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Statistical and empirical analyses of the triggers of coastal chalk cliff failure

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ABSTRACT:

The triggering factors of rock falls remain unknown due to a lack of exhaustive, regular and accurate surveys. Based on an inventory of 331 rock falls collected weekly between 2002 and 2009 from Veules-les-Roses to Le Treport (Upper Normandy), the relationships between coastal chalk cliff rock falls (dates and geomorphological features) and external factors commonly agreed as triggering (rainfall, temperature variations, tide and wind) are studied. The combination of multivariate statistical and empirical analyses indicates that (1) “cold and dry weather” and “high rainfall and high wind” are the conditions most likely to trigger rock falls, (2) the main triggering factors of rock falls are effective rainfall (for rock falls mostly between 200 and 1,400 m^3 or larger than 10,000 m^3 and coming from the whole cliff face), freeze/thaw cycles (especially for rock falls smaller than 200 m^3 and

coming from the foot and top of the cliff face) and marine roughness (rock falls mainly smaller than 200 m^3 and coming from the cliff foot). However, the contribution of each factor to triggering is difficult to determine because of combinations of factors (85 % of 331 cases), relays of processes and hysteresis phenomena. In view of these first results, it is still presumptuous to predict the location and time of triggering of rock falls. However, the statistical and naturalistic approaches adopted and the observations made in this study are from an original database, and constitute a real starting point for the prediction and prevention of the hazard of coastal chalk cliff rock falls in Upper Normandy.

KEYWORDS: coastal chalk cliff rock falls, triggering factors, statistical analyses, empirical analysis, Upper Normandy

Introduction

Except for a consensus about the influence of structural features, external triggering factors of rock falls are still under scientific debate. In this paper, the term “rock fall” is used to describe movements of coherent rock (Varnes, 1978).

Many studies emphasize the importance of sub-aerial actions over marine actions (Brossard and Duperret, 2004; Pierre and Lahousse, 2006), which are assumed to be just a transport agent. The role of rainfall through surface runoff, infiltration, and water table levels may reduce the stability of cliffs (Sunamura, 1992; Duperret et al., 2002; Hénaff et al., 2002a; Young et al., 2009). Because of the porosity of coastal chalk cliffs, they are particularly sensitive to processes induced by water (Hutchinson, 1972; May and Heeps, 1985; Duperret et al., 2002, 2004; Lahousse and Pierre, 2003; Pierre and Lahousse, 2006). Freezing action is also mentioned. Many

geomorphological studies have focused mainly on the freezing process (Robinson and Jerwood, 1987) whereas thermoclasty has been less studied (Hall, 1999). This freezing process has been extensively studied and sometimes quantified, especially in periglacial environments, and may be conducive to triggering rock falls (Fournier and Allard, 1992; Bernatchez and Dubois, 2008). The porosity of chalk leads to a high sensitivity to temperature variations, with freezing often being considered a triggering factor. For the coastal chalk cliffs studied, the porosity ranges between 32 % and 46 % from the Turonian to Campanian stages (Duperret et al., 2005). The characteristics (including its porosity range) and salt content (Robinson and Jerwood, 1987; Jerwood et al., 1990a, 1990b) of chalk identify it as a “frost-shattered” rock. It is the number of freeze/thaw cycles that is important rather than the intensity of freezing (Letavernier, 1984). Cryoclastism can be quite remarkable in terms of debris production: during the thaw of 31/12/1995, the volume of debris was estimated at 900 m^3 for a cliff face surface of 44,000 m^2 (Costa, 1997).

