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The influence of the rainfall data temporal resolution on the results of numerical modelling of landslide reactivation in flysch slope

Abstract There are numerous examples in the literature where numerical modelling has been used as a valuable tool in the study of rainfall-induced landslides. While much attention has been paid to the influence of different rainfall characteristics and patterns, spatial variability or temporal patterns of rainfall intensity, very little attention has been paid to the influence of the temporal resolution of rainfall data used in numerical simulations of rainfall infiltration and slope stability analysis. This is particularly true for deep-seated landslides occurring on slopes composed of soils with relatively low hydraulic conductivity, as in the case of flysch deposits presented in this study. A recently developed 2D numerical model is used to investigate the results of transient infiltration and slope stability analysis for flux boundary conditions derived from three temporal resolutions of realistic rainfall data: (i) 10-min, (ii) hourly and (iii) daily rainfall measurements. The results obtained show that deriving the time-dependent flux boundary conditions using the coarse resolution rainfall data (e.g. daily rainfall measurements) can lead to a calculation of unrealistically high infiltrated volumes, a faster increase in water content and pore water pressure in a slope cross-section, and a reduction in the factor of safety at an unrealistically high rate, resulting in a conservative prediction of the time to slope failure. The results suggest hourly rainfall data as the optimal form of input data for the case study under investigation.

Keywords Rainfall data · Infiltration · Flysch · Landslide reactivation · Slope stability · Partially saturated soil

Introduction

In recent decades, considerable progress has been made in understanding the mechanisms of rainfall-induced landslides and the effects of various slope factors on the stability of slopes exposed to rainfall in different climatic and geological contexts. It became clear, for example, that depending on the hydro-mechanical properties of the soil and local climatic conditions, both natural and engineered slopes may be subjected to pore water pressure (pwp) conditions that differ from those obtained in conventional slope stability analyses where saturated, steady-state water flow is usually assumed (Collins and Znidarcic 2004). It has been shown that matric suction ($u_a - u_w$) plays a crucial role in maintaining the stability of steep slopes with deep groundwater level (GWL), while an accurate determination of the distribution of pwp in a slope

requires solving the equation describing the flow of water through a partially saturated soil. It is widely accepted that both rainfall characteristics (or weather conditions in general) and soil properties play a key role in rainfall-induced landslides (e.g. Rahardjo et al. 2007; Rahimi et al. 2011).

Most landslides triggered by rainfall are shallow landslides where the sliding surface is typically up to several metres deep. Dissipation of $u_a - u_w$ due to rainfall infiltration is widely recognised as the main triggering mechanism for shallow landslides (e.g. Rahardjo et al. 2001, 2010, 2016; Crosta and Dal Negro 2003; Li et al. 2005; Casagli et al. 2006; Lu and Godt 2008; Gofar and Lee 2008; Godt et al. 2009, 2012; Cascini et al. 2010; Pagano et al. 2010; Rahimi et al. 2011; Kim et al. 2012; Greco et al. 2013; Leung and Ng 2013; Pirone et al. 2015; Toll et al. 2016; Comegna et al. 2016; Chen et al. 2017, 2018; Ebel et al. 2018; Marino et al. 2020). Shallow landslides usually involve small volumes of displaced mass and are largely triggered by meteorological extremes, such as intense rainfall of relatively short duration. Depending on various factors, the slip surface can develop under conditions of partial or complete soil saturation on a slope.

On the other hand, deep-seated landslides are typically associated with persistent rainfall and rising GWL on slopes composed of materials with low hydraulic conductivity. The slip surface typically develops at a depth of several tens of metres and is mostly submerged. Therefore, the sliding mechanism is mainly related to the reduction in shear strength due to the build-up of positive pwp. Even if the GWL level does not coincide with the slope surface (a condition often considered a worst-case scenario in conventional analyses of slope stability), the shear strength component associated with $u_a - u_w$ present along a part of the sliding surface above the phreatic line usually has a negligible effect on the overall stability of the landslide body. Although several studies suggest that the interaction at the soil-atmosphere interface may also be the cause of deep-seated landslides, there are far fewer studies that consider the influence of transient rainfall infiltration on the stability of deep-seated landslides in slopes made of materials with low hydraulic conductivity (e.g. Sun et al. 2009; Comegna et al. 2013; Lollino et al. 2016; Zhao et al. 2017; Cotecchia et al. 2019; Tagarelli and Cotecchia 2020b, 2022; Peranić et al. 2021; Pedone et al. 2022). The latter is particularly true for deep-seated landslides triggered by rainfall in flysch deposits.

Physically based models, addressing two complex problems related to the failure mechanism of rainfall-induced landslides,

i.e. (i) transient rainfall infiltration and (ii) slope stability analysis, have been successfully used to study the hydromechanical response of slopes subjected to various natural or artificial rainfall events. Different models of varying complexity and capabilities have been developed. For instance, conceptual infiltration models, mostly based on a wetting front concept (e.g. Green and Ampt 1911; Leach and Herbert 1982; Srivastava and Yeh 1991; Boger 1998; Nie et al. 2017), generally have some serious limitations in terms of the ability to account for highly nonlinear unsaturated soil property functions, complex geometric and boundary conditions (BCs), etc. On the other hand, computationally intensive iterative numerical methods allow sophisticated constitutive soil models, advanced physical processes and realistic time-dependent flux BCs (q) to be incorporated in the analysis. For example, Zhang et al. (2009), Ran et al. (2011), Cho (2016) and Kang et al. (2020) have used advanced coupled liquid–gas two-phase flow numerical models to investigate the effects of airflow due to rainfall infiltration on slope stability. Numerical models have been used to quantitatively assess the role of vegetation on the hydro-mechanical response of slopes exposed to different rainfall conditions (e.g. Leung and Ng 2013; McGuire et al. 2016; Liu et al. 2021). Numerical models have proven to be a particularly useful tool for determining how different rainfall characteristics, antecedent rainfall events and especially alterations in rainfall patterns (very commonly associated with global climate change) affect the stability of soil slopes (e.g. Rahardjo et al. 2001, 2016; Rahimi et al. 2011; Kim et al. 2012; Comegna et al. 2013; Kristo et al. 2017; Yeh and Tsai 2018).

Numerical modelling has been successfully used to investigate the influence of advanced, delayed and regular rainfall patterns, as well as the effects of spatial variability of rainfall and intermittency or temporal patterns of rainfall intensity on the stability of soil slopes (e.g. Rahimi et al. 2011; Muntohar et al. 2013; Von Ruetten et al. 2014; Fan et al. 2020). Several studies have used synthetic rainfall datasets at different scales (single slope or catchment) to investigate how different rainfall characteristics and patterns affect the triggering of shallow or deep-seated landslides. However, to the authors' knowledge, none of the studies have investigated how the temporal resolution of rainfall data affects the results of numerical seepage

