A data-driven method for assessing the probability for terrain grid cells of initiating rockfalls on a large area

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Abstract—**Rockfalls are one harmful kind of landslide, due to their rapidity, destructive potential and high probability of occurrence on steep topographies, often found along transportation corridors. Various factors can trigger rockfalls, including intense rainfall and seismic activity, and diverse phenomena affect their occurrence, like rock weathering and fracturing. Existing approaches for the assessment of rockfall susceptibility range from purely phenomenological to purely deterministic, physically based methods. A common requirement for many approaches is the need to locate the potential point locations of source areas, often located uphill on cliffs. Application of a physically based model, in particular, allows the calculation of material runout stemming from rockfalls originating from such point locations. In this work, we propose a method for the location of rockfall source points, on a digital elevation model, suitable for large areas. We deem the method as data-driven, because it relies on expert delineation of potential source areas from Google Earth images in few sample locations, representative of the study area at large. We measure the slope distribution of grid cells encompassed by expert-mapped source areas, and generalize the distribution of sources to the whole of the study area. We apply the method to a corridor of about 17,000 km in length and varying width, containing the entire Italian railway network. The map of source areas represents the main input for a physically based simulation of rockfall trajectories with the model STONE, and likely of other similar physically based or phenomenological models for rockfall runout assessment.**

I. INTRODUCTION

Location of potential sources of rockfalls requires expert analysis of the cliffs in the study area, which is typically a time consuming and expensive procedure. This makes identification of potential sources a limiting factor for systematic rockfall studies over large areas. Existing analyses are limited to individual hillslopes or portions of slopes along transportation corridors of limited length. Moreover, a reliable extraction of potential sources requires availability of high-resolution images and digital elevation models (DEMs), which allows observation of existing sources [1-2], or continuous monitoring of slopes with various technologies, typically feasible in small areas [3, 4]. Moreover, once a potential source is located on a digital model, it is desirable to assign a probability for the likelihood of that location to evolve into an actual rockfall [5].

The common way of straightforwardly selecting source areas is to establish a slope threshold above which any grid cell acts as a potential rockfall source. In this work, we describe a method to both locate and assign a probability of failure in a homogeneous way in a very large area.

The procedure presented here represents nothing but a starting point for the assessment of rockfall susceptibility, or rockfall hazard, depending on the additional available data and purpose of the study [6]. In fact, for such purposes, we run STONE, a kinematic model to simulate rockfall trajectories originating from given source pixels on a digital topography [7]. Additional inputs of the model are friction and energy restitution grids of parameters, initial velocity of the simulated falling boulders, and other optional quantities [1, 7-9]. The model assumes point-like boulders, considering them in a state of either free fall, bouncing or rolling, at each time step of the simulation. Trajectories end when the boulders exhaust their initial kinetic energy due to simulated friction with the terrain (air drag is neglected).

II. METHODS

In this work, we performed the following steps to calculate the probability for grid cells to initiate rockfalls on a 10 m-resolution DEM of Italy (TINITALY) [10]:

1) selection of a 1 km-wide buffer around the railway track;
2) selection of the set of slope units (SUs) [11, 12] intersecting the buffer;
3) expert mapping of a subset of potential rockfall source areas within the selected SUs, in regions we considered representative of the conditions that could trigger rockfalls in the particular topographic unit [13] under investigation;

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4) development of a statistical procedure to generalize the source areas of point 3) to different grid cells, with the same characteristics in terms of local terrain slope, within the same topographic unit [14];
5) visual analysis of the source areas map obtained from the statistical procedure of point 4), in relation to the railway track, and assimilation in the final source area map of potential source areas left out by the procedure;
6) additional set of analysis, not described here, necessary for execution of the program STONE [7].

In point 2) above, we introduced the use of slope units. A national SU map is available for the whole of Italy [11, 12]. An extension of the method and software first described in Ref. [14] allowed preparation of such map. Slope units are suitable for landslide modeling [14, 15], particularly where available data is heterogeneous [15]. In our case, using SUs also allows to put a well-defined spatial boundary around the railway track, with some confidence that the runout of simulated rockfalls stays within the boundary.

In point 3) above, we introduced topographic units of Italy. We adopted a (slightly) revised version of the units from Ref. [13], as in Ref. [12]. This step allows selection of representative areas for expert mapping in each of the 29 different units, and statistical generalization of them within physiographical homogeneous areas. Table I lists the total area of each topographic unit and, in each of them, the area covered by slope units selected for simulation.

Point 4) consisted in a regression of the distribution of the number of grid cells encompassed by the expert-mapped source areas as a function of their slope, *S*, using a suitable functional form. We opted for a non-linear quantile regression with a single parameter probability function P_{FIT}, of the following form:

$$P_{FIT}(S) = c \left(\frac{S}{90}\right)^4, \quad (1)$$

where *S* is expressed in degrees and *c* is the regression parameter. We assigned values of probability with a lower bound, set as the minimum between 0.1 and the value that provides a map in which 80% of the mapped sample has non-null probability.

