Geomechanical study and rock fall hazard analysis in the historical Centre of Forza d’Agrò (Messina – Italy)

O Barbagallo¹ and F Calvi²

¹ Geologist, Catania Italy
² Geomorphologist, Palermo Italy.

orbarbagallo2@gmail.com

Abstract. The present study shows the results of a rock fall hazard evaluation of the area downstream the Norman Castle that overlooks Forza d'Agro (Messina Province – Italy). The study was aimed at evaluating the penetration capacity of a rockfall in the inhabited center, to evaluate the number of houses involved in the transit area of the boulders. On the basis of the data obtained, a hazard assessment was developed that took into account not only the type and magnitude of the landslide phenomenon, but also the probability of occurrence of the event or its return time.

1. Introduction

The article presents the results of a geological study for the rock fall hazard assessment of the historical center of the town of Forza d'Agrò (Messina Province – Italy). The study was commissioned by the city municipality to detail the risk area (code:097-5FZ-007) indicated in the Regional Geomorphological Structure Plan (PAI) of Sicily River Basin District [1], involving the most part of the old town of Forza d'Agrò.

The study area is located on a narrow ridge that develops in the NW-SE direction, ending at the Norman Castle, which descends from the town towards the sea in a south-easterly direction up to Capo Sant'Alessio, a promontory where the ruins of another Castle are located along the Ionian coast line between Messina and Taormina.

From a geostuctural point of view, the area under observation is affected by the frontal part of the complex system of geological units, corrugated and superimposed, which emerge along the entire north-eastern sector of Sicily.

In particular, it can be observed that the western part and the top of the ridge are characterized by the outcrop of dolomites and crystalline limestones from the Mandanici unit. The outcrop is conditioned by the presence of a fault; direct NW-SE, which lowers the dolomites and crystalline limestones towards the valley. The same fault intersects another left trans current fault, developed in the NE-SW direction.

2. Identification of the structural homogeneity areas

In relation to the structural complexity of the area, the rocky outcrop of the carbonate formation involved in the rock fall, has been divided into two different Homogeneous Zones (HZ), i.e. sectors of the rock that have homogeneous fracturing and structural set-up characteristics.

The Homogeneous zone 1 (figure 1), is located in the downstream side of the medieval tower and in part of the north-eastern side of the Norman Castle. It is a strip of land marked by the outcrop of
gray dolomites and crystalline limestones from the Mandanici Unit (formerly the Novara unit) characterized by a moderate degree of fracturing that split the mass into elongated boulders of parallelepiped-prismatic shape, which can be assimilated to polyhedral or prismatic boulders by Dearman [2] or to compact or to long boulders by Palmström [3].

The homogeneous zone 2 is situated in the north-western part of the escarpment and in the west part of the ridge. In this case it is a strip of land characterized by a state of fracturing higher than HZ1, with four families of joints that divide the rock into boulders of a polyhedral to elongated prismatic shape, with a unit rock volume of smaller dimensions than the HZ1.

![Figure 1. Identification of the homogeneous zones. 1 = HZ1; 2 = HZ2; 3 = limestones and dolomites with anthropogenic soil covers; 4 = debris;](image)

3. Boulder dimension
The size of the unit rock volume is an extremely important indicator of the behaviour of the rock mass. It is determined by the spacing of the joints, by the number of joint systems detected and by the persistence of the joint that delimit the potential boulders.

The unit rock volume in the two homogeneous zones was calculated on the basis of the values of the Jv (volumetric number of discontinuities) which depends on the average spacing of the joints.

For the HZ1, the value of the Jv is 8.18 (RQD = 88.0%), corresponding to medium-sized boulders from 0.10 m$^3$ to 0.97 m$^3$. For the HZ2, the value of the Jv is 12.42 (RQD = 74.0%), corresponding to small-sized boulders from 0.02 m$^3$ to 0.38 m$^3$.

4. Evaluation of impact resistance of the vulnerable houses
Before the analysis of the trajectories, we carried out an evaluation of the vulnerability of the residential houses. The calculation of the impact resistance of the walls of the houses was assumed as starting point, considering it a fundamental parameter that strongly influences the capacity to resist at the impact with the boulders of the rockfall.

