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STATIC AND DYNAMIC ANALYSES OF THE STABILITY OF MINING WASTES (RAVANETI) IN THE CARRARA MARBLE AREA (APUAN ALPS, ITALY)

ANALIZA STATYCZNA I DYNAMICZNA STABILNOŚCI HAŁD ODPADÓW GÓRNICZYCH W REGIONIE WYDOBYCIA MARMURÓW CARRARA (ALPY APUAŃSKIE, ITALIA)

The problem of the stability of "ravanetos" (debris piles of mining waste material extracted from the Apuan Alps, Italy) is very relevant, because of the consequences a landslide would have on the people and the existing civil infrastructures throughout the territory.

In this work, the stability of two ravanetos that can be considered as representative of those in the Carrara area has been studied: the Polvaccio ravaneto, a recent type of debris pile and the Torrione-Tecchione, an old debris pile at present undergoing re-naturalisation.

The study using the LEM (Limit Equilibrium Method) in a static and pseudo-static field, has made it possible to first carry out a back-analysis to define the most probable apparent cohesion and friction angle values of the material that makes up the ravanetos. Subsequently, it was possible to determine the intensity of the seismic wave that would be able to lead the two ravanetos to limit stability conditions and to determine the probability of such a seismic wave occurring in the next 50 years.

A more accurate analysis, carried out with a numerical method in the dynamic field, of the most critical condition (the Polvaccio ravaneto) has led to more conservative results (higher safety factors) than those obtained with the LEM. This result allows us to reveal how the LEM can be considered a cautionary instrument to judge the stability of debris piles during a seismic event and that the likelihood of a landslide occurring in the two studied representative ravanetos over the next 50 years is very slim.

Keywords: mining waste disposal site, slope stability, safety factor, dynamic analysis, numerical calculation, effect of a seismic event.

Zagadnienie stabilności hałd odpadów górniczych w regionie Alp Apuańskich, Italia) jest niezmiernie ważne z uwagi na skutki jakie ewentualne osunięcia gruntu mogłyby mieć dla ludności oraz budowli znajdujących się na tych terenach.

W pracy tej rozpatrywano zagadnienie stabilności dwóch hałd odpadów, które uznać można za reprezentatywne dla regionu Carrera: hałda w Polvaccio (hałda nowszego typu) oraz Torrione-Tecchione, stara hałda, obecnie poddawana procesom rekultywacji.

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W badaniach zastosowano metodę równowagi granicznej (LEM) w polu statycznym i pseudo-statycznym. Metoda ta umożliwia w pierwszym rzędzie przeprowadzenie analizy wstecznej w celu określenia najbardziej prawdopodobnego pozornego kąta kohezji i tarcia dla materiału hałdy. Następnie określono intensywność fali sejsmicznej, w wyniku oddziaływania której hałdy mogłyby utracić stabilność a także obliczono prawdopodobieństwa wystąpienia takiej fali sejsmicznej w ciągu najbliższych 50 lat.

Bardziej szczegółowa analiza warunków krytycznych, wykonana przy pomocy metod numerycznych w polu dynamicznym, dała bardziej ostrożne wyniki (wyższe współczynniki bezpieczeństwa) niż te uzyskane przy pomocy metody równowagi granicznej. Wyniki badań sugerują, że metoda równowagi granicznej stanowi ostrożne narzędzie do określania stabilności hałd odpadów w trakcie zjawisk sejsmicznych. Pokazano także, że prawdopodobieństwo wystąpienia osunięcia terenu w przeciągu kolejnych 50 lat w przypadku dwóch rozpatrywanych hałd jest bardzo niewielkie.

Słowa kluczowe: składowisko odpadów górniczych, stabilność zbocza, współczynnik bezpieczeństwa, analiza dynamiczna, obliczenia numeryczne, skutki zjawisk o charakterze sejsmicznym

1. Introduction

The Apuan Alps are located in north-west Tuscany and they constitute a mountainous group where an important marble quarrying activity takes place. This activity is conducted over a vast territory and involves several orographic and valley systems, from medium-low altitudes (about 500 m a.s.l.), in the area closest to Carrara, to higher and higher altitudes (up to 1500 m a.s.l.) in the central part of the mountain chain (Barducci et al., 2008; Coli et al., 2002; Università degli Studi di Siena-Centro di Geotecnologie, internet site).

The quarrying activities in this area, which have been extensively carried out for many centuries (about 2000 years), are basically conducted to obtain three types of products:

- Ornamental stones of great value;
- Material that can be used for industrial and for civil construction purposes;
- Reject material from the quarrying activities in the marble quarries.

At present there are about 160 quarries operating in the Apuan mountain complex and more than two thirds of these are in the Carrara and Massa marble areas, while the remaining part is spread out in smaller divisions between Versilia, Garfagnana and Lunigiana.

Marble quarrying has evolved over the years: it was the Romans, in the 1st century a.C., who first set up quarrying at an "industrial" level, and reduced the quantities of rejects to a minimum, considering the arduous and long quarrying work at that time, due to the lack of advanced techniques.

A new marble quarrying technique known as "explosive mega-blasting" was introduced in the XVI century. This technique was introduced to satisfy the increasing market request. The consequence of the application of this innovation was the accumulation of vast portions of rejects at the foot of the quarries, which eventually lead to the creation of debris piles that today are commonly known in Italy as "ravanetos" (D'Amato Avanzi & Verani, 1998; Coli et al., 2000).

Marble is presently quarried by initially detaching large portions of marble from the mountain, using explosives which are inserted into boreholes. These boreholes are made by drillers that are mounted onto self-moving machines which are able to create several boreholes at the same time and guarantee an elevated quarry production. For this reason, these ravanetos continue to increase in size and now cover vast areas (over 400 ha).

Fig. 1. View of a "ravaneto" (Polvaccio ravaneto) located in the Carrara area

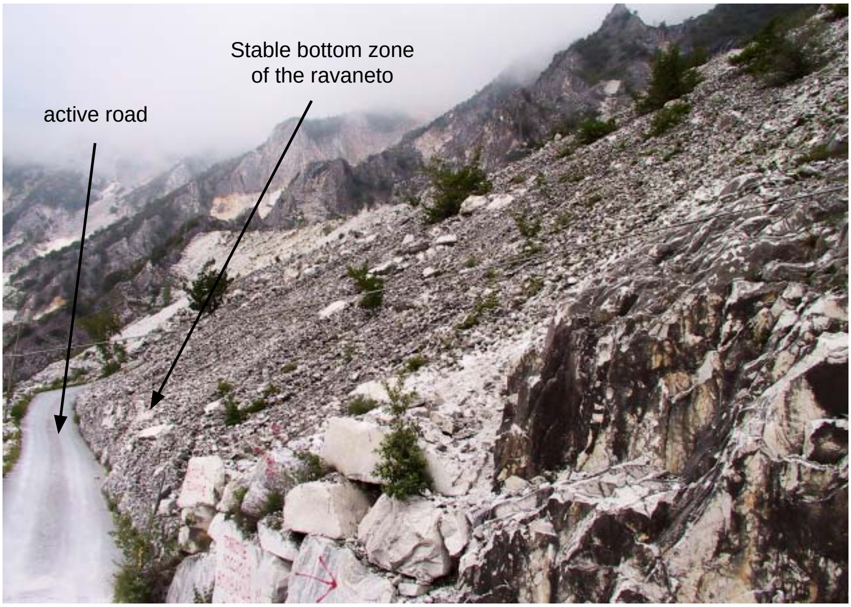


Fig. 2. View of ravaneto and an old

The ravanetos can be divided into:

- *active*: those adjacent to a quarry which is currently being open and from which the pile is supplied with reject material;
- *inactive:* those that are no longer supplied with reject material;
- *old:* those where the supply of reject material finished many years previously and a certain natural cover can be observed on the surface.

