

# **PARAMETERIZATION OF A DRY RETAINING WALL IN A TERRACED SLOPE IN VALTELLINA (NORTHERN ITALY) AND STABILITY ANALYSIS**

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## **ABSTRACT**

The mechanical characterization of dry retaining walls is a key issue for the stability analysis of slopes in Valtellina, where vineyard cultivated terraces have already been involved in rapid mass movements. The study presents the solution adopted to approach the problem by numerical modelling, focusing on the difficulties in the parameterization of dry walls.

While geotechnical field and laboratory measurements allow to define the backfill soil properties following conventional procedures, no standards are proposed for dry walls. In this study, walls are likened to equivalent rock masses, where blocks with different shapes and dimensions are separated by “discontinuities” characterized by aperture, filling and roughness. Direct observations and images analysis allowed to assign a Geological Strength Index to the walls, applying the Hoek & Brown criterion, and to calculate the wall equivalent values of cohesion and friction angle.

The performed stability analysis is supported by a previous hydrological model, which allows to define a temporary perched groundwater level when a rainfall is simulated. The infiltration phase was calibrated and validated comparing the in situ water levels, recorded by continuous piezometric datalogger, with the simulated ones, using as input the rainfalls registered by a local meteorological station. Two different rainfall scenarios were then reproduced, with similar duration and return period: the former caused three mass movements in 1983 while the latter had no instability consequences. Once the hydrological models were reconstructed, the stress-strain modeling was performed to verify the worth of the geomechanical parameters assigned to the wall, and eventually to calibrate them.

The present work emphasizes the importance of direct measurements and monitoring activities to develop reliable conceptual models for numerical analysis of groundwater flow and stability in an anthropogenic impacted geological context. Moreover it highlights the importance of field measures to reduce the uncertainty of parameters that are almost impossible to be measured directly.

## INTRODUCTION

Slope stability analysis is a key issue in the Alpine environment, where landslides often represent an important risk factor for anthropogenic structure. Valtellina (Northern Italy) is an extended area within Italian Alps, where many landslides occurred historically with a great variety of predisposing factors. In May 1983 and in November 2002, the village of Tresenda (Teglio) was affected by superficial landslides that, given the high gradient of the slope, evolved in debris flows causing casualties (in 1983) and damages to infrastructure (Cancelli and Nova, 1985; Quan Luna et al., 2010). The Tresenda slope, as a wide part of the northern flank of the Valley, is terraced by means of dry stone retaining walls for agricultural purposes. These anthropogenic settings caused a dramatic change in the hillslope hydrology favoring the decreasing of superficial runoff and an increment in the amount of infiltration, with positive effects on agricultural activities, but resulting in situations that may lead to local instabilities. Indeed, it is demonstrated that in Valtellina terraced slopes are more prone than woodland areas to trigger superficial mass movements (Crosta et al., 2003). These movements often originate from soil slips or shallow landslides, after a Coulomb-type failure, and then evolve into flows, due to the increase of pore pressure, or for dilatancy (Fleming et al., 1989; Iverson et al., 1997; Johnson and Rahn, 1970), that, in the case of Tresenda, is caused by a sudden change of slope steepness (Azzola and Tuia, 1983).

The study of factors that lead to instability in a terraced slope should mainly consider the role played by the dry stone walls. Several authors studied the mechanisms of failure of these structures by means of numerical modeling, considering different geometrical characteristics (Harkness et al., 2000; Powrie et al., 2002; Zhang et al., 2004; Walker et al., 2007), or through analytical models at different scale (Villemus et al., 2007), or combining the two approaches (Lourenço et al., 2005). On the other hand, one of the most widespread approaches to study the triggering of landslides, at various scales, consists in coupling a hydrological model to a stability one (Angeli et al., 1998; Crosta and Frattini, 2003; Delmonaco et al., 2003; van Beek and van Asch, 2004; Biavati et al., 2006;; Tofani et al., 2006; Meisina and Scarabelli, 2007; Talebi et al., 2008; Simoni et al., 2008; Kuriakose et al., 2009; Cho, 2009).

In the present work, an approach at a very detailed scale (one terrace) was applied, using the output of an unsaturated-saturated and groundwater flow numerical model in the stability analysis, in which the mechanical and hydrogeological characteristics of the dry stone retaining wall are taken into account. A previous work (Camera et al, in review) deeply analyzed the mechanism of perched water table formation in the area, quantifying the process in terms of transient pore-water pressures distribution in the slope. Once clarified how perched groundwater tables form on a terraced slope, the attention was turned to their influence on stability. The principal aim of this part of the work is in fact to analyze and determine which are the main causes that lead the terrace to

generate superficial landslides, basing on a modeling approach. Once the stability model was calibrated, the effects of factors such as extreme rainfall events calculated on a statistical base, together with variations of initial hydrogeological conditions, state of maintenance of walls, and different pattern of distribution of rainfalls were analyzed.