The characteristics of the existing houses immediately downstream of the Castle are represented by old single-storey houses in masonry and concrete. So we have calculated the dissipation of energy due to the impact of the boulder considering the two external walls of the houses with a thickness of 40 cm, constructed by masonry walls made of limestone bound with cement mortar.

We used two different verifications of the walls resistance: the first one through the parameters given by the Italian Construction Norms (NTC 2008) [4] and especially to the explanatory circular n. 617/2009; the second by applying the method of Mavrouli et alii [5] which use the FEM finite element method for the evaluation of the mechanical properties and the modelling of the masonry structure.
4.1. Verification 1
In the first case, the Table of circular n. 617/2009 [6], give reference values of mechanical parameters (minimum and maximum) and average specific weight for different types of masonry. Referring to the conditions founded on site, the table indicated a variable value between 100 and 180 kJ. For greater caution we have chosen the lower value of 100 kJ.

| Type of masonry                        | 1 (N/cm²) | 2 (N/cm²) | 3 (N/mm²) | 4 (N/mm²) | 5 (kN/m³) |
|---------------------------------------|-----------|-----------|-----------|-----------|-----------|
| Messy stonework (bound, stones inconstant and irregular) | 100 - 180 | 2.0 - 3.2 | 690 - 1050 | 230 - 350 | 19        |
| Masonry with limited facing thickness and inner core | 200 - 300 | 3.5 - 5.1 | 1020 - 1440 | 340 - 480 | 20        |
| Split stone masonry with good texture | 260 - 380 | 5.6 - 7.4 | 1500 - 1980 | 500 - 660 | 21        |
| Masonry with soft stone (tuff, calcarenite, ecc.) | 140 - 240 | 2.8 - 4.2 | 900 - 1260 | 300 - 420 | 16        |
| Square stone block masonry            | 600 - 800 | 9.0 - 12.0 | 2400 - 3200 | 780 - 940 | 22        |

1 = average compressive strength of the masonry, 2 = average shear strength of the masonry, 3 = mean value of the modulus of normal elasticity, 4 = mean value of the modulus of tangential elasticity, 5 = average specific weight of the masonry.

4.2. Verification 2
For a further control on the damage threshold value previously indicated (100 kJ), we applied the method of fragility curves [5], which allows performing a probabilistic evaluation of the performance of a stone and concrete wall.

The input variables applied are: the structure of the masonry; width of the wall and tensile strength of the masonry; the properties of the impacting rock boulder: speed and volume. In the studied case: wall thickness from 0.3 to 0.5 m; tensile strength from 0.2 to 0.3 MPa; boulder velocity from 5 to 15 m/s; boulder volume from 1 to 2 m³.

The result, with energy of 100 kJ shows a 74% of possibility exceeding moderate damage threshold, and the possibility of exceeding high damage threshold is equal to 37%. So if the result of a kinetic energy level of 100 kJ would cause the collapse of the walls only in 37% of cases, we can believe that the assumed level of theoretical collapse of the walls is sufficiently precautionary.

5. 3D Rockfall Runout Modelling
We used “CDM-DOLMEN srl Is GeoMassi” software [7], in which the geometry of the slope is represented by a mesh of triangles, generated from a Digital Terrain Model (DTM). In order to calculate the trajectories of the boulders, the "Hybrid Lumped Mass" method was applied, where the motion of the boulder occurs with a series of impacts and rebounds or by rolling.

The calculation of the post-impact velocities was defined through the CRSP (Colorado Rockfall Simulation Program) [8] model based on energy conservation. Stopping of the boulders is imposed when the translational energy became less than $1 \times 10^6$ kJ or the translational speed is less than 0.005 m/s. The effect of the aerial part of the vegetation, if present, is represented by an equivalent linear viscous resistance.

