From creep to rapid sliding: back analysis of the Vajont landslide with the numerical DDA method

Juan Pablo Ibañez
Department of Civil Engineering, National University of Cuyo, Mendoza, Argentina

Yossef H. Hatzor
Department of Geological and Environmental Sciences, Ben-Gurion University of the Negev, Beer-Sheva, Israel

ABSTRACT: The catastrophic Vajont landslide was preceded by a long creeping phase concentrated in a clay basal layer. Recent experimental investigations performed at high velocities under both dry and wet conditions contributed to the understanding of the friction degradation experienced by those clays. Here we analyze the Vajont failure with the numerical DDA method by implementing two alternative friction degradation models: (1) scale dependent roughness degradation, appropriate to clean and initially rough rock discontinuities, and (2) transition from creep to runout, appropriate to clay-filled discontinuities. Our back-analyzed results expand the range that can be obtained from laboratory rotary shear tests by an order of magnitude with respect to both velocity and shear distance. We found that the upper limit for degradation is μ_{ss} = 0.16 assuming clean and initially rough basal plane; the lower limit is μ_{ss} = 0.035 to 0.052 assuming sliding commenced by creeping on wet clays.

1 INTRODUCTION

The Vajont landslide occurred on 9 October 1963 in the dolomites of Friuli, on the Veneto Region, north of Italy. A mass of approximately 300 million m^3 of rock and debris collapsed into the reservoir, generating a wave that over-topped the 261.6 m high dam. The flood filled the Piave valley destroying the town of Longarone downstream, and other villages nearby.

Nowadays, more than hundred scientific papers and technical reports on the Vajont failure are available (Superchi et al. 2010). Most noted are the technical report by Giudici & Semenza (1960) from at the time of dam construction, the studies of Prof. Muller on the failure mechanisms (Müller 1964, 1968), and the expert report by Hendron and Patton (1985) that provides comprehensive description and analysis of the case.

The catastrophic runout was preceded by a long creeping phase, believed to have lasted more than three years prior to the final failure. The slip concentrated in a water saturated clay-rich layer (60–70% smectite, 30–40% of calcite and minor quartz) interbedded within limestones layers (Ferri et al. 2011). The slide displaced a whole block of Jurassic-Cretaceous rocks of the Socchér Formation, a 250 m thick and ~2 km wide rigid body. Field mapping and limiting equilibrium analyses (Hendron and Patton 1985) indicate that it was displaced a horizontal distance of 450 to 550 m in less than 45 seconds, reaching peak velocities of 25 - 30 m/s. Figure 1 shows the cross section from Mt. Toc to Mt. Salta including the sliding mass configurations before and after the landslide.

From a mechanical point of view, the main issue that must be clarified is the very high value of the estimated velocities. Mechanisms such as excessive, heat generated, pore pressure across the sliding surface, as well as low dynamic friction of the clayey interbeds across the sliding surface (Vardoulakis 2000, Tika & Hutchinson 1999) have been explored.

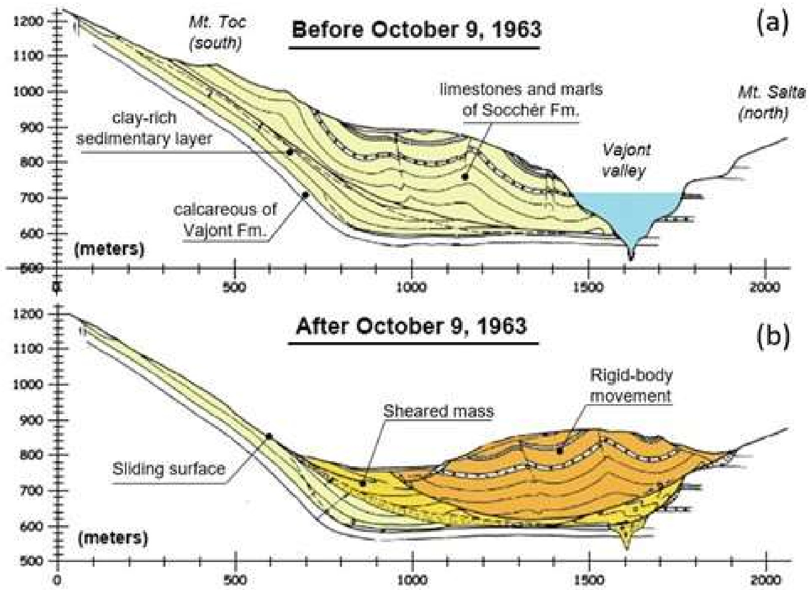

Figure 1. Geological cross section N° 5 of Vajont landslide (modified from Hendron and Patton 1985).