Most of these ravanetos (about half) are at present undergoing a spontaneous re-naturalisation process (old ravanetos), while the remaining part is made up of active ravanetos (about 20%) and inactive ones (about 28%) (Baroni et al., 2000, 2001, 2003; Coli et al., 2000, 2002).

These debris piles represent one of the greatest environmental problems throughout the Carrara territory. The accumulation of residual debris material has involved larger and larger areas over the years and in some cases has led to the blockage of the surface groundwater network and hindered the natural drainage of the water. Furthermore, the fine fraction of the waste material (which is often contaminated by mineral oils) reaches the Karstic system involved in the groundwater and underground water circulation in the area, penetrates the springs and provokes serious pollution problems (Cortopassi et al., 2008).

In order to deal with these problems, land reclamation methods have been introduced which involve the removal of a part of the piles and completion of the remaining part with a protection layer which has the purpose of immobilising the finer and more plastic fractions derived from the cutting of the marble.

The quarrying of the ravanetos to recycle stone material that cannot be used for ornamental purposes, but can be used for the production of material of less value (above all external paving material, linings and cubic construction elements for urban furnishings and completion of road works), is by now consolidated practice. These activities have become so important that the quantity of material recuperated actually exceeds the production of ornamental stone material. About 31% of the ravanetos in the Carrara area are currently involved in activities concerning the recuperation of material (Coli et al., 2000, 2002).

The stability of the ravanetos, in particular the most recent ones, is an aspect of great interest as landslide events of a certain seriousness have occurred which could involve inhabited areas and civil infrastructures (Brunsden, 1979; Blijenberg, 1993; Cala, 2007; Domanska & Wichur, 2006).

Two representative ravanetos in the Carrara area (Torano Basin) are analysed in detail in this article from the static and dynamic point of view. One of these piles (Polvaccio) is still active, while the other (Torrione-Tecchione) is old and currently at a re-naturalisation stage. It is therefore possible to evaluate the hazard degree of the debris (Kidybinski, 2010).

2. Formation and classification of the ravanetos

In the formation of ravanetos, the debris is first arranged according to the repose angle of the material, which is generally rather high (up to about 40°-45°), in function of the roughness of the clasts and of their irregularity of shape and dimensions; the granulometric assortment usually involves dimensions ranging from pluri-centimetrical to metrical (Plewa & Sobota, 2002).

The continuous supply from above often leads to the repose angle being exceeded and therefore to a partial gravitational redistribution of the material along the slope, with a tendency to have the coarser elements towards the lower parts of the debris piles.

The ravanetos can have the following shapes:

- similar to a debris cone, with a conic apical termination at the top, as in the case of a debris pile accumulated through impluvium or in a torrential river bed;
- similar to a frustum of a cone, for example when the summit zone is used as a quarry yard.

The hazard factors of the Apuan ravanetos have been studied in recent years from the instability point of view (Baroni et al., 2000, 2001; Kasparyan, 2008). For this purpose, some parameters that influence the degree of stability of the ravanetos have been identified: the mean dip, the height, the granulometric composition and the permeability of the rocky substratum.

It has been noted how the debris piles composed of fine material are more unstable than those made up of coarse material (Baroni et al., 2003; Bruschi et al., 2003). The activities concerning the recuperation of material from the debris piles involve removing the coarser material, which means leaving the finer material: these activities therefore lead to a decrease in the degree of stability of the ravanetos.

It has also been shown how the permeability of the rocky substratum also influences the degree of stability of the debris piles to a great extent: a remarkable permeability allows a regular drainage of the pile and a quick elimination of any interstitial pressure inside it. From an investigation that has been carried out it results that 65% of the ravanetos in the Carrara zone lie on a sound and non fractured rock, which is therefore characterised by poor permeability, while 24% of the piles lie on rock that falls into a medium class and only 11% lies on rock with a high permeability class due to intense fracturing. Therefore, most of the Apuan ravanetos are potentially at risk to interstitial pressure, due to the water that is not drained away by the rocky substratum (Coli et al., 2000; Baroni et al., 2003; Bruschi et al., 2003).

A recent study conducted on Apuan ravanetos reached the conclusion that 75% of these piles are at a high risk of geological instability and 6% are at an extremely high risk (Cortopassi et al., 2008). It was also observed that the ravanetos that showed evidence of instability phenomena all had steep slopes and elevated heights.

The Polvaccio ravaneto is made up of prevalently fine material, with a fractured and permeable rocky substratum and a mean dip of between 35° and 45°; it is currently subject to waste disposal and removal activities which continuously disturb the morphological layout. The Torrione-Tecchione ravaneto is also prevalently made up of fine material, but the rocky substratum is not fractured and can be considered impermeable. Its mean dip is between 35° and 45°. No accumulation or removal activities are currently under way and a re-naturalisation process can easily be seen.

Both of these ravanetos, which are here analysed in detail, have a risk of instability considered high.

3. Stability analysis of the ravanetos using LEM (the limit equilibrium method)

The stability conditions of the ravanetos should be analysed not only to avoid risks for the people and the territory, but also in relation to the optimisation of the spaces destined for these piles as the greater the slope of the debris pile, and therefore the lower the degree of stability (safety factor), the more it is possible to pile up material. The safety factor considered to be the minimum admissible to maintain a debris pile stable is evaluated in function of the reached knowledge and the degree of reliability of the available data, of the geological and geotechnical complexity, of the local experience on similar slopes and of the consequences of a possible landslide.

Reference is often made to the limit equilibrium methods (LEM) in order to develop stability analysis (Brunsden, 1979; Cheng et al., 2007; Cheng & Lau, 2008; Hammouri et al., 2008). This kind of method is able to resolve the static conditions for a given breaking mechanism, such as sliding along a composite or curvilinear surface (Hoek & Bray, 1981). It is common practice in all LEMs to operate on equilibrium equations that compare resistant forces and/or moments (defined according to a breaking condition) with destabilising forces and/or moments, through the definition of a single safety factor F_s for the entire portion of rock or ground considered potentially unstable.

The various methods generally involve the subdivision of these potentially unstable portions into “vertical slices”; the methods can be divided into groups according to different calculation hypotheses. The hypotheses concerning the direction of the internal resulting forces are those that are most commonly used.

The Sarma method (Sarma, 1973; Jie et al., 1999) is one of those LEM methods that divides the potentially unstable rock into vertical slices (Fig. 3).

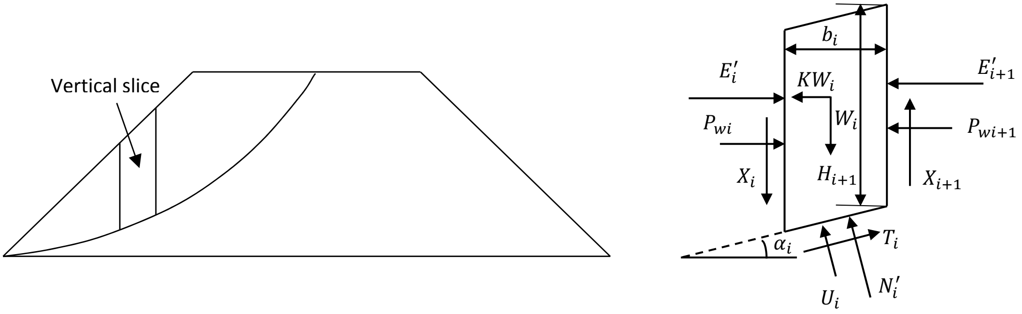


Fig. 3. The Sarma method for the stability analysis of a slope. Left: subdivision into vertical slices

Right: details of the forces acting on the single slice. Key: E'_i and E'_{i+1}: effective horzontal force on the lateral faces of the i-th slice; X_i and X_{i+1}: shear force on the lateral faces of the i-th slice; P_{wi} and P_{wi+1}: hydraulic force on the lateral faces of the i-th slice; W_i: weight of the i-th slice; KW_i: horizontal force acting in the centre of gravity of the i-th slice; N'_i : normal effective force at the base of the slice; U_i: hydraulic underthrust at the base of the slice; T_i: shear force at the base of the slice; z_i: height of the application point of E_i with respect to the sliding surface at the centre of the slice; c'_i and φ'_i : cohesion and friction angle (effective values) of the ground in correspondence to the sliding surface; $N_i = N'_i + U_i$; $E_i = E'_{i+1} + P_{wi}$; H_i: height of the unstable mass on the right side of the i-th slice; b_i: width of the i-th slice; α_i: angle between the tangent to the sliding surface in the mean point of the slice and the horizontal plain; x_i and y_i : coordinates of the mean point of the slide base with respect to the xy reference system.