## GEOLOGICAL AND GEOMORPHOLOGICAL FEATURES

Valtellina is a typical U-shaped glacial alpine valley whose slope is sometimes interrupted by both natural and anthropogenic morphological terraces. Its trend is strictly connected to structural and tectonic factors, indeed along its northern flank is recognizable the Periadriatic Line that, in this area, takes the name of Insubric Line or Tonale Fault (“Foglio 19 Tirano” of the Carta Geologica d’Italia 1:100000, 1969) and divides the Variscan basement of the Southern Alps from the Alps *strictu sensu* (Austroalpine, Penninic and Helvetic nappes).

The study area extends uphill the village of Tresenda, in the middle part of the Valtellina right flank, to the village of Sommassassa, in the municipality of Teglio (0.6 km<sup>2</sup>) (Fig. 1). The geomorphological configuration of this part of the valley and the presence of important elements exposed to risk make the study of this area crucial. The main road of the valley, the railway and the village itself are located at the foot of the slope within a bend of the Adda river, and so in case that a mass movement occurs, as happened in 1983 and 2002, the safety of people, buildings and infrastructure is directly compromised, and also severe indirect losses are expected.



**Fig. 1: geographical setting of study area**

on the morphological characteristics of the slope, such as slope angle and soil depth, but generally they vary between 20-100 m in length and 5-25 m in width.

The Tresenda slope is terraced mainly by dry stone retaining walls, and it is cultivated by vineyards. Walls are therefore the critical feature of the study area. In order to understand their mechanical behaviour it is necessary, at first, to analyze their geometrical properties: their height can range from 70 cm up to 5 m, but 90% of the walls are between 1.40 and 2.50 m in height; strip length and width depend

The bedrock is composed of mica schists (Edolo schists, Foglio 19 of the Carta Geologica d'Italia 1:100000, 1969) while the covering soils have varying origins, including morenic, fluvio-glacial, and colluvial, and, on the terraces, they are the result of anthropogenic activity. A morphological terrace, some trenches and counterslopes surveyed in the upper part of the study area highlight a condition of general instability. Runoff water drainage is enhanced by an artificial network of channels, named *valgelli*. Cemented paths built after the events of 1983 are used to facilitate the access to the vineyards and to cut off the hydrogeological continuity of the slope. The local geological context and the past occurrence of landslides make this sector of the valley highly representative of many other sectors in the area.

## **SOIL, BEDROCK AND WALL GEOTECHNICAL PROPERTIES**

The mechanical and hydrogeological characteristics of the backfill were determined by laboratory and field tests. Double ring infiltrometric tests, hole infiltrometric tests, and soil density measurements were performed by the sand-cone method (ASTM D1556, 2007). Samples were collected for laboratory tests, including grain size analysis (ASTM D2487, 2010), falling and constant head (ASTM D2434-68, 2006) permeability tests, and direct shear tests (ASTM D3080, 2004), where both peak and residual shear strength parameters were determined.

Physical and hydrogeological parameters were used to model infiltration and the formation of perched groundwater tables (Camera et al., in review), that was then used as input in the stability model. Mechanical properties of the materials were defined as follows. For the backfill soils, the laboratory tests provided all the needed data; for bedrock, geomechanical surveys were performed to assign proper value of GSI (Geological Strength Index) (Hoek et al., 1998; Marinos et al., 2005), and then the bedrock modulus of deformation and the values of the equivalent Mohr-Coulomb cohesion and friction angle were determined by the Hoek and Brown criterion (Hoek et al., 2002).

Regarding the walls, a similar procedure was originally followed basing on the consideration that the wall is not built up as a continuum material but it can be roughly considered as a fractured rock mass. A dry stone retaining wall (Fig. 2) can in fact appear as a very jointed rock mass: stones represent the intact rock while spaces among them are discontinuities. Nature, size and geometry of blocks, together with the characteristics of the contact surfaces, were described, and a value of Geological Strength Index (GSI) was assigned. Usually two main discontinuities sets can be recognized, one almost horizontal and the second vertical.



**Fig. 2: a typical dry stone wall of the study area, made up prevalently of elongated stones, founded on bedrock and 1.50 m height.**

Spacing depends on the construction technique of the wall, mainly geometry and dimension of blocks. In the past small stones were preferably used with an elongated form resulting in an irregular pattern with a spacing of few centimeters, both vertically and horizontally;. Nowadays, almost squared stones are used, with side dimension of 10-20 cm or more in few cases, that cause a more regular pattern but a wider spacing. Joints can be filled or not with fine material and in some cases also weeds can

be seen. During or immediately after wet periods, discontinuities can be interested, mainly at their base, by water flow. By applying the Hoek and Brown criterion, it was possible to obtain indicative values of cohesion and friction angle of the walls. Later, these mechanical parameters have been calibrated during the modeling phase (Tab. 1).

