

Modelling of Moisture Effect in Safety Evaluation of Soil-Interacting Masonry Wall Structures

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Abstract. This paper deals with analytical models of retaining walls interacting with soil, whose mechanical properties are influenced by penetrating moisture. Specifically, urban masonry walls are here considered. The proposed simplified procedure takes rainfalls as the intensity measure dependent on rain duration and return period. Growing levels of imbibition of the soil behind the wall determine a de-crease of the strength parameters of the soil. A geometry of the section at each step of imbibition is analyzed considering a set of soil layers with modified properties over time. The method is applied to a section of the Volterra historical urban walls named "Sperone" which was affected by a relevant collapse occurred in March 2014: a back analysis of the soil-structure section is also proposed to re-place the collapse.

Keywords: Historical urban walls · Moisture effects · Landslide risk · Volterra urban walls

1 Introduction

The effects of moisture in soils involve widespread infrastructures such as slopes, embankments, retaining walls and urban masonry walls. These last are irregular constructions situated along the external perimeter of historical city centers and built with retaining and defensive functions. In the last ten years there have been several collapses which were triggered by rainfall induced landslides as reported in [1–3]. In the presented case study, prolonged rainfalls of medium to high intensity caused long lasting wet periods in the days before the collapse: this suggests that soil moisture played a key role.

An increase of the action as hydraulic thrust and a contemporary decrease in shear strength of the soil leading to instability are well-known phenomena. The evaluation of the effects of moisture as an external action and its non-deterministic characterization remains an open issue for both traditional and bio-aggregate based masonry [4]. While other natural phenomena such as wind or snow are widely regulated by international codes, together with seismic effects on cultural heritage buildings [5, 6], no in depth details are provided for this variable [7, 8].

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Non-linear analyses taking into account an increasing level of hydraulic thrust on a section of Volterra urban walls were performed in [9]. Moisture depends not only on rainfalls but also on permanent conditions such as soil properties, drainage systems and human interferences. This has been investigated in [10] where the role of antecedent soil moisture on the critical rainfall intensity-duration that caused the landslide is considered.

The procedure here explained considers the imbibition only due to rainfalls. Starting with a short discussion on survey strategy [11–13] a section of Volterra urban walls is set up for the evaluation of the safety of the infrastructure with the increase of moisture. The SLIP model proposed by Montrasio and Valentino [14] and the results of Yoshida [15] are implemented and adapted to predict the risk of landslide.

2 State of the Art

Many studies have been conducted on the complex relationship between slopes stability and rainfalls, especially where there has been a recent increase in rainfall amounts and intensity [16–19].

Rainfalls induce changes of soil behavior: an increase of degree of saturation S_r, density γ and hydraulic thrust and a decrease of cohesion c' and angle of friction ϕ.

The effects of saturation ratio on the strength parameters of partly saturated soils were investigated in [15]. A major role is played by effective accumulative infiltration and the capacity of permeability of the soil [20]. Numerical methods can represent the problem considering many variables, however the computational burden is high and time-consuming [14].

A simplified method of analysis (SLIP model) aimed at highlighting the main aspects of the triggering event with a small amount of parameters is proposed by Montrasio and Valentino [14]. This physical phenomenon is reproduced into a mathematical model which can be described in Fig. 1.

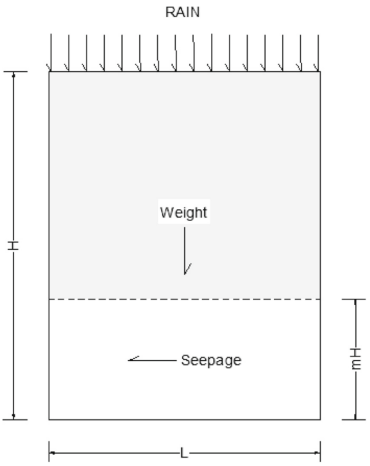


Fig. 1. Scheme of the infinite partially saturated slope of height H, as proposed in [14]

The SLIP model is applied to the case of an indefinite slope of reduced thickness and evaluates the safety factor taking into account the increase of the degree of saturation (S_R) with varying rainfall amounts. Other input parameters are the slope geometry, soil state, mechanical and hydraulic characteristics.