The thickness of the vertical slices is assumed to be sufficiently small to be able to consider the normal force N_i applied to the mean point of each slice. In the case in which no other forces are acting on the free surface, as in Fig. 3, the vertical and horizontal equilibrium condition is given by the following expressions:

$$\sum \Delta E_i = 0 \quad \sum \Delta X_i = 0$$

In order to obtain the static safety factor, it is necessary to reduce the strength parameters along the sliding surface using a single safety factor for all the slices.

A pseudo-static analysis is carried out to verify stability in seismic conditions, where it is possible to separately insert the horizontal and vertical seismic coefficients. While the horizontal seismic component is always considered towards the valley, the vertical seismic component is applied both upwards and downwards. Only the single situation is then considered with a minimum safety factor.

4. Characterisation of the Polvaccio and Terrione-Tecchione ravanetos

An accurate topographic survey of the two studied ravanetos has been conducted using a Leica TCR 1105 x-range theodolite with a distance measuring laser device belonging to the Mining Engineering Operative Unit of ASL No. 1 in Massa Carrara. The results of the topographic surveys, referring to a central portion of the two debris piles, are shown in Fig. 4.

The mechanical characteristics of the material that makes up the debris piles are difficult to evaluate in the laboratory, considering the centrimetrical dimensions of the rock particles. The dimensions of the samples that can be studied in the laboratory are in fact narrow if compared with the granulometry of the material.

For the friction angle φ, Charles and Watts (1980) has affirmed that coarse material thrown onto the pile in a pell-mell manner assumes a minimum friction angle value of 37°, while Sherard et al. (1963) stated that the value of this parameter for coarse masses thrown away pell-mell can vary from between 40° and 45°. Furthermore, it is known that, all the other conditions being equal, the peak friction angle of this kind of mass is nevertheless greatly dependent on the stress level that exists at the site (Hanlong et al., 2008; Krzyszton, 2005, 2007).

Considering the difficulty of defining with precision the friction angle of the material in the pile, it was decided to assume a very large variation interval of φ, of between 37° and 50°.

Recourse was also made to a literature relative to the disposal of carbonatic materials, with a very similar granulometric assortment to those under examination, in order to define the specific weight γ of the material that makes up the ravanetos. It was possible to estimate γ = 22 kN/m^3, a value which is obviously lower than the specific weight of the marble at the site (28 kN/m^3).

5. Back-analysis of the mechanical parameters of the ravanetos

As it is almost impossible to obtain a precise evaluation of the strength parameters of the material that makes up the ravanetos through in situ or laboratory tests, it was decided to carry out a back-analysis of their present static conditions. Through an analysis of the static conditions

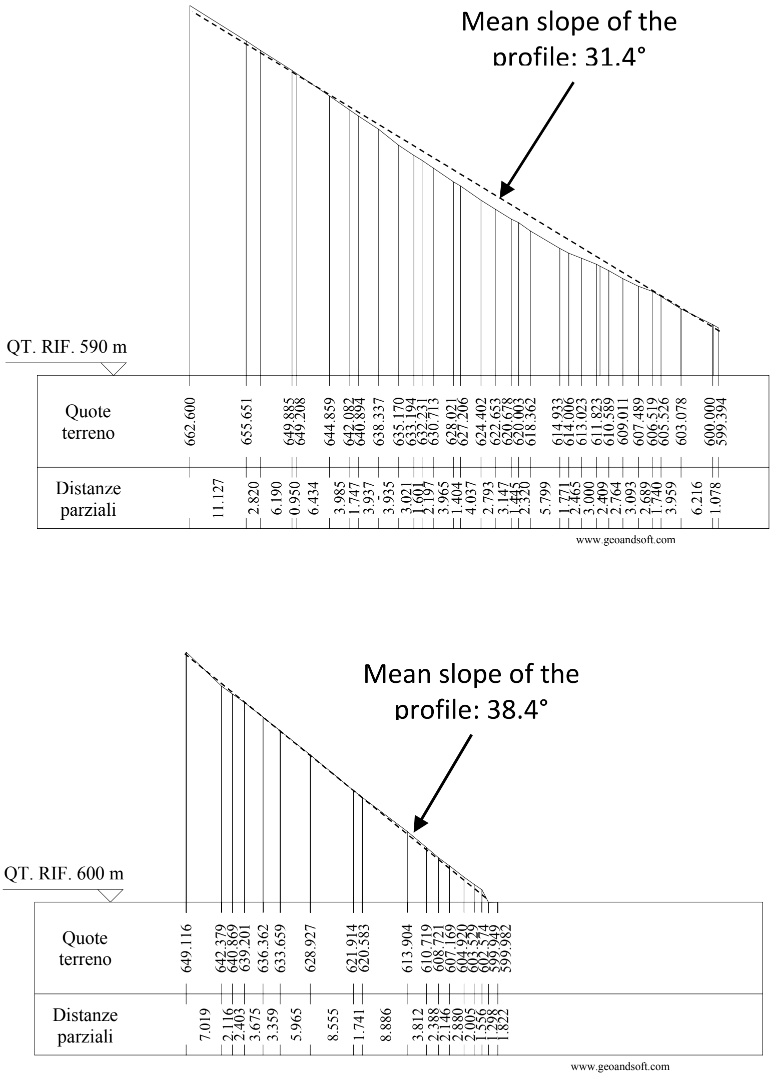


Fig. 4. Altimetrical profile of the Polvaccio ravaneto (above) and the Torrione-Teccione ravaneto (below), obtained from topographic surveys using a theodolite and distance measuring laser device by the Mining Engineering Operative Unit of ASL No. 1 in Massa Carrara

using the Sarma method (section 3), a safety factor of the studied ravanetos equal to 1 has been imposed, hypothesising a limit stability condition when the rocky formation is completely saturated (an event that could occur during a period of intense and prolonged rainfall). The result of the back-analysis has led to a series of possible couples of values of the apparent cohesion and the friction angle (having adopted the Mohr-Coulomb strength criterion) that are able to reproduce the desidered value of the safety factor (Fig. 5).