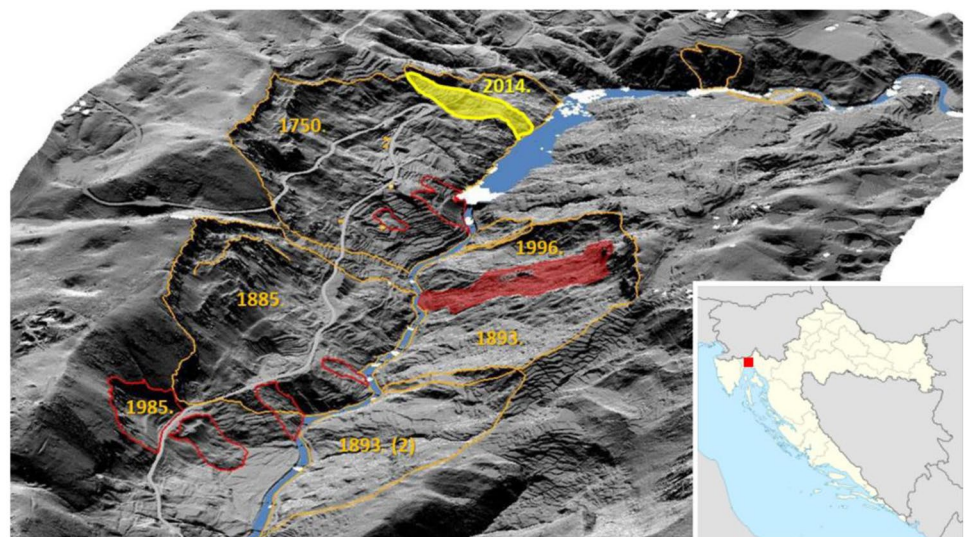
and slope stability analysis in general. The lack of high-quality, reliable rainfall data collected at or near the site under study often becomes a limiting factor in deriving a realistic, time-dependent q representing the rainfall event. The latter is often a reason why q is applied as a constant value in seepage analysis, usually representing the average or maximum rainfall intensity over a considered period. This is particularly the case for studies dealing with extreme rainfall events of short duration, lasting from a few hours to a day or two, which typically exhibit strong temporal and spatial variability (e.g. Cascini et al. 2010; Tu et al. 2019). Numerical models used to investigate the influence of rainfall or soil–vegetation–atmosphere interaction on deformations and/or stability of deep landslides built of soils with relatively low hydraulic conductivity usually use daily (e.g. Cotecchia et al. 2015, 2019; Vassallo et al. 2015; Pedone et al. 2016, 2018; Tagarelli and Cotecchia 2020a, b) or even monthly average rainfall (e.g. Vassallo et al. 2015; Tsiampousi et al. 2017) to derive q that is applied along the soil–atmosphere interface.

In this study, we use a numerical model recently developed by Peranić et al. (2021) that can reproduce the conditions that led to the reactivation of the Valiči Landslide, Croatia, on 14 February 2014. The aim of the study is to investigate how different temporal resolutions of rainfall data (10 min, hourly and daily) used to derive q in the transient seepage analysis affect the outcome of the numerical simulations. Both the influence on the results of the transient seepage analysis and the state of the slope stability are investigated. Ten-minute rainfall data collected in the vicinity of the reactivated landslide for the period from 1 September 2013 to the day of landslide reactivation, 14 February 2014, are used to perform three separate numerical simulations with q in the form of (a) 10', (b) hourly and (c) daily rainfall data.

Investigation area

The Valiči Landslide is located in the Rječina River Valley, just in the outback of the City of Rijeka, Croatia. The valley, known for numerous recent and historical landslides (Fig. 1), is part of a larger, 100-km-long morphostructural unit stretching from Ilirska Bistrica in Slovenia to Novi Vinodolski on the Adriatic coast in Croatia.

Fig. 1 LIDAR-derived bare-earth DTM of the Rječina River Valley (red square in the inset) with contours of historical (orange) and more recent (red) landslides. The zones coloured in red and yellow represent the two known major rainfall-induced landslides in the valley that occurred recently: the Grohovo Landslide (1996) and the Valiči Landslide (2014), respectively (modified from Arbanas et al. 2017)



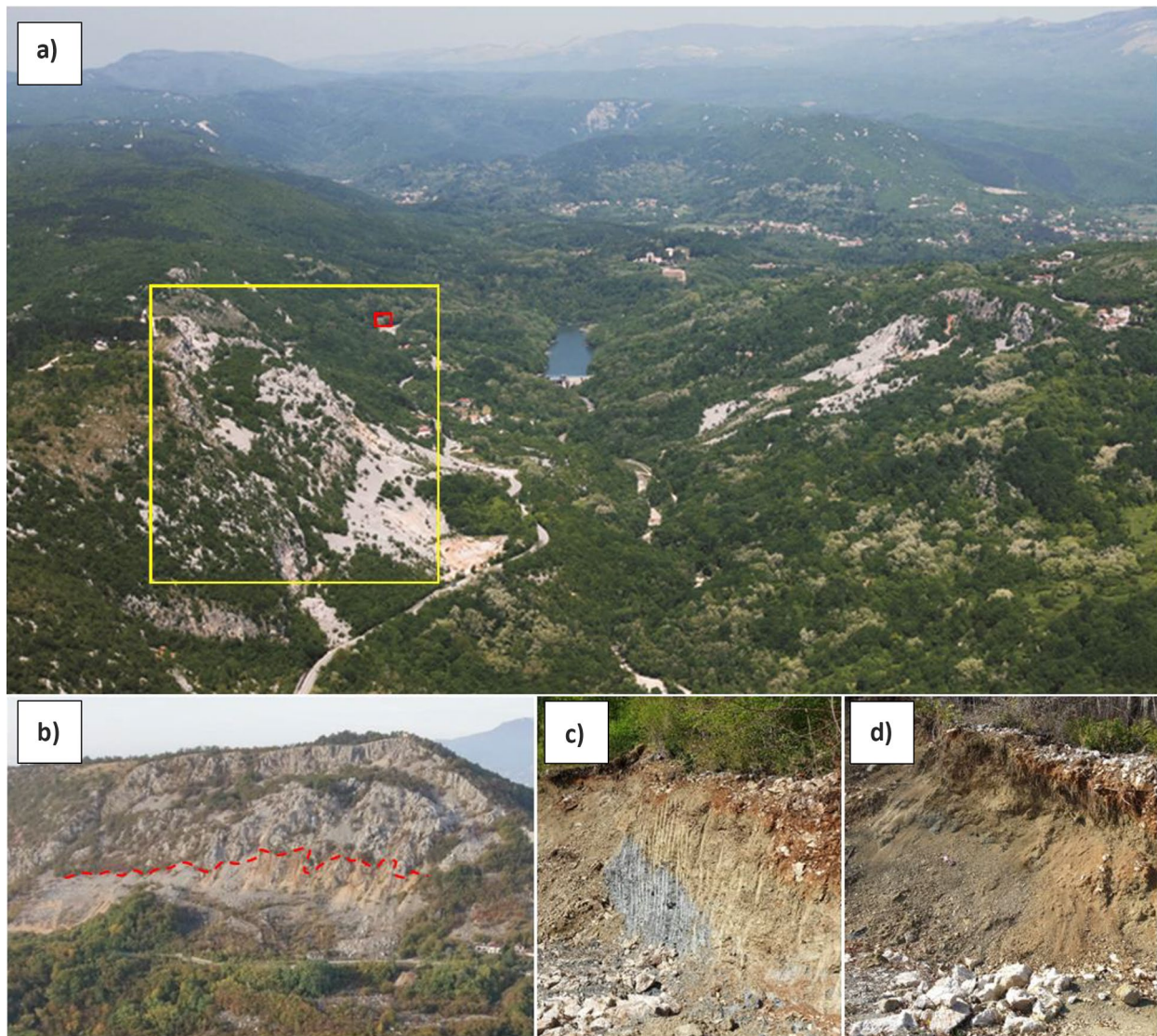


Fig. 2 Some details about geological environment of the valley: **a** aerial view of the Rječina valley; **b** contact between limestone and flysch rock mass partially covered by rockfall talus material; and weathering of a vertical cut in flysch rock mass (location indicated with red square in **a**): photos from **c** April 2020 and **d** February 2021

Like the entire morphostructural unit, the geological environment of the valley is characterised by the presence of Cretaceous and Paleogene limestone in the upper part of the slopes, while Paleogene siliciclastic and flysch rocks are present in the lower part and at the bottom of the slopes, where landslide processes were mainly developed (Fig. 2) (Benac et al. 2005; Mihalić Arbanas et al. 2017).

Frequent vertical and lateral changes in lithological sequences, including sandstones, siltstones and marls, result in lithological heterogeneity characterising the flysch rock mass in the valley (Vivoda Prodan et al. 2017). The flysch rock mass is often covered by weathered surface material that originates from the weathering of incompetent lithological components such as siltstones and marls. Depending on local conditions, the thickness of the weathered material may vary in depth and degree of weathering. Residual soil, which can be classified as clay of low plasticity, is usually found

as a covering soil layer on gently sloping flysch slopes in the valley (Peranić et al. 2018a). Typically, the residual soil is directly exposed to the atmosphere or covered by rockfall talus originating from the higher parts of the slopes.

