Ceccatelli *et al. Geoenvironmental Disasters* (2017) 4:23
DOI 10.1186/s40677-017-0087-8

Geoenvironmental Disasters

SHORT REPORT **Open Access**

Numerical modeling and characterization of a peculiar flow-like landslide

Mattia Ceccatelli*, Giovanni Gigli, Luca Lombardi, Massimiliano Nocentini and Teresa Salvatici

Abstract

Background: On March 25th, 2015, a rapid landslide occurred upstream of the village of Gessi-Mazzalasino, in the municipality of Scandiano, affecting two buildings.

Rapid landslides, due to their high velocity and mobility, can affect large areas and cause extensive damage. Considering the often unpredictable kinematics of landslides, the post-failure behavior has been studied by many authors to predict the landslide runout phase for hazard assessment.

Findings: With the aim of characterizing the Gessi-Mazzalasino landslide, field surveys were integrated with the results of laboratory tests. The geometric characteristics (thickness, area and volume) and kinematic aspects of the landslide were estimated by using a laser scanning survey and geomorphological data.

To model the landslide and obtain its rheological parameters, a back analysis of the event was performed by means of a depth-averaged 3D numerical code called DAN3D. The results of the back analysis of the landslide propagation were validated with field surveys and velocity estimations along selected sections of the landslide.

Finally, potential areas prone to failure or reactivation were identified, and a new simulation was performed that considered the back-calculated rheological parameters.

Conclusions: Rapid landslides are one of the most dangerous natural hazards and are one of the most frequent natural disasters in the world. Therefore, prediction of post-failure motion is an essential component of hazard assessment when a potential source of a mobile landslide it is located.

To assess the risk affecting the area, both numerical and empirical methods have been proposed, in order to predict the runout phase of the phenomenon.

For the numerical modelling of the landslide, carried out with DAN-3D code, the best results were obtained by using a Voellmy reological model, with a constant turbulence parameter (ξ) of 250 m/s^2 and a friction parameter (μ) comprised between 0.15 and 0.19.

The rheological parameters obtained through dynamic back analyses were used to evaluate the propagation phase and the deposition areas of new potential landslides, that could affect the same area of the 25th March 2015 event.

The predicted runout length obtained by the DAN3D software was compared to runout lengths predicted by the Corominas (Can Geotech J 33:260–271, 1996), (Nat. Hazards 19, 47-77) and (UNICIV Report, R-416, School of Civil & Environmental Engineering, UNSW, Sydney Australia 2003) empirical relations.

All the data confirm that the impact area of possible future events will be smaller than the 2015 event, probably due to the safety measures established after the landslide.

Keywords: *Landslide*, *Geotechnical characterization*, *Runout simulation*, *Scandiano*

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Introduction

Rapid landslides such as debris flows, debris avalanches, rock avalanches and flow slides are instability phenomena that affect superficial deposits as a consequence of intense and prolonged rainfall events. Rapid landslides are one of the most dangerous and frequent natural hazards in the world and can cause significant damage to goods and people in their path.

Guzzetti (2000) showed that more than 80% of the deaths and injuries due to landslides in Italy were related to fast-moving failures, including debris flows, rockfalls, rockslides, and soil slips.

At approximately 07:00 PM on March 25th, 2015 a rapid landslide was triggered upstream of the village of Gessi-Mazzalasino, in the municipality of Scandiano (Emilia Romagna region), in north-central Italy (44°34′45″N,10°39′18 E, Fig. 1) due to days of heavy and persistent rainfall.

The landslide was triggered at approximately 220 m a.s.l. and reached the village, causing slight damage to two buildings that were evacuated.

One of the main challenges regarding the analysis of rapid landslides is that they are affected by different mechanisms during the failure and post-failure stages

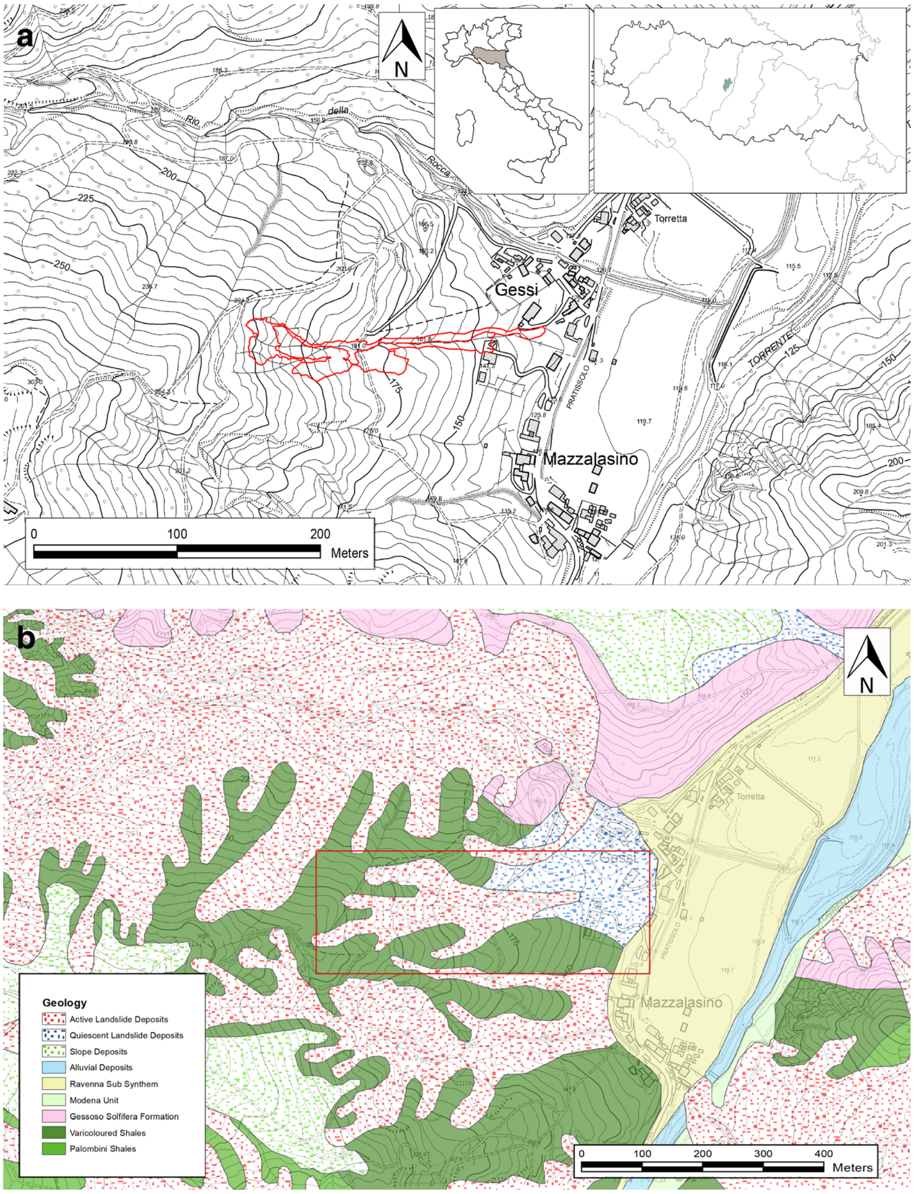

Fig. 1 **a** Topographic map and **b**) geological map of the study area (from Servizio Geologico Sismico e dei Suoli, Emilia Romagna region, 2011)

(Bandara et al., 2016). Many studies can be found in the literature that are focused on the analysis of landslides using experimental and mathematical methods.