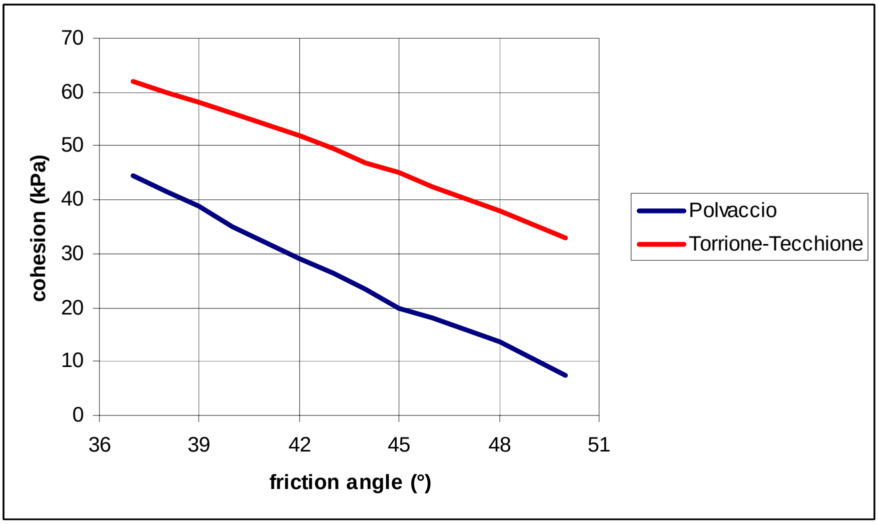


Fig. 5. Couples of values of the apparent cohesion and the friction angle that make it possible to obtain a limit stability condition ($Fs = 1$) for the two ravanetos considered in completely saturated conditions, which could refer to periods of intense and prolonged rainfall

From a comparison of the two curves shown in Fig. 5, it emerges that the apparent cohesion value obtained for the Torrione-Tecchione ravaneto is higher than that obtained for the Polvaccio ravaneto, when a same value of the friction angle is considered. This can be considered a reasonable result, considering that the Torrione-Tecchione ravaneto is older than the Polvaccio ravaneto. Loose materials usually show a greater degree of thickening in older disposal sites and therefore also higher friction angle and apparent cohesion values.

6. Stability analysis of the ravanetos considering the dynamic actions induced by a seismic event

While intense and prolonged rainfall usually only leads to a remodelling of the geometric shape of a ravaneto, following instability phenomena of limited and surface portions of the mass, a seismic event could cause an instantaneous landslide of relevant portions of the ravaneto, with serious consequences for both passersby or those who work in the neighbourhood and for the existing infrastructures.

It is therefore of fundamental importance to evaluate what the effects of a seismic wave would be on the stability of a ravaneto, and in particular to determine what the characteristics of the seismic wave are (its intensity in terms of maximum acceleration) that could cause instability of the debris pile (Bourdeau et al., 2004; Bray et al, 1998; Li et al, 2009; Lo Presti et al., 2008; Pham & Fredlund, 2003).

A simple and reliable way of studying the effects of a seismic wave on a slope is that of evaluating the total pseudo-static forces applied by the seismic event to the potentially unstable portion of the mass. Two forces are evaluated (a vertical one that is usually upwards and another horizontal one towards the valley), starting from the maximum accelerations of the seismic wave in the vertical and horizontal directions. As an alternative, it is possible to determine the couple of values of the horizontal c_h and vertical c_v components of the maximum acceleration of the seismic wave that lead to the stability limit conditions ($Fs = 1$). Obviously is here hypothesised the drained conditions of the ravaneto mass, as it is highly unlikely that a seismic event would occur at the same time as a period of intense and prolonged rainfall (conditions that should lead to considering the debris pile in saturated conditioned).

The two acceleration components of a seismic wave that lead to $Fs = 1$ are not independent, but instead depend on the dip of the direction of the seismic wave with respects to the horizontal plain. In this context, it is possible to identify an angle α between the direction of the seismic wave and the horizontal axis directed towards the valley, which increases until it reaches 90°, when the direction of the seismic wave coincides with the vertical axis directed upwards. For the sake of simplicity, it is hypothesised that the acceleration due to the seismic wave occurs in the same propagation direction of the wave.

The values of the horizontal c_h and vertical c_v components, expressed in relative terms with respect to the acceleration of gravity g, calculated for the Polvaccio ravaneto varying the angle α and the friction angle φ of the material that makes up the debris pile, are shown in Table 1 (an apparent cohesion value is associated to each value of φ on the basis of the graph shown in Fig. 5). The same values obtained for the Torrione-Tecchione ravaneto are shown in Table 2.

TABLE 1

Values of the c_h and c_v components of the maximum acceleration of the seismic wave compared to the gravity acceleration with variations in the direction of the seismic wave (α) and the friction angle of the material (φ) for the Polvaccio ravaneto. Conditions for $Fs = 1$ and the absence of water inside the debris pile pores.

c_h

	$\alpha = 0°$	$\alpha = 15°$	$\alpha = 30°$	$\alpha = 45°$	$\alpha = 60°$	$\alpha = 75°$
1	**2**	**3**	**4**	**5**	**6**	**7**
$\varphi = 37°$	0.340	0.330	0.315	0.290	0.275	0.234
$\varphi = 38°$	0.350	0.338	0.320	0.295	0.280	0.235
$\varphi = 39°$	0.360	0.340	0.325	0.300	0.285	0.236
$\varphi = 40°$	0.365	0.350	0.330	0.300	0.285	0.236
$\varphi = 41°$	0.380	0.350	0.335	0.305	0.285	0.236
$\varphi = 42°$	0.385	0.368	0.345	0.308	0.290	0.237
$\varphi = 43°$	0.395	0.368	0.345	0.310	0.290	0.237
$\varphi = 44°$	0.400	0.370	0.350	0.310	0.292	0.238
$\varphi = 45°$	0.410	0.375	0.350	0.310	0.292	0.238
$\varphi = 46°$	0.420	0.380	0.358	0.313	0.293	0.238
$\varphi = 48°$	0.440	0.395	0.365	0.320	0.293	0.238
$\varphi = 50°$	0.440	0.395	0.365	0.320	0.293	0.238

c_v

	$\alpha = 0°$	$\alpha = 15°$	$\alpha = 30°$	$\alpha = 45°$	$\alpha = 60°$	$\alpha = 75°$
$\varphi = 37°$	0.000	0.079	0.161	0.290	0.379	0.565
$\varphi = 38°$	0.000	0.081	0.161	0.295	0.380	0.567
$\varphi = 39°$	0.000	0.083	0.166	0.300	0.392	0.569

TABLE 1. Continued

1	2	3	4	5	6	7
$\varphi = 40°$	0.000	0.084	0.168	0.300	0.392	0.569
$\varphi = 41°$	0.000	0.086	0.170	0.305	0.392	0.569
$\varphi = 42°$	0.000	0.088	0.176	0.308	0.399	0.572
$\varphi = 43°$	0.000	0.088	0.176	0.310	0.399	0.572
$\varphi = 44°$	0.000	0.089	0.178	0.310	0.402	0.574
$\varphi = 45°$	0.000	0.090	0.178	0.310	0.402	0.575
$\varphi = 46°$	0.000	0.091	0.182	0.313	0.403	0.575
$\varphi = 48°$	0.000	0.094	0.186	0.320	0.403	0.575
$\varphi = 50°$	0.000	0.094	0.186	0.320	0.403	0.575

TABLE 2

Values of the c_h and c_v components of the maximum acceleration of the seismic wave compared to the gravity acceleration with variations in the direction of the seismic wave (α) and the friction angle of the material (φ) for the Torrione-Tecchione ravaneto. Conditions for Fs = 1 and the absence of water inside the debris pile pores

c_h

	α = 0°	α = 15°	α = 30°	α = 45°	α = 60°	α = 75°
1	**2**	**3**	**4**	**5**	**6**	**7**
$\varphi = 37°$	0.360	0.350	0.340	0.320	0.305	0.263
$\varphi = 38°$	0.370	0.353	0.345	0.325	0.310	0.267
$\varphi = 39°$	0.380	0.362	0.350	0.330	0.314	0.269
$\varphi = 40°$	0.390	0.370	0.358	0.335	0.318	0.272
$\varphi = 41°$	0.400	0.380	0.364	0.340	0.320	0.272
$\varphi = 42°$	0.410	0.390	0.372	0.345	0.324	0.274
$\varphi = 43°$	0.420	0.396	0.374	0.348	0.326	0.274
$\varphi = 44°$	0.430	0.420	0.380	0.350	0.328	0.275
$\varphi = 45°$	0.434	0.420	0.385	0.354	0.330	0.275
$\varphi = 46°$	0.440	0.420	0.390	0.360	0.334	0.276
$\varphi = 48°$	0.460	0.430	0.400	0.360	0.338	0.276
$\varphi = 50°$	0.468	0.440	0.420	0.364	0.338	0.277