In general, slopes undercut by the Rječina River are the most hazardous slopes in the flysch deposits in Croatia, with numerous historical and recent small- to medium-sized/large-scale landslides that have developed within the flysch rock mass (Arbanas et al. 2014), as well as many small reactivated landslides in the colluvium of ancient landslides (Arbanas et al. 2014; Benac et al. 2005; Vivoda et al. 2012). With more than 1500-mm mean annual precipitation (Fig. 3), the City of Rijeka and its surroundings are known for high rainfall during the rainy season. The study area falls under the maritime type of annual pattern of monthly precipitation, with the main minimum and maximum amounts typically occurring in

Fig. 3 Cumulative annual precipitation measured at the meteorological station of Kozala, Rijeka, for the period 1957 to 2015 (data provided by the MHSC). The mean value is indicated by the dashed purple line

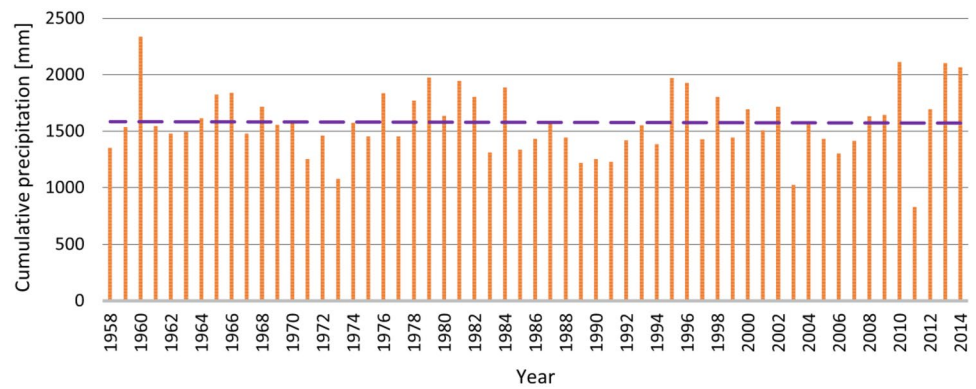


Table 1 Average, maximum and minimum monthly and annual precipitation (in mm) measured by the Kozala meteorological station, Rijeka (approx. aerial distance from the Valiči Landslide 4 km) for the period 1958–2015 (data provided by the Meteorological and Hydrological Service of Croatia, MHSC)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Avg	134	119	118	112	105	106	75	103	178	180	187	162	1579
Max	448	347	388	248	276	230	201	351	481	527	483	456	2339
Min	1	3	0	1	2	19	2	1	11	0	13	28	832

July and November, respectively. The mean annual air temperature in the northern Adriatic ranges between 14 and 15 °C, with rare (but not uncommon) sub-zero temperatures in winter (Zaninović et al. 2008). Snowfall accounts for only 3 to 5% of the days with precipitation on the Adriatic coast (Zaninović et al. 2008). According to the daily rainfall amounts measured at the meteorological station Kozala, Rijeka, for the period from 1958 to 2015, the average annual rainfall of 1567 mm has hardly changed, with the maximum of 2339 mm recorded in 1960 and the minimum of 832 mm in 2011. The average, maximum and minimum monthly and annual rainfall amounts are summarised in Table 1.

The Valiči Landslide case study

The last known major landslide in the valley occurred on 13 February 2014 on the right bank of the Valiči Reservoir, named the Valiči Landslide. Two instruments installed nearby (approx. aerial distance 900 m for both instruments), the rain gauge (Osasi Technos Inc.) and the weather station (Davis Instruments Inc.), showed that the area has experienced more than 1160 mm of rainfall during the period from 1 September 2013 to 13 February 2014, with 500 mm of rainfall falling in a month preceding the landslide reactivation. Figure 4 shows the daily rainfall amounts measured for the period.

Preliminary investigations conducted immediately after the landslide occurred (Mihalić Arbanas et al. 2015; Arbanas et al. 2017), as well as the field, laboratory and numerical investigations carried out in the period from 2016 onwards (Peranić et al. 2018a, 2020a, b, 2021; Peranić and Arbanas 2020) confirmed that the instability occurred as a reactivation of part of a larger historical landslide, which confirms the prognostic model defined by Mihalić Arbanas et al. (2015) in Fig. 5. The identification and mapping of the landslide based on the interpretation of light detection and ranging and

digital elevation model (DEM)–derived maps and ground survey, as well as field mapping and inclinometer surveys, confirmed that the displaced soil mass, measuring approximately 230 m in length and 120 m in width, experienced translational sliding along part of the old sliding surface. The results of various field investigations and laboratory tests for advanced hydromechanical characterisation of the residual soil covering the slope (Peranić et al. 2018a, 2020a; Peranić and Arbanas 2020), as well as the results of the back-analysis of slope stability (Peranić et al. 2021) were used to build an advanced numerical model capable of determining the transient pwp distribution in a flysch slope exposed to rainfall and how it affects the stability condition over time (Peranić et al. 2021). The results highlighted the important role of the partially saturated zone in maintaining the stability of a flysch slope during prolonged and intense rainfall,

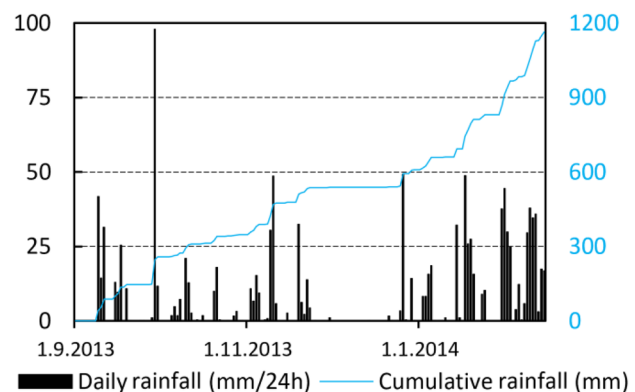
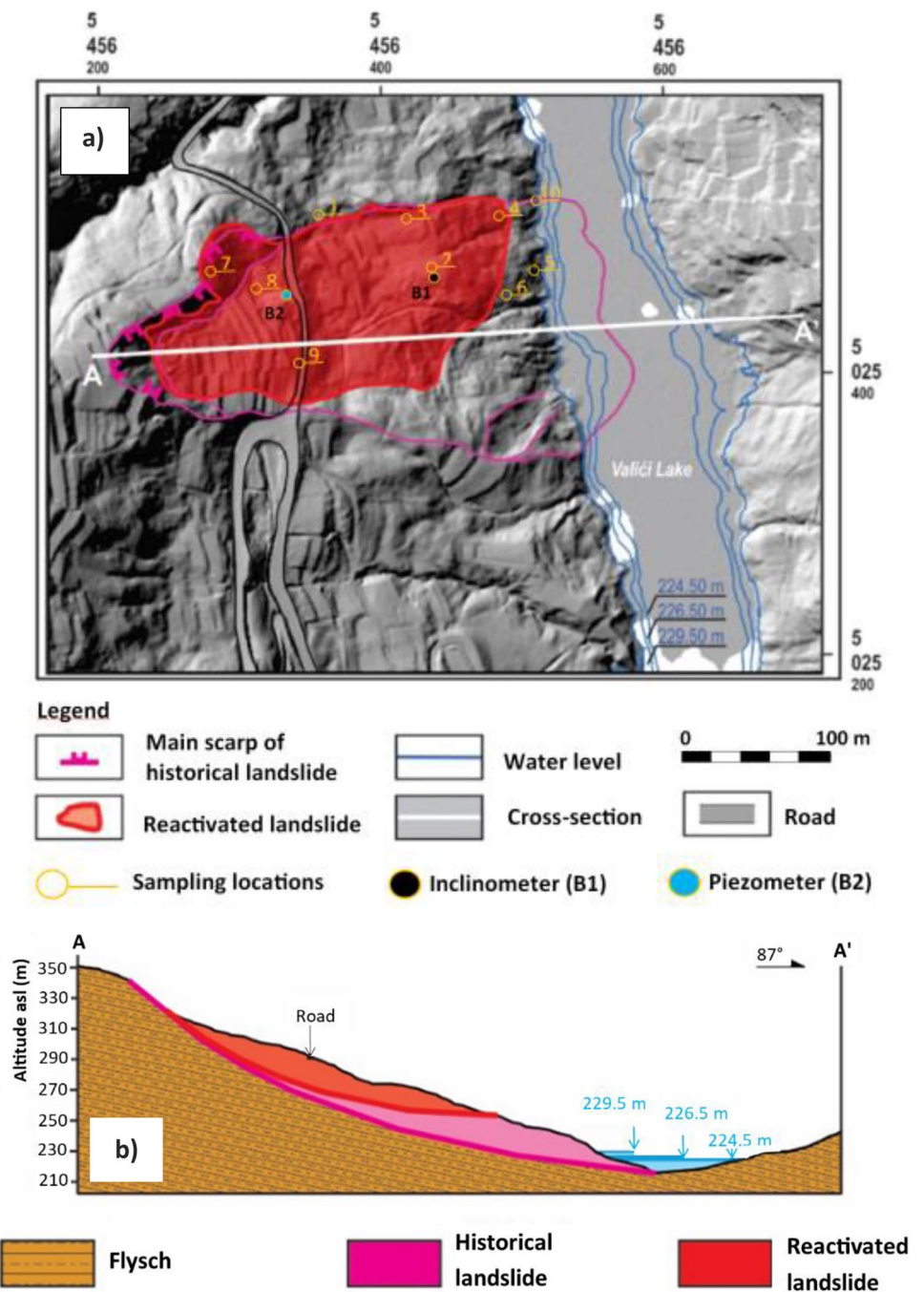