To select the restitution coefficients (Kn and Kt on table 2) we based on the data provided on similar lithotypes by Piteau and Clayton [9], by Hoek [10] and by Pfeifer and Bowen [11] (values often derived from on-site tests carried out in specific test fields) and from the results of a Back Analysis we carried out on a rockfall event in Castelmola (close to the study area) which affected similar terrains.
Table 2. Values of restitution coefficients

| Outcrop rock (normal distribution) |
|-----------------------------------|
| **Kn** | **Kt** | **Standard deviation** |
| Minimum value | 0,35 | 0,37 | 0,07 |
| Maximum value | 0,92 | 0,85 | 0,40 |
| Average | 0,69 | 0,62 | 0,31 |

| Debris (normal distribution) |
|-----------------------------|
| **Kn** | **Kt** | **Standard deviation** |
| Minimum value | 0,32 | 0,62 | 0,60 |
| Maximum value | 0,66 | 0,82 | 0,80 |
| Average | 0,50 | 0,74 | 0,70 |

We have considered two different horizons: the one composed of outcropping rock, visible in the top part of the slope and the debris present in the medium-low portion. The value of the rolling friction angle was obtained by applying the formula of Kirkby and Statham [12]. We gave a variable volume between 0.16 and 1.26 m³ to the boulders, with a cautious increase of 30% respect the calculated ones.

Moreover, we have developed a fall trajectory analysis in which the simulation of energy loss along the slope was evaluated by inserting two “virtual” rockfall barriers.

5.1. Barriers
In the used model, 4 barriers are considered, 2 rockfall protection barriers was made by an emergency project and 2 barriers are virtual, following the external wall of the first and second row of houses (figure 2). The resistance of the virtual barriers has been set equal to the wall resistance previously calculated; 100 kJ each with a high of 3 meters. To the existing barriers have been assigned strength of 500 kJ and a high of 3 meters.

Figure 2. Distribution of barriers and top of the cliff: (A) Virtual barriers, (B) existing barriers, (C) top of the cliff
5.2. Simulation performed without considering the virtual barriers

In figure 3 we have reported a simulation carried out not considering the braking action due to the houses, but only to the two existing rockfall barriers. It is evident that the paths of the boulders involve over four rows of houses.

![Figure 3. Boulder trajectories without virtual barriers](image)

5.3. Simulation performed considering the virtual barriers.

Figure 4 shows the trajectories and impacts on the walls of the houses (virtual barriers). The braking action of the buildings significantly reduces the lengths of the tracks compared to the previous simulation. It should be noted the existing upper barrier that intercepts almost all the trajectories, but it is still insufficient, because some boulders continue their trajectory towards the valley up to the street and beyond.

On the first virtual barrier 120 impacts, over 900 simulated throwing of boulders, are found validating the extreme hazard of the upstream portion of the town of Forza d'Agro, with maximum kinetic energy up to 421.8 kJ. On the second virtual barrier, only 10 impacts with maximum kinetic energy equal to 336.1 kJ are found, demonstrating that almost all the boulders stop before the impact with the virtual barrier 2, i.e. energy of the falling boulders is almost completely absorbed by the collisions with the first row of upstream houses.

![Figure 4. Boulder trajectories with virtual barriers](image)

6. Hazard assessment methodology

Hazard is defined as the probability that a potentially harmful natural phenomenon occurs in a given period of time and in a given area (UN-ISDR) [13]. Hazard assessment involves estimating the intensity of an event over time.

The methodology adopted is the Switzerland ERHA (Evolving Rockfall Hazard Assessment procedure) [14], where a semi quantitative evaluation with matrix method defines the Hazard level.

As regards to the energy levels (intensity of the event) the method indicates the following classes:

- Low (<30 kJ);
- Medium (30 - 300 kJ) and High> 300 kJ;

This classification in our case is not conform with our elements at risk, in fact if the 1-30 kJ class in Switzerland is very important because it represents the breaking level of the wooden fences that protect the railway tracks, in our specific case the energy thresholds become more important over 100 kJ (strength of the walls of one row of buildings) and over 200 kJ (total strength of two virtual barriers). So in our case the energy ranges are: Low (<100 kJ); Medium (>100 kJ - <200 kJ); High (>200 kJ - <400 kJ) and Very High (> 400 kJ).