The water flowing vertically causes the progressive saturation of the soil until stability cannot be maintained.

The safety factor is defined applying the limit equilibrium method to an equivalent infinite slope. It is composed by two soil parts: a partially saturated one and another which is fully saturated.

Through a process of homogenization reduced shear strength parameters are obtained [6, 9]. The parameter m represents the thickness of the saturated layer and is a function of the height of rain. The model allows a quick evaluation of the decrease of the apparent cohesion and if applied to a chosen time frame provides an estimation of the safety factor.

Through the studies of Yoshida on silty sands and clays, it is possible to estimate the variations of the angle of friction. In [22] the angle is shown to decrease nearly at a constant rate with increasing saturation ratio depending on soil type and density.

The above studies are suitable to predict landslide events in a simplified and more rapid way. While the risk of these phenomena is related to their speed, to the difficulty of foreseeing their location and to the large amount of interferences also with other infrastructure that may be involved [23, 24], a swift and prompt method can help communities and authorities in the activity of monitoring and prevention.

3 Methods of Analysis

With the presence of infrastructures, the SLIP Model has been implemented to definite slopes (which contain retaining walls) in order to evaluate the reduction in shear strength due to the increase of the degree of saturation.

Moreover, to consider increasing rainfall durations, the soil layer involved in the weakening process has been discretized into horizontal strata. These are progressively affected by a process of imbibition which corresponds to a reduction of shear strength. The original application of the SLIP model discusses only superficial indefinite slopes. This hypothesis is here removed because of the "retaining" effect of the wall.

The experience of recent collapses highlights that the moisture of the soil is a recurrent condition in urban walls' failures. The degradation of the masonry due to the presence of water is not considered in this work.

The profundity and the number of chosen strata depend on the height of the wall and on the eventual presence of possible impermeable layers, as well as, in this case, on the considered rain duration. In the case of absence of imbibition, it is proposed to relate the overall height of the soil to the height of drainage. With this assumption two different areas of soil are highlighted, with (1) and without imbibition (2).

This approach is substantially different from the traditional drained and undrained conditions usually analyzed in the case of cohesive soil. The different strata are characterized by a different saturation level related to rainfall heights.

This approach can also be adapted to the case of imbibition derived from other sources as well as filtrating water or leakage of water pipes, taking into account the effective geometry of the filtrating system.

3.1 Evaluation of the Safety Factors

Considering a portion of soil of height *H,* which is chosen equal to 1 m, the portion *mH* ($m < 1$) is completely saturated. A representation of the model was already given on Fig. 1. The parameter *m* is directly linked to the cumulative height of rainfall in a certain duration of time and represents the percentage of saturated soil. It is given by the following [14, 21]:

$$m = \frac{\beta^* h}{n(1 - S_r)H} \tag{1}$$

where *h* is the amount of rainfall registered for a certain time duration; β^* represents the capacity of imbibition; *H* is the height of the layer altered by the rainfall; *n* is the soil porosity; S_r is the saturation grade.

The saturation grade is function of the initial saturation of the soil, S_{r0} which depends on the time of the year we are analyzing (higher values correspond to wet seasons such as autumn, winter or early spring [25]), and can be calculated from the following equation [14]:

$$S_r(h) = S_{r0} + \frac{\beta^* h}{nH} \tag{2}$$

The degree of saturation varies according to the amount of rainfall happening on a given time frame. This means that previous rainfalls may play an important role on the stability of the slope.

The *m* parameter is linked to *h*, rainfalls registered and to their durations meaning that *m* is time dependent.