Fig. 4 Daily and cumulative rainfall measured from 1 September 2013 to 14 February 2014

Fig. 5 The Valiči Landslide: **a** Landslide map with sampling positions, location of inclinometer (B1) and piezometer (B2); **b** engineering-geological cross section (modified from Mihalić Arbanas et al. 2015)



confirming the duration of rainfall as the most important triggering factor for flysch slopes. Rainfall intensities greater than about $2k_s$, i.e. 0.33 mm/h or 7.95 mm of uniformly distributed rainfall per day, did not affect the calculation results. For a detailed overview of the field investigation works, including field mapping, drilling and collection of intact soil samples, inclinometer surveys and continuous GWL monitoring, and natural water content determination campaigns, see Arbanas et al. (2017), Mihalić Arbanas et al. (2015) and Peranić et al. (2018a; 2020a; 2020b). For details on laboratory tests to determine basic geotechnical and advanced hydromechanical properties (including the water retention curve and the hydraulic conductivity

function of the soil in the surface layer of the slope, as well as the (un)saturated shear strength properties of the soil at the slope surface and from the slip surface zone), derivation and build-up of the engineering geological and numerical, see Mihalić Arbanas et al. (2015) and Peranić et al. (2020a; 2021).

Numerical model

Peranić et al. (2021) used the GeoStudio 2021 software suite (GEO-SLOPE International, Ltd.) to create the 2D numerical model of the Valiči Landslide, capable of determining the pwp distribution in

the slope subjected to a realistic or artificial rainfall event, and how changes in pwp during the transient infiltration process affect the stability of a flysch slope over time. The model consists of two main parts: a finite element (FE) analysis of transient groundwater seepage and a limit equilibrium (LE) analysis of slope stability. The numerical model was developed under the working assumption of a single-phase flow through a homogeneous slope assigned with hydraulic properties representative of the surficial residual soil undergoing the wetting process. Due to the nature of the rainfall event considered in the study, which is mostly an uninterrupted rainfall event characterised not only by extreme amounts but also by a long duration, another important simplification of the model was that only positive (downward) water fluxes were considered in the derivation of q . Under these assumptions, Peranić et al. (2021) showed that the numerical model was able to reconstruct the reactivation event of a landslide and achieve good agreement with field investigations and observations regarding the conditions and timing of a reactivation event. The model is briefly described in the following sections.

Rainfall infiltration analysis

The FE code SEEP/W is used for the numerical integration of the well-known Richard's nonlinear partial differential Eq. (1), which describes the transient water flow through a partially saturated soil:

$$\frac{\partial}{\partial x} \left(k_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial h}{\partial y} \right) + q = m_2^w \rho_w g \frac{\partial h}{\partial t} = \frac{\partial \theta_w}{\partial t} \quad (1)$$

where h is the total head, k is the permeability coefficient with respect to a water phase, q is the applied flux at the boundary, m_2^w is the water storage modulus, ρ_w is the density of water and t is time.

To obtain a solution to Eq. (1), the non-linear relationship between the volumetric water content of the soil and $u_a - u_w$ (i.e. the water retention curve, WRC) and between the permeability coefficient with respect to a water phase and $u_a - u_w$ (i.e. the hydraulic conductivity function, HCF) must be defined for soils through which transient rainfall infiltration occurs. In this case, a homogeneous slope is presented with the hydraulic properties representative of the residual soil from flysch rock mass undergoing the wetting process (Peranić et al. 2018a, 2020a). Table 2 summarises the best-fit parameters and the saturated permeability coefficient (k_s) used to define WRC and HCF in SEEP/W according to the model proposed by van Genuchten (1980):

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha\psi)^n]^m} \quad (2)$$

$$k_w(\psi) = k_s \frac{\{1 - (\alpha\psi)^{n-1} [1 + (\alpha\psi)^n]^{-m}\}^2}{[1 + (\alpha\psi)^n]^{0.5}} \quad (3)$$

Table 2 Van Genuchten's best-fit parameters and k_s used to define SWRC and HCF in SEEP/W (according to Peranić et al. 2020b)

Branch	SSR(r^2)	θ_s	θ_r	α	n	m	k_s
	[/]	[$\text{m}^3 \text{m}^{-3}$]	[$\text{m}^3 \text{m}^{-3}$]	[kPa^{-1}]	[/]	[/]	[m s^{-1}]
Adsorption	0.00021	0.463	0.011	0.005	0.973	0.348	4.60E-08

SSR sum of squared residuals; θ_s/θ_r = saturated/residual water content; k_s = sat. hyd. cond.

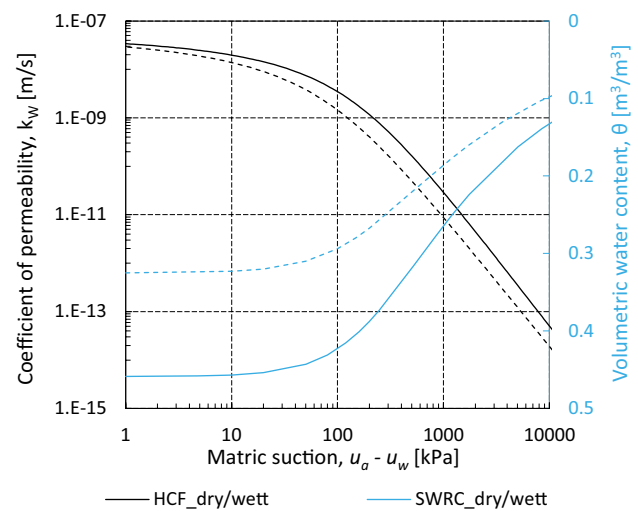


Fig. 6 SWRC and HCF of the residual soil from flysch rock mass (modified from Peranić et al. 2020a)

where α , n and m are WRC constants obtained by nonlinear regression of measurement results on intact samples (Peranić et al. 2018a) and k_s saturated coefficient of the permeability (Peranić et al. 2020a).