The frictional properties of the Vajont clay-rich gouge materials and their dependence on water content and slip rate were investigated by Hendron & Patton (1985) and Tika & Hutchinson (1999). More recently, Ferri et al. (2011) investigated the frictional properties of the clay-rich layers under similar deformation conditions as during the landslide: 1–5 MPa normal stress, 2×10^{-7} to 1.31 m/s slip rate and displacement of up to 34 m using both bi-axial and rotary shear testing devices.

Veveakis et al. (2007) modeled the long-term phase of creep localized in a clay-rich water-saturated layer, proposing shear heating as the primary mechanism. They modeled the rock mass as a rigid block moving over a thin zone of high shear strain rates. The proposed model included a thermal softening and velocity strengthening law for the basal material.

The numerical discontinuous deformation analysis (DDA) method (Shi 1993; Hatzor et al. 2017) was used to study the Vajont slide by Sitar et al. (2005) who have focused primarily on the kinematics of the failure process. They found that peak velocity increased by up to 50% with increasing number of blocks (from 12 through 28 to 105 in different DDA block models), suggesting that internal disintegration of the sliding mass prompted increased slide accelerations. Wang et al. (2013) proposed a trilinear friction law to model the Vajont landslide with DDA, however their model consisted of only 9 blocks and no velocity time history was presented.

In previous works (Ibanez & Hatzor 2018a, b) we studied the velocity evolution of the Vajont slide with DDA using a very detailed block model based on accurate field maps and cross sections, consisting of 3096 blocks. We implemented friction degradation across the joints as a function of displacement in DDA and obtained velocity time histories for increasing amounts of friction degradation. Our numerical results confirmed the analytical results obtained by Hendron and Patton (1985) with respect to the velocity time history of the slide and the runout distance. With the aid of numerical analysis, therefore, we used the Vajont landslide as a natural experiment at the field scale that provided ultimate friction degradation values for specific discontinuity roughness and infilling condition. It expanded the range of velocity induced friction degradation values that can be obtained in laboratory tests by an order of magnitude in terms of sliding velocity and shear distance.

Here we analyze the failure of the Vajont slide with the numerical DDA method by implementing two alternative friction degradation models: 1) scale dependent roughness degradation (Barton and Bandis 1980), appropriate for clean and initially rough rock discontinuities, and 2) transition from creep to runout (Ferri et al. 2011), appropriate for clay filled discontinuities. By using these two alternative models we constrain the range of friction degradation that can be expected during rapid shearing across clay-filled weakness planes in geological materials such as dolomites.

2 SHEAR PARAMETERS

2.1 *Hendron and Patton (1987) report*

Regarding the shear strength along the basal sliding plane, early studies (Müller 1964; Lo et al. 1972; Chowdhury 1978; Müller 1968) assumed that the residual shear strength of the multiple clay layers governed deformation rather than the higher shear strength of rock-to-rock contacts. The residual shear strength was assumed to be the most significant factor in the stability of the rock mass. Table 1 shows the friction values obtained by laboratory tests and the weighted values recommended by Hendron and Patton (1985) for stability analysis.

Table 1. Friction values for clay layer and rock mass (Hendron and Patton 1985).

Material	Range of ϕ values	Recommended ϕ value	Shear Strength
Clay layer	5° - 16°	12° (μ=0.21)	Residual
Rock mass	30° - 40°	40° (μ=0.84)	Peak

2.2 *Recent studies*

Recently a comprehensive experimental investigation of clays from the basal plane was performed at a range of velocities from 2×10^{-7} to 1.31 m/s at both dry and wet conditions (Ferri et al. 2011). Transition from friction degradation during the creeping phase to rapid sliding under residual (steady – state) friction during the runout stage was proposed to have taken place after a displacement of some 20 to 30 m, depending on the humidity conditions. Here we define the critical distance "dc" as the sliding displacement associated with the transition from creep to runout. Table 2 shows a summary of steady-state friction values and critical distances for both dry and wet conditions, as well as the adopted values for this study.