However, if long periods of time (such as entire seasons) are considered, each daily increment of *h* would correspond to an increase of *m* without considering natural phenomena such as seepage or evapotranspiration: *m(t)* is a negative exponential law as in Eqs. (3)-(7).

In this way it is possible to realistically evaluate the fluctuation of the safety factor over a long-time span [14].

$$m(t) = \sum e^{-K_T \frac{\sin\beta}{n(1-S_r)}(t-t_{0i})} \frac{h(t_{0i})}{nH(1 - S_r)} \tag{3}$$

$$F_s = \frac{\cot\beta \tan\phi'[\Gamma + m(n_w - 1)] + C'\Omega}{\Gamma + mn_w} \tag{4}$$

$$\Gamma = G_s(1 - n) + nS_r \tag{5}$$

$$n_w = n(1 - S_r) \tag{6}$$

$$\Omega = \frac{2}{\sin 2\beta \cdot H \cdot \gamma_w} \tag{7}$$

In the Eqs. (3)–(7) t_0 represents the starting instant (day in the case of this work); ß is the angle of inclination of the slope; H is the thickness of the soil layer; G_S is the soil gravity; *n* is the soil porosity; γ_M is the unit weight of water.

The proposed procedure takes advantage of this application to analyze backwards events of collapse which have triggered the city of Volterra. The analysis of rainfall characteristics in the area of study is the starting point. A record of the rainfalls with durations can be found on regional pluviometry charts [26].

3.2 Shear Strength Reduction

The aim of this work is to evaluate the shear strength reduction of soil layers under progressive imbibition corresponding to increasing rainfalls within 24 h. With this purpose, five layers one meter thick are considered and represent 1 h, 3 h, 6 h, 12 h, 24 h rain durations.

The coefficient m will be evaluated using Eq. (1) without considering the time dependent variable which is assumed constant throughout the application (rainfall of 24h). Moreover, the height of rain is considered dependent on the return period as well thanks to the well-known hydrology theories. The height of rain, h, is function of the rain duration d and return period t_r through:

$$h = a \cdot d^{\kappa} \cdot t_r^{\eta} \tag{8}$$

The rain duration is expressed in hours and the return period of the event in years; a *(26,543),* κ *(0,264)* and η (0,219) are dimensionless parameters given by multiple linear regression of regional rainfall records.

For our case studies they were deduced from. Equation (8) is a recurrent function of interpolation of pluviometry data. Similar equations are provided for specific zones depending on determined models of interpolation. The function is plotted on Fig. 2 for four different return periods and five rain durations in the range 1–24 h. Each increment of rainfall determines a variation of S_r which allows the calculation of the apparent cohesion expressed by the following:

$$c = c'(1-m)^{\alpha} \text{ where } c' = A \cdot S_r \cdot (1-S_r)^{\lambda} \tag{9}$$

where A and λ are two dimensionless coefficients depending on soil type [14, 27].

A base section and five progressively imbibed models with simplified geometries are created. These can be analyzed both with limit analyses and numerical methods with FEM geometries.

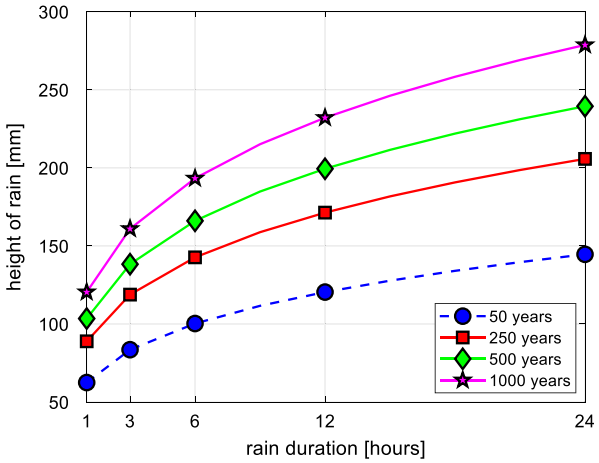


Fig. 2. Heights of rain from Eq. (8) for the site of Volterra.