The experimental procedures used to obtain a complete SWRC of the residual soil from flysch rock mass, including suction-controlled oedometer apparatuses, volumetric extractors, pressure plates, mini tensiometers and dew point potentiometer, are described in detail in Peranić et al. (2018a) and Peranić et al. (2018b). Saturated hydraulic conductivity was measured on both intact and remoulded samples using the falling head and constant head methods in conventional oedometer and triaxial apparatuses, while for partially saturated conditions $k_w(u_a - u_w)$ values were determined using the evaporation method and HYPROP measurement system (Decagon Devices, Inc.). Full details of the measurements results and determination of HCF can be found in Peranić et al. (2020a) and Peranić et al. (2020b). SWRC and HCF relevant for the rainfall infiltration analyses are shown in Fig. 6.

Figure 7 shows a 2D model with an unstructured pattern of automatically generated quadrilateral and triangular FEs used for discretisation in SEEP/W, together with initial conditions and BCs used in the transient infiltration analysis. The approximate element size is 1×1 m, except in the near-surface zone where four additional 0.5-m-high regions parallel to the slope surface were added. A constant total hydraulic head of 228 m, applied along the right edge of the model, represents the average working level of the Valiči Reservoir (see Fig. 5 and Arbanas et al. 2017). According to the GWL

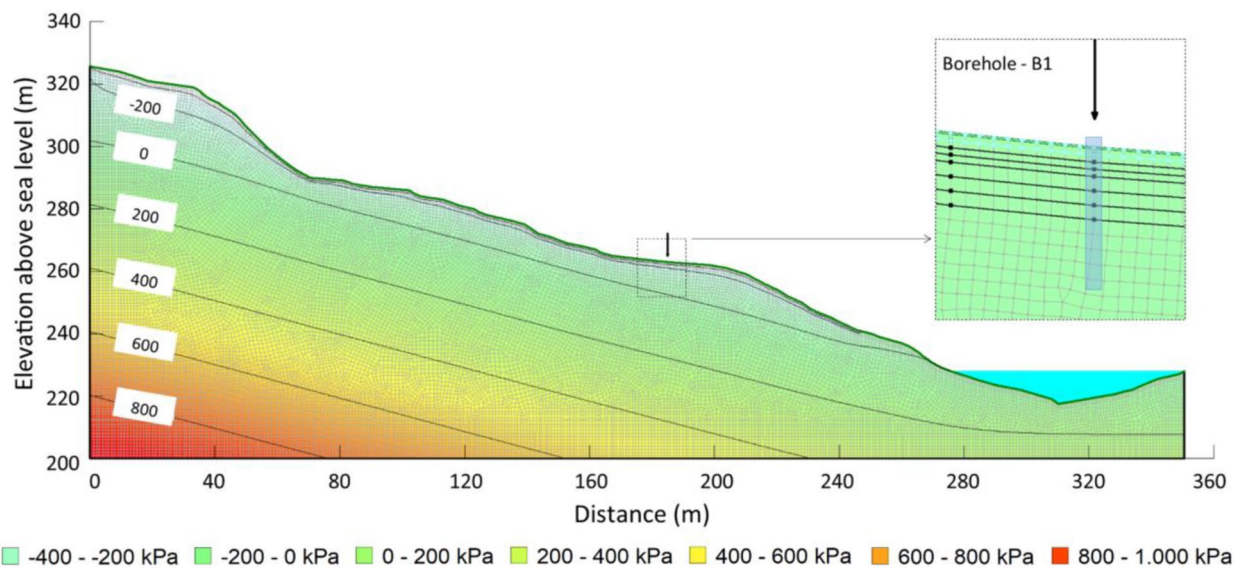


Fig. 7 2D numerical model with FE mesh and pwp distribution obtained from the steady-state analysis in SEEP/W

measurements and the results of the slope stability back analysis (Peranić et al. 2021), a constant total hydraulic head of 301.8 m is defined along the left boundary of the model. The lower boundary is modelled as impervious, while a q derived from hourly rainfall measurements is applied along the slope surface. To account for increased $u_a - u_w$ values in the near-surface soil, typically observed at the end of dry summer periods (Peranić et al. 2018a, 2020a; Peranić and Arbanas 2020), a model is initialised by performing a steady-state analysis with $u_a - u_w = 300$ kPa in the uppermost region to a depth of 0.5 m. The resulting pwp distribution and GWL, shown in Fig. 9, are consistent with measurements on intact soil samples collected in summer 2016 and 2017 (Peranić and Arbanas 2020), as well as with measurements of natural water content carried out in several campaigns (e.g. Peranić et al. 2018a, 2020a), and with GWL measurements (Peranić et al. 2021). Following this, a transient seepage analysis was performed in combination with a slope stability analysis to investigate the influence of the temporal resolution of the rainfall data on the obtained results. High-resolution ($10'$) rainfall data collected for the period from 1 September 2013 to 14 February 2014 were used to derive 10-min, hourly and daily rainfall flux BCs, as shown in Fig. 8. The derived q were applied along the soil-atmosphere interface and three separate analyses were performed. Since the objective of the study is to investigate the role of temporal resolution of rainfall data on the outcome of numerical analysis of rainfall infiltration and slope stability, and considering that the rainfall event considered in this study is a long-lasting and mostly uninterrupted rainfall event, only positive (downward) water fluxes were considered in this study. However, an important limitation of the study is that upward water fluxes due to evaporation and transpiration were completely neglected, which may have slowed down the wetting process and had a different impact on each of the analyses performed.

Further details on the derivation of the 2D landslide cross-section from the high-resolution DEM, details on the discretisation, selection of ICs and BCs and determination of the representative

unsaturated property functions used in the numerical model can be found in the cited literature.

Slope stability analysis

SLOPE/W is a component of the GeoStudio software suite (GEO-SLOPE International, Ltd.), which implements the LE method for 2D slope stability analyses. In this case, the pwp distributions obtained from SEEP/W were integrated into SLOPE/W.