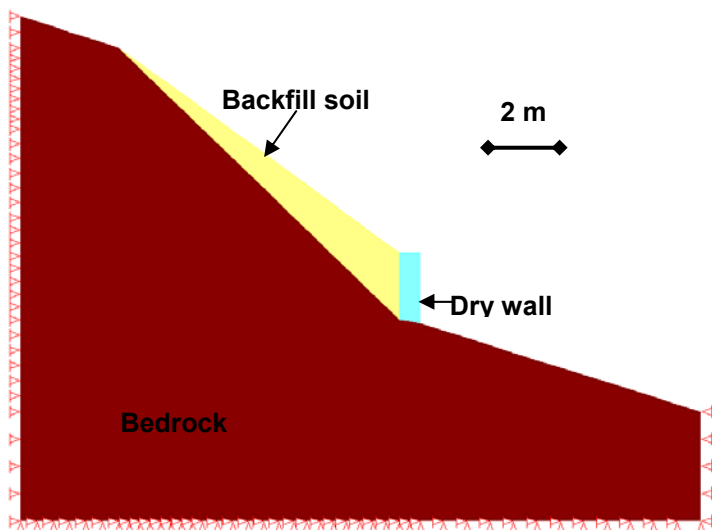
	$\gamma$ [kN/m <sup>3</sup> ]	E [kPa]	$\nu$ [-]	c [kPa]	$\phi$ [°]	dil [°]	$\phi_{ib}$ [°]	$k_s$ [m/s]	n [-]
<b>Soil</b>	16	$2.0 \times 10^4$	0.30	10	30	1	15	$1 \times 10^{-5}$	0.50
<b>Bedrock</b>	26	$1.8 \times 10^6$	0.35	345	57	2	28	$1 \times 10^{-8}$	0.07
<b>Wall<sub>ini</sub></b>	24	$4.2 \times 10^5$	0.32	25	45	1	22	$5 \times 10^{-4}$	0.25
<b>Wall<sub>cal</sub></b>		$2.5 \times 10^5$		120	55		30	$1 \times 10^{-6}$	

**Tab. 1: Parameters used during simulation for soil and bedrock. Those of walls are both initial (Wall<sub>ini</sub>) and after calibration (Wall<sub>cal</sub>).  $\gamma$ : bulk density; E: elastic modulus;  $\nu$ : Poisson's ratio; c: cohesion;  $\phi$ : friction angle;  $\phi_{ib}$ , matric suction friction angle dil: dilation angle;  $k_s$ : saturated hydraulic conductivity; n: porosity. The two values of  $k_s$  indicated for walls, state a different condition of maintenance of these structures. The higher value represents a well-maintenance state that permits the wall drainage function.**

## STRESS-STRAIN MODELING

The geometry of the model is simple and it represents a single terrace, with the dry stone wall, backfill and bedrock (Fig. 3). The wall is founded directly on an outcrop of the bedrock; this is common in the eastern part of the study area, and rare in the western part, where the slope is more gentle and only few evidences of walls founded on outcropping bedrock were recognized. A bedrock slope angle of 44° was assumed based on geometrical and structural evidences on

various outcrops in the area. It is similar to the average terrain gradient of  $42^\circ$  for terraced slopes indicated by Crosta et al. (2003). The height of wall was put equal to 2 m, which is the mean value of the range in which it is possible to find more or less the 90% of the walls. Considering an horizontal width of 8 m, the surface angle results in approximately  $35^\circ$  being this an extreme case, compared to the mean terraces gradient of  $15^\circ - 25^\circ$  suggested by Crosta et al. (2003).



**Fig. 3: Geometry of the model and boundary conditions.**

In a previous work (Camera et al., in review), groundwater numerical modeling through the SEEP/W code was used to determine the relationships between rainfall events and the formation of perched groundwater table. An intensity-duration threshold for the appearance of a first saturated level, on the basis of rainfall data registered quite near the study area and water table levels acquired by continuous data logger specifically installed, was determined. Furthermore, it the mechanism of formation of these water tables was investigated through numerical modeling, and this allowed to understand the influence of different hydrogeological and geometrical factors on this process, such as variations of isotropic or anisotropic hydraulic conductivity of soil and dry stone walls, and changing in the slope of bedrock and in the height of walls.

SEEP/W provides a series of saved timesteps, with their own pore water pressure distribution resulting from defined material properties, boundary conditions and recharge characteristics, Such recorded output can be used in sequence in SIGMA/W. For every different saved distribution of pore pressure, SIGMA/W calculates its relative state of stress that consequently controls the strain behavior.