The upstream soil surrounding the infrastructure is discretized into horizontal strata each representing the level of imbibition caused by increasing rain durations in terms of decrease of mechanical parameters. Figure 3 represents the most serious condition with 24 h rainfall considered.

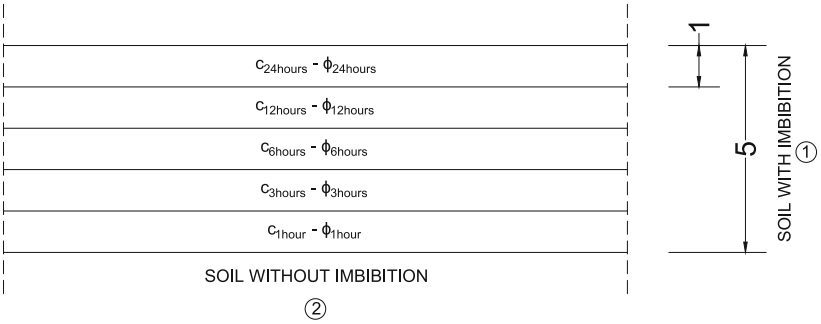


Fig. 3. Vertical section of the soil with discretization in horizontal layers. The condition shown is the worst corresponding to a rain duration of 24 h.

In the analytical models masonry is nowadays modelled also considering a parametric approach [28, 29]. This work is focused on the probabilistic effects of moisture that affects a decrease of mechanical properties of the soil only.

Both masonry and soil are modelled as continuous isotropic and homogeneous materials within the elastoplastic range and with the Mohr-Coulomb resistance criteria to only define the materials through the angle of friction and cohesion.

The simplified analysis are carried out using the SSAP2010 code [30, 31] which provides quick results through an easy interface. To evaluate the slope stability, the

Morgestern and Price method is used. The results are provided in terms of evaluation of the safety factor, FS, critic return period and rain duration.

A flow chart of the procedure is reproduced in Fig. 4.

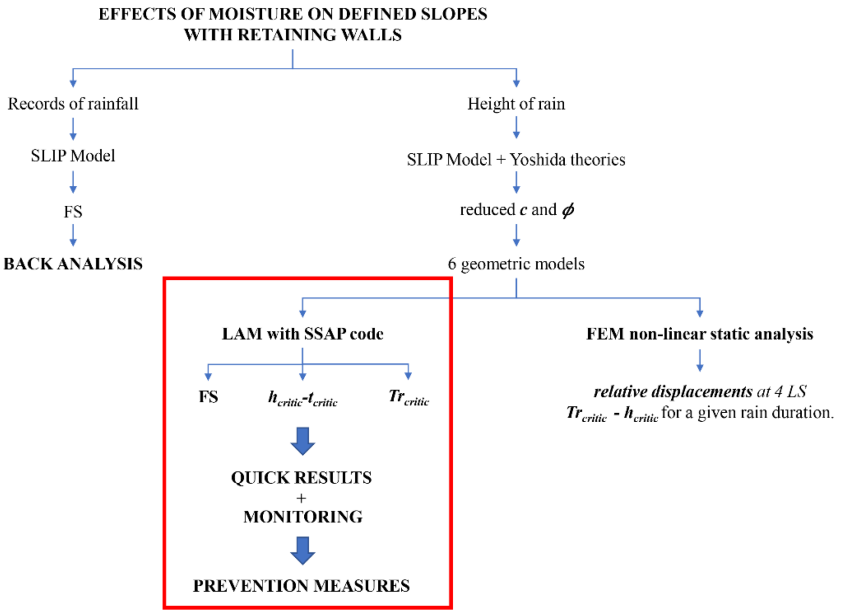


Fig. 4. Flow chart. In red the simplified procedure exposed in this paper. (Color figure online)

4 Application of the Method

The model has been applied to a section of the Volterra masonry walls, named "Sperone". The results of the simplified procedure described in 3 are here applied to a real collapse.