It was estimated by theoretical calculation based on rigid-block mechanism that a 22.3° (μ=0.41) friction angle across the basal plane was required to ensure static stability of the landslide (Vardoulakis 2002, Veveakis et al. 2007). We also find the same value based on numerical DDA analyses (Ibañez & Hatzor 2018a, b). This value should be considered as a lower boundary of the peak friction angle value that was available across the basal plane before any motion took place in the geological history of the cross section.

Table 2. Steady-state friction values for clay layer (based on Ferri et al. 2011).

Condition	Steady state ϕ values	critical distance dc (m)
Dry	5° – 11°	25 – 35 m
Wet	0° – 3°	20 – 30 m
Adopted in this study	2°– 3° (μ=0.035 to 0.052)	20 – 25 m

3 TWO FRICTION DEGRADATION MODELS

3.1 *Scale dependent roughness degradation*

We propose a bilinear friction law based on empirical evidence (Barton and Bandis 1980) that peak friction (ϕ_p) is mobilized in rough rock discontinuities after the displacement distance "d" equals a critical value $d_c \approx 1\%$ of overriding block length (Ibañez & Hatzor 2018a, b). After this amount of sliding, initial roughness (dilation) angle "i" is fully degraded, and frictional resistance is controlled by the steady-state, residual friction angle (ϕ_b). The friction angle (ϕ) evolution during dynamic sliding can therefore be described by a simple bilinear law:

$$\phi = \phi_p - D \qquad if\ (d < d_c) \tag{1}$$
$$\phi = \phi_b = \phi_p - i \quad if\ (d \geq d_c)$$

where “D” is the degradation parameter that scales the amount of degradation that is applied to the friction angle. It increases linearly with displacement from 0 to i.

It has been established by previous researchers that the Vajont slide moved across a basal plane that possessed a friction angle of 12° (μ_0 = 0.231) prior to the catastrophic runout, due to previous historic sliding/creeping events. We adopt this value as the initial friction value of the basal plane. Friction is further degraded to a residual value ϕ_b (μ_{ss}) in each block contact after a displacement equals to 1% of each block length has taken place. We thus find the amount of friction degradation that was necessary to explain the mapped runout distance and the back analyzed peak velocity of the slide as reported by Hendron and Patton (1987). We find that a degradation of the friction angle from 12° to 9° (friction coefficient from 0.231 to 0.16) is sufficient for explaining the runout event (see Table 1). Figure 2 shows the adopted friction degradation model.

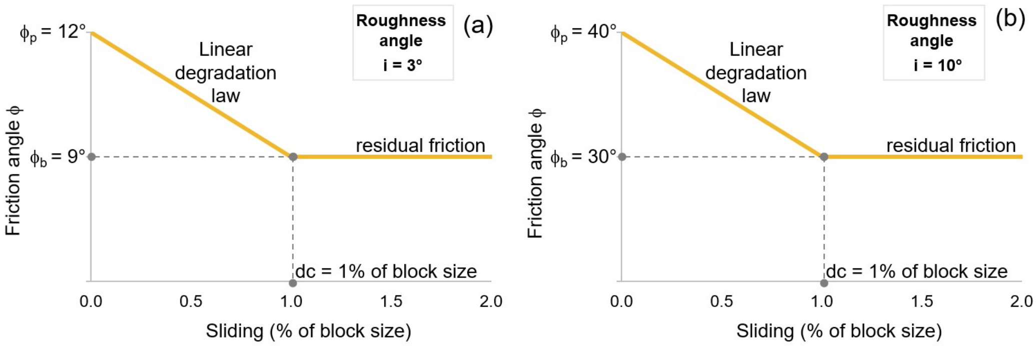

Figure 2. Bilinear friction degradation model for: a) clay layer; b) rock mass.