For the stress-strain analysis horizontal and vertical displacement were forbidden at the base of the model, and the side boundaries were fixed in vertical direction. Before applying pore pressure

For groundwater modeling and stability analysis, the finite elements codes SEEP/W and SIGMA/W were respectively used (GEO-SLOPE International Ltd. 2002) .

The great advantage in using two codes of the same package as SIGMA/W and SEEP/W is represented by the simplicity with which it is possible to use the output of one as input for the other.

configurations, the state of stress was reproduced at the dry state by simulating the construction of wall and its backfill in three different phases.

## **MODEL CALIBRATION**

The first step in the stability model was to calibrate it, especially referring to the mechanical parameters of walls. The outputs of the calibrated groundwater model (Camera et al., in review) were used for three different real rainfall events; only one of these caused slope instabilities. In the hourly time series of rainfall data, a precipitation is considered an event if it lasts at least two hours and if it is separated from another by at least 12 hours of absence of precipitation.

In particular the events of the 22<sup>nd</sup> May 1983 (unstable slope) and those of 25<sup>th</sup> May 1981 and 30<sup>th</sup> November 2009 (stable slope) were studied. The event of 1983 lasted 82 hours for a total rainfall of 196.8 mm. During this event three superficial landslides occurred. The first one was triggered after 41 hours and 119 mm of rain; the second after 60 hours and 150 mm and the third after 66 hours and 176 mm. The analyzed event of November 2009 lasted 44 hours with 121 mm of rain, so very similar to the first trigger. The event of May 1981 lasted 64 hours with a total rainfall of about 178 mm, very similar to the third triggering event. The major difference between these two events and the one of May 1983 is the antecedent rainfall; indeed, in the 15 days that preceded the analyzed events the registered total rainfall was 51.4 mm in 1981, 162.6 mm in 1983 and 1.8 mm in 2009. If the five days antecedent are considered, the relative situation of the three rainfall events is more or less the same: 17.6 mm in 1981, 59.6 mm in 1983, 1.0 mm in 2009.

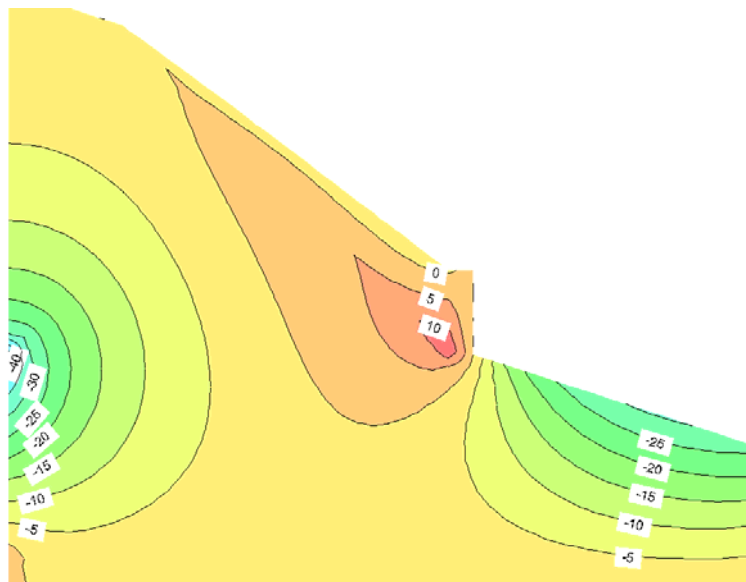
The idea was to calibrate the parameters of walls with a back analysis procedure, starting from the values assigned with the "GSI method" (Tab. 1,  $Wall_{ini}$ ). The problem is related to the initial conditions of the hydrogeological model. This model was in fact previously calibrated with events that, similarly to the one of the 30<sup>th</sup> November 2009, have almost no antecedent rainfall in the 15 days that lead up to the onset of precipitation. The influence of initial conditions on the resultant perched groundwater tables was analyzed and it was noticed that the model is quite sensitive to this condition. Having no direct data about soil suction values just before the precipitation event, it was chosen to model the events of 1981 and 1983 by including in the numerical model all the 15 days of antecedent rainfall using the same initial conditions of the event of 2009. In this way the initial conditions were calculated and distinguished for each of the two intense events. The model was able to well differentiate the behavior of soil respect to the moment of onset of the event analyzed and to lead to different pore water pressure conditions for precipitations that appear very similar.

The parameters of wall were therefore calibrated with a sort of convergence method considering that with the event of 1983 collapse should be observed, and the event of 1981 and 2009 should result in stability. In particular it was possible to obtain a collapse in 1983 after about 61 hours from the onset of the intense rainfall event, so in accordance with the time of triggering of the second of the three instability events.