Empirical formulas derived from the statistical data of past landslides can provide valuable information (Hsü, 1975; Corominas, 1996), but these formulas are generally approximations, and the obtained information is usually limited to specific contexts. To better understand the effects of landslides, numerical modeling is a particularly useful tool that is capable of capturing the entire landslide process in both space and time. In this paper, we conduct a combined analysis, via both empirical and numerical approaches, to characterize the 2015 phenomenon and to obtain additional information for a risk assessment of the area.

A back analysis of the post-failure behavior was conducted with the DAN3D code (McDougall & Hungr, 2004; Hungr & McDougall, 2009), using a trial and error procedure, to obtain the rheological parameters of the March 25th, 2015 phenomenon.

DAN3D was developed for the simulation of extremely rapid landslides, even in complex topographies (McDougall & Hungr 2004, Salvatici et al. 2017). Since this code is also capable of simulating material motion and its corresponding rheological changes (Hungr, 1995), DAN3D was used to study the 2015 event. The simulation results were validated by means of runout lengths and flow velocities derived from empirical runout prediction methods.

Finally, a forecast analysis was carried out to evaluate the characteristics of potential landslides that could occur in the area in the future, using the rheological parameters obtained by the back analysis of the 2015 event and the post-event digital elevation model (DEM) of the area.

Study area and landslide description

Study area

The study area is located in the municipality of Scandiano, in the Emilia Romagna region. The landslide affected the western slope of the Tresinaro Valley, above the village of Gessi-Mazzalasino.

The area is geologically characterized by units of the External Liguride domain and the Neogene-Quaternary succession of the Northern Apennines. The External Liguride domain consists of thin calcareous turbiditic formations known as the Palombini Shales and Varicolored Shales, while the Neogene-Quaternary succession in this area is represented by the Gessoso-Solfifera Formation, the alluvial units of the Ravenna Subsynthem, and the Modena Unit (Amorosi, 1999).

Several active and inactive landslide deposits are also located in the area; the 2015 landslide originated from one of these deposits (Fig. 1).

Landslide description

The landslide source area is located on the slope upstream of the village of Gessi-Mazzalasino (Fig. 2) at an elevation between 230 and 215 m a.s.l. The triggering event was likely heavy rainfall that occurred a few days before the event. The Cà de Caroli weather station, located 1 km northeast of the study area, recorded more than 100 mm of rainfall over a 10-day period (Fig. 3), with a peak rainfall intensity of approximately 60 mm on March 25th (Fig. 4); for comparison, the annual average rainfall at this station is approximately 750 mm.

The source area is approximately 1700 m^2 and has an irregular shape. The average slope of the source area is approximately 17–20°, but the slope increases up to 30–35° in the triggering area.

The initial failure triggered at approximately 220 m a.s.l., approximately 20 m below the ridge. This altitude difference may reflect an increase in the pore pressure due to the hydraulic head, which may represent an additional instability parameter of the slope in addition to the heavy rainfall.

The flow-like landslide, after initially spreading in a flat area in the middle sector of the slope, moved through an existing impluvium and reached the inhabited area at the foot of the hill, 450 m below the source area.

The thickness of the deposits ranges from a few decimeters up to 2–3 m in the most significant accumulations areas.

Field evidence showed that the mass movement started as a sliding mass of the surface layers at the upper part of the slope and evolved into a rapid mud flow at the top of the impluvium, where the flow was channeled into, probably due to the addition and mixing of surface water during the mass movement. The source volume, approximately 10,000 m^3, and the planimetric area of the landslide have been identified from the field observations and aerial images that were collected after the event.

Geotechnical characterization

Two soil samples were collected from the landslide deposits immediately after the event to perform a geotechnical characterization of the materials and recreate the initial flow conditions.

The first soil sample was collected in the deposit area at the beginning of the channelized section, and the second sample was collected at the landslide toe (Fig. 5). These samples were subjected to the following laboratory tests: index property testing, Atterberg limits testing, grain size analysis, and direct shear testing.

In addition, three geotechnical in situ tests were carried out with the aim of collecting further information about the soil in its natural condition. Specifically, two

Fig. 2 Aerial photograph of the Gessi-Mazzalasino landslide (photo by G. Bertolini)

permeability measurements were carried out with a constant compact head permeameter (Amoozemeter) and one measurement of shear strength was carried out with a borehole shear test (BST).

The in situ tests were carried out both outside of the landslide area (test number 3) and within the landslide deposit (test number 4).

The BST tests were performed on soils in unsaturated conditions; at an equivalent depth, matric suction values $(u_a - u_w)$ were measured with tensiometers.

The BST results were interpreted using the Fredlund et al. (1978) shear strength equation for unsaturated soils.

$$\tau = c' + (\sigma - u_a)\tan\Phi' + (u_a - u_w)\tan\Phi'_b \qquad (1)$$

where τ is the shear strength, c' is the effective cohesion, σ is the total normal stress, u_a is the pore air pressure due to surface tension, ϕ' is the effective friction angle, u_w is the pore water pressure, and ϕ_b is the angle