3.2 *Transition from creep to steady state*

In this alternative model we focus on the whole sliding episode, from static condition, to creep, to rapid sliding, based on comprehensive rate and state friction experiments on clays from the basal plane performed by Ferri et al. (2011). The experimental data suggest that full lubrication (μ_{ss} < 0.050) due to the formation of a continuous water film in the gouge can explain the extraordinarily high slide velocity. For initial static conditions it has been established (e.g. Hendron and Patton 1987; Veveakis et al. 2007) that a friction angle of 22.3° (μ_0 = 0.410) is required for the basal plane. We adopt this value as initial peak friction value ϕ_p (μ_0). Ferri et al. (2011) results show that total friction degradation is achieved in the clays after a displacement of 20 – 25 m after which sliding proceeds under steady-state friction. Based on the description of these experimental results, we propose an exponential displacement - dependent law for describing the entire friction degradation process:

$$\phi = \phi_b + (\phi_p - \phi_b)\, e^{[-c(d/d_c)]} \qquad (2)$$

where d = sliding distance, d_c = critical distance (for the case of the Vajont 20 to 25 m based on experimental data), and c = exponential coefficient, adopted as being 5 based on fitting of experimental data (see Table 2 and Figure 3).

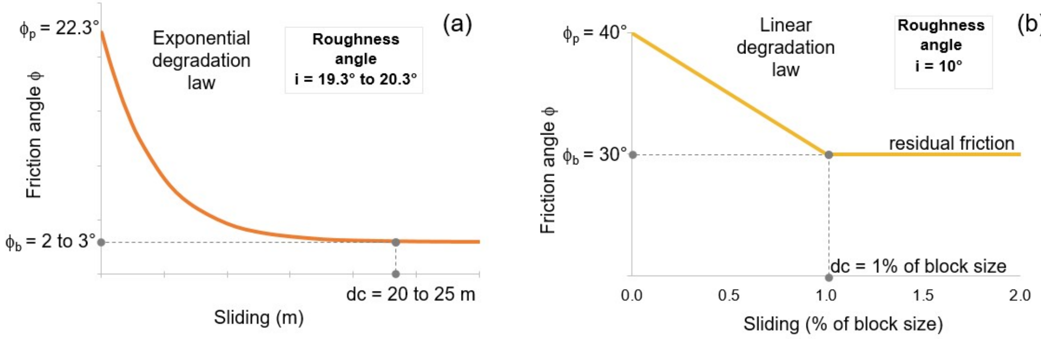

Figure 3. Alternative friction degradation models for: a) clay layer (exponential); b) rock mass (bilinear).

We implement the proposed exponential friction degradation law at all contacts in DDA that belong to the clay-rich basal plane. For all the other contacts that are inside the rock mass, we maintain the bilinear friction law for rock to rock contacts (see Figure 3b). We analyze the response of the sliding mass and find the residual friction value necessary to simulate the mapped runout distance and the estimated duration of the event with the modified DDA.

4 DDA MODEL

A full model based on geological cross section in Hendron and Patton's report (Figure 1a) was used to check the validity of their conclusions regarding the effects of friction degradation on slide velocity and distance, as discussed above. The rock mass involved in the slide extends 1400 m over a clay layer that constitutes the sliding surface. Three principal joint sets are included in the DDA mesh in order to reproduce the main features observed in the field, as follows:

- vertically dipping joint set (dip=90°);
- gently dipping bedding-plane set parallel to the basal plane attitude (dip=34.5°);
- The basal plane across which the side took place (dip=1.5°).

Results of a previous study on the effect of block size (Ibañez & Hatzor 2018a, b) suggest that with a mean block size of 8 m or less the block size effect is minimized. This can be achieved using a mean joint set spacing of about 10m in the DDA mesh. This value was used here for block system generation. The generated mesh, consisting of 3096 blocks, is shown in Figure 4 and is used here to explore the effects of friction degradation on slide velocity and run out distance. We use bilinear degradation model for the rock mass, and bilinear or exponential degradation model for the clay layer. The five combinations used for clay-layer parameters are listed in Table 3.