4.1 Case Study

On March 3rd, 2014 the Etruscan Spur close to Place "Martiri della Libertà" collapsed after some days of heavy rainfalls and an overall wet season. Indeed, in January of the same year another relevant event of collapse happened and was investigated in [7].

A picture of before and after the collapse is provided on Fig. 5 where it can also be seen how the collapse affected the entry of the parking facilities in the immediate surroundings.

Earlier than March, the spur already showed sign of incipient failure and unsuccessful interventions, such as the installation of tie-rods, took place to safeguard its stability. To prevent water from infiltrating and weaken the upstream soil, protective covers were placed. All these safeguarding measures can be seen on Fig. 6. A continuous monitoring



(a) (b)

Fig. 5. The spur before *(a)* and after the collapse *(b)*.



Fig. 6. Evidence of the tie-rods and other protections applied on the slope.

remote system was also installed on the infrastructure providing real time information about the displacements [32].

The mechanical features of the soil are provided by on site surveys performed after both the January and March collapses (Table 1).

The main lithotype is a medium to thick sand. The masonry is made of layers of irregular porous sandstone blocks typical of the area and its characteristics are confirmed by literature reports of masonry with the same characteristics (D.M. 17/01/2018) [9]. Reports show that the "Sperone" underwent many interventions with partial reconstruction and elevation leading to a very irregular texture.

4.2 Evaluation of the Safety Factors (FS)

Through the procedure discussed in Sect. 3.1, it was possible to perform a back analysis and calculate the variation of the safety factor over 3 months including the two events of collapse. The pluviometry records are found on the Tuscany Region archive. Through Eqs. (3)–(7), it's possible to evaluate the fluctuation of FS (Fig. 7a) and of the degree of

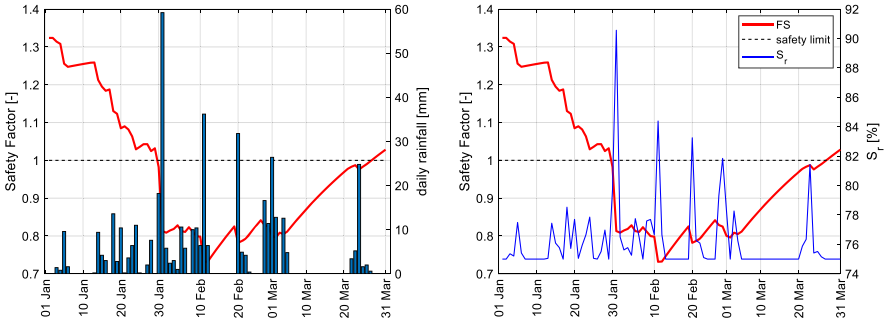
Table 1. Mechanical parameters of the masonry and soil.

Materials	ϕ (°)	c' (kPa)	C_u (kPa)	γ (kN/m^3)	γ_{sat} (kN/m^3)
Masonry	44,00	410,00	0,00	21,00	21,00
Sand 30%	37,00	0,00	0,00	20,00	22,00

saturation S_r [%] (Fig. 7b). The initial saturation grade is fixed as 75% as suggested in [25] for wet seasons.

As Fig. 7 shows, the safety factor reaches its minimum mid-February, with a sudden decrease between the 30th and 31st January where the first collapse happened. Values < 1 are recorded until mid-March. This means that on the 3rd March low values were recorded.

The graph on Fig. 7b shows an increase of saturation in correspondence of the events of collapse, with values reaching the 90% of saturation at the end of January and values slightly over than 80% at the beginning of March.



(a) (b)

Fig. 7. Variation of FS in the period January – March 2014 and of daily rainfall amounts *(a)* or degree of saturation *(b)*.

4.3 Shear Strength Reduction

The first step consisted of the definition of the slope geometry as shown in Fig. 8.