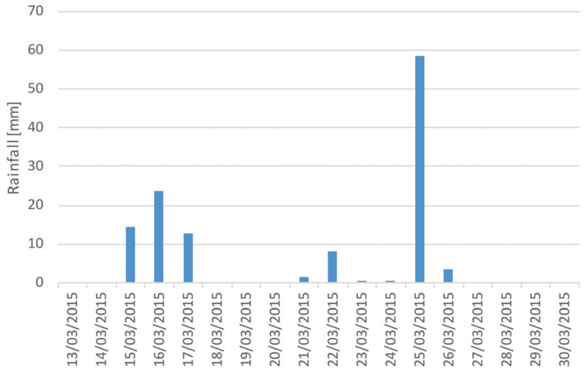

Fig. 3 Daily rainfall intensity from 13/03/2015 to 30/03/2015

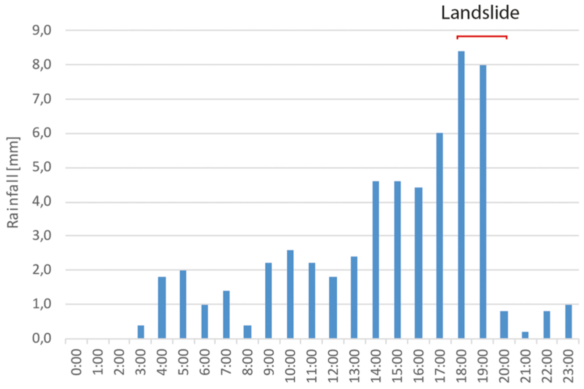

Fig. 4 Hourly rainfall intensity on 25/03/2015

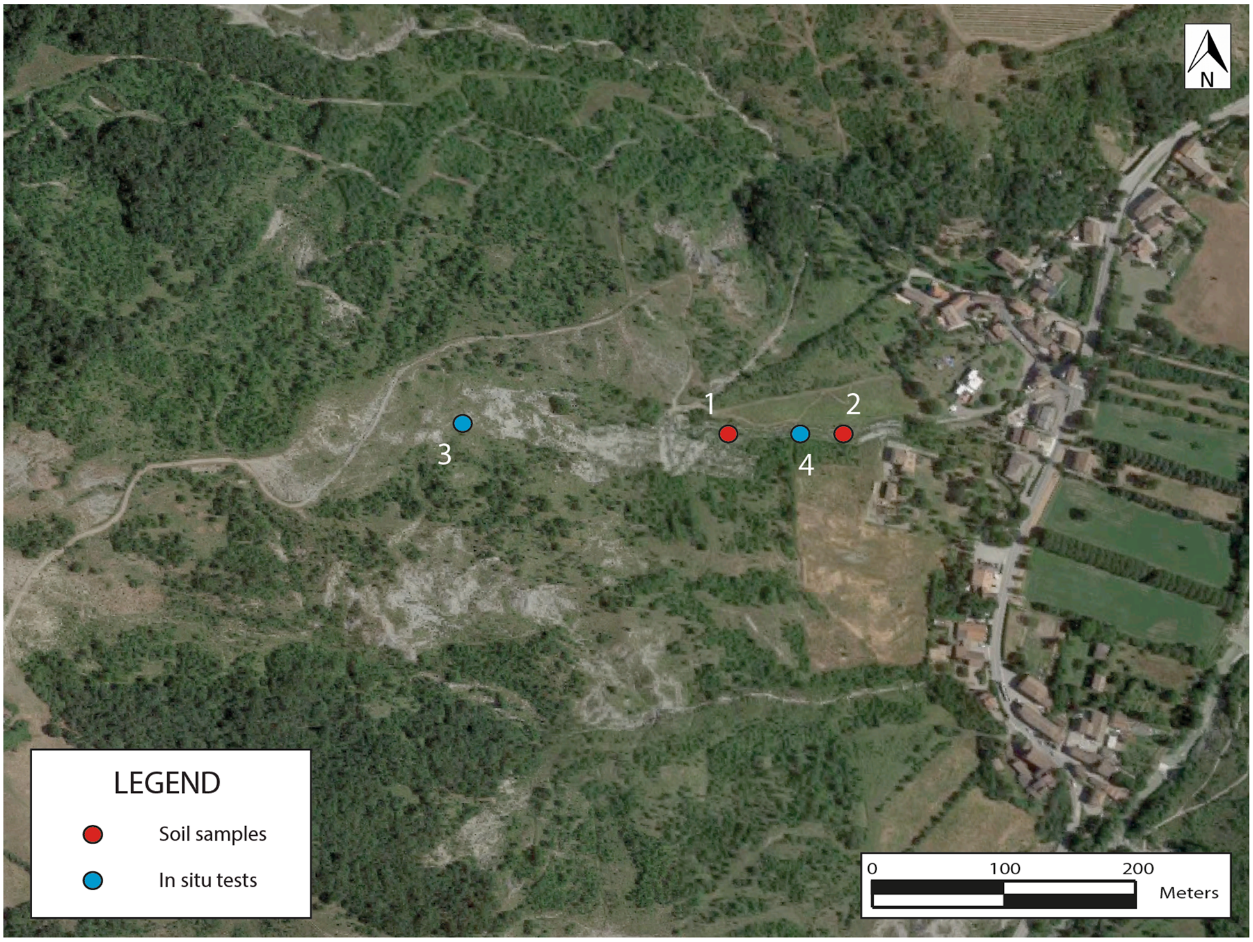

Fig. 5 Location of the soil samples (in red) and the geotechnical field investigation (in cyan); point 3: permeability measurement; point 4: permeability measurement and BST

expressing the rate of the increase in strength related to matric suction. The BST test results show that the internal friction angle equals 33.8°.

The procedure used for measuring k_s in the field is called the constant-head well permeameter technique (Philip, 1985), and it is carried out in a borehole. This procedure allowed us to measure the amount of water flowing through the soil in a given time interval under soil-saturated conditions. The saturated permeability of the soil is evaluated with the Glover solution:

$$k_s = \frac{Q\left[\sin^{-1}(h/r) - \left(\frac{r^2}{h^2} + 1\right)^{\frac{1}{2}} + r/h\right]}{2\pi h^2} \qquad (2)$$

where Q is the steady-state rate of water flow from the permeameter into the soil, $\sinh^{-1}$ is the inverse hyperbolic sine function, h is the depth of water in the borehole, and r is the radius of the borehole.

The measured saturated hydraulic conductivity ranges from 2.19×10^{-6} m/s to 5.19×10^{-7} m/s, corresponding to samples 3 and 4.

Samples 1 and 2 are primarily unsorted silty soils (Fig. 6) and are classified as a clay of low plasticity (CL) and a silt (ML), respectively, following the Unified Soil Classification System (USCS, Wagner, 1957). The samples have plasticity index (IP) values ranging from 8 to 11.

Direct shear tests were performed on reconstituted samples, using normal stresses between 40 and 80 kPa, determined from the in situ characteristics. The internal friction angle ranges from 29.1 to 30.1°, while the cohesion (c') is very low. The results of the laboratory and in situ tests are shown in Table 1.

In Fig. 7, the matrix compositions of the two soil samples from the 2015 landslide are compared with the compositions of earth flows, debris flows and mud flows from several areas of the world (Hungr et al., 2001).

Hungr et al. (2001) distinguished different materials involved in flow-like landslides on the basis of several

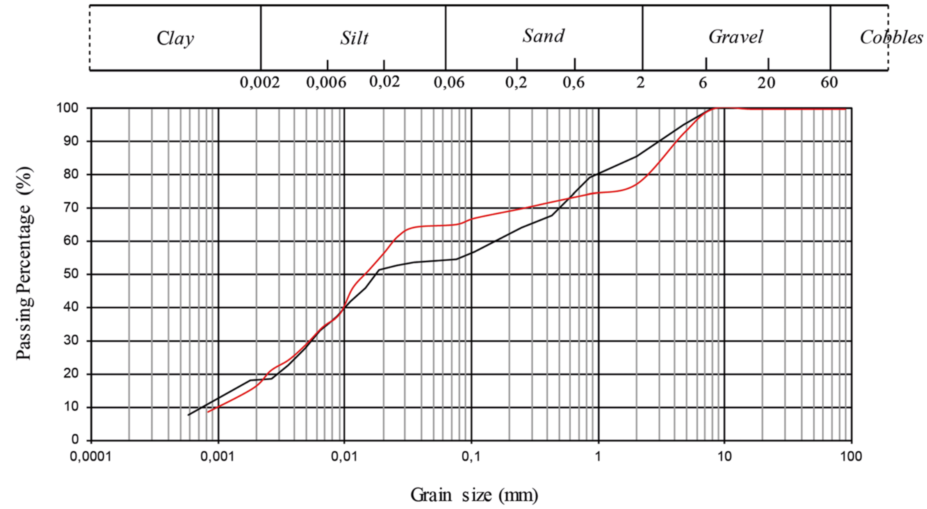

Fig. 6 Granulometric curves for the two soil samples (black line for sample and red line for sample 2)

material geotechnical properties. Both the samples from the 2015 landslide deposit had low plasticity indices (IP =11 for sample 1 and IP = 8 for sample 2) and the liquidity index (IL) values were approximately 0.6 and 0.5, respectively.