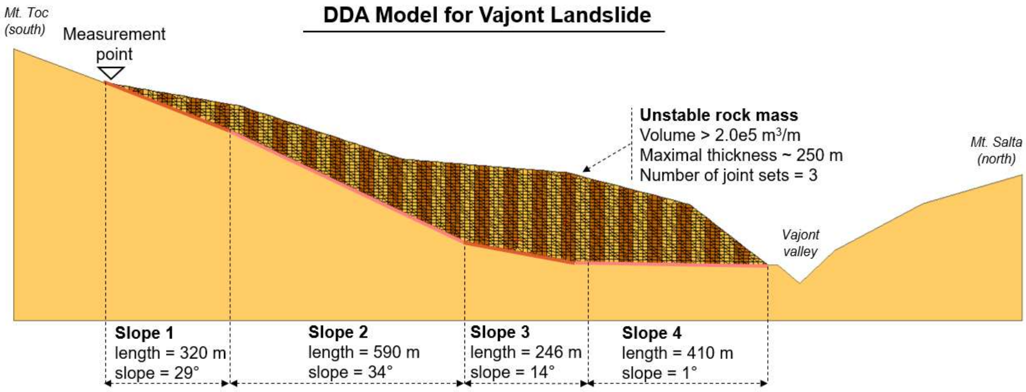

Figure 4. DDA model for Vajont landslide with indication of slope segments and the measurement point.

Table 3. Clay-layer parameters for the two proposed models

Model	Initial friction ϕ_p (μ_0)	Steady state friction ϕ_b (μ_{ss})	critical sliding dc (m)
Bilinear	12.0° (0.23)	9° (0.158)	1% block size
Exponential	22.3° (0.41)	3° (0.052)	20 m
Exponential	22.3° (0.41)	2° (0.035)	20 m
Exponential	22.3° (0.41)	3° (0.052)	25 m
Exponential	22.3° (0.41)	2° (0.035)	25 m

5 DDA RESULTS

The mapping of the deformed rock mass after sliding in Section 5 is shown in Figure 5a (see also Figure 1b) and results of forward DDA modeling are shown in Figure 5b. It is evident that results of DDA simulations are in excellent agreement with field mapping after the failure. This agreement includes the geometry of deformed and sheared rock mass as well as the formation of failure surfaces within the siding rock mass above the basal plane. We believe the formation of these inner-surfaces corresponds to shear bands produced during sliding due to the adjustment of the rock mass to the irregularities of base geometry. Over these regions, the rock mass slipped in a rigid-body like manner, maintaining its internal coherence.

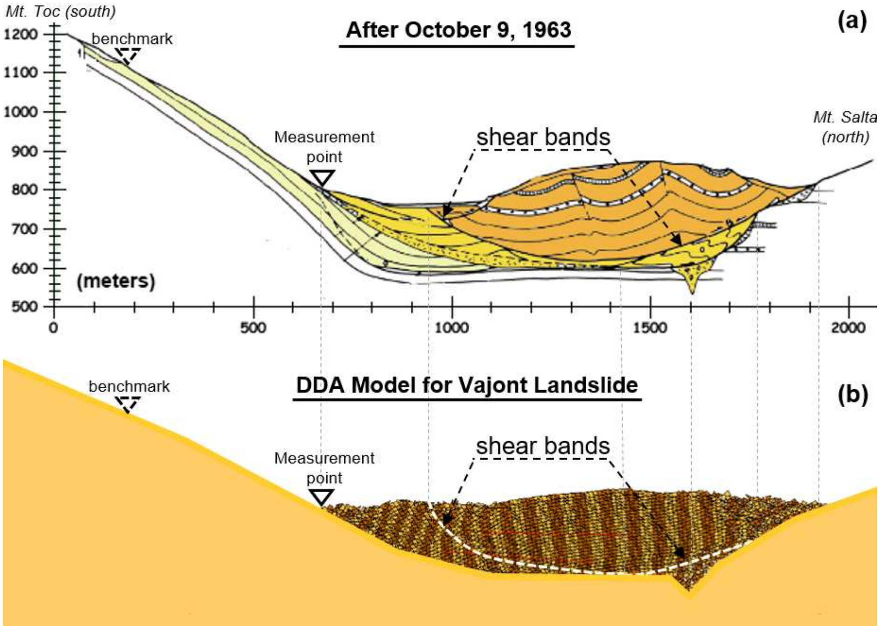

Figure 5. DDA results and comparison with section N° 5 (modified from Hendron and Patton, 1985).

Figures 6, 7 and 8 show the results obtained for the measurement point as shown in Figure 5, in terms of distance-time-velocity charts. Note that the displacement and velocity vectors plotted for each profile are in the horizontal direction downslope.

