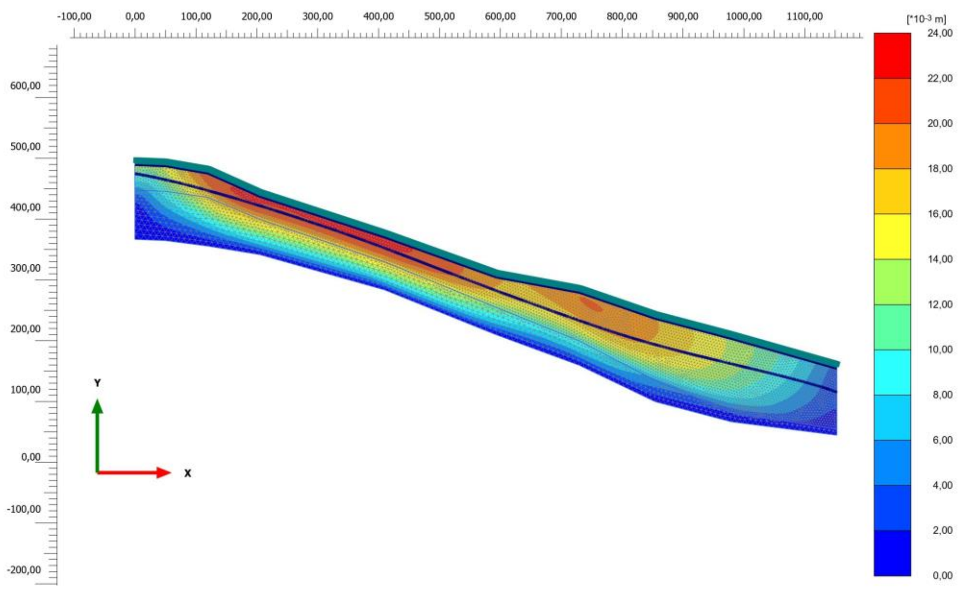

Fig. 5 Distribution of total displacements at the end of the 2° stage (30 days following 24/04/2018). It is also represented the water load on the upper surface due to the infiltration boundary condition and the groundwater level (blue line).

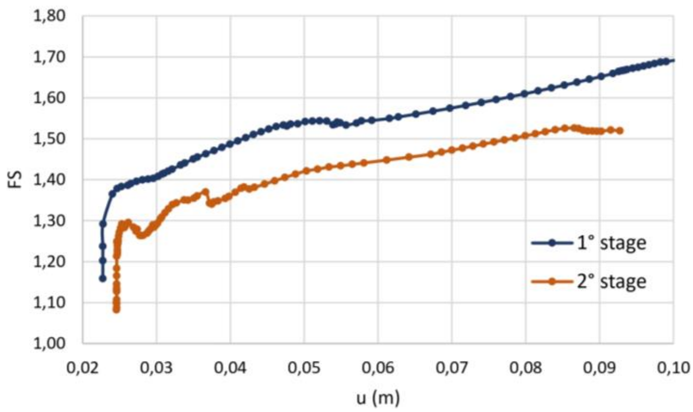

Fig. 6 Evaluation of safety factor at 1° stage (initial condition) and 2° stage (after the increase of groundwater level).

5 Conclusion

In this work, the hydromechanical behaviour of the Champlas du Col deep-seated landslide (Susa Valley, NW Italy) was evaluated. Spectral analysis and numerical modelling approaches clarified the cause-effect relationship between precipitation, rising groundwater levels and the acceleration of landslide movements. A preliminary comparison of the displacement time series with cumulative snow height over the years has shown that landslides accelerate mainly in the spring and summer period due to the annual snowmelt action. This suggests that it is not the single intense rainfall event that triggers the landslide, but rather the complete saturation of the landslide body due to continuous infiltration. In addition, the contribution of heavy rainfall to the rise in groundwater levels was also recognised (Amarasinghe et al. 2024; Cappa et al. 2014; Conte and Troncone 2011). In the second part of the analysis, dedicated to numerical modelling, the case of the spring 2018 was used to demonstrate that the main acceleration phases occur after a period of intense precipitation. The analysis could be extended to simulate other possible scenarios, such as the spring of 2024, or to derive landslide movement thresholds for a possible early warning system.