During this calibration phase all the pore water pressure distributions used as input in the stability model were calculated considering a bad maintained wall, which results almost impermeable by clogging. It was then verified that this variable plays a key role in the complete saturation of the backfill soils (Camera et al., in review) and this situation was observed in site, both during collapse and not, as repeatedly reported by the local population

## MODEL PRELIMINARY RESULTS

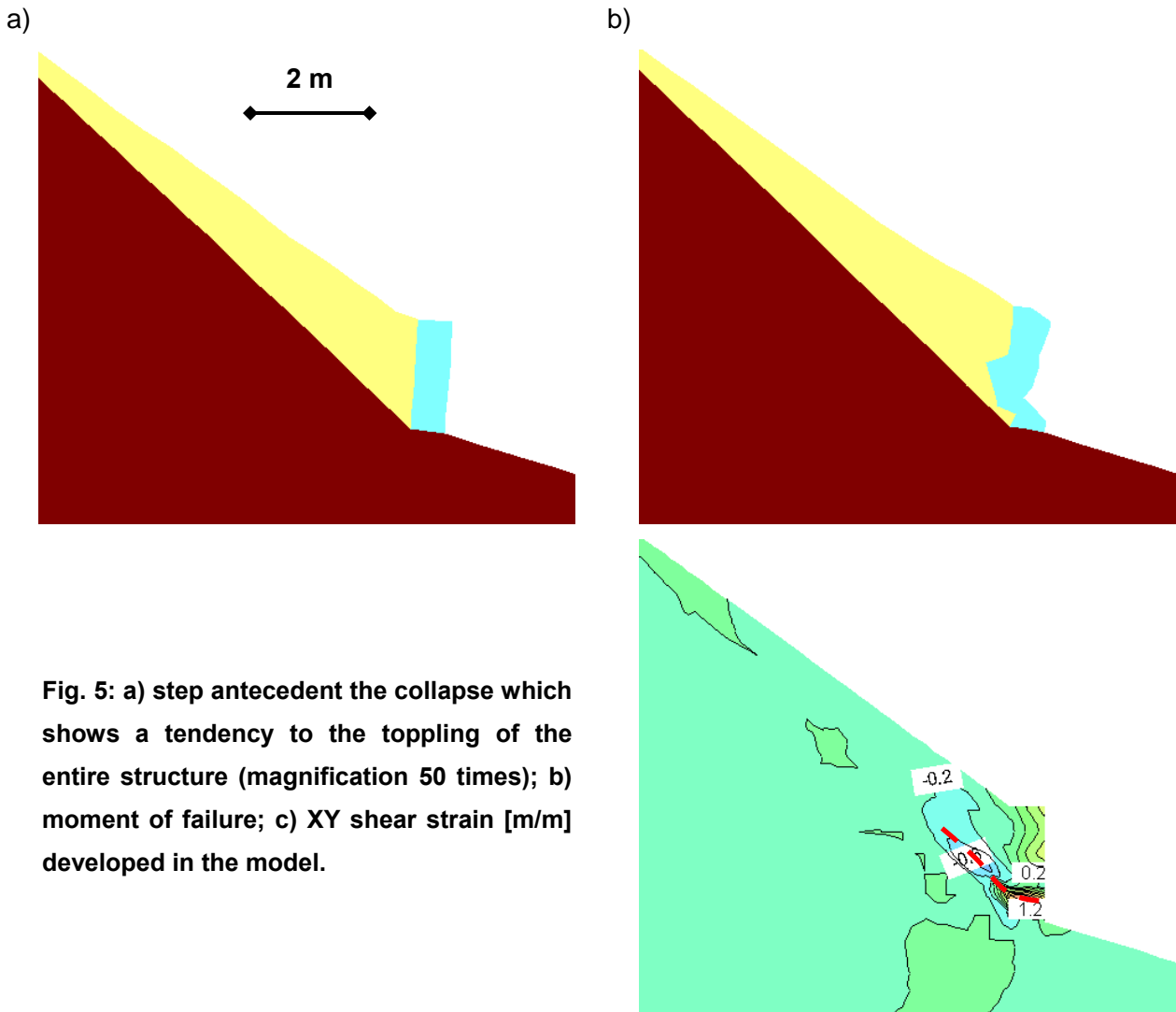
The wall parameters that permit to reproduce stability and instability as observed in reality resulted in an apparent cohesion of 120 kPa, a friction angle of  $55^\circ$ , an Elastic Modulus of  $2.5 \times 10^5$  kPa and a Poisson's ratio of 0.32. The pore water pressure distribution at collapse, obtained simulating the May 1983 event (Fig. 4) is coherent with the description of Azzola and Tuia (1983) who observed saturated backfill soils during the