c_v

	α = 0°	α = 15°	α = 30°	α = 45°	α = 60°	α = 75°
$\varphi = 37°$	0.000	0.084	0.173	0.320	0.420	0.640
$\varphi = 38°$	0.000	0.085	0.176	0.325	0.430	0.645
$\varphi = 39°$	0.000	0.087	0.178	0.330	0.432	0.649
$\varphi = 40°$	0.000	0.089	0.183	0.335	0.438	0.657
$\varphi = 41°$	0.000	0.091	0.185	0.340	0.441	0.657
$\varphi = 42°$	0.000	0.093	0.189	0.345	0.446	0.661
$\varphi = 43°$	0.000	0.095	0.191	0.348	0.449	0.661
$\varphi = 44°$	0.000	0.100	0.194	0.350	0.451	0.664
$\varphi = 45°$	0.000	0.100	0.196	0.354	0.454	0.664
$\varphi = 46°$	0.000	0.100	0.199	0.360	0.459	0.666
$\varphi = 48°$	0.000	0.103	0.204	0.360	0.465	0.666
$\varphi = 50°$	0.000	0.105	0.214	0.364	0.465	0.669

If the angle α and the values of c_h and c_v are known, it is also possible to identify the trend of the maximum acceleration of the seismic wave that leads to the limit stability condition ($Fs = 1$) for the two studied ravanetos (Fig. 6 and 7).

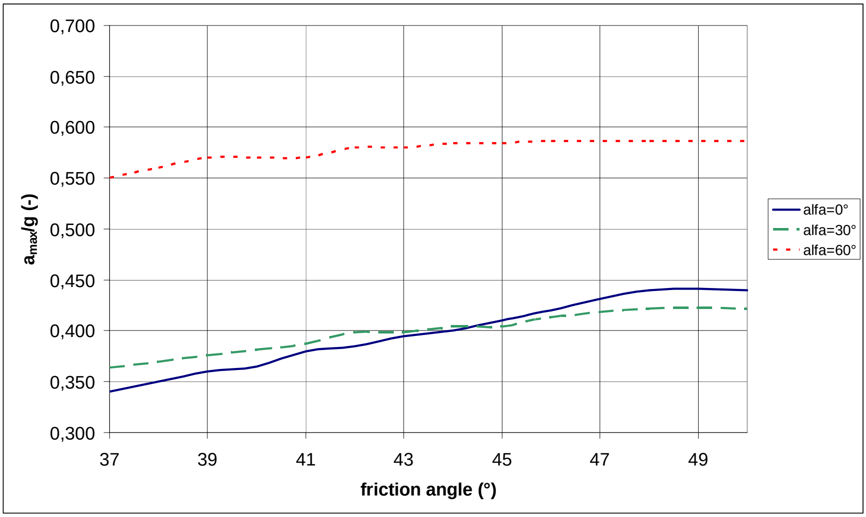


Fig. 6. The Polvaccio ravaneto: Maximum acceleration trend of the seismic wave (compared with the gravity acceleration) that provokes the reaching of the limit stability condition ($Fs = 1$) with variations of the angle α and the friction angle of the material

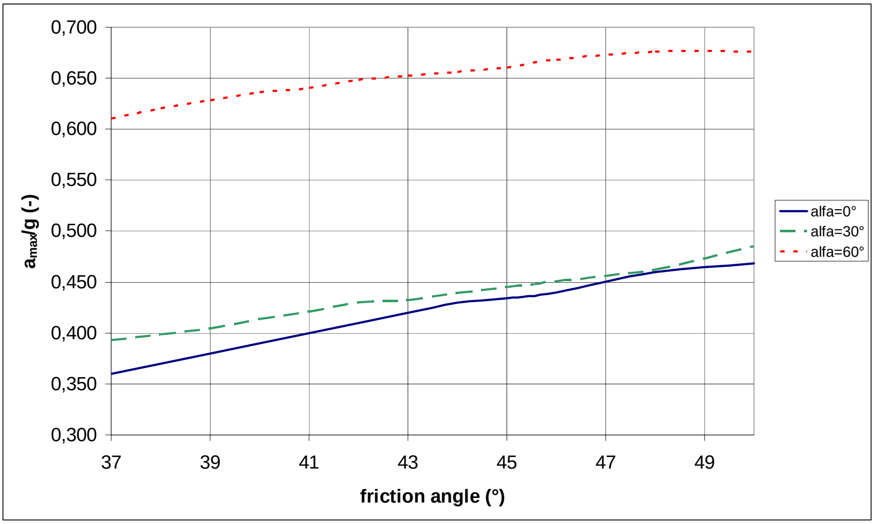


Fig. 7. The Torrione-Tecchione ravaneto: Maximum acceleration trend of the seismic wave (compared with the gravity acceleration) that provokes the reaching of the limit stability condition ($Fs = 1$) with variations of the angle α and the friction angle of the material

As can be noted in figures 6 and 7, the maximum acceleration of the seismic wave that allows the limit stability condition ($Fs = 1$) of the ravanetos to be reached increases with the friction angle of the material. The influence of the friction angle is greater for low values of α. In the Polvaccio ravaneto, the condition of the presence of only horizontal dynamic acceleration ($\alpha = 0°$) is the most critical for $\varphi \leq 44°$ since it requires a lowest maximum acceleration of the seismic wave compared to the other values of α. Instead, for the Torrione-Tecchione ravaneto, the condition $\alpha = 0°$ is the most critical for any value of φ.

As it can be presumed that the friction angle of the material that makes up the ravanetos does not exceed 44°, it is possible hereafter to only refer to the condition that foresees the presence of the horizontal dynamic acceleration during a seismic event ($\alpha = 0°$). Furthermore, the Polvaccio ravaneto requires a less intense seismic wave than the Torrione-Tecchione one to reach limit stability conditions.

7. Seismic mapping of the study area and probability of landslides due to a seismic event

The Italian National Institute of Geophysics and Vulcanology (2004) has drawn up seismic risk maps on the basis of analysis and interpretation of a considerable mass of data collected by a seismic survey network that is made up of 283 measurement stations spread throughout the national territory. A seismic risk map is available for the Carrara area with indications of the maximum horizontal acceleration values that could be reached in the next 50 years (Fig. 8).

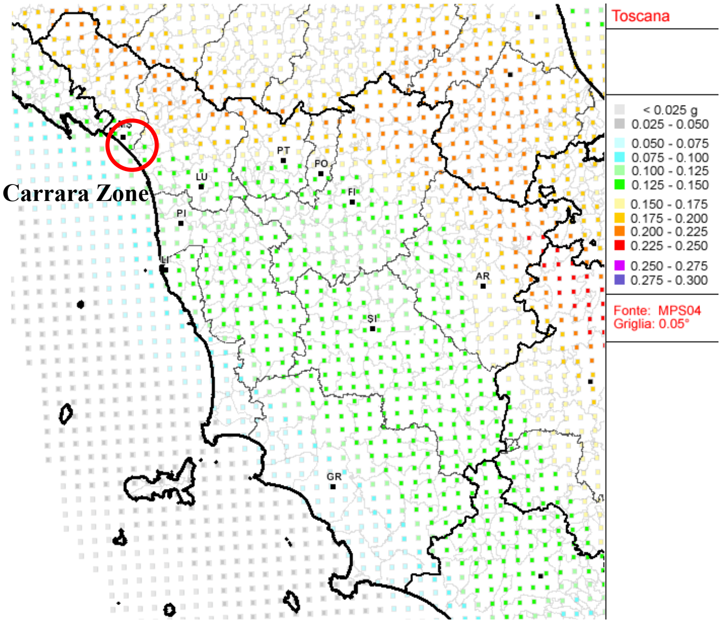


Fig. 8. Indications, for the Carrara zone, of the mean values of the probabilistic distribution of the maximum acceleration of a seismic wave for the next 50 years (from National Institute of Geophysics and Vulcanology, 2004)

These are mean values of the probabilistic distribution of the maximum acceleration produced by a possible seismic wave.

