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Stability of a retaining wall in severe hydraulic conditions (Northern Italy)

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1 INTRODUCTION

Northern Italy has always been affected by strong rainfalls which trigger instability in the territory (Barla et al. 1998, Luino 2005). Therefore, drainage and regulation of water have been key issues in evaluating the stability in the area. For this reason, in a sequence of papers Camera et al. described the relation between hydrology and slope stability in Valtellina (Northern Italy). Camera et al. (2011) provided a hydrological model and reproduced the hydrological dynamics of a slope with retaining walls; they then used the previous hydrological model to study the stability and failure mechanisms of slopes by numerical modeling (Camera et al. 2013, 2014); finally, they presented an alternative approach based on the global method of equilibrium (Camera et al. 2015). In their analyses, the model was calibrated with monitoring data, and no structural and drainage elements were involved.

In this work we study an event in Borgiallo, located in Piemonte (Northern Italy) in Spring 2018, when after a particularly intense rainfall, a segment of the dry stone retaining wall built in the vicinity of the main road collapsed. There were no casualties, but part of the road was damaged. After the event, the collapsed section of the wall was redesigned, and a numerical model supported the standard geotechnical and structural analyses. The main unknown in this problem was the position of the water table in the backfill of the wall, and it was estimated by numerical modeling. We calibrated the numerical model with qualitative information obtained in situ after the collapse, and we introduced the hydrologic data registered by a local meteorological station as input data. The purpose of this study is to validate the use of a numerical model to guarantee the stability of the wall in severe weather conditions.

2 DESIGN AND ANALYSIS

On Thursday 12th April 2018, a dry stone retaining wall collapsed on a slope below the main road (SP45 della Valle Sacra). This followed rainfall events which reached 55 mm on the Wednesday 11th and 75 mm on the Thursday. From the hydrologic data and the geometry of the slope-road system, we estimated that the road collected a total amount equal to 630,000 liters of water on Wednesday and 805,000 liters on Thursday. More importantly, the rain rate reached a peak of 55 mm/hr on Wednesday and 75 mm/hr on Thursday. It was the 75 mm/hr rate which triggered the event and the subsequent collapse of the wall; in fact, the week before, the rain rate peak was only 30 mm/hr. The possibility that a significant water table reaches the back of a wall mainly depends on the combination of the soil hydraulic characteristics and geometry coupled with rainfall intensity and duration (Camera 2014). Because of the morphology and the lithology of the area, and the lack of superficial drainage and regulation of water, all the water inflowed into two specific points above and below the main road in the vicinity of the wall (see Fig. 1). The backfill of the wall was constituted by a low permeability soil, so overpressures occurred causing the collapse.

Two different models were built: the initial condition of the system that led to the collapse of the retaining wall (Case 1) and the new alternative condition proposed to mitigate the risk (Case 2). To design the new portion of the retaining wall, several scenarios were simulated by *FLAC* software (Itasca 2011). Because of its capacity to simulate groundwater flow, mechanical-fluid interactions and structure-soil interaction, *FLAC* was particularly suitable for this work. We simulated three consecutive flow periods that reproduced both the rainfall before the event and the rainfalls of Wednesday and Thursday. The equation governing the infiltration and groundwater flow is Darcy's law, which relates fluid flow rate and pressure gradient in a given formation (Barends & Uffink 2006). For a single fluid flow, in a 3D geometry, the Darcy's equation is:

$$q_i = -\frac{1}{\mu} k_{ij} \hat{k}(s) \frac{\partial}{\partial x_j} (P - \rho_w g_k z_k) \tag{1}$$

Where q_i is the flow rate vector, k_{ij} is the intrinsic permeability tensor, $\hat{k}(s)$ is the relative permeability, μ the fluid viscosity, P the pressure, ρ_w the fluid density and $g_k z_k$ the gravity vector. The intrinsic permeability k has units $[m^2]$. Note that in *FLAC*, instead of the intrinsic permeability (k), the mobility coefficient λ is implemented (Itasca 2011):

$$\lambda = \frac{k}{\mu} \tag{2}$$

λ has units of $[m^2/(\mathrm{Pa} - \mathrm{s})]$. The relative permeability $\hat{k}(s)$ is a function of the saturation (s) through the equation (Itasca 2011):

$$\hat{k}(s) = s^2(3 - 2s) \tag{3}$$

Often, in hydrogeology Darcy's law is written using the hydraulic conductivity K_H $[\mathrm{m/s}]$ instead of the intrinsic permeability or the mobility coefficient (Fitts 2002). Hydraulic conductivity is defined as:

$$K_H = \lambda \rho_w g \tag{4}$$

In *FLAC* the permeability is a property assigned to the material and it can be anisotropic. However, in our numerical model we assumed isotropic permeability for each soil layer.