As regards to the probability of occurrence, the ranges are associated with the corresponding return periods (RT): High RT 1-30 years; Medium RT 30-100; Low RT 100-300 years; Very Low RT > 300 years.
Below the matrix (figure 5) used that modify the Swiss method in order to compare the result with the classes of hazard used in the PAI in Italy (P1 = low; P2 = medium; P3 = high and P4= very high).

**Figure 5.** Hazard classification matrix used in this work.

7. Discussion
To calculate the return times (RT), we have evaluated a frequency of falling rocks not exceeding 3 boulders/year, based on the municipal register and in relation to the number of boulders of significant volume fallen in recent years and visible at the foot of the escarpment and along it. To create a simulation covering a time span of 300 years, a trajectory analysis was therefore performed comprising a total of 900 jumps,

The simulation developed shows that the greater number of boulders with RT between 1 and 30 years are in the slope upstream of the houses, close to which (virtual barrier 1) there are areas with R.T. between 30 and 100 years and to a lesser extent between 100 and 300 years. Beyond the virtual barrier n ° 1 the return times are higher than 300 years (figure 6); this indicates a medium or low probability of the event.
The 2D analysis of the kinetic energies shows on figure 7 that the areas where the greatest energies are developed are in central area and south-eastern part of the front studied. In correspondence with the first row of the houses there is a rapid decrease of the energies.

Finally we define a hazard map based on the matrix of figure 5 that identify the affected houses. Some of those have less probability (hazard level medium) to be destroyed. The figure 8 shows the houses impacted by the simulation of the rockfall.

![Figure 8. Hazard and risk map. With: 1 = P2 medium level; 2 = P3 high level; 3 = P4 very high level; 4 = houses with maximum level of risk; 5 = houses with less temporal probability of risk.](image)

Therefore, the risk simulation shown in figure 8 is not directly comparable with that obtained from the application of the Italian PAI method (generally does not include the return time).

Moreover applying a complete hazard evaluation is possible to better detail the risk consequences already in this first step and have good indications on the intervention priorities for prevention and protection actions.

**8. Conclusions**

We have developed a study applying the analytical kinematic models to determine the real condition of the hazard due to a rock fall landslide in the area immediately upstream of the old centre of Forza d’Agrò.

To evaluate the real transit and stopping area of the boulders it was necessary to measure the penetration capacity of a falling boulder in the urban area and the consequent number of houses involved. To estimate this, it was necessary to ascertain the minimum damage threshold capable of causing the collapse of the walls. The purpose was achieved through the application of two different methodologies given respectively by Italian norms for technical works and by a FEM analysis through fragility curves of the wall structures. Based on these two methods we have established a damage threshold of 100 kJ for each wall.
To define the actual degree of hazard in an urban area, we suggest, that it is also necessary to quantify the probability of occurrence of the event or its return time. To calculate this parameter, various semi-quantitative methods to assess the hazard level have been developed in many countries.

We decided to use the Swiss methodology with some adjustments due to the local conditions. The following intervals have been chosen as significant periods of return times: 1-30 years (high probability of the event), 30-100 years (moderate probability), 100-300 years (low probability), >300 years (very low probability). The classes of energy chosen are: 0 – 10 kJ low; 100 – 200 kJ medium; 200 – 400 kJ high and over 400 kJ very high. The range values were related to the vulnerability of the houses. The calculation of the return times has been carried out on the basis of direct observations over the last few years from the municipal technicians, determining an estimate of the frequency of falling rocks not exceeding 3 boulders/year. Taking into account the trajectory analysis was performed on a total of 900 launches, we obtained a simulation covering a period of 300 years.

Concluding, the possibility of differentiating the effects of the phenomenon on the houses considering the return time, allow to identify those that are most affected by energy impact and temporal frequency. In this way it is possible to act directly on the behavior of the residents, operating transfers or limitations of use and reducing vulnerability interventions (with moderate costs) or mitigation projects with effectiveness capacity.

To encourage the risk assessment policy, we highlight the need to introduce at national level the “acceptable risk concept” (generally in the world it is higher than one case in 100,000 or in 1,000,000 of exposed people), to direct the risk management actions, concerning also some inevitable relocations of resident houses.

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