III. Results and Conclusions

The procedure described by the enumerated list in Section II applies to each of the topographic units adopted in this work. Table I and Fig. 1 summarize the results of the procedure.

The statistical procedure produces a 10 m x 10 m grid map aligned with the TINITALY DEM used in this work. We assigned grid cells with the probability for a rockfall trajectory to originate from within that specific location. Thus, cell-by-cell comparison between modeled probability and expert-mapped source areas is meaningful. To this end, we calculated the percentage of grid cells encompassed by polygons representing mapped source areas in which the statistical procedure assigned non-null probability, and the number of cells with values of probability larger than 0.8.

Table I lists results for each of the topographic sections in which we run the statistical procedure independently.

ZONE CODE	**Total Area** [km^2]	**SU Area** [km^2]	**HR** (Total)	**HR** (P > 80%)
1.1	16,274	1,590	77%	0.13
1.2	35,735	2,620	80%	0.19
2.1	32,702	373	80%	0.27
2.2	9,426	164	11%	0.06
2.3a	3,103	458	75%	0.16
2.3b	1,298	88	-	-
3.1	2,322	332	16%	0.00
3.2	3,991	1,778	51%	0.04
4.1	22,393	2,067	78%	0.07
4.2	16,835	1,894	79%	0.09
4.3	4,920	457	77%	0.13
4.4	8,097	1,585	75%	0.14
4.5	12,890	1,379	79%	0.18
4.6	6,203	383	50%	0.03
4.7	5,337	598	59%	0.09
4.8	4,262	511	48%	0.03
5.1	25,346	2,086	58%	0.12
5.2	6,136	972	79%	0.05
5.3	6,375	859	62%	0.04
6.1	9,023	930	78%	0.10
6.2	20,236	706	44%	0.11
6.3	1,731	-	-	-
7.1&7.2	14,285	2,195	56%	0.12
7.3	5,321	691	46%	0.09
7.4	1,499	210	80%	0.28
8.1	16,404	428	63%	0.14
8.2	258	-	-	-
8.3	1,946	4	58%	0.21
8.4	2,844	42	76%	0.22

Table I. Numerical evaluation of the statistical generalization for the probability of grid cells to initiate a rockfall trajectory (see text). We also list the total area of each section (Zone code, Ref. [10, 12]) and the area occupied by selected slope unit area.

We evaluated the agreement between expert-mapped areas and statistical generalization by hit rate, HR = TP = (TP + FN), where TP stands for true positives and FN for false negatives.

Figure 1 shows a sample subset of the results, in four of the 29 units. The figure shows the empirical probability for a grid cell of initiating a rockfall, represented by slope values calculated for the set of 10 m x 10 m grid cells encompassed by the expert-mapped