Some authors consider that marine actions are too often overlooked and emphasize the prevalence of these actions in cliff retreat (Hoek and Bray, 1977; McGreal, 1979; Sunamura, 1982, 1992; Trenhaile, 1987; Trenhaile and Kanyaya, 2007). Their role as a factor in erosion is widely recognized (King, 1972; Emery and Kuhn, 1982; Sunamura, 1982; Trenhaile, 1987; Stephenson, 2000; Woodroffe, 2002; Costa et al., 2006a; Lee, 2008; Castedo et al., 2012). The potential of wave action to destabilize cliffs has been demonstrated by modeling (Emery and Kuhn, 1982; Sunamura, 1982; Trenhaile 2009, 2010) and in the field by microseismic sensors (Adams et al., 2002; Senfaute et al., 2009; Young et al., 2012) or with high resolution laser tools to view the effects of undercutting and extraction (Dewez et al., 2013). Moreover, waves may use gravels and boulders as projectiles to increase their attack power, causing

undercutting (Robinson, 1977; Costa et al., 2006b). On rocky chalk coasts, wave action has been increasingly studied as a triggering factor of rock falls (Brossard and Duperret, 2004; Costa, 2005; Costa et al., 2006a and b; Dornbusch et al., 2008). Although Brossard and Duperret (2004) stated that the impact frequency of waves without projectiles seems to be too low to trigger large rock falls, it appears that the triggering of rock falls related to marine actions often occurs during paroxysmal storm conditions.

In the recent scientific literature, the triggering of rock falls seems increasingly the result of a combination of factors, as the coastal environment is a complex system. However, this may reflect the difficulty of identifying the contribution of each factor, which results from a lack of precise dating of rock falls over long periods, a lack of high frequency data about the factors involved in the triggering and the diversity of scales at which the data are recorded (Genter et al., 2004; Naylor et al., 2010). Moreover, the results are often valid only for the study sites because of specific contexts of morphostructural features and local meteorological and marine conditions.

Collaboration between the LETG-Caen Geophen laboratory and the non-profit organization ESTRAN led to the creation of a weekly inventory of rock falls between 2002 and 2009 from Veules-les-Roses to Le Treport (37.5 km). Using this original database of 331 events over 7 years, the objective of this work is to participate in the debate about the triggering factors of rock falls with two main research questions:

1) which marine and meteorological conditions are conducive to rock falls?

2) what is/are the triggering factor(s) of rock falls?

To answer these questions, this paper describes the application of two methods: statistical analyses to identify the meteorological and marine conditions conducive to

rock falls and an empirical analysis to give a hierarchy of factors leading to the triggering of rock falls. For each type of analysis, geomorphological features of rock falls (fallen volume and the part of the cliff face area affected by the rock fall) are integrated in our analyses to improve understanding of the relationships between triggering factors and the types of movements generated. In fact, this work aims to determine whether triggering factors generate various types of movements. If this is not the case, the geomorphological characterization of rock falls per triggering factor will improve the prediction of this hazard.

Climate and rock fall database along the studied coastline

In north-west France, the Upper Normandy coast (N 50°0’0’’, E 1°0’0’’) is located along the English Channel (Figure 1). The environment is macrotidal with an average tidal range of 8 m. Swell is limited but the wind sea can reach a significant wave height of 4 m in Dieppe (annual return period) (Augris et al., 2004). Upper Normandy presents a marine temperate west coast climate. Winter temperatures are positive but an average of 26 daily freeze/thaw cycles is recorded per year (minimal temperature can reach -15°C). Rainfall is distributed over the year (≈800 mm) although fall and winter are the wettest seasons (min: 51 mm in August and max: 94 mm in November). Daily rainfall can reach 77 mm in October (Meteo-France, 1971-2000) (Table I).

Located at the northwestern end of the sedimentary Paris Basin, Upper Normandy coastal chalk cliffs consist of Upper Cretaceous chalk (from the Cenomanian to Campanian stages) (Figure 1). These cliffs recede with an average retreat rate of 0.15 m/y but with a high spatial variability (0.23 m/y between Saint-Valery-en-Caux and Dieppe (Costa et al., 2004, 2006b; Letortu et al., 2014a)). These values are not

representative of rock dynamics because, in reality, retreat occurs in jerks (rock falls). These rock falls, currently unpredictable, threaten urbanization settled too close to the coastline (Figure 2).