When the bilinear degradation model is applied at the basal plane, the rock mass is highly accelerated from the very beginning of the sliding, due to the reduced d_c value (1% of block size, around 0.10 m). Therefore essentially, all of the sliding episode occurs under steady-state friction (μ_{ss}). When the exponential degradation model is applied, the rock mass is initially in a state close to limiting equilibrium as discussed above, then it begins to creep until displacement reaches the d_c value where frictional resistance reaches steady state condition. At that stage the sliding mass accelerates to peak velocities higher than developed with the bilinear degradation model due to the strong friction degradation in the exponential model (see Figure 3).

The predictions of the bilinear and exponential friction degradation models in terms of velocity vs. distance charts are plotted in Figure 9 and compared with the upper and lower limits estimated for the Vajont landslide by Hendron and Patton (1985). We argue that these two models constrain the lower (bilinear) and upper (exponential) boundaries for ultimate friction degradation that could have taken place during the catastrophic Vajont landslide.

6 SUMMARY AND CONCLUSIONS

Using the scale dependent roughness degradation model which is more suitable for initially clean rough rock joints we find that friction degradation of at least 25% (from 12° to 9°, $\mu_{ss} = 0.158$) must have taken place across the basal plane to explain the velocities and displacements assumed to have taken place during the Vajont failure. This degradation resulted in peak velocity of 22 m/s, runout distance of 470 meters, and event duration of 37 seconds as computed with DDA. Using the exponential friction degradation model for the clays we reproduced the entire sliding evolution from limiting equilibrium conditions ($\mu_0 = 0.410$), to creep , and finally to run out at high velocities. With steady-state friction of 2° to 3° ($\mu ss = 0.035$ to 0.052) we obtained peak velocities of 25 to 29 m/s, runout distance of 470 to 500 meters, and event duration of 37 seconds.

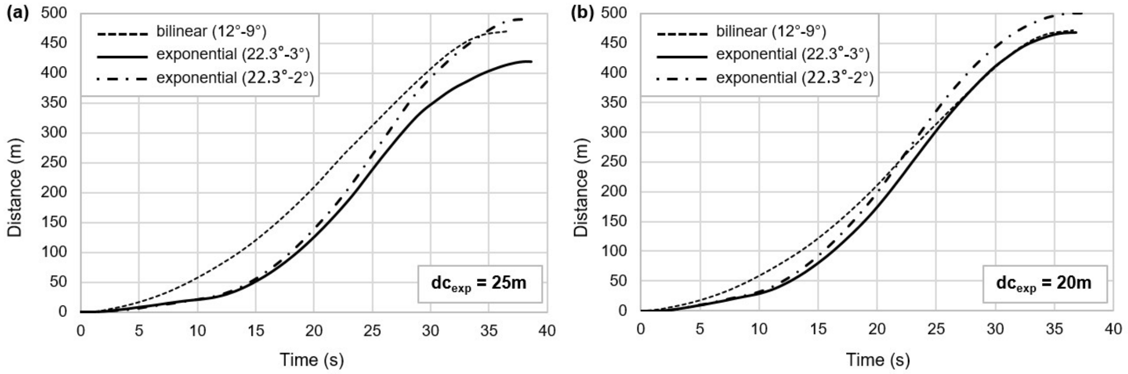

Figure 6. Bilinear distance x time chart compared with exponential charts: a) dc_{exp}=25m, b) dc_{exp}=20m.

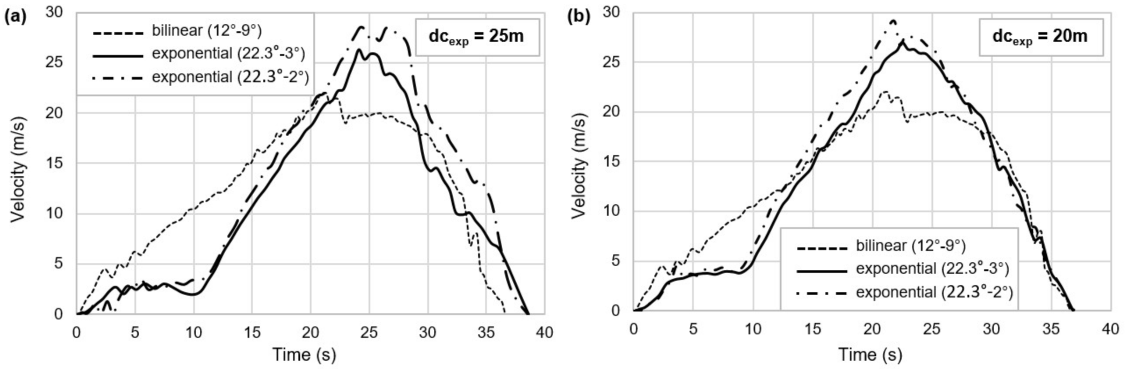

Figure 7. Bilinear velocity x time chart compared with exponential charts: a) dc_{exp}=25m, b) dc_{exp}=20m.