Since no laboratory and in situ tests were available in the area of interest, we estimated the geotechnical parameters by back analysis of a landslide on the opposite side, where the failure surface and the stratigraphy were known. The analysis was conducted by *FLAC*, starting from an equilibrium configuration and lowering the combination of friction angle and cohesion parameters, until failure occurred. These values should be considered as the characteristic values of the parameters (see Table 1). There are three main geological formations: one shallow formation composed by shale, an underlying shaly bedrock and compact bedrock. The total depth of interest is 15 m.

Table 1. Geotechnical parameters.

	Specific Weight (γ)	Saturated Specific Weight (γsat)	Friction Angle (φ)	Cohesion (c)
	[kg/m3]	[kg/m3]	-	[kg/cm2]
Shallow Shale	1800	2000	24	0.07
Shaly Bedrock	2000	2200	38	0.1
Compact Bedrock	2100	2300	38	0.3

In Figure 1 is reported a cross section of the dry stone retaining wall in both cases. The numerical models take into consideration all the elements present in the physical models. In Case 1, the retaining wall was built by heavy coarse boulders placed on a concrete foundation, then a micropile anchored to the bedrock was inserted. In the numerical model, the wall was modeled with a rock material with high permeability, separated from the soil by means of an interface; the concrete foundation was modeled with a beam structural element and the micropile with a pile element. The backfill material was modeled as low permeability soil. Regarding the hydraulic boundary conditions, the rainfall was modeled by the *discharge* boundary condition, which caused a prescribed inflow of fluid. The *discharge* points were applied at the backfill top boundary and in the left boundary of the model; the values of discharge vary with the evaluated hydraulic scenario (initial rain of 30m/hr, Wednesday rain of 55m/hr and Thursday rain of 75mm/hr). This boundary condition allowed us to study the phenomenon in transient conditions and then observe the final saturation distribution (Itasca 2011).

The numerical model used to simulate Case 2 was the same as the one described above, except that a cable anchored to the bedrock was inserted as a cable structural element, the backfill was constituted by higher permeability material (gravel) and, finally, a drainage pipe was placed above the foundation. Furthermore, in this model the drainage pipe was modeled by a *leakage* imposed at the bottom of the backfill layer.