As shown in Fig. 7, the matrix compositions of the 2015 landslide samples fall in the textural field of earth flows and mud flows, while debris flows typically contain less than 30% silt and finer particles.

A comparison of colloidal indices does not allow a clear distinction to be made between these two different classes. Earth flows have clay contents ranging from 10% to 70%, averaging approximately 35%, while debris and mud flows are usually not plastic or are only weakly plastic. However, some mud flows derived from volcanic sources may have clay contents greater than 10% and plasticity indices of more than 10 (Jordan, 1994).

Table 1 Geotechnical parameters obtained from laboratory and in situ tests

Sample	1	2	3	4
USCS classification	CL	ML	–	–
Porosity [%]	40.1	39.7	–	–
Void ratio [–]	0.67	0.7	–	–
Saturation degree [%]	118.3	117.9	–	–
Total unit weight [kN/m^3]	20.2	19.9	–	–
Statured unit weight [kN/m^3]	19.5	19.3	–	–
Liquid limit	34	33	–	–
Plastic limit	23	25	–	–
Plasticity index [%]	11	8	–	–
Liquidity index [%]	0.6	0.5	–	–
Friction angle [°]	30.1	29.1	33.8	–
Cohesion [kPa]	2	5	0	–
Permeability [m/s]	–	–	2.19×10^{-6}	5.19×10^{-7}

Therefore, the distinction between “mud” and “earth” should not be based solely on grain size distribution but should instead be derived from the context of each landslide class.

Specifically, earth flows and mud flows may involve material of similar texture but are significantly different in other ways; in particular, the velocity of movement during an earth flow differs from that of a mud flow.

Velocity analysis

There are many equations in the literature for estimating the velocity of the frontal part of flow-like landslides (Hungr et al. 1984). These relations provide a useful parameter to validate the back analysis results (Salvatici et al., 2017, Nocentini et al., 2015).

In this work, flow velocity was estimated in the channelized section of the landslide, along the cross sections shown in Fig. 8, by using two methods: the superelevation of the debris surface in the channel belt (Johnson & Rondine, 1984) and the Poiseuille equation (Hungr et al., 1984).

The Johnson & Rondine (1984) relation is based on the difference in the splash heights on the inside and outside of the bends in the flow path (Nocentini et al., 2015).

The superelevation of the debris wave around the channel bends tends to be higher than that on the opposite side due to the centrifugal force (Fig. 9).

Thus, in cross sections 1 and 2, the velocity can be calculated by using the following equation:

$$v = \sqrt{gR\cos\delta\tan\beta} \qquad (3)$$

where β is the angle between the line connecting the top of the debris waves at both sides of the section and a

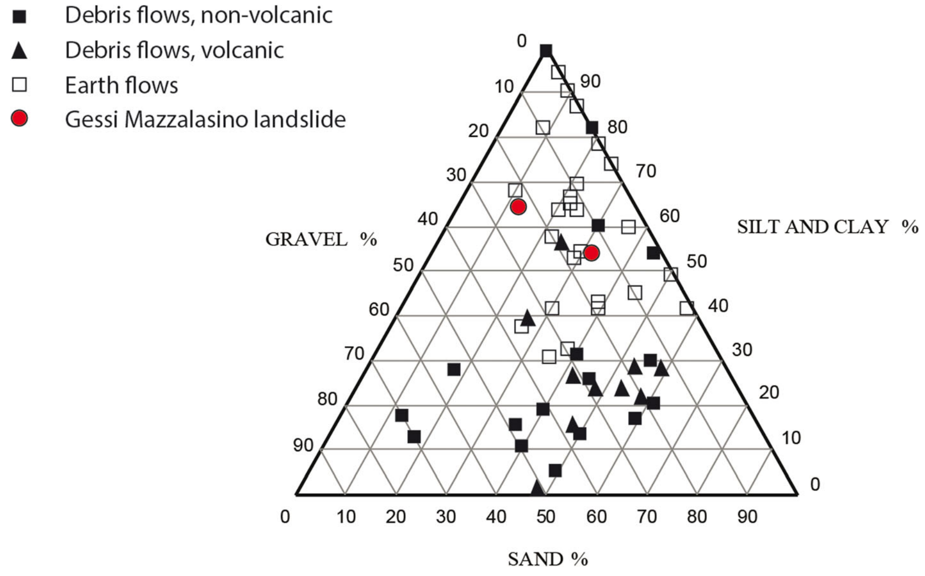

Fig. 7 Ternary plot of the two soil samples with textural classification (from Hungr et al., 2001)

horizontal line, δ is the slope angle of the flow path, R is the radius of curvature and g is the gravity acceleration.

The radius of curvature of the channel was obtained graphical processing using a 1:5000 topographic map.

The Hungr et al. (1984) relation, which is based on the Poiseuille equation, can be used to evaluate the flow velocity in the straight sections (cross sections 3 and 4). This equation relates the velocity to the geometric characteristic of the path, the unit weight of the flow mass, and the viscosity of the flow mass:

$$v=\frac{\gamma\,\sin\delta H^2}{lv} \tag{4}$$

where y is the unit weight of the material and is obtained by laboratory test, δ is the slope angle of the flow path, H is the flow depth, l is a constant based on the cross-sectional shape of the channel (3 for a broad channel and 8 for a semicircular channel) and v is the dynamic viscosity of the flow (assumed to be 3, as indicated by Hungr et al., 1984).

The results of the estimated velocity and the geometric parameters of the path are summarized in Tables 2 and 3.

Laser scanning survey

New high-resolution surveying techniques, such as terrestrial laser scanning, quickly obtain detailed 3D terrain models that can be employed in runout analyses (Gigli et al., 2014).

A laser scanning investigation was performed during two field surveys, on April 1st, 2015, and April 16th, 2015, by means of a long-range 3D terrestrial laser imaging sensor (RIEGL LMS-Z420i device), which is able to determine the position of up to 12,000 points per second, with a maximum angular resolution of 0.008° and an accuracy of ±10 mm from a maximum distance of 800 m.

To completely cover the intervention areas and avoid the shadow areas, were captured four scans from different positions (Fig. 10).

Several laser cylindrical reflectors were placed on the hill slopes, and their coordinates were defined by performing a GPS survey. These tie points were later used to align the point clouds. This process is required for correctly georeferencing the point cloud on a chosen reference system and for merging two or more scans of the same object realized from different points of view.

On April 22nd, 2015, another GPS survey was carried out to reconstruct the exact geometry of the landslide body, define the source area and identify trenches that could develop into the edges of potential detachment areas.

The data obtained from the laser scanning surveys have been processed to obtain a high-resolution DEM of the area (Fig. 11).