From 2002 to 2009, the non-profit organization ESTRAN monitored the cliff face evolution between Veules-les-Roses and Le Treport (37.5 km) to provide an inventory of rock falls .These cliffs are made of Turonian to Campanian chalk (Figure 1). For each of the 331 rock falls inventoried, photographs and measurements were taken and recorded on an index card with information about the location, length, height, width, and date of the rock fall (if the latter was unknown, the date of observation was used) (Figure 3A). The rock falls have a variable distribution in time and location (Figures 3B and 3C) (Letortu et al., 2014b). However, they occur especially along the Cap d'Ailly (Varengeville/Sainte-Marguerite-sur-Mer; 53 % of total fallen volume; 75 % of total number of rock falls) and in winter (53 % of total fallen volume; 41 % of total number of rock falls).

Geomorphological features were added to this database (Table II). Using photographs, it was possible to observe the departure area of material on the cliff face (10 rock falls have an unknown departure area due to the lack of photographs). The cliff face was divided into 3 parts (foot/middle/top and combinations): 32 % of rock falls occur at the foot, < 1 % in the middle part, 6 % at the top, 42 % include the whole cliff face and 20 % the foot and middle part of the cliff face.

This spatial distribution is important because it may give some clues about the triggering factor. For example, a rock fall with a cliff top departure is more probably due to sub-aerial agents than marine agents.

From rock fall measurements made by ESTRAN, the volume was calculated (rock fall shape as a straight prism with a rectangular base; overall bulking factor of 33 %

(Hénaff et al., 2002b)). Twelve rock falls have an unknown volume due to the lack of measurements. The fallen volume ranges from 1 m^3 to 236,000 m^3 but almost 40 % of rock falls are smaller than 200 m^3 (Figure 4A). The biggest example (236,000 m^3 according to ESTRAN field measurements) occurred on the night of 13th to14th March 2008 in Dieppe.

Due to the statistical range of the fallen volumes, and in order to perform statistical and empirical analyses, the population was divided into different classes, determined from the volume frequency histogram between 2002 and 2009 (method of observed thresholds). Four classes appeared (Figure 4B):

- rock falls with a volume less than 200 m^3 (126 rock falls, 39 %). Some may have been evacuated in a few days (according to Hénaff et al. (2002b): about 40 m^3 per day are removed by marine actions along the Upper Normandy coast) and have left few traces for the weekly inventory of the ESTRAN organization. Thus, the analysis and results of these small volumes should be treated with caution;
- rock falls with a volume between 200 and 1,400 m^3 (100 rock falls visible from one week to another, 31 %). These mainly concern only one part of the cliff (foot, middle, top);
- rock falls with a volume between 1,400 and 10,000 m^3 (77 rock falls, 24 %). These usually affect one part of the cliff face and sometimes the whole section;
- rock falls with a volume greater than 10,000 m^3 (16 cases, 5 %). These movements mainly affect the whole cliff face (15 cases, only 1 case from the cliff top).

The originality of the database lies in (1) the length of the observation period (7 years) and the coastline monitored (37.5 km), which enable statistical analyses of 331 rock falls, (2) the high periodicity of the readings (every week), (3) the precise date of the discrete retreat events (from the 10-day period to the day), (4) the

horizontal point of view, which is the best one to follow all cliff changes (Young et al., 2009), especially small ones, (5) the measurements and photographs of the rock falls, which enable geomorphological characterization of the movements (volume, departure area of the rock fall). This database can thus contribute to the current debate about triggering factors of coastal chalk cliff rock falls.

Methods

The rock fall database offers great potential for statistical analyses due to the size of the population (331 individuals), its accuracy and reliability. Rock falls (number or fallen volume per decade) correspond to Y (dependent variables to explain) while the independent variables X (assumed explanatory) are meteorological and marine conditions (external factors influencing the occurrence of rock falls). This work is based solely on the analysis of external factors (marine and continental factors), the only homogeneously quantifiable elements across the sector considered. Obviously, internal factors are also fundamental, but these data (fracturing, karstification, lithostratigraphy) along 37.5 km of coastline are heterogeneous, at different scales, and not always available (Laignel, 2003; Duperret et al., 2004; Mortimore et al., 2004; Costa et al., 2006a; Hoyez, 2008).