**Fig. 4: pore water pressure (kPa) distribution at collapse. Rainfall input data coherent with the May 1983 event.**

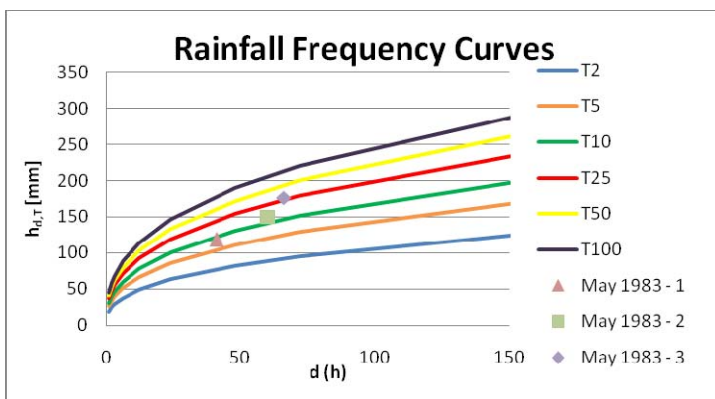
triggering of the second superficial landslide. The mechanism of failure is, on the contrary, different. The same authors reported about a bulging at the toe and a consequent collapse that involved the entire height of wall. Instead, in the step antecedent the collapse, the model shows a tendency to the toppling of the whole structure, that in the moment of failure, evolves in a sort of flexure in the lower/middle part of the wall (Fig. 5a,b). As expected, the positive shear strain are concentrated at the base of the wall (Fig. 5c), but probably for numerical reasons the model balances them with an uphill displacement of the middle-low part of the wall rather than with a homogeneous movement towards downhill. Such a numerical solution could be affected by the different rigidity of the wall respect to the one of bedrock to which it is bound.





**Fig. 5: a) step antecedent the collapse which shows a tendency to the toppling of the entire structure (magnification 50 times); b) moment of failure; c) XY shear strain [m/m] developed in the model.**

The model was then used with rainfalls events of duration and constant intensity defined by statistical methods. The database is composed of 27 years of hourly data in the two period 1980-2002 and 2007-2010. In particular return periods of 10, 50 and 100 years were used, each of them with total durations of the events of 72 hours (Fig. 6).



**Fig. 6: duration-total rainfall frequency curves, calculated with statistical method. The three points show the characteristic of the rainfall event of May 1983 at the moment of the triggering of the three occurred landslides.**

For every combination of duration and return period, it was decided to vary the initial conditions and the state of maintenance of the wall. Initial conditions were therefore considered dry, applying the pore pressure distribution used also in the previous steps of the work, or very wet, adding the recorded rainfall of the 15 days that preceded the May 1983 event, before the project precipitation. Regarding maintenance, two cases are simulated: in the first, the hydraulic conductivity of the wall was imposed higher than that of the backfill soil, maintaining its draining function; then a lower hydraulic conductivity was assumed considering a bad maintained wall clogged with fine (Tab. 1). Results are summarized in Tab. 2.

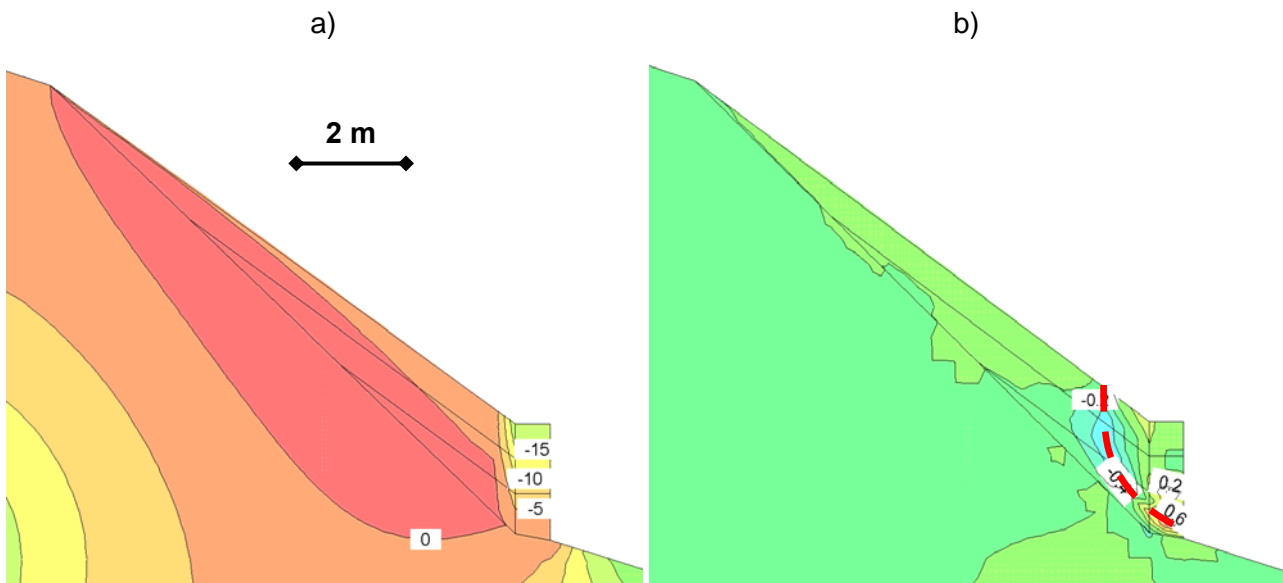
ID	Return period	draining function	Initial condition	Result
1	10 years	yes	Dry	Stable
2	10 years	yes	15 days previous 22 <sup>th</sup> May 1983 event	Stable
3	10 years	not	Dry	Stable
4	10 years	not	15 days previous 22 <sup>th</sup> May 1983 event	Stable
5	50 years	yes	Dry	Stable
6	50 years	yes	15 days previous 22 <sup>th</sup> May 1983 event	Stable
7	50 years	not	Dry	Stable
8	50 years	not	15 days previous 22 <sup>th</sup> May 1983 event	Stable
9	100 years	yes	Dry	Stable
10	100 years	yes	15 days previous 22 <sup>th</sup> May 1983 event	Unstable
11	100 years	not	Dry	Stable
12	100 years	not	15 days previous 22 <sup>th</sup> May 1983 event	Unstable