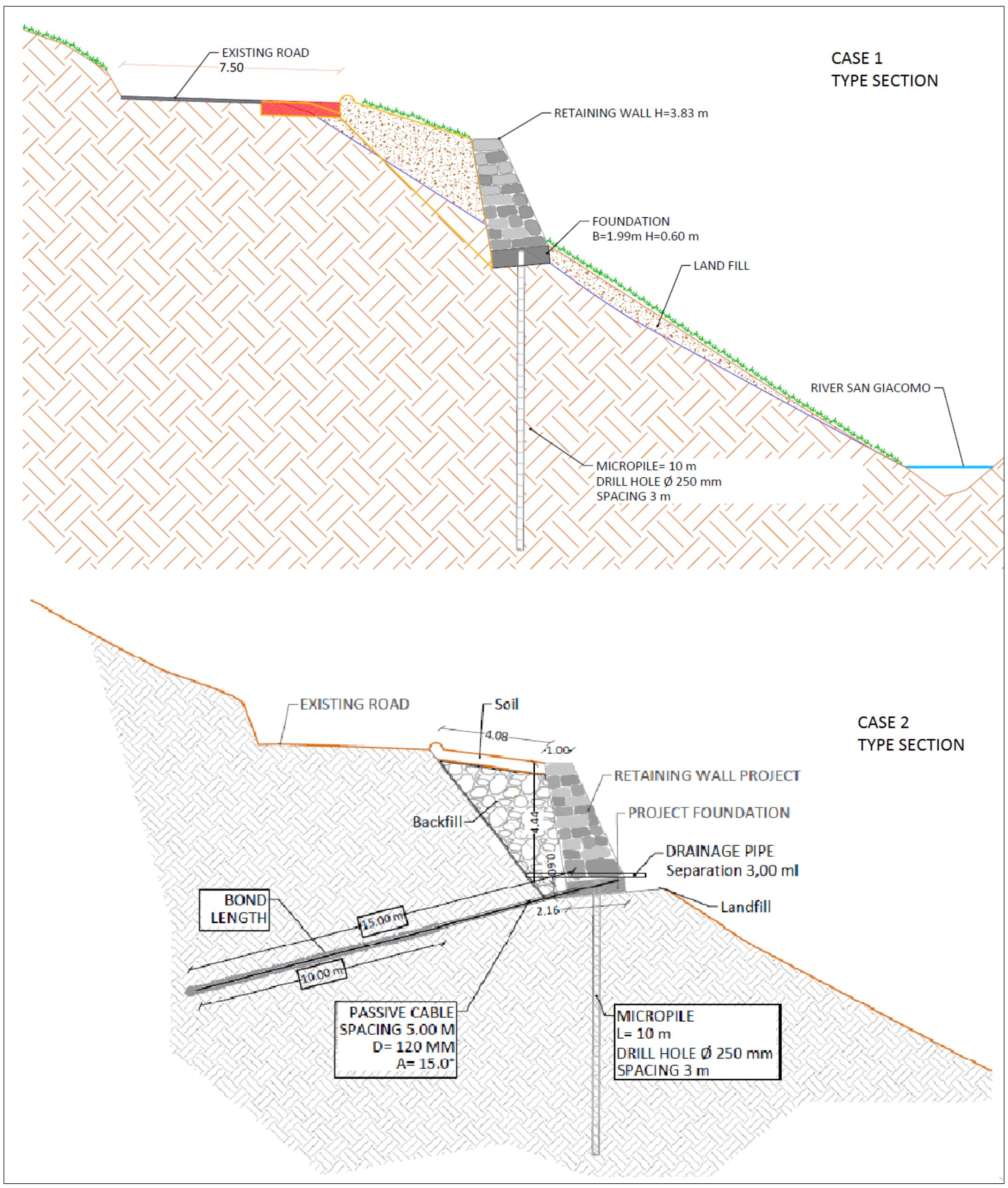

Figure 1. Cross sections of the area of interest in Case 1 and Case 2.

3 RESULTS AND DISCUSSION

In order to calibrate the numerical model, a simulation in dry conditions (no hydraulics and no presence of static water table) was run in Case 1, and stability was verified: this is an important outcome because it matched the behavior of the system before the strong rainfall. Then, the same model was run in wet conditions, and in the last scenario no convergence was reached (the simulation was stopped at 50,000 cycles), as expected, and the instability and collapse were reproduced. At the time the simulation was stopped, the water table reached the surface level as was shown in the full saturation of the backfill. From an inspection in situ after the collapse, it was known that all the backfill soil was saturated and no water was drained by the dry stone wall: this information is consistent with the simulated results and it was used for the calibration of the numerical model. In Case 2, at the end of the simulation, the water table was risen only until 0.5 m above the foundation, respecting the design limit (water table at 1.5 m above the foundation). In these conditions, all the structural elements were successfully designed to support the acting forces. To confirm this, Figure 2 shows that the maximum total displacement was only 3.4 mm and the maximum total displacement of the micropile was 0.4 mm. The maximum value of bending moment on the micropile was 357 N m, while on the cable the maximum displacement is 0.6 mm and the maximum axial force is 27 kN. Finally, comparing the results in terms of shear strain, in Case 1 a failure surface was clearly visible as a result of instability, whereas in Case 2 no severe strain concentration was present along that surface; this could be reaffirmed by the trend of the displacement vectors in Figure 2. The main results are summarized in Table 2.