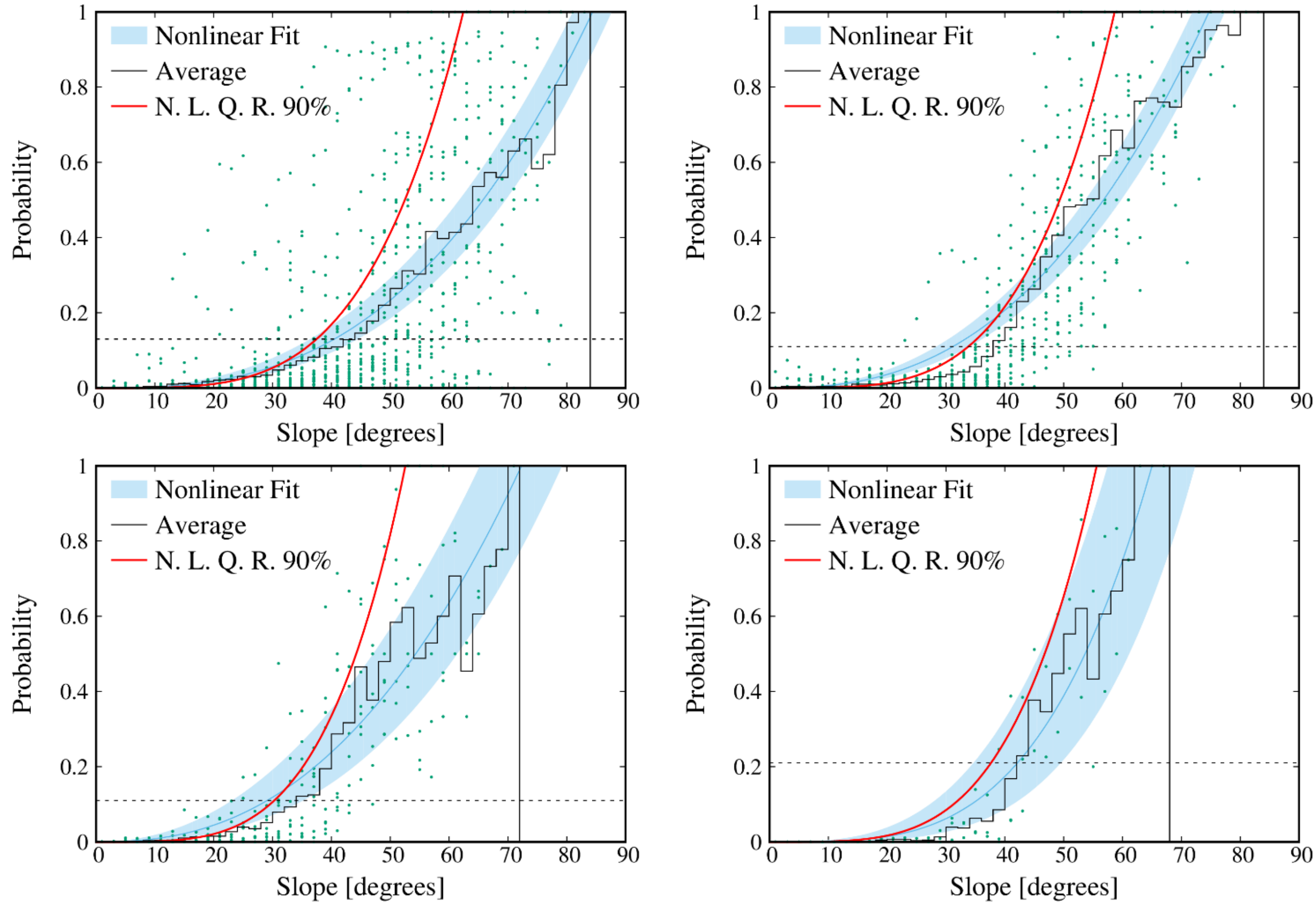

Figure 1. Example result of statistical assessment of the probability of a grid cell with given slope to represent a source area for rockfalls. Data (green dots) and numerical models (curves) correspond to four out of the 29 topographic from Ref. [10, 12], adopted in this work. The red curve, a non-linear 90% quantile regression corresponding to Eq. (1), is the adopted model. The horizontal line represents the probability limit under which probability is set to null.

polygons (green dots). The figure also shows different curves, corresponding to the following quantities. Blue curve with confidence band: a non-linear fit with an expression similar to Eq. (1), but with the exponent also being a fitting parameter. Black curve: piecewise average of the data values. Red curve: the 90% non-linear quantile regression, *i.e.* the function of Eq. (1) with a value of c that leaves 90% of the data points below the curve. Our choice falls on the last quantity, as anticipated, because both the other ones would assign many cells with large values of slope with very small probability of generating rockfalls. We empirically observed that it is not the case.

Numerical results listed in Table I indicate that in three of the units the map produce by the proposed procedure accounts for 80% of the mapped source areas in three topographic units; the agreement is poor (less than 16%) in two units and low (less than 50%) in four units. We show no results for a few units, in which we do not expect rockfalls at all (no mapped source areas), or they do not overlap with the railway track.

We can make sense of the low values of hit rate appearing in Table I with the following considerations. We hypothesized a relationship between the probability of a grid cell of initiating a rockfall and local slope. This represents a good compromise between an acceptable overall time needed for the procedure over a large study area and a realistic product, for our purposes, but it certainly does not embed all of the local terrain properties of that influence the expert criteria applied for mapping potential source areas. Errors may also arise from the discrepancy between the DEM used in the analysis and the apparent resolution of Google Earth imagery, especially in the locations with largest relief, in which we are mostly interested. Eventually, we used a DEM generated from a triangulated irregular network (TIN); visual inspection of a shaded relief generated form the DEM highlighted locations in which the triangulation used to prepare the DEM is manifest, which surely affects the slope map nation-wide.

Numerical results in Table I correspond to comparisons limited to the slope units overlapping with a buffer along the national railroad network. Applicability of this method for a national rockfall susceptibility map remains to be investigated.

Preliminary results of simulations of rockfall trajectories with the STONE program were compared with mapped rockfalls in the Italian Inventory of Landslide Phenomena Inventory of landslide phenomena, known as IFFI [17, 18]. The IFFI inventory contains over 620,000 landslide polygons, of which 4,051 correspond to rockfalls. Rockfall polygons contain both source and runout areas. The comparison shows nice agreement with empirical evidence. Detailed results, and assessment of their impact on the national railway network, will be reported elsewhere.

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