**Tab. 2: summary of the results of the analysis performed with statistical project rainfall events and constant intensity.**

Results strengthen the findings obtained during calibration about the importance of the initial hydraulic conditions; in fact the collapse is reached only if the 15 days of rainfall before the event of 1983 are used to determine the soil moisture initial condition of the triggering event.

Furthermore, they emphasize some details that did not emerge during the previous calibration phase. In particular, the collapse is reached only for very high return periods (100 years) and in both conditions of well and bad maintained wall. With a well maintained wall, the rainfall event of 1983 with its 15 days of previous rainfall does not cause any instability. This fact highlights that the failure occurring during very extreme events, could originate not only because of the water overpressure directly acting on the wall, but also for the previous failure of the backfill soil, as shown by the XY shear strain at the moment of collapse of the simulation number 10 (Tab. 2) in Fig. 7b. In addition, despite the simulation 8 (Tab. 2) has a return period higher than that of the second trigger of May 1983 (Fig. 6) used for calibration and well reproduced by the model, it

results in stability. An explanation of this result could be that also the rainfall pattern could have an effect on stability.



**Fig. 7: results of the simulation 10. a) pore water pressure distribution at collapse and b) XY-shear strain that enlighten the possible surface of failure.**

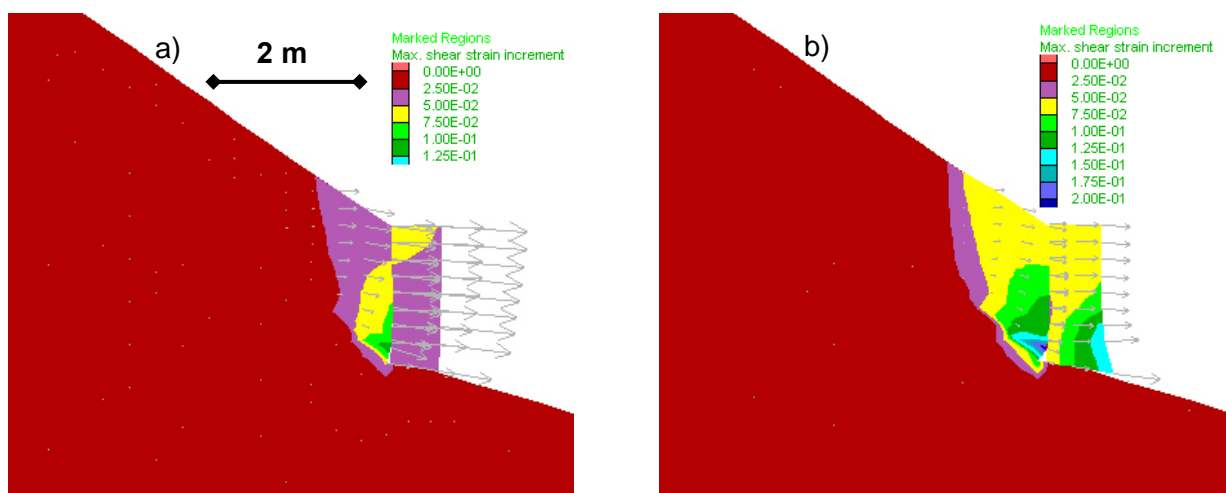
## FLAC

In order to better reproduce the actual mechanism of the dry stone wall failure, a finite difference numerical analysis through the FLAC 6.0 (Fast Lagrangian Analysis of Continua - Itasca Consulting Group Inc, 2008) code was performed. General results of the two different codes were also compared to see if they were consistent each other and so increasing their degree of reliability.