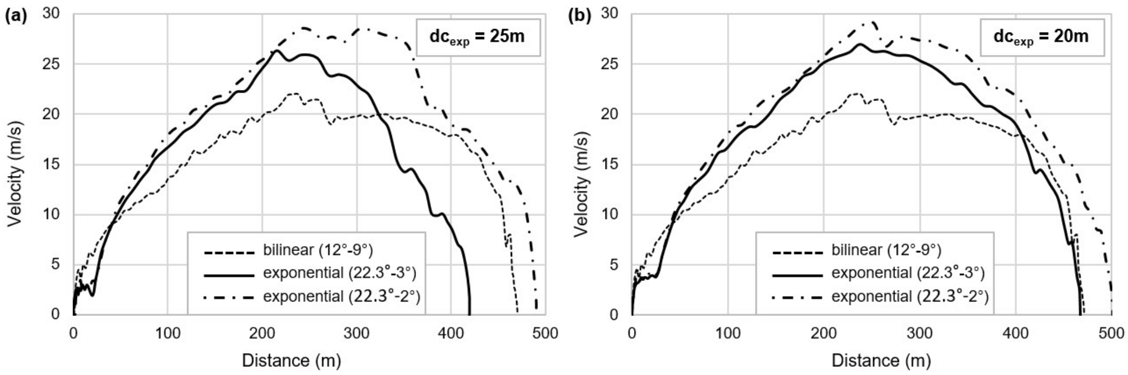

Figure 8. Bilinear velocity x distance chart compared with exponential charts: a) dc_{exp}=25m, b) dc_{exp}=20m.

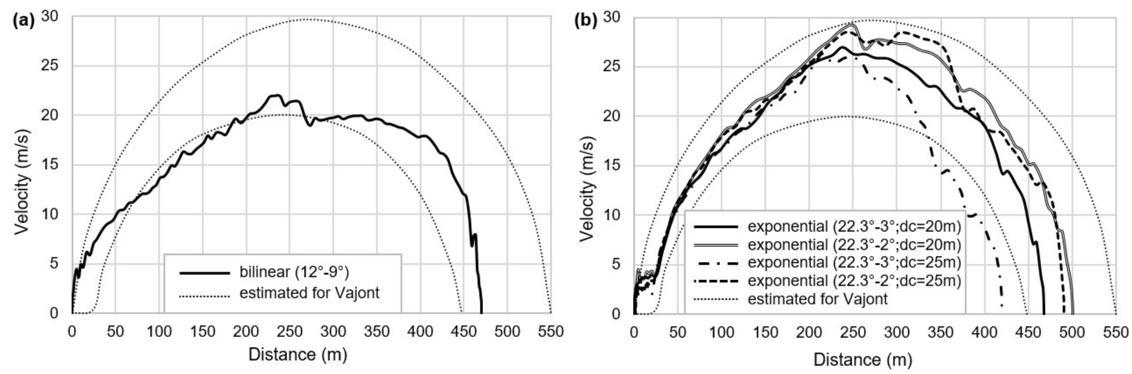

Figure 9. a) Bilinear and b) exponential velocity x distance profiles, compared with upper and lower limits estimated for Vajont landslide.

Our back-analyzed friction – velocity relationships expand the range of velocity induced friction degradation values that can be obtained in laboratory rotary shear tests by an order of magnitude with respect to both velocity and shear distance. With the aid of numerical analysis, therefore, well documented landslides can be used as natural experiments at the field scale to provide ultimate friction degradation values for various discontinuity roughness and infilling conditions. For the Vajont landslide that sheared across clay filled bedding planes in dolomites, we find that the upper limit for friction coefficient is $\mu_{ss} = 0.16$ assuming a clean rough basal plane, and the lower limit is $\mu_{ss} = 0.035$ to 0.052 assuming shear across a wet, clay filled, basal plane interface.