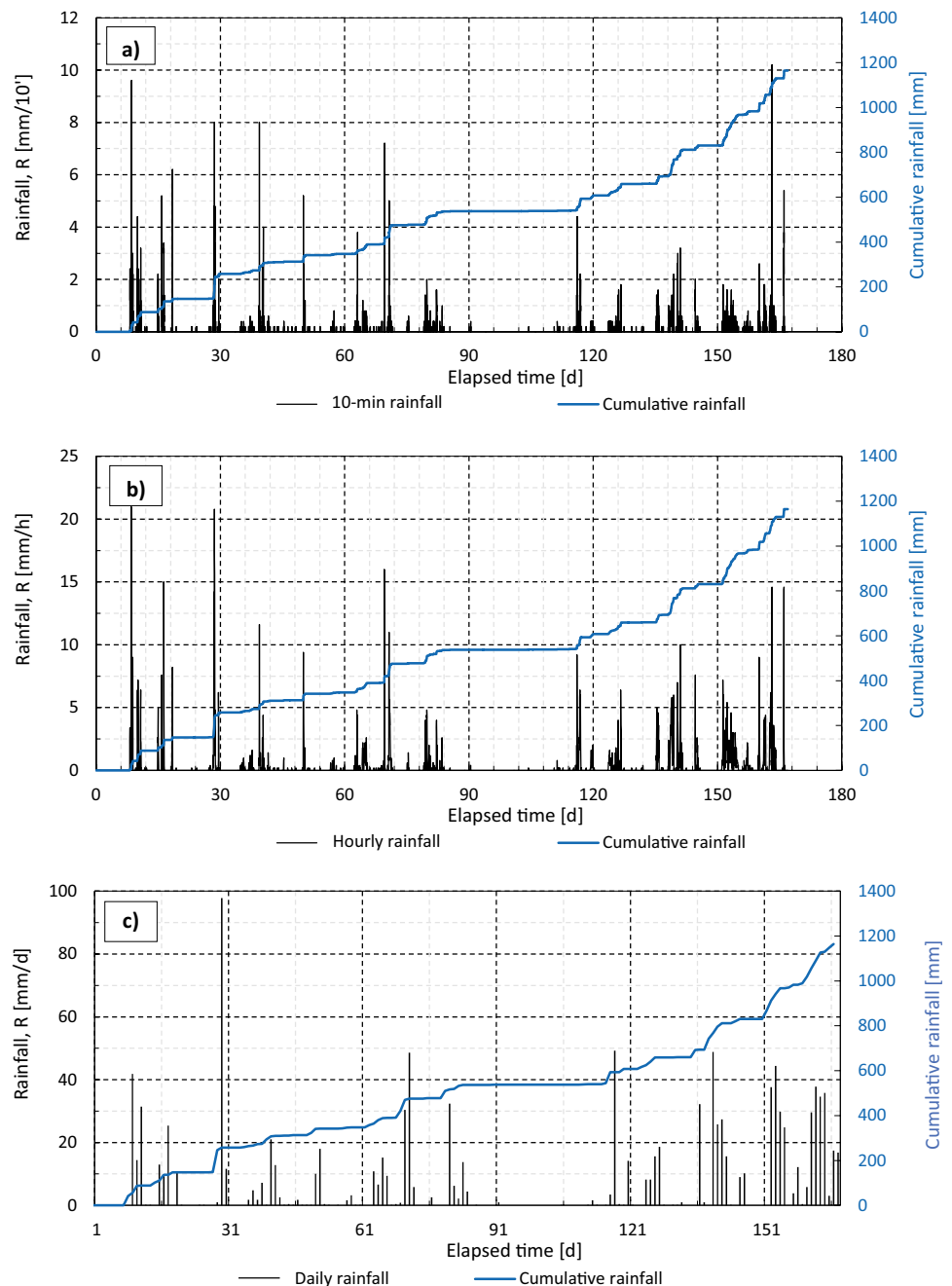
The shear strength properties for the homogeneous slope were defined according to the results of the slope stability back-analysis obtained by Peranić et al. (2021), which found that the resulting slip surface shown in Fig. 9 is consistent with the slip surface estimated by Mihalić Arbanas et al. (2015) and Arbanas et al. (2017) and confirmed by inclinometer measurements reported in Peranić et al. (2021). The slope stability analyses investigate the effect of transient rainfall infiltration on the factor of safety (FoS) value of the considered slip surface. The increase in shear strength due to $u_a - u_w$ is determined under a transient infiltration condition using a functional relationship respective to the WRC, as proposed by Vanapalli et al. (1996):

$$\tau = c' + (\sigma - u_a) \tan \phi' + (u_a - u_w) \left[(\tan \phi') \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right) \right] \quad (4)$$

where θ is the volumetric water content, θ_r is the effective cohesion, θ is the angle of internal friction and $(\sigma - u_a)$ is the net normal stress at the sliding surface.

As shown by Peranić et al. (2021), the shear strength component associated with $u_a - u_w$ increases the FoS value only in the early part of the analysis, when a significant portion of the slip surface is exposed to negative pwp. During persistent rainfall, $u_a - u_w$ is eventually dissipated from the slope profile and the stability of the slope depends only on the frictional shear strength component associated with the effective normal stress. It was also found that the change in

Fig. 8 Collected **a** 10-min, and derived **b** hourly, and **c** daily rainfall data used for derivation of a flux boundary condition in transient seepage analysis using SEEP/W



soil unit weight during transient infiltration has negligible effects on slope stability. Therefore, a constant (saturated) soil unit weight is used in this study. Table 3 summarises the material properties used in the slope stability analyses performed.

Results and discussion

Figure 9 shows the pwp distribution and FoS value obtained for initial conditions representative of 1 September 2013 (Peranić and Arbanas 2020; Peranić et al. 2020b, 2021). According to the results of the numerical simulation performed by Peranić et al. (2021), a homogeneous slope subjected to a realistic q derived from hourly rainfall data and represented with the hydraulic and shear strength

properties presented in Table 2 and Table 3 becomes unstable after 167 days of the simulation, i.e. on 14 February 2014—the day of reactivation. The FoS value fell below 1 only when the GWL for almost the entire domain reached the slope surface, zeroing $u_a - u_w$ in the soil cross-section. High GWL is often observed as a prerequisite for the occurrence of rainfall-induced landslides in flysch slopes of the valley (e.g. Benac et al. 2005; Vivoda et al. 2013).

In this study, analyses were conducted using the flux BCs with different temporal resolution; i.e. q was derived from (i) 10-min, (ii) hourly and (iii) daily rainfall collected from 1 September 2013 to 14 February 2014 in the vicinity of the Valići Landslide. In order to investigate the effect of the applied rainfall loads on the numerical results of the transient seepage and slope stability analysis, the pwp

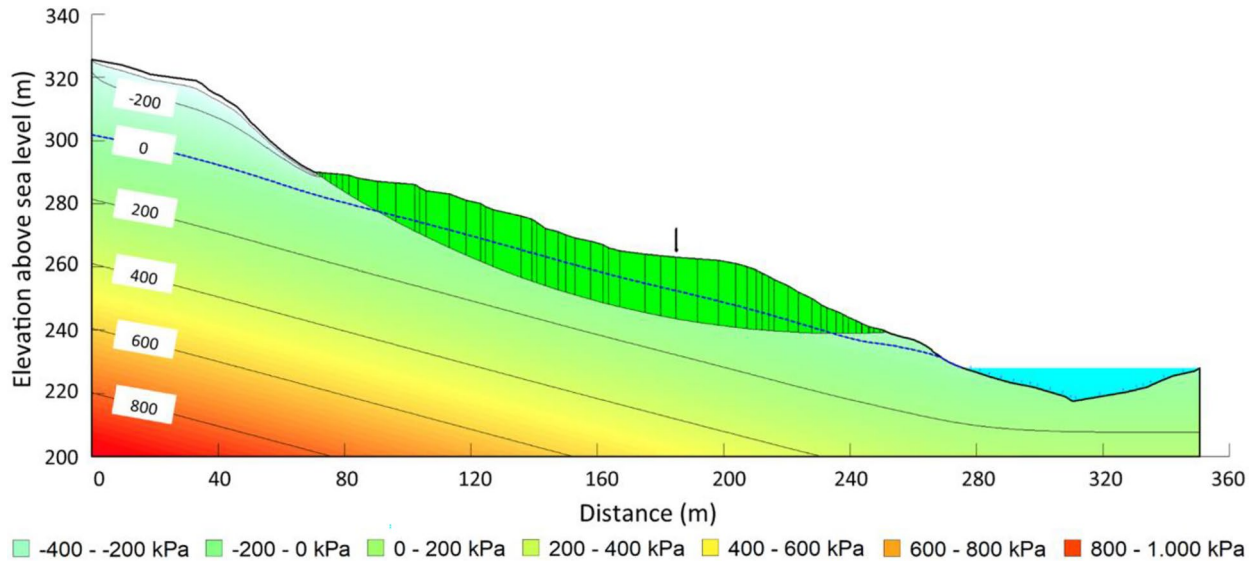


Fig. 9 Initial FoS value of the reactivated sliding surface for conditions representative of 1 September 2013

distributions obtained in SEEP/W were saved after each 24 h of simulation. In this way, a total of 167 pwp distribution profiles were obtained and introduced into the programme SLOPE/W to calculate the FoS values of the sliding surface under consideration, starting from conditions representative of 1 September 2013. In this sense, the results obtained provide information on how rainfall infiltration affects the change in the state of slope stability over time and, in this case, how different temporal resolutions of rainfall used to derive q affect the results of the numerical analysis. The calculation step chosen in the hydraulic analyses performed was always equal to the minimum temporal discretisation of the rainfall flux (i.e. 10 min, 1 h and 1 day) and the results were saved after each 24 h of analysis. For the LEM analysis, the discretisation in time was 1 day for all three types of analysis.