From an analysis of the figure, it is possible to note a mean probabilistic distribution value of the maximum accelerations equal to $0.15 \cdot g$. Apart from the mean value, the values referred to the 16° percentile ($0.10 \cdot g$) and to 84° percentile ($0.20 \cdot g$) are also available. If we hypothesise a normal distribution, it is possible to estimate that the probability of a seismic wave producing a maximum horizontal acceleration of more than $0.34 \cdot g$ (maximum acceleration that leads to reaching the limit stability condition of the Polvaccio ravaneto for a minimum friction angle of 37°) in the next 50 years: 6.3/100.000. As the friction angle increases, the maximum acceleration of the seismic wave increases, and the probability of a seismic event making the debris pile unstable diminishes. The probability that a seismic wave could cause a maximum horizontal acceleration above $0.36 \cdot g$ (Torrione-Tecchione ravaneto for $\varphi = 37°$) is 0.6/100.000 over the next 50 years. This values allow us to consider that it is highly unlikely that a seismic event could cause landslide phenomena in either of the studied ravanetos.

8. Numerical analysis of the Polvaccio ravaneto in the dynamic field

Over the last twenty-five years, the use of numerical methods in the geotechnical and rock mechanics fields, alongside traditional analytical methods, has undergone a remarkable development (Bourdeau et al., 2004; Hammouri et al., 2008; Lo Presti et al., 2008; Pham & Fredlund, 2003). The numerical methods generally assume a continuous or pseudo-continuous mechanical model which represents the investigated physical system. These methods lead to the solution of complex equations through a large number of iterations for each of the thousands of elements into which a studied area is divided.

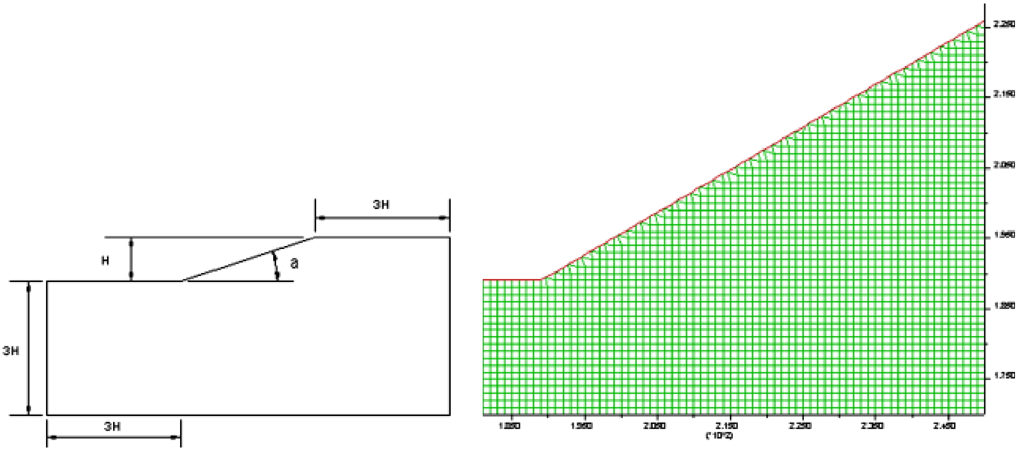
An important characteristic of numerical methods is the possibility of reproducing complex situations in a faithful way. It is in fact known that the determination of an analytical solution of a real problem, in closed form, requires introducing remarkable simplifying hypotheses, and this makes the solution representative of an ideal case and often far from the physical reality. Numerical methods are instead much more versatile and adherent to the real case being studied: it is possible to consider the real geometry of the problem, take into consideration the non homogeneity, the anistrophy and the non linear behaviour of the natural material that is present, correctly reproduce the original stress state and simulate the different excavation and construction operations in great detail. Obviously, using similar assumptions involves the necessity of having an elevated degree of knowledge of the problem.

The numerical method that was adopted in this work is FLAC (Cundall, 1976; Itasca Consulting Group, 1994). FLAC uses a finite difference explicit numerical solution (FDM). This type of solution is particularly suitable for dynamic type analysis.

The adopted calculation code considers the medium as an equivalent continuous. In the present case the medium is constituted by a set of rock particles of variable size, but always much smaller than the size of the ravanetos. For this reason it is permissible to be resorting to the equivalent continuous, without running the risk of making considerable errors.

On the other hand, the numerical simulation of individual rock particles would require a thorough knowledge not only of their size, but also of the physical and mechanical characteristics of their interaction and of the exact shape of the particles with the size. A numerical model capable of considering all these aspects should first be three dimensional and then have an high degree of complexity that requires very long calculation times. It could also lead to large errors in the calculation results due to assumptions made about the geometry of the rock particles and about the physical and mechanical interaction parameters.

An analysis of the Polvaccio ravaneto was carried out, in the dynamic field, using the aforementioned numerical method (Fig. 9).



a) b)

Fig. 9. a) Geometry of the FDM numerical model to analyse the stress-strain behaviour of the Polvaccio ravaneto in the dynamic field. b) Detail of the adopted mesh

A horizontal seismic wave p, coming from the right portion of the model, was simulated with a frequency of 20 Hz (the natural frequency of the basement rock below the debris pile) and a maximum acceleration equal to $0.34 \cdot g$ (the maximum acceleration that led to the limit stability condition of the debris pile for $\varphi = 37°$ according to the LEM calculation). The duration of the dynamic impulse was set to 3 seconds.

The geomechanical parameters reported in Table 3 were used for the considered debris pile.

TABLE 3

Geomechanical parameters of the debris pile assumed in the numerical modelling in a dynamic field

Apparent cohesion (kPa):	44.2
Friction angle φ (°):	37
Volumic modulus of elasticity (static) K_s (MPa):	333
Shear modulus of elasticity (static) G_s (MPa):	200
Volumic modulus of elasticity (dynamic) K_d (MPa):	999
Shear modulus of elasticity (dynamic) G_d (MPa):	600
Specific mass ρ (kN/m^3):	22
Velocity of the elastic wave C_P (m/s):	904.53

After the dynamic input was introduced, the stress state induced along the potentially sliding surface revealed with the LEM was analysed; using the LEM, a safety factor of 1.91 was obtained on this surface in static conditions and a safety factor of 1 was obtained in dynamic conditions (Fig. 10).

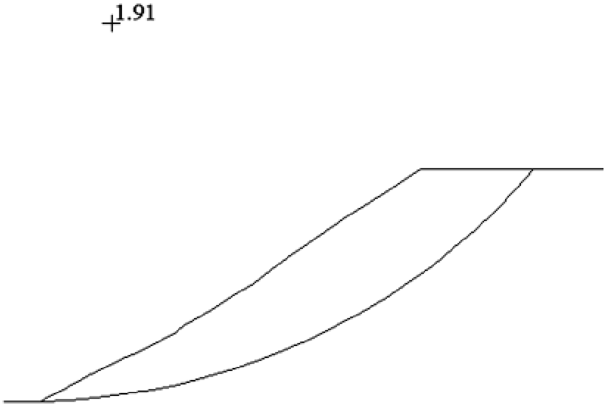


Fig. 10. Potentially sliding surfaces in the Polvaccio ravaneto obtained with the LEM

Seventy-five successive temporal phases were considered, starting from time 0 (arrival of the seismic wave on the potential sliding surface) up to a time of 0.6 seconds, with intervals of 20 ms. The trend of the local safety factors along the potential sliding surface and the global safety factor were evaluated for each temporal phase. The local safety factor of a point on the sliding surface is defined as the ratio between the shear strength in that point and the shear stress acting in the direction parallel to the sliding surface. The global safety factor instead is the ratio between the integral of the strength shear stresses along the sliding surface and the integral of the acting shear stresses.