ACKNOWLEDGEMENT

We thank Dr. Giulio Di Toro for pointing us to the exponential degradation model obtained experimentally by his research group for the Vajont slide material, and for stimulating discussions.

REFERENCES

Barton, N., Bandis, S., 1980. Some effects of scale on the shear strength of joints. Int. J. Rock Mech. Mining Sci. Geomech. 17 (1), 69–73.

Chowdhury, R., 1978. Analysis of the Vajont Slide - new approach. *Rock Mechanics, Jour. Int. Soc. Rock Mechanics* 11, 29-38.

Ferri, F., G. Di Toro, T. Hirose, R. Han, H. Noda, T. Shimamoto, M. Quaresimin, and N. de Rossi, 2011, Low- to high-velocity frictional properties of the clay-rich gouges from the slipping zone of the 1963 Vaiont slide, northern Italy, J. Geophys. Res., 116, B09208.

Giudici, F., Semenza, E., 1960. *Studio geologico sul serbatoio del Vajont. Unpublished report for SADE, Part A: text, Part B: photos with discussions, Venezia, Italy.*

Hatzor, Y.H., Ma, G., Shi, G., 2017. *Discontinuous Deformation Analysis in Rock Mechanics Practice.* CRC Press,Feng, X.T.ISRM Book Series. The Netherlands

Hendron, A.J., Patton, F.D., 1985. *The Vaiont slide, a geotechnical analysis based on new geologic observations of the failure surface.* . Technical Report GL-85-5, Department of the Army, US Corps of Engineers, Washington, DC.

Hendron, A.J., Patton, F.D., 1987. The Vaiont slide – a geotechnical analysis based on new geologic observations of the failure surface. *Eng Geol* 24, 475–491.

Ibañez, J. P. & Hatzor, Y. H., 2018a, Friction degradation in rapid sliding: Back analysis of the catastrophic Vajont landslide using DDA. ARMA Congress, Seattle, USA, 18–684.

Ibañez, J. P. & Hatzor, Y. H., 2018b, Rapid sliding and friction degradation: Lessons from the catastrophic Vajont landslide, Engineering Geology, Volume 244, 2018, Pages 96-106,

Lo, K.Y., Lee, C. F. , Gelinas, P., 1972. *Alternative Interpretation of the Vaiont Slide*, in: Cording, E.J. (Ed.), Stability of Rock Slopes: Proc. 13th Symp. on Rock Mech. ASCE, New York, pp. 595-623.

Müller, L., 1964. The rock slide in the Vajont valley. *Rock Mech. Eng. Geol.* 2, 148–212.

Müller, L., 1968. New considerations in the Vaiont slide. *Eng. J.* 6, 1–91.

Shi, G.H., 1993. *Block System Modeling by Discontinuous Deformation Analysis*. Computational Mechanics Publication,Brebbia, C.A., Connor, J.J.Topics in Engineering Southhampton, UK

Sitar, N., MacLaughlin, M.M., Doolin, D.M., 2005. Influence of kinematics on landslide mobility and failure mode. *J Geotech Geoenviron* 131, 716-728.

Superchi, L., Floris, M., Ghirotti, M., Genevois, R., Jaboyedoff, M., Stead, D., 2010. Technical Note: Implementation of a geodatabase of published and unpublished data on the catastrophic Vaiont landslide. *Natural Hazards and Earth System Sciences* 10, 865-873.

Tika, T.E., Hutchinson, J.N., 1999. Ring shear tests on soil from the Vaiont landslide slip surface. *Geotechnique* 49, 59–74.

Vardoulakis, I., 2000. Catastrophic landslides due to frictional heating of the failure plane. *Mechanics of Cohesive-Frictional Materials* 5, 443-467.

Vardoulakis, I., 2002, Dynamic thermo-poro-mechanical analysis of catastrophic landslides, *Geotechnique*, 52, 157– 171.

Veveakis, E., Vardoulakis, I., Di Toro, G., 2007. Thermoporomechanics of creeping landslides: The 1963 Vaiont slide, northern Italy. *J Geophys Res-Earth* 112.

Wang, L.-z., Jiang, H.-y., Yang, Z.-x., Xu, Y.-c., Zhu, X.-b., 2013. Development of discontinuous deformation analysis with displacement-dependent interface shear strength. Computers and Geotechnics 47, 91-101.