Figure 10a–c show the initial (FoS = 1.61) and pwp distributions calculated after 90 (FoS = 1.37, 1.47 and 1.47) and 142 days of transient seepage analysis (FoS = 0.99, 1.23 and 1.25) with q derived using daily, hourly and 10-min rainfall data, respectively, for the 5-m depth at the location of borehole B1 where the inclinometer measurements were taken (the location is indicated in Figs. 5a and 7). The calculated values of the degree of saturation are shown in the same form in Fig. 10d–f. The calculated pwp values at the location of borehole B1 are plotted against time for all three types of q in Fig. 11 to show how the temporal resolution of the input rainfall data affects the transient pwp values in the numerical model. Figure 11a and b show the values calculated at points of the FE mesh that are 5 and 2 m below the ground surface along the corresponding profile

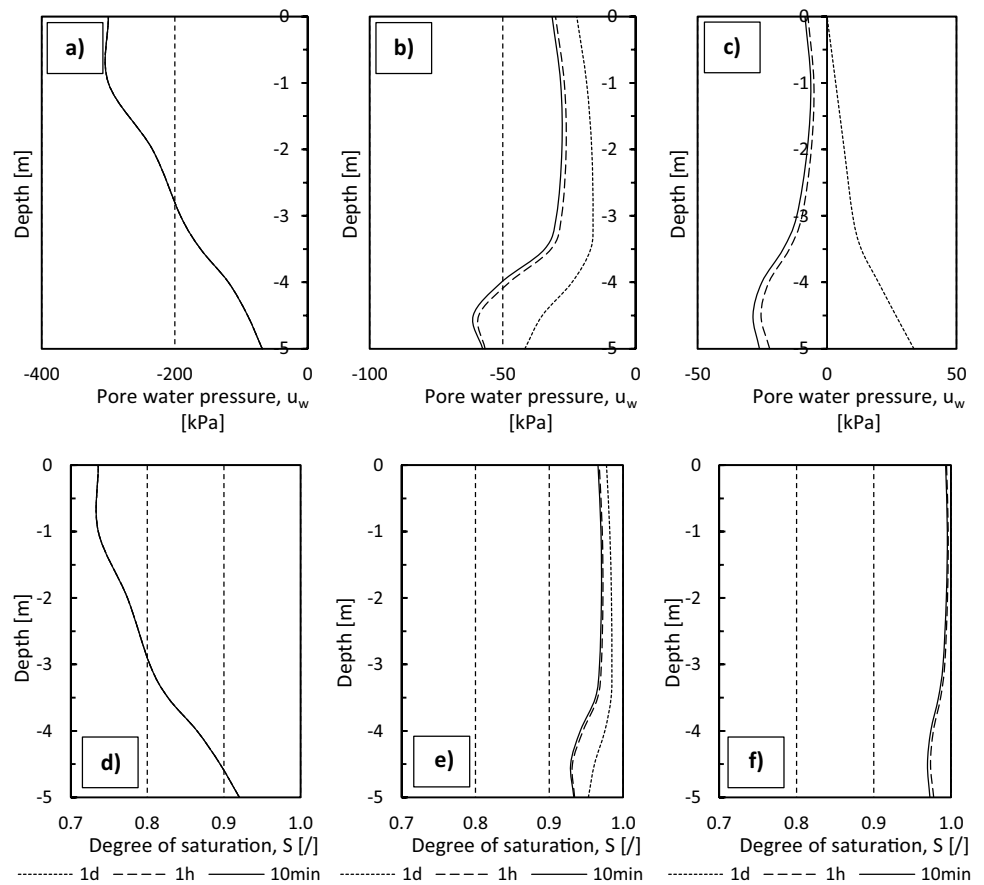
(see Fig. 7). The results of the slope stability analysis performed in SLOPE/W using 167 pwp distribution profiles from the transient infiltration analysis with different temporal resolutions of rainfall data used to derive q are summarised in Fig. 12. The results obtained show that the use of coarse resolution rainfall data, such as daily rainfall measurements, for the derivation of q leads to higher values of calculated infiltrated volumes and pwp in a slope consisting of soil with relatively low hydraulic conductivity. The data presented in Fig. 12 suggest that the differences in calculated FoS values are negligible when 10' or hourly rainfall data were used to define q . However, the numerical simulation predicted the occurrence of slope failure after only 142 days of analysis when daily rainfall was used, i.e. on 19 January 2014 or 25 days earlier than observed in the field. Potentially critical hydraulic conditions are also evident from the results of the infiltration analysis. For example, the data in Fig. 10c and f show that the $u_a - u_w$ has been completely dissipated in the profile under consideration, with the degree of saturation reaching the value of 1 up to the slope surface.

As the number of calculation steps in each considered case is equal to the number of input rainfall data q , the differences in numerical simulation results suggest the effects of averaging permeability and rainfall quantities on different temporal basis. According to the results presented, averaging on a coarser temporal basis leads to a greater reduction in the calculated FoS values than is the case with finer resolution. When rainfall is applied to initially dry soil, as in the case considered in this study, the hydraulic conductivity of the soil gradually increases, while the hydraulic gradient simultaneously decreases with the advancement of the wetting front. Eventually, the infiltration capacity drops to a constant value. The calculated infiltrated volumes are therefore closely related to the temporal variations in rainfall intensity and the hydraulic conductivity of the soil: if the applied rainfall exceeds the instantaneous infiltration capacity of the soil, the excess water that cannot be infiltrated into the soil can either generate a positive pwp by

Table 3 Material properties used in SLOPE/W

Failure envelope	c' [kPa]	ϕ' [°]	γ [kN/m ³]
Extended Mohr–Coulomb	0	29	19

Fig. 10 Pore water pressure and degree of saturation calculated from daily (1 day), hourly (1 h) and 10-min rainfall data for the first 5-m depth at the site of borehole B1 at the beginning (a, d), after 90 (b, e) and 142 (c, f) days of transient seepage analysis



ponding at the soil surface or generate surface runoff. Since the formation of ponding on a natural or artificial slope is unrealistic, numerical modelling usually applies a special condition to prevent

the build-up of a positive pwp at the slope surface. Normally, the algorithms equal the pwp value to 0 when the formation of a positive pwp is detected, eliminating the excess of water volume that

Fig. 11 The calculated pwp values at the location of borehole B1 against time for all three types of q with respect to a point of the FE mesh located a) 5 m and b) 2 m below the ground surface