The global safety factor reaches a minimum value (1.45) for $t = 220$ ms and for $t = 420$ ms. Nevertheless, this value is higher than that which was obtained with the LEM analytical method (Sarma method) for the Polvaccio ravaneto in the presence of the considered seismic wave ($Fs = 1$). Instead, the global safety factor in a static field (for $t = 0$) coincides with the value obtained with the LEM ($Fs = 1.91$).

The trend of the global safety factor, in function of time ($t = 20$-600 ms), obtained using the numerical analysis in the dynamic field, is shown in Fig. 11.

The trend of the local safety factors along the sliding surface for the condition $t = 0$ (static condition before the arrival of the seismic wave), $t = 220$ ms, $t = 420$ ms and finally for $t = 3$ s (static condition after the depletion of the dynamic action due to the seismic wave) is shown in Fig. 12. It can be noted that during the seismic event the Polvaccio ravaneto is particularly stressed ($Fs < 1$) close to the lower portion of the potential sliding surface and presents almost the same values of the static condition ($t = 0$ and $t = 3$ s) in the intermediate sector. Lower values of Fs are recorded in the dynamic field in the upper zone of the potentially sliding surface than in static conditions, which are, however, always above 1.5.

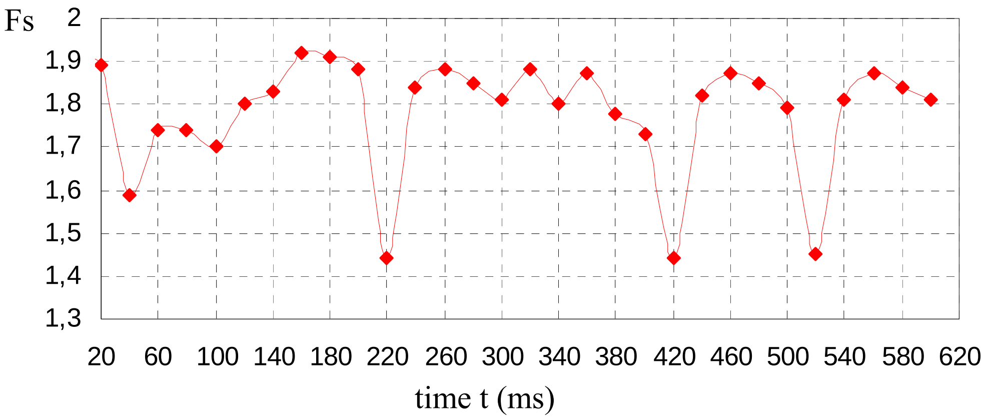


Fig. 11. The Polvaccio ravaneto. Trend of the global safety factor in function of the time during the dynamic action produced by a horizontal seismic wave with a frequency of 20 Hz and a maximum acceleration equal to $0.34 \cdot g$

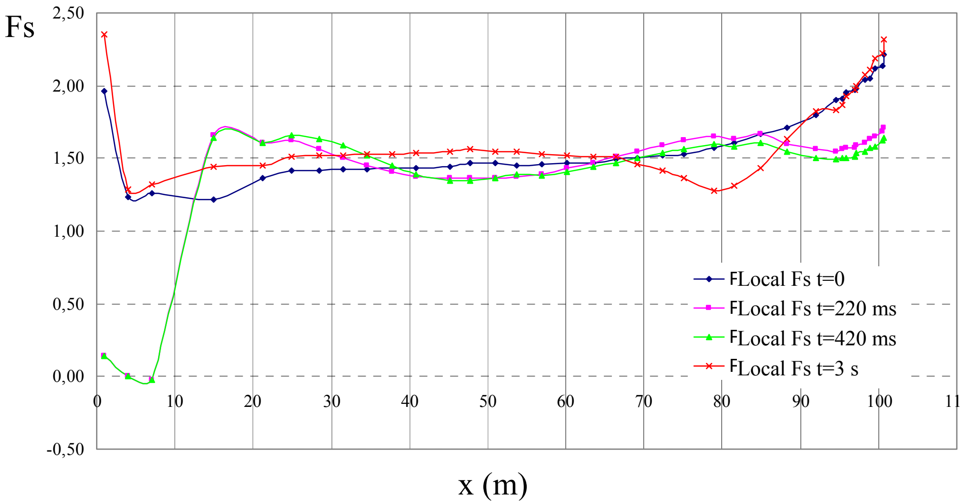


Fig. 12. The Polvaccio ravaneto. Trend of the local safety factors along the potentially sliding surface with a variation of the horizontal progressive *x*, for different values of time *t*

The difference between the trends of the local safety factors in the two static conditions (before and after the seismic event) can be considered negligible.

9. Conclusions

Already back at the end of the Middle Ages, with the new techniques developed for the quarrying of precious marble in the Apuan Alps (Italy), large quantities of waste material accumulated along the slopes below the quarries (known as "ravanetos"). These ravanetos continue to increase in size and presently create many serious problems from the geological risk point of view. Their stability, and in particular that of the most recent ravanetos, is an aspect of great topical interest.

In this work, after having conducted a detailed analyses of the characteristics of the ravanetos in the Apuan Alps, a stability analysis has been performed of two representative ravanetos: Polvaccio, a typical recent ravaneto and Torrione-Tecchione, an old ravaneto at present undergoing re-naturalisation. First, stability analyses were conducted in a static field using the LEM (the Sarma method) and a back-analysis which was able to give couples of the most probable values of the apparent cohesion and friction angle of the material that makes up the ravanetos was developed. For this purpose, a limit stability condition was hypothesised in completely saturated conditions (that is, typical of an intense and prolonged rainfall event). After this, the intensity of a seismic wave that could make the two ravanetos unstable in dry conditions (the absence of a water table inside the debris piles) was evaluated using a pseudo-static approach. Thanks to the probabilistic evaluations supplied by the Italian Institute of Geophysics and Vulcanology on the intensity of the seismic events expected in the next 50 years in the Apuan Alps zone, it has been possible to determine the probability of a seismic event making the two studied ravanetos unstable. As such a probability is of the order of 6/100.000, it can be considered highly unlikely that such a catastrophic event could occur.

The study was then continued with a more detailed calculation of the more critical condition, from the stability point of view, using a finite difference method in the dynamic field. The situation of the Polvaccio ravaneto was then analysed, hypothesising a seismic wave with a maximum acceleration of $0.34 \cdot g$, which the pseudo-static calculation with the LEM had indicated as being sufficient to reach a limit stability condition ($Fs = 1$). The results of the numerical calculation have made it possible to verify that the global safety factors of the ravaneto never go below a value of 1.45 during the hypothesised seismic event, and that the safety factor, after the event, is equal to the initial one ($Fs = 1.91$). This result, on one hand, would seem to indicate that the use of LEM calculation methods can be considered cautionary to simulate the effect of seismic wave on the stability of ravanetos and, on the other hand, it confirms the extreme unlikelihood of a seismic event making large portions of the two studied representative ravanetos unstable.

References

Barducci A., Carmignani L., Conti P., Disperati L., Fantozzi P.L., Mancini S., Massa G., Rondinella A., Simoncini D., Vaselli L., 2008. *Approccio multidisciplinare per la valorizzazione della risorsa lapidea apuana*. Atti del Simposio "Stato del Territorio e delle risorse naturali in Toscana", Ordine dei Geologi della Toscana, 23-25.10.2008.