The collapsed wall section height varies from 8.50 m to 14.00 m. A medium value of 12.10 m was considered. The top thickness of the wall was deduced from previous surveys in possession of the Municipality of Volterra. The upstream filling is almost full and the slope quite relevant.

While implementing the geometry into the SSAP2010 code it was necessary to consider the parking facilities at the base of the wall. They consist of a reinforced concrete construction approximately 4 m high. In the view of keeping the model as

simple as possible it was considered as an "obstacle" not interacting with the stability analysis. The application of the method exposed in 3.2 allows the calculation of the reduced strength parameters at each increasing level of imbibition.

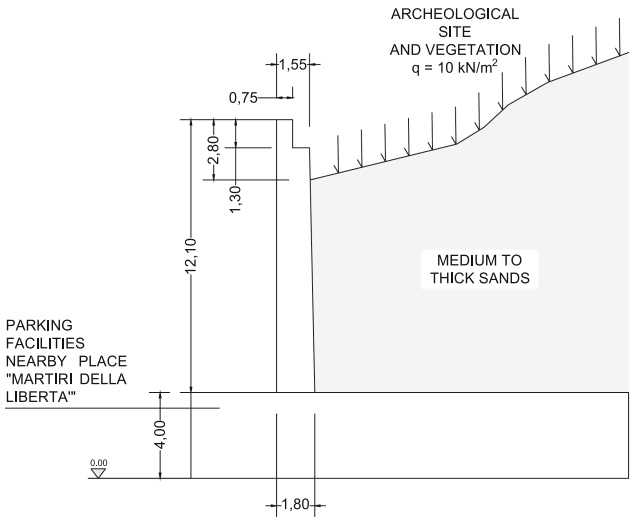


Fig. 8. Schematic geometric of the standard section.

The *m* parameter is calculated with Eq. (1) and depends on *h,* height of rain which is evaluated with Eq. (8) for four return periods and 5 rain durations. Globally, 20 values of *m* are calculated. The imbibition grade *m* also depends on the capacity of imbibition of the soil, β^*. However, assessing the percentage of water seeping into the soil and the percentage of runoff water is an open issue. In this circumstance, it has been estimated that the 30% of the total rainfall height doesn't affect the soil; thus, the value of $ß^*$ is equal to 0,70 [33, 34].

The results are shown on Fig. 9 for a return period of 250 years. The exponential interpolation of the values proves a good trend with R^2 close to 1. The cohesion reaches almost 0 with values of S_r close to 80% for rain durations of 24 h.

Once the mechanical characteristics are determined, LAM analyses are performed. First step is the analysis of the standard section. Then, 5 modified geometries corresponding to different rain durations are modelled. The process is repeated for each return period. The results are first expressed in terms of slope safety factor, FS.

The results for $t_r = 500$ years are plotted on Fig. 10.

The linear interpolation shows a good trend. The value FS = 1 is reached for rain duration close to 6 h and rainfall heights of 175 mm.

Lower return periods (50 years) show FS > 1. A decrease is expected for rain durations greater than 24 h.

The results are also presented in terms of critic return periods for each rain duration, Fig. 11, (Table 2). These correspond to values of FS < 1 which means that the stability of the slope is no longer guaranteed.

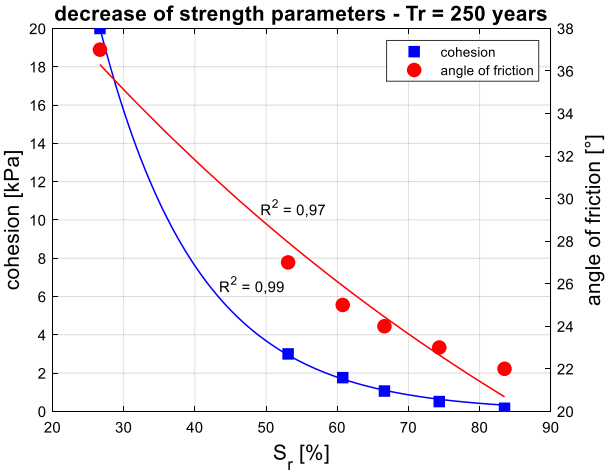


Fig. 9. Decrease of the strength parameters with the increase of Sr.