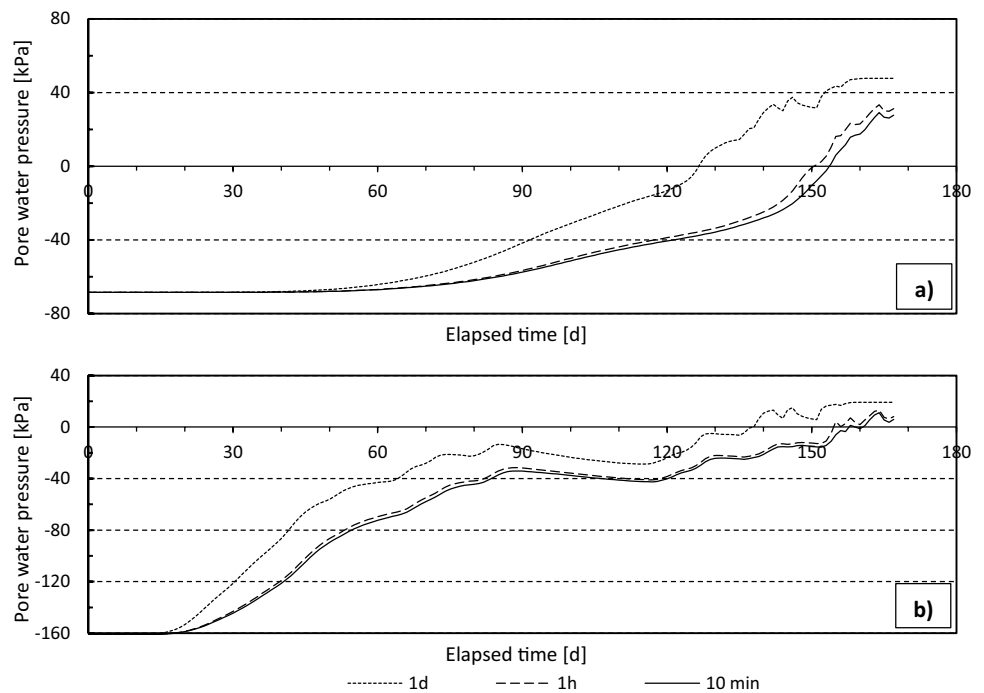
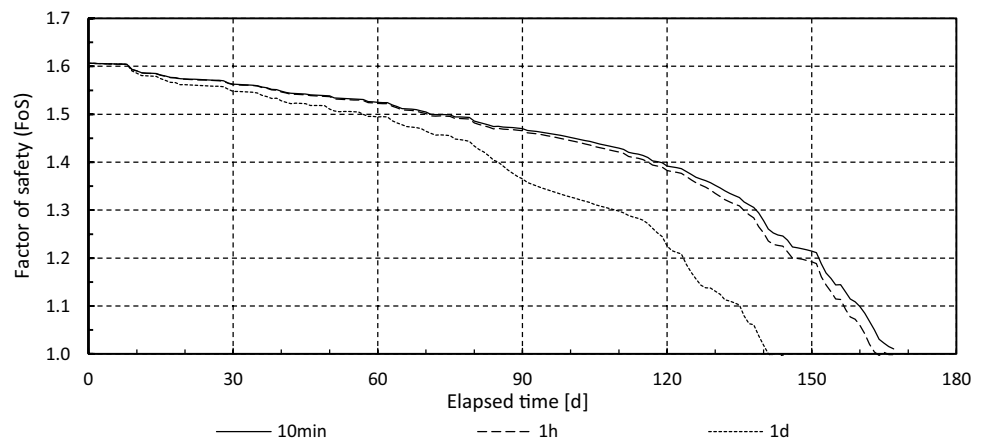


Fig. 12 FoS values calculated for pwp profiles obtained for different temporal resolutions of rainfall data

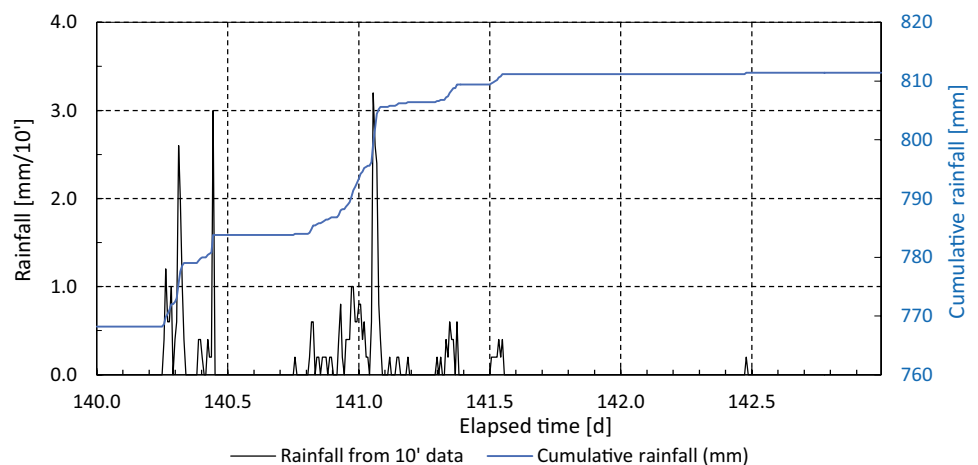


cannot be infiltrated during the simulation step (Geoslope 2005). The latter can be considered a numerical tool to account for the formation of a surface runoff.

The results presented suggest that in analysis of the transient infiltration of rainfall into the slope built of soils with relatively low hydraulic conductivity, the rainfall data used in derivation of the q should be defined using high-resolution rainfall measurements. Although the measurement interval of 10 min probably results in the most realistic hydromechanical response of slope, hourly collected rainfall measurements seem to be the optimal form of input data for the case under consideration, in terms of computational effort and accuracy of the results obtained compared to those from 10-min input data. On the other hand, coarse rainfall input data and the averaging of hydraulic conductivity on a daily basis can, for example, lead to the calculation of unrealistically high amounts of infiltrated water. This seems to be the case especially for rainfall events of short duration and high intensity. For example, Fig. 13 shows 10-min rainfall data measured on 19, 20 and 21 January 2014

(days 141 to 143 in the numerical analysis, with the 142nd day being the one for which $FoS = 1$ when daily rainfall is used to derive q). On these three days, 25.2, 17.8 and 0.2 mm of the total daily rainfall fell, respectively. Assuming that the k_s value roughly represents the amount of rain that can be infiltrated into the slope at a hydraulic gradient of 1, averaging the hydraulic conductivity and rainfall on a daily basis would result in about 16% of the daily rainfall (4 mm) being infiltrated into the slope on 19 January. Averaging on an hourly and 10-min basis, on the other hand, reduces the infiltrated amounts to 1.7 mm and 1.1 mm (or 6.8% and 4.3% of the daily rainfall) for the rainfall record. Similarly, the following day received a total of 17.8 mm of rainfall. The averages on a daily, hourly and 10-min basis show infiltration of 4, 1.5 and 0.9 mm or 23.4, 8.6 and 4.9% of the daily rainfall. Finally, when hydraulic conductivity and rainfall amounts are averaged, there is no surface runoff on a daily basis on the 143rd day of analysis, 15% of daily rainfall does not infiltrate the slope on an hourly basis and only 14% of daily rainfall infiltrates when averaging on a 10-min basis is considered.

Fig. 13 Rainfall data singled out for the analysed period: 141st to 143rd day of numerical analysis (19–21 January 2014)



Conclusions

Numerical modelling has proven to be a useful tool for studying rainfall-induced landslides. While much attention has been paid to the influence of different rainfall patterns, the effects of spatial variability and intermittency of rainfall, or the temporal patterns of rainfall intensity, very little attention has been paid to the influence of the temporal resolution of the rainfall data used in derivation of q in numerical modelling of rainfall induced landslides—especially in the case of deep-seated landslides occurring in slopes composed of soils with low hydraulic conductivity.

In this study, a 2D numerical model recently developed by Peranić et al. (2021), capable of reproducing conditions that led to reactivation of deep-seated landslide in flysch slope due to prolonged rainfall, was used to investigate how different temporal resolutions of realistic rainfall data (10-min, hourly and daily rainfall measurements) used in the derivation of the q in the transient seepage analysis affect the numerical simulation results. The obtained results are analysed and discussed with respect to both the hydraulic analysis and the stability analysis. Important limitations of the study are that the model considers a single-phase flow through a homogeneous slope assigned with hydraulic properties representative of the surficial residual soil undergoing the wetting process, and that upward water fluxes due to evaporation and transpiration have been completely neglected in the derivation of q .

The results obtained indicate that the use of coarse resolution rainfall data, such as daily rainfall, could lead to the calculation of unrealistically high infiltrated volumes for the case of slopes built of fine-grained soils with relatively low hydraulic conductivity. Consequently, a faster increase in pwp and a reduction in the FoS at an unrealistically high rate are predicted by the model, leading to a conservative prediction of the time to failure of the slope. The latter is related to the averaging of hydraulic conductivity and rainfall on a coarse time basis. In reality, a smaller portion of the rainfall would be infiltrated, while the rest would lead to runoff generation. The results obtained show that the use of daily rainfall data leads to a faster reduction of the FoS value, which could be of great importance in the integration of numerical modelling in landslide early warning systems to reduce the number of false alarms. The results obtained for the case study considered, i.e. landslide reactivation in flysch slopes, suggest that hourly rainfall data is the optimal form of input data. To what extent the temporal resolution of rainfall data affects the results of numerical models in case of slopes in different geological and climatic contexts and to what extend upward water fluxes due to evaporation and transpiration affect the results of the analyses carried out are some of the questions for the following studies. The approach used in this study could serve as an example for such research.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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