Baroni C., Bruschi G., Ribolini A., 2000. *Human-induced hazardous debris flows in Carrara Marble basins (Tuscany, Italy)*. Earth Surface Processes and Landforms, 25, p. 93-103.

Baroni C., Bruschi G., Criscuolo A., Ribolini A., 2001. *Il rischio geomorfologico indotto dall'attivita estrattiva nei bacini marmiferi apuani (Alpi Apuane, Toscana)*. Atti della Societa Toscana di Scienze Naturali Residente in Pisa, Memorie, Serie A: Processi Verbali, v. 107, pp. 87-96.

Baroni C., Bruschi G., Criscuolo A., Mandrone G., Risolini A., 2003. *Complete grain-size analyses on debris-flows source area in the Carrara Marble Basins, Apuane Alps, Italy*. Proceedings of Third International Conference on "Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment", Davos, Switzerland, Rickenmann, Chen (Eds), Millpress, Rotterdam, 203, pp. 809-820

Blijenberg H.M., 1993. *Modelling of debris flows*, in Flageollet J.C. (Ed.), "Temporal Occurrence and Forecasting of Landslides in the European Community", Final Report, European Community, Programme EPOCH, Contract 90 0025, Part I, 162-189.

Bourdeau C., Havenith H.B., Fleurisson J.A., Grandjean G., 2004. *Numerical Modelling of Seismic Slope Stability*. Engineering Geology for Infrastructure Planning in Europe, Springer Berlin / Heidelberg, 671-684, Volume 104.

Bray J.D., Rathje E.M., Augello A.J., Merry S.M., 1998. *Simplified Seismic Design Procedure for Lined Solid-Waste Landfills*. Geosynthetics International Journal, Vol. 5, Nos. 1-2, pp. 203-235.

Brunsden D., 1979. *Mass movements*, in Embleton C. and Thornes J. (Eds), "Process in Geomorphology", Edward Arnold, London, 131-186.

Bruschi G., Criscuolo A., Zanchetta G., 2003. *Stratigrafia delle discariche di detrito dei bacini marmiferi di Carrara. I ravaneti antichi di Carbonera, Strinato, Gioia e Scalocchiella*. Acta apuana, v. 2, pp. 26-32.

Cala M., 2007. *Convex and concave slope stability analyses with numerical methods*. Arch. Min. Sci., Vol. 52, No 1, p. 75-89.

Charles J.A., Watts K.S., 1980. *The influence of confining pressure on the strength of compacted rockfill*. Geotechnique, 30(4), 353-367.

Cheng Y.M., Lansivaara T., Wei W.B., 2007. *Two-dimensional slope stability analysis by limit equilibrium and strength reduction methods*. Computers and Geotechnics, Vol. 34, Issue 3, p. 137-150.

Cheng Y.M., Lau C.K., 2008. *Slope Stability Analysis and Stabilization*. Routledge Ed.

Coli M., Appelius V., Pini G., 2000. *Studi sui ravaneti dei Bacini Marmiferi Industriali del Comune di Carrara: ubicazione, tipologia e consistenza*. GEAM, Atti del Convegno "Le cave di pietre ornamentali", Torino, 28-29/11/2000, 59-63.

Coli M., Pini G., Piccini L., Mariottoni E., Frosini S., Rossi M.L., Livi V., Appelius V., Carmignani L., Meccheri M., Fantozzi P.L., Sciuto P.F., Bocci M., Antompaoli L., Chiereghin F., Graziosi B., Fornaro M., Lovera E., Bergamasco L., 2002. *Studi Conoscitivi sui Bacini Marmiferi Industriali di Carrara: Un Contributo per la gestione Pianificata dell'Attività*. GEAM - Geoingeneria Ambientale e Mineraria, v. 24, 104 pages.

Cortopassi P.F., Daddi M., D'Amato Avanzi G., Giacomo A., Giannecchini R., Lattanzi G., Merlini A., Milano P.F., 2008. *Quarry waste and slope instability: preliminary assessment of some controlling factors in the Carrara marble basin (Italy)*. Italian Journal of Engineering Geology and environment, 99-118.

Cundall P.A., 1976. *Explicit Finite Difference Methods in Geomechanics, in Numerical Methods in Engineering*. Proceedings of the EF Conference on Numerical Methods in Geomechanics, (Blacksburg, Virginia, June 1976), Vol. 1, 132-150.

D'Amato Avanzi G., Verani M., 1998. *Valenze ambientali ed economiche dei ravaneti delle Alpi Apuane (Toscana)*. Memorie della Società Geologica Italiana, v. 53, pp. 489-501.

Domanska D., Wichur A., 2006. *The researches on slope stability evaluation with inclinometric measurements*. Arch. Min. Sci., Vol. 51, No 4, p. 503-528

Hammouri N.A., Malkawi A.I.H., Yamin M.M.A., 2008. *Stability analysis of slopes using the finite element method and limiting equilibrium approach*. Bulletin of Engineering Geology and the Environment, Volume 67, Number 4, 471-478.

Hanlong L., An D., Yang S., 2008. *Shear behavior of coarse aggregates for dam construction under varied stress paths*. Water Science and Engineering, Vol. 1, No. 1, 63-77.

Hoek E., Bray J.W., 1981. *Rock Slope Engineering*. Institute of Mining and Metallurgy, London, 358 p.

Itasca Consulting Group, Flac Manual, Minneapolis (USA), 1994.

Kasparyan E.V., 2008. *Hierarchic-Block models of rock mass in modern geomechanics*. Arch. Min. Sci., Vol. 53, No 3, p. 439-448.

Kidybinski A., 2010. *The role of geo-mechanical modelling in solving problems of safety and effectiveness of mining production*. Arch. Min. Sci., Vol. 55, No 2, p. 263-278.

Krzysztoń D., 2005. *The influence of friction force on the post-critical failure of rock samples subjected to triaxial compression*. Arch. Min. Sci., Vol. 50, No 4, p. 517-536.

Krzysztoń D., 2007. *Frictional resistance in the post-critical failure of rock samples caused by triaxial compression*. Arch. Min. Sci., Vol. 52, No 3, p. 387-408.

Jie M., Chen C.Y., Zhang J.J., 1999. *General stability of two-dimensional slopes based on Sarma's method*. International Journal for Numerical and Analytical Methods in Geomechanics, Volume 23 Issue 5, Pages 413-426.

Li A.J., Lyamin A.V., Merifield R.S., 2009. *Seismic rock slope stability charts based on limit analysis methods*. Computers and Geotechnics, Volume 36, Issues 1-2, Pages 135-148.

Lo Presti D., Fontana T., Marchetti D., 2008. *Slope Stability Analysis in Seismic Areas of The Northern Apennines (Italy)*. AIP Conf. Proc. Seismic Eng. Conference, July 8, 2008, Volume 1020, pp. 525-534.

National Institute of Geophysics and Vulcanology, Maps of values of the probabilistic distribution of the maximum acceleration of a seismic wave for the next 50 years in Italy (2004), internet site.

Pham Ha T.V., Fredlund D.G., 2003. *The application of dynamic programming to slope stability analysis*. Can. Geotech. J., 40: 830-847.

Plewa F., Sobota J., 2002. *Physical and mechanical properties of differently composed mixtures used for a stabilized backfill*. Arch. Min. Sci., Vol. 47, No 1, p. 35-49.

Sarma S.K., 1973. *Stability analysis of embankments and slopes*. Geotechnique, 23, 423-433.

Sherard J.L., Woodward R.J., Gizienski S.F., Clevenger W.A., 1963. *Earth and Earth-Rock Dams*. Wiley, New York.

Università degli Studi di Siena-Centro di Geotecnologie, Carta Giacimentologica dei Marmi delle Alpi Apuane e sua informatizzazione-Relazione Finale, http://www.marmiapuane.info/Documenti/documents/html/RelazioneMarmi-Web.htm

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