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References

ARPA Piemonte (2024a). Scheda SIFraP ii livello frana Champlas du Col. https://webgis.arpa.piemonte.it/geodissesto/sifrap/sifrap_ii_liv_scheda.php?cod_frana=001-76807-00. Accessed at November 2024

ARPA Piemonte (2024b). Il clima in Piemonte - Primavera 2018. https://www.arpa.piemonte.it/pubblicazione/clima-piemonte-primavera-2018. Accessed at November 2024

ARPA Piemonte (2024c). Il clima in Piemonte - Primavera 2024. https://www.arpa.piemonte.it/pubblicazione/clima-piemonte-primavera-2024. Accessed at November 2024

Chatra AS, Dodagoudar GR, Maji VB (2017) Numerical modelling of rainfall effects on the stability of soil slopes. International Journal of Geotechnical Engineering, 13(5), 425–437. https://doi.org/10.1080/19386362.2017.1359912

Amarasinghe MP, Robert D, Kulathilaka SAS. (2024) Slope stability analysis of unsaturated colluvial slopes based on case studies of rainfall-induced landslides. Bull Eng Geol Environ 83, 476. https://doi.org/10.1007/s10064-024-03933-1

Bonomo N (2023) Multidisciplinary study on the gravitational phenomena of Thures and Champlas du Col in the upper Susa Valley. Rel. Adriano Fiorucci, Mauro Tararbra, Bartolomeo Vigna. Master thesis, Politecnico di Torino.

Cappa F, Guglielmi Y, Viseur S, Garambois S (2014) Deep fluids can facilitate rupture of slow-moving giant landslides as a result of stress transfer and frictional weakening. Geophysical Research Letters, 41(1), 61–66. https://doi.org/10.1002/2013GL058566

Conte E, Troncone A (2011) Analytical Method for Predicting the Mobility of Slow-Moving Landslides owing to Groundwater Fluctuations. Journal of Geotechnical and Geoenvironmental Engineering, 137(8), 777–784. https://doi.org/10.1061/(asce)gt.1943-5606.0000486

Cruden DM, Varnes D.J (1996) Landslide types and processes in Landslides investigation and mitigation (special report 247). Editors A. K. Turner, and R. L. Schuster (Washington, DC, USA: Transportation Research Board, US National Research Council), 36–75.

Fioraso G et al (2014) Note Illustrative della Carta Geologica d'Italia alla scala 1:50.000, F. 171 Cesana Torinese, ISPRA - Serv. Geol. d'It., Roma. DOI: 10.15161/oar.it/14317

Fiorillo F, Doglioni A (2010) The relation between karst spring discharge and rainfall by cross-correlation analysis (Campania, Southern Italy). Hydrogeology Journal, 18(8), 1881–1895. https://doi.org/10.1007/s10040-010-0666-1

Narcisi R, Pappalardo SE, Taddia G, De Marchi M (2024) Assessing climate impacts on slow-moving landslides in the western Alps of Piemonte: integration of monitoring techniques for detecting displacements. Frontiers in Earth Science, 12. https://doi.org/10.3389/feart.2024.1365469

Oppenheim AV, Schafer RW (1989) Discrete-time signal processing, Prentice-Hall, Englewood Cliffs, NJ, 870 pp

Prokešová R, Medveďová A, Tábořík P, Snopková Z (2013) Towards hydrological triggering mechanisms of large deep-seated landslides. Landslides, 10(3), 239–254. https://doi.org/10.1007/s10346-012-0330-z

Schanz T, Vermeer PA, Bonnier PG (1999) The Hardening SoilModel: Formulation and verification, Beyond 2000 in Computational Geotechnics–10 years of PLAXIS, Balkema, ISBN 90 5809 040 X

Vallet A, Charlier JB, Fabbri O, Bertrand C, Carry N, Mudry J (2016) Functioning and precipitation-displacement modelling of rainfall-induced deep-seated landslides subject to creep deformation. Landslides, 13(4), 653–670. https://doi.org/10.1007/s10346-015-0592-3

Van Asch TWJ, Van Beek LPH, Bogaard TA (2007) Problems in predicting the mobility of slow-moving landslides. Engineering Geology, 91(1), 46–55. https://doi.org/10.1016/j.enggeo.2006.12.012