Some DEM sectors outside of the landslide were not acquired due to the presence of buildings and dense vegetation, particularly near the toe portion; therefore, it was necessary to integrate the model with an existing 1:5000 topographic map.

During the data processing, the safety works on the landslide started. These works, in an initial phase, included the construction of an earthfill dam (Fig. 12) to prevent the excessive expansion of future landslides and to channel the flow of those potential landslides towards the existing channel. One last GPS survey, on September 9th, 2015, was carried out to detect the geometry and

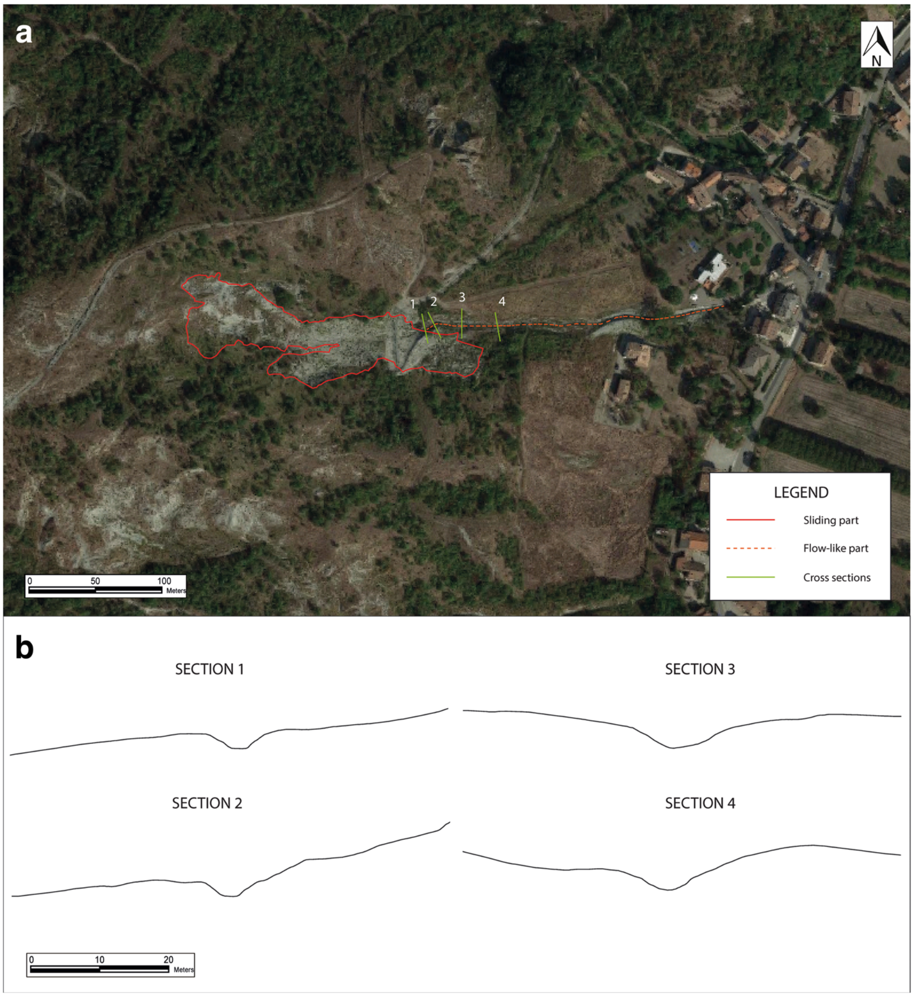

Fig. 8 Location of the cross sections for flow velocity estimation. **a**) Location of the cross sections for flow velocity estimation and **b**) Sections profiles

location of the earthfill dam, which was then implemented in the digital terrain model, to capture the modified shape of the slope and the post-landslide conditions.

Runout simulation methods

Methods to predict landslide runout were grouped into two categories by (Rickenmann 1999): the first group includes empirical methods that are based on statistical analyses of past events (Iverson, 1997; Corominas, 1996; Hunter & Fell, 2003), and the second group includes analytical methods that account for conservation of momentum and energy to simulate the propagation of flow using 2D or 3D models (Hungr, 1995; McDougall & Hungr, 2004; Hungr & McDougall, 2006). In this work, the runout distance obtained by the DAN3D code was compared with that from empirical methods.

DAN3D numerical model

DAN3D is a 3D numerical model that uses the continuous Lagrangian approach for integrating the equations of Saint-Venant with depth.

The mass conservation equation governs the model:

$$\frac{\partial h}{\partial t} + h\left(\frac{\partial v_x}{\partial v_y} + \frac{\partial v_y}{\partial y}\right) = \frac{\partial b}{\partial t} \tag{5}$$

where b is the bed-normal erosion-entrainment depth, v_x and v_y are local flow velocities, and t is time.

DAN3D employs a simple semi-empirical approach based on the concept of "equivalent fluid", as defined by (Hungr 1995).

In this method, the landslides are considered one material governed by simple rheological relations. Therefore, an internal frictional rheology is considered, as well as a basal rheology that depends on one or two parameters (depending on the chosen rheological model) that

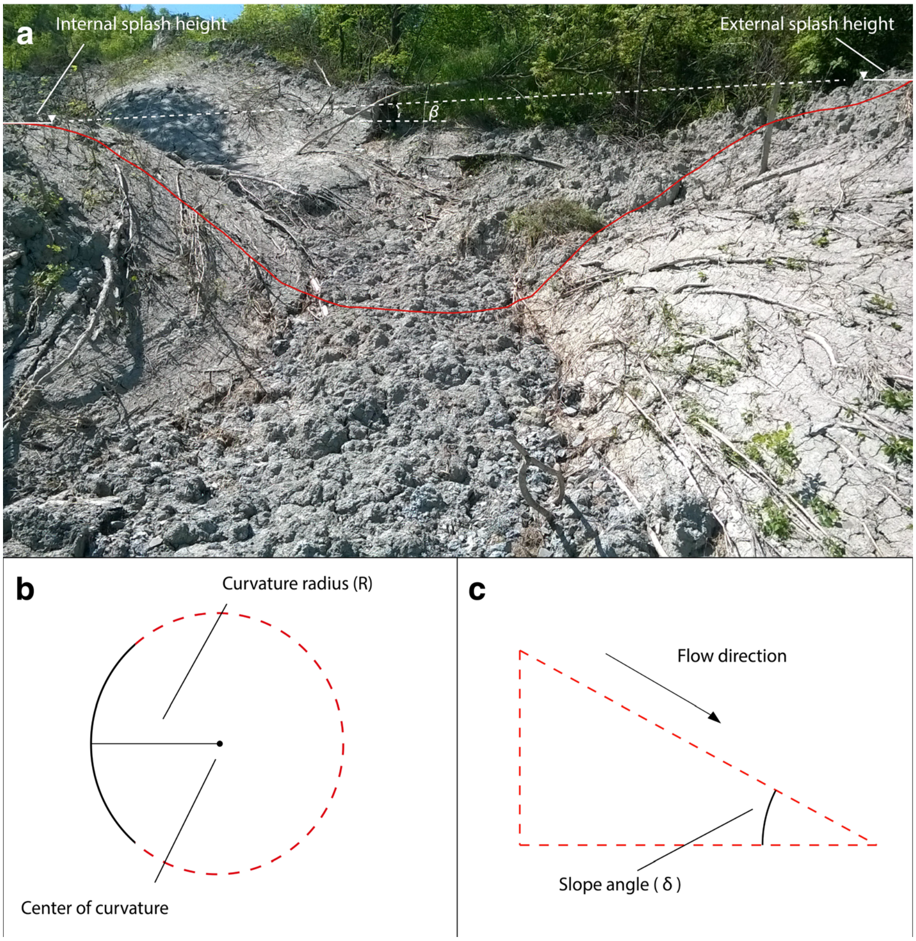

Fig. 9 Empirical formula parameters for flow velocity estimation: **a**) splash heights on the inside and outside of the bends of the flow path (cross section 2); **b**) radius of curvature; and **c**) slope angle

are established with a calibration procedure by using back analysis.