The same geometry was reconstructed and also the grid was created as similar as possible to the one of SEEP/W and SIGMA/W. The main difference lies in the fact that with FLAC the wall is separated from soil and bedrock by means of two interfaces, in order to react to forces and pressures in an independent way, without being bonded to the rest of the system. Mechanical and hydrogeological properties were assigned to materials, using the calibrated values got with the previous modeling phases and an initialization of the state of stress was obtained, cycling the model in dry conditions till an elastic equilibrium was reached. As the infiltration and groundwater movement process was well described by SEEP/W (Camera et al., in review), it was decided to calculate only the groundwater table geometry with FLAC 6.0 applying a constant infiltration at the terrain surface, cycling subsequently the model, only for groundwater flow purposes, till arriving to the pore water pressure distribution obtained by the groundwater numerical modeling.

The most critical water table levels for the three events of 1981, 1983, and 2009 as calculated by SEEP/W were reproduced, both for a draining and a not-draining wall. Concerning the mechanical

analysis, the physical parameters of wall calibrated with SIGMA/W resulted to be too high, above all in terms of cohesion, as the system was always stable. Instability is observed for the 1983 event and a not-draining wall, lowering the cohesion value of wall from 120 kPa to 15 kPa. This lower value seems also more reliable and it would strengthen the procedures "GSI and Hoek-Brown method" applied to define the parameters of the wall, which gave a closer value of cohesion. Changing only this value, the results obtained with SIGMA/W can be replicated by FLAC, with the exception of the events 8 and 10 (Tab. 2) that resulted in collapse and in stability respectively. Additionally, the FLAC simulation appears to better reproduce the mechanism of failure. With FLAC 6.0 it's in fact possible to observe an initial toppling (Fig. 8a) that later evolves in bulging and sliding at the base of the wall (Fig. 8b) until collapse occurs. It is also possible to see how the failure surface resembles the one that forms in SIGMA/W for a draining wall (Fig. 7b), although the model in Fig. 8 represents a condition of bad maintenance of the retaining structure. This difference in behavior is controlled by the presence and mechanical properties of the interface at the contact between the wall and bedrock.



**Fig. 8: results obtained from FLAC showing the shear strain increments and the displacement vectors. (a) At the beginning the displacement is greater in the upper part of the wall as in a toppling but later (b) the collapse occurs for bulging at the toe and sliding of the base of the wall.**

## Conclusion

Defining and understanding the conditions and the processes that could lead to a collapse in a terraced slope are the main objectives of this work. Numerical modeling, supported by an intense in situ and laboratory tests and a groundwater monitoring plan, demonstrated to be a good methodology to approach such analysis. In particular, the comparison of the results obtained with two different codes allowed to calibrate the mechanical parameters of the dry retaining walls and in the meantime to deeply analyzed the importance and the effects on slope stability of different

factors such as initial moisture content conditions, return periods of the rainfall events, maintenance characteristics of walls, and rainfall patterns.

The processes were studied at a very detailed scale, reproducing the model of a single terrace with a dry wall and its backfill, laying on a semi-impermeable bedrock. In particular, it was possible to calibrate the mechanical parameters of walls by back analysis, coupling a groundwater numerical model with a stability one. The two codes show only a difference in the value of cohesion of wall, being therefore consistent one with the other and giving a good proof of their reliability.

Once calibrated, the SIGMA/W model was used to analyze the influence of initial backfill moisture content conditions, and different drainage capacities of dry wall, using as input rainfalls with a duration of 72 hours (similar to those that in past years led to instability), and constant intensities, calculated on the basis of different return periods.

The only drawback of this model is that it does not reproduce the dynamic of failure as observed on field. However it confirms a great influence of antecedent rainfall on stability, and for very high return period it suggests that the drainage capacity of the wall influences the mechanism of failure. Finally, the comparison of simulations with measured rainfalls and with constant intensity, both characterized by similar or higher return period, shows a different proneness to instability, suggesting a possible influence of different rainfall patterns in the developing of failures.

The subsequent analysis, carried out with FLAC 6.0, confirms almost all the results obtained with SIGMA/W even if it demonstrates that the most important role in the triggering of the landslides is played by the overpressure that is created behind the wall. This factor, that is related to a condition of the wall that does not permit an effective drainage, seems to be crucial also for rainfall events of very high return period. The possibility that a landslide is triggered lies in the groundwater level just behind the wall. FLAC 6.0 can reproduce well the mechanism of failure also with mechanical parameters of wall more similar to the expected ones than those set with SIGMA/W, appearing therefore in a first approximation the most appropriate instrument to describe the phenomena. On the other hand it is worth mentioning that the coupled analysis performed with SEEP/W and SIGMA/W takes into account processes with a greater detail. From the SIGMA/W analysis it seems that the triggering is also influenced by the combination of different factors; the conditions of wall above all but also the pattern of distribution of rainfall and so the evolution of the water table and the relationships between the behavior of the saturated and the unsaturated soil.

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