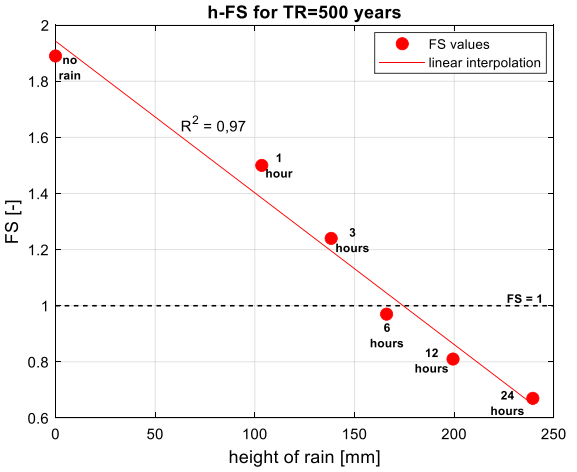


Fig. 10. Values of FS for increasing rainfalls for $t_r = 500$ years.

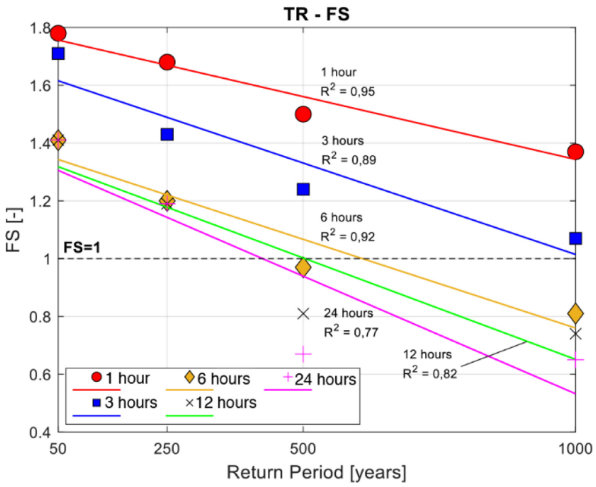


Fig. 11. TR-FS graph for 1–24 h rain durations.

Table 2. Values of critic return periods and corresponding values of h.

d [hours]	1	3	6	12	24
Tr [years]	1945	1079	623	505	432
IM - h [mm]	173	168	166	186	213

5 Conclusions

The aim of this work is to show a quick procedure to investigate the effect of moisture on soil interacting masonry wall structures. The theories for partially saturated soils and the model of Montrasio and Valentino [14] are adapted to the case of a finite slope with a retaining infrastructure. This allows the evaluation of the global safety factor for growing imbibition scenarios up to a maximum rain duration of 24 h.

The height of rain, which is the intensity measure, represents a probabilistic characterization of the meteorological event. The simplified methodology shows that moisture can significantly affect the global stability of the slope. This procedure combined with continuous monitoring techniques could help understand which are the most vulnerable sections of these extended infrastructures. The back analysis suggests a good predictability of the model, with values of FS < 1 when the relevant collapses occurred.

The results of this work highlight the role played by superficial imbibition in the stability analysis of urban walls. Indeed, the worst scenario (24-h rainfalls) considers a superficial 5 m high portion of the upstream section of the slope affected by a reduction of the strength parameters.

Some indications are provided to mitigate the vulnerability of this kind of infrastructure characterized by a strict relationship with other structures [35, 36] and with the earth [37]. A possible design strategy to mitigate the phenomena could be that of arranging

drainage systems at different heights, also superficially. As well as this, superficial water management systems to avoid excessive imbibition are to be planned.

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