The model requires three input files that describe the topography (path file), source area (source file), and number of materials used with their rheologies and erosion parameters (erosion file).

With the aim of simulating different types of fast landslides, DAN3D can implement the following rheological relations: frictional, plastic, turbulent, Bingham and Voellmy. The selection of rheological model to use during the dynamic modeling of a landslide is related to the expected event type and depends on the rheological characteristics of the landslide material.

The post-failure phase processes that are triggered during the movement of rapid landslides are extremely complex, and the direct measurement of either the parameters of the involved materials or of the characteristics of the landslide is impossible. Therefore, the best rheological model is determined by performing a back analysis for to the investigated case by using similar phenomena.

Table 2 Velocity values of the flow obtained according to the Johnson & Rondine (1984) formula

Section	g	R	δ	β	v
	[m/s^2]	[m]	[°]	[°]	[m/s]
1	9.81	13.7	12	4.17	3.10
2	9.81	15.9	12	2.75	2.71

Table 3 Velocity values of the flow obtained according to the Hungr et al. (1984) formula

Section	γ	δ	H	I	v	v
	[kN/m^3]	[°]	[m]	[–]	[kPa]	[m/s]
3	9.81	12	3.3	8	3	1.89
4	9.81	12	3	8	3	1.56

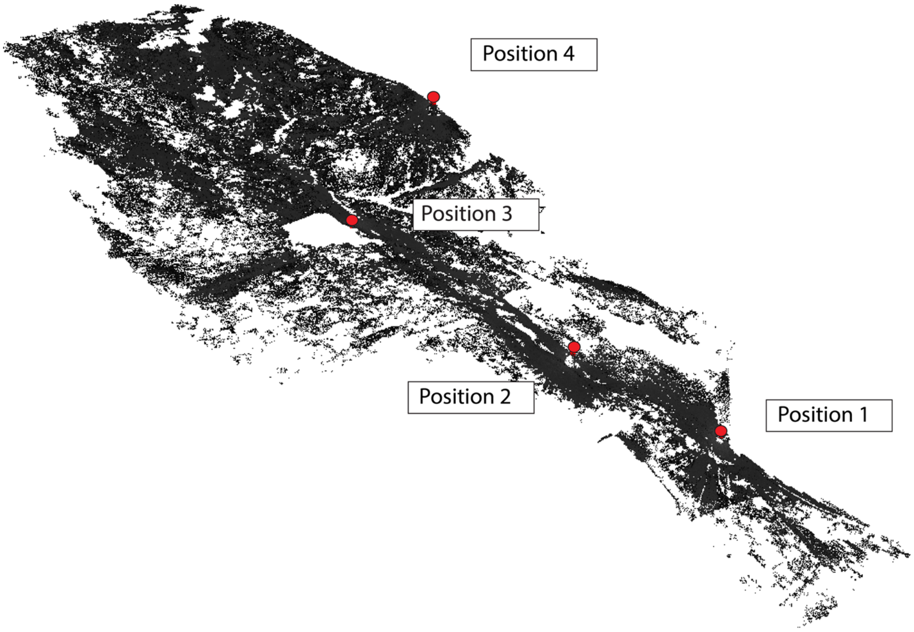

Fig. 10 Laser scanner point cloud from four scan positions

Empirical relations

There are several empirical methods that relate the geometric parameters of landslides to the runout distance; in this case study, three methods, presented by (Corominas 1996), (Rickenmann 1999) and Hunter & Fell (2003), were used to correlate the angle of reach (fahrboschung) with the volume.

$$Log\frac{H}{L} = BlogV + A \tag{6}$$

$$L = 1.9V^{0.16}H^{0.83} \tag{7}$$

$$\frac{H}{L}0.69tan\alpha_2 + 0.086 \tag{8}$$

where A and B are coefficients that depend on the landslide types and α_2 is the slope inclination. The fahrboschung was defined by (Heim 1932) as the inclination of the line connecting the crest of the landslide source with the toe of the deposits and can be evaluated by the

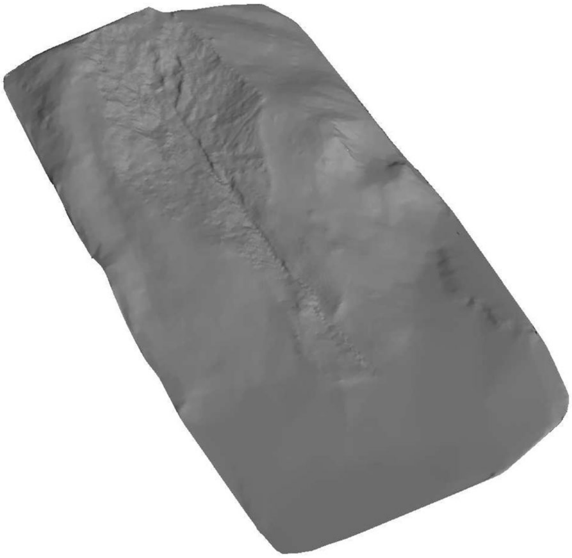

Fig. 11 DEM of the area

Fig. 12 Earthfill dam, built during safety operations in the landslide area

ratio between the elevation difference of the highest and lowest points of flow (H) and the corresponding horizontal distance (L):

$$\tan\alpha = \frac{H}{L} \tag{9}$$

These methods may be applied in preliminary hazard assessments, and they may be compared with the dynamic analysis.

Findings and Results

Back analysis

The calibration procedure is based on a trial and error back analysis of the Gessi-Mazzalasino landslide, to identify the most suitable rheological parameters for describing the flow motion. The path file used for the back analysis was the DEM of the slope, obtained from a 1:5000 topographic map of the area. The source file was defined by the triggering area obtained from the field survey. Since no significant erosion was observed during the field surveys, the erosion file was neglected.

The numerous study cases analyzed with the DAN3D code have shown that the Voellmy rheological model is particularly suitable to describe this type of phenomena and that, accordingly, it should be used for modeling the Gessi-Mazzalasino landslide (Nocentini et al., 2015; Gigli et al., 2014).

This model, introduced by (Voellmy 1955) for snow avalanches, contains a friction term and a turbulence term:

$$\tau_{zx} = -\left(f\sigma_z + \frac{\rho g v_x^2}{\xi}\right) \tag{10}$$

where f is the frictional coefficient; ξ is a turbulence parameter representing all possible sources of velocity-dependent resistance in landslide dynamics; and ρ, g and v are the density, gravity and velocity, respectively.