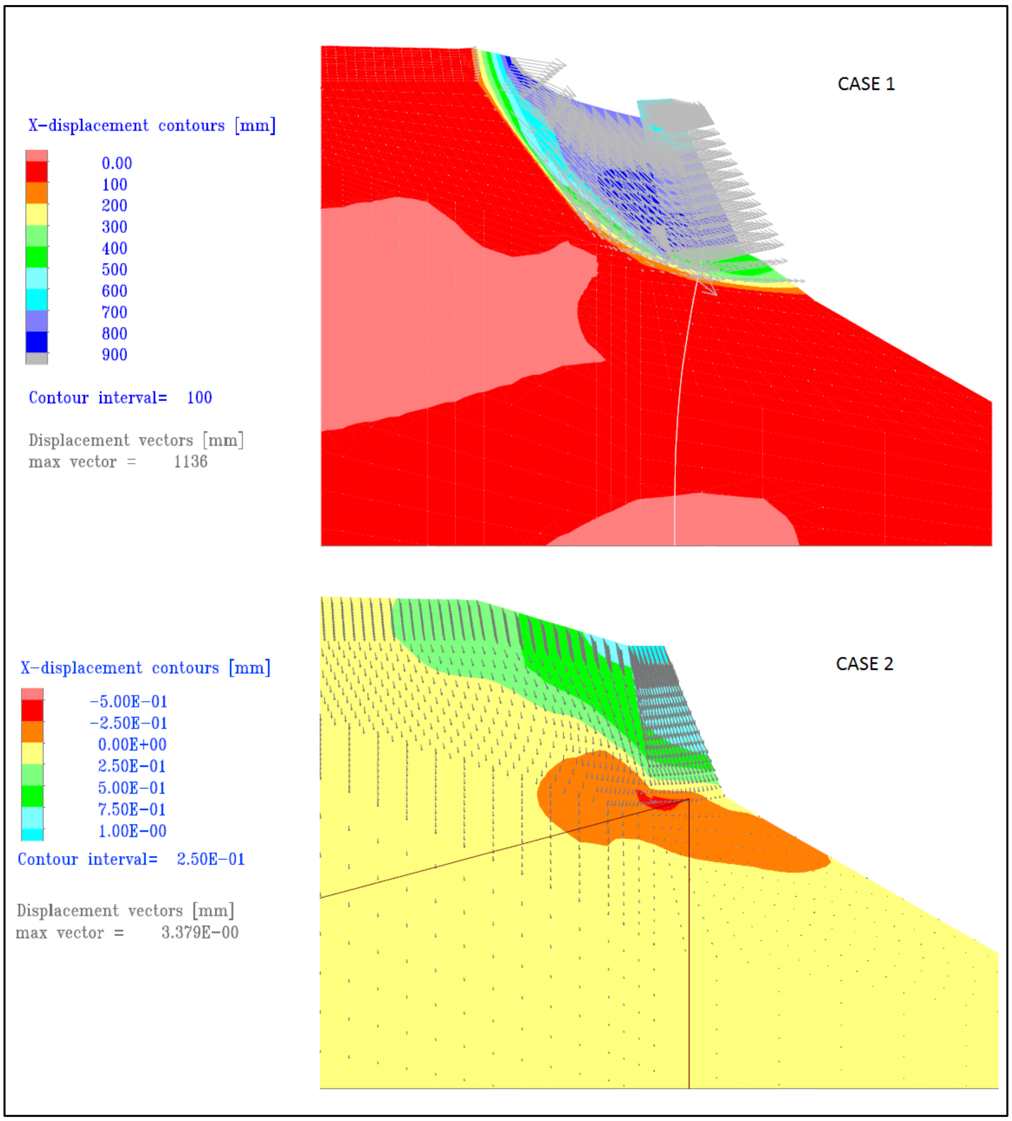

Figure 2. Total displacements in Case 1 and Case 2.

Table 2. Summary of the results.

	Max Total Displacement	Max Micropile Displacement	Water table (above foundations)
	[mm]	[mm]	[m]
Case 1	no convergence	no convergence	5
Case 2	3.4	0.4	0.5

4 CONCLUSIONS

After the rainfall events in Borgiallo in the Spring 2018 and the subsequent collapse of a segment of the dry stone retaining wall in below the main road, some modifications to the project were made. For this purpose, numerical simulations able to reproduce the behavior of the system in such adverse hydraulic conditions were run and important considerations regarding the water table were made. In fact, the results showed that the stability of the wall was verified in ordinary rainfall conditions, but instability occurred in case of severe weather conditions and in absence of a drainage pipe. Therefore, the presence of a drainage pipe is necessary to ensure the fluid outflow and to avoid overpressures in the vicinity of the wall. Periodic maintenance and cleaning is also necessary to ensure the correct functioning of the pipe and prevent materials from blocking the water outflow. In conclusion, we can certainly affirm that a numerical study assists standard geotechnical analyses and provides important information when hydraulics and groundwater flow are involved.

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