For the determination of the rheological model parameters, a back analysis was performed based on the study of the deposits from the March 2015 collapse. Two main phases of motion were simulated, according to the field evidence, assuming that the mass movement started as a sliding mass involving the surface layers of the upper part of the slope and evolved into a rapid mud flow as it entered the impluvium, where the flow was channelized.

Two basal shear resistances were chosen, according to the landslide dynamics; one rheology material was used for the source area between 226 and 173 m a.s.l., and another was assumed for the channelized area between 173 and 131 m a.s.l. The Voellmy resistance parameters were adjusted by trial and error to achieve the best simulation match in terms of velocity, thickness of deposits and runout distance.

The best match between the actual and simulated material distributions was obtained using a frictional coefficient of f = 0.19 for the upper material and a frictional coefficient of f = 0.15 for the lower material, while the turbulence term of ξ = 250.00 m/s^2 remained constant throughout the event (Fig. 13).

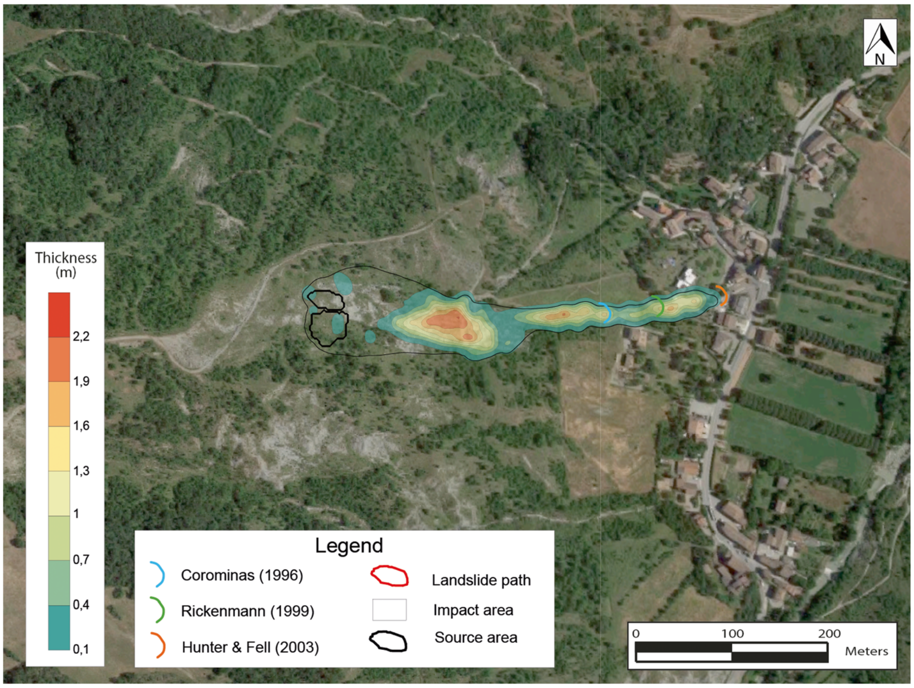

Fig. 13 Comparison between the maximum runout distances obtained from the empirical and numerical methods with the field data (in red)

Additionally, DAN3D requires the internal frictional angle and the unit weight of the material as input parameters. On the basis of the performed laboratory tests, we used an average internal frictional angle of 30° and a unit weight of 20 kN/m^3.

The simulation results show that the landslide reaches the flat area located in the middle sector of the slope, where most of the mobilized material was deposited in a layer up to 2 m thick, and then moves through the impluvium until it reaches the inhabited area.

Runout distances

As show in Fig. 13, there is good agreement between the simulation output and the field data obtained by the GPS survey (landslide path), for both the average thickness and the planar extension of the deposits, especially in the lower part of the slope.

The results are summarized in.

Table 4 and show some differences between the methods used to evaluate the runout distance.

The (Corominas 1996) and (Rickenmann 1999) relations, which produced predicted runout distances of 311 m and 379 m, respectively, underestimate the maximum runout distance of the landslide. However, the Hunter & Fell (2003) relation, with a predicted runout distance of approximately 431 m, agrees with the modeling results and field data; therefore, this is the most suitable empirical method to describe the Gessi-Mazzalasino landslide.

Velocity calculations

By comparing the flow velocity values obtained by using the empirical equations and the numerical model results, a similar trend along the flow travel distance was observed (Salvatici et al., 2017).

The flow velocity was obtained with the models along the four cross sections, the DAN3D results were slightly higher than the velocities obtained by the empirical relations (Table 5).

These differences derive from the assumptions made during the simulation phase, making it difficult to model both the kinematic and the depositional parameters of the flow, which were the focus of our study.

According to the model results, the flow reached a maximum velocity of approximately 8–12 m/s in the upper part and then slowed down as it entered the impluvium, and it finally stopped when the slope decreased. These results agree with the testimonies of local residents, who evaluated the flow velocity in the final meters of movement at approximately 0.2–1 m/s.

Table 4 Comparison between the calculated and measured runout distances

Corominas (1996)	Rickenmann (1999)	Hunter & Fell (2003)	DAN3D	Field data
[m]	[m]	[m]	[m]	[m]
311	379	430	426	412

Table 5 Comparison between the DAN3D and empirical velocity values

Cross section	DAN3D	Johnson & Rondine (1984)	Hungr et al. (1984)
	[m/s]	[m/s]	[m/s]
1	7.1	3.10	–
2	6.9	2.71	–
3	5.1	–	1.89
4	4.6	–	1.56

Examples of velocity observations from various sources are shown in Fig. 14, together with the velocity values calculated in this paper. These velocities represent point observations or maximum values at randomly chosen locations and are not necessarily maxima for a given event.

A clear distinction can be made between extremely rapid processes such as debris flows, mud flows and debris avalanches and slow process such as earthflows (Hungr et al., 2001).

Landslide characterization

As shown in the previous paragraphs, the distinction between “mud flows” and “earth flows” cannot be based solely on grain size distribution but can instead be derived in other ways, in particular, from the velocity of movement.

From the velocities obtained with three direct methods (including resident testimonies and empirical methods), the Gessi-Mazzalasino landslide has an estimated velocity ranging between 0.2 and 3 m/s, while the velocities from the numerical simulation are higher, ranging between 4.5 and 12 m/s.

These differences derive from the assumptions made during the simulation phase, resulting in an overestimation of the flow velocity.

Analysis of the velocities allow better classification of the Gessi-Mazzalasino event, which has characteristics of a landslide with behaviors between those of mud flow and earthflow phenomena.

The Gessi-Mazzalasino landslide material is an unsorted deposit composed of a mixture of sand, gravel and cobbles as well as varying proportions of silt and clay, and the landslide event is characterized by low plasticity and an intermediate velocity.

Future conditions

To evaluate the characteristics of potential landslides that could occur in the area, another numerical simulation was performed with DAN3D using the rheological

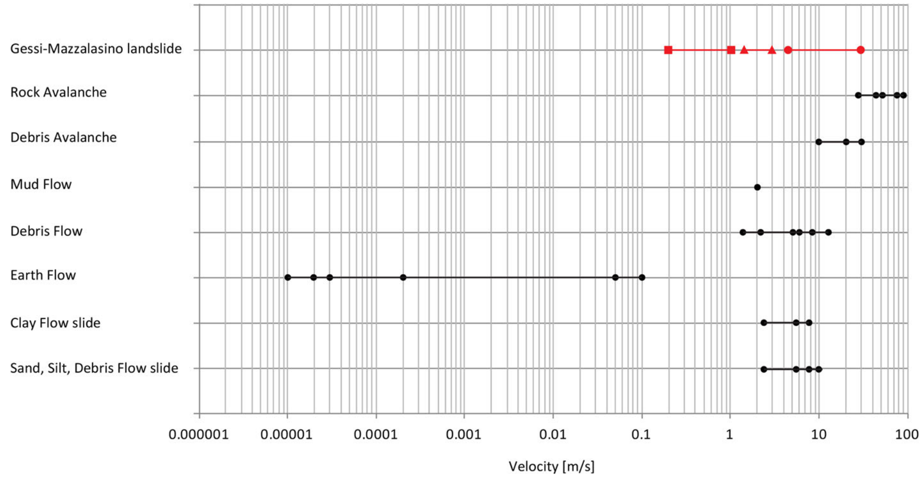

Fig. 14 Range of velocities for various types of flow-like landslides; the range of the estimated Gessi-Mazzalasino landslide velocity is shown in red (square symbols for resident testimonies, triangular symbols for empirical methods and circle symbols for numerical simulation)

parameters obtained by the back analysis of the 2015 event.

For this analysis, the most recent DEM obtained by laser scanner survey was used, representing the topography of the slope after the landslide.

During the analysis, a single volume of 10,000 m^3 was investigated based on the field survey and on the conservative assumption that failure occurred for a single volume.

Figure 14 shows the maximum runout distances obtained from the numerical methods used in this study.

The results of the potential landslide show that, due to the safety works, the landslide impact area was predicted to be smaller than that of the 2015 event (Fig. 15), with the mass stopping 70 s after the start of the simulation at the beginning of the impluvium, where the earthfill dam was constructed. A maximum thickness of approximately 2.8 m was reached in the flat area at the middle of the slope, and a maximum velocity of approximately 12 m/s was predicted.

Conclusions

Rapid landslides represent one of the most dangerous natural hazards and are one of the most frequent natural disasters in the world.

Therefore, prediction of post-failure motion is an essential component of hazard assessment when a potential source of a mobile landslide can be located.

On March 25th, 2015, at approximately 07:00 PM, a rapid landslide was triggered upstream of the village of Gessi-Mazzalasino, in the municipality of Scandiano (Emilia Romagna), and it reached the village, causing slight damage to two buildings that were evacuated for many days.

To assess the risk affecting the area, different methods have been proposed to predict the runout phase of the phenomenon.

A back analysis based on the path and the deposits of the 2015 event was performed in order to identify the optimal rheological model and to simulate the behavior of potential landslides.

The dynamic modeling was carried out by using the DAN3D code, which estimated the extent of the impact area and mapped the distribution of landslide parameters.

The predicted runout length obtained by the DAN3D software was compared to runout lengths predicted by the (Corominas 1996), (Rickenmann 1999) and Hunter & Fell (2003) empirical relations.

There is good agreement between the simulation output and the observed field data for both the average thickness and the planar extension of the deposits, especially in the lower part of the slope.

The Hunter & Fell (2003) results agree with the numerical results, but the (Corominas 1996) and (Rickenmann 1999) equations seem to underestimate the runout distance.

To obtain more information about the 2015 landslide, the flow velocity was calculated along four cross sections by means of the superelevation of the debris surface in the channel belt (Johnson & Rondine, 1984) and the Poiseuille equation methods.

We classified the Gessi-Mazzalasino landslide into an intermediate category between mud flow and earthflow phenomena on the basis of the velocities and textural composition.

All the data, obtained by using a range of methods, confirm that the impact area of possible future events will be smaller than that of the 2015 event, since a

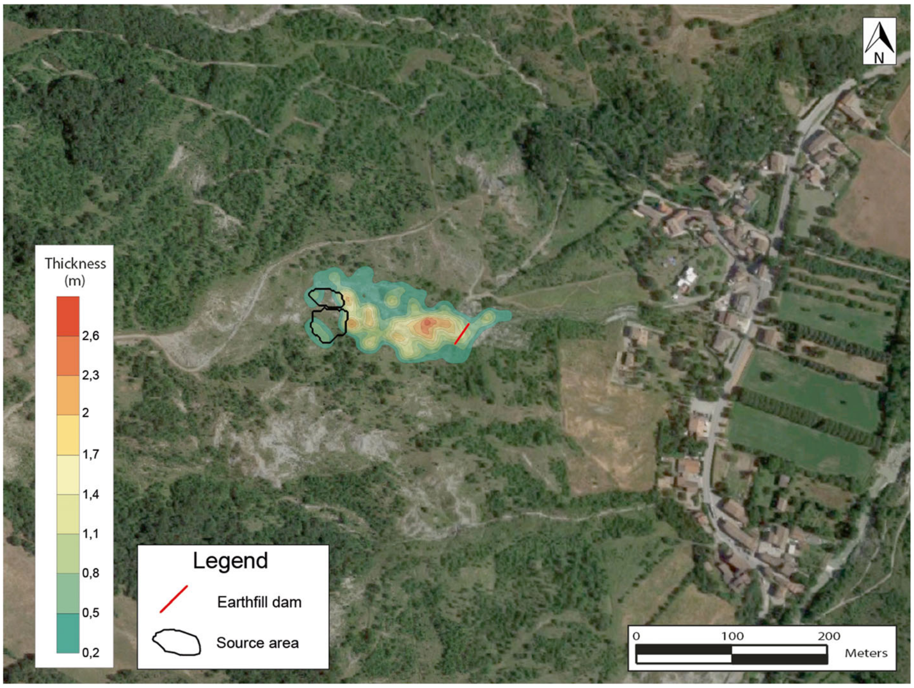

Fig. 15 Deposit flow thickness from the DAN3D simulation

potential landslide should stop upstream of the village of Gessi-Mazzalasino due to the safety works constructed after the landslide.

The methodology presented in this paper could become a standard procedure in areas affected by different types of flow-like landslides, providing a complete description of hazards.

Acknowledgments

This work was carried out within a research contract between the municipality of Scandiano and the Department of Earth Sciences, University of Florence, entitled: "Studio e Monitoraggio della frana di Gessi-Mazzalasino". The authors would like to thank the local people of the study area for their assistance during fieldwork. We would also like to thank Mr. Giovanni Cantoni for his help during the entire project and Dr. Giovanni Bertolini for providing the aerial photos of the landslide.

Authors' contributions

MC, LL, MN and TS contributed to the fieldwork and were responsible for collecting, integrating and interpreting the field data, as well as preparing the manuscript. GG gave technical support and conceptual advice and contributed to the preparation of the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

Publisher's Note

Received: 7 June 2017 Accepted: 17 October 2017

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