To choose external variables, many data are available (Meteo-France, SHOM (French Naval Hydrographic and Oceanographic Service)) but variables must:

- have a meaning in terms of agents and processes potentially conducive to triggering (thermal variations such as freeze/thaw cycles, hydroclasty, marine roughness);

- be non-redundant (determined by a correlation matrix carried out with all factors) in order not to alter statistical analyses (e.g. two variables about rainfall against one for wind give a higher statistical weight for rainfall);
- be the most discriminating variable per type of factor (rainfall, temperature, wind, tide). This is observable by the variable contributions from Principal Component Analysis (PCA) performed with all meteorological and marine data (minimum temperatures, maximum temperatures, sum of rainfall, sum of effective rainfall, maximum tide coefficient, and mean tide coefficient).

After being selected, the meteorological and marine variables were used for analyses. Some of these are more relevant with the mean value (or sum) or, in contrast, with the extreme value:

1) MinTmin (temperature index): minimum daily temperature during a 10-day period (°C) in Dieppe. We are interested in minimum temperatures because it is possible to take into account freeze/thaw periods for a frost-shattered material such as chalk;

2) MReff (rainfall index): mean of daily effective rainfall over a 10-day period (mm) in Dieppe. The mean of rainfall that actually affects the cliff is interesting because it informs about runoff and infiltration (with widening of fissures), and thus about aquifer recharge with delay. For these reasons, effective rainfall is chosen (equal to the difference between total rainfall and actual evapotranspiration) and is calculated from the hydric balance. The mean of effective rainfall gives the same information as the sum of effective rainfall because the latter is divided by the ten days of the 10-day period;

3) MaxWFmax (wind index): maximum of daily wind force over a 10-day period (m/s) in Dieppe. Wind provides interesting data because it has an influence on swell and

thus on marine actions that affect the cliff foot. The maximum wind gives a good indication of swell (linked to wind force);

4) MCoef (tide index): mean of tide coefficient over a 10-day period in Dieppe. Tide has an influence on cliff stability. Combined with wind, it gives information about marine roughness and thus instability at the cliff foot. Clearly, the tide coefficient mean over a 10-day period might appear unrepresentative. However, 1) this period is chosen to be consistent with the other factors; 2) despite this time gap, many rock falls are distinguished by spring or neap tides.

The time scale chosen is the mobile 10-day period for three reasons:

- the frequency of the inventory is weekly, so ten days include this time lag between two surveys;
- generally, ten days before a rock fall are often necessary to identify the triggering factor because it may be due to a cumulative effect (e.g. rainfall reaching a threshold with few but continuous rainfalls over many days);
- the period of 10 days is often used in meteorological data (e.g. evapotranspiration) because it enables the inertia of the system to be taken into account.

The fixed 10-day period scale (used in many meteorological studies) was not used because it is unsuited to the problem. For example, a rock fall identified on the first day of the month is for the 10-day period of 1 to 10, while the conditions responsible for triggering correspond to the previous fixed 10-day period. Thus, the time scale used is a mobile 10-day period (with the day of the date of the rock fall and the previous nine days) for each variable.

Preparatory analyses: descriptive and bivariate statistics

First, the descriptive statistics (quartiles and median) of “factor” and “rock fall” variables (number and fallen volume) were calculated in order to determine some mathematical properties of the data that can influence the choice of analyses to use: asymmetry distributions, outliers, and non-linear relationships between variables. Thus, one of the conditions necessary for the application of linear regression models and appropriate tests (distribution of residuals according to a law close to a centered normal distribution) was checked graphically (Figure 5).

The “factor” variables are generally well distributed on either side of the mean, except those indicators describing the intensity of effective rainfall. This shows a skewed distribution, characterized by an over-representation of high outliers.

The dependent variable “number of rock falls” is strongly influenced by the presence of 10-day periods with a high number of rock falls (15-20). It therefore highlights an asymmetric distribution, characterized by a large number of outliers whatever the observation scale. For the fallen volume, the median seems much more suited to the application of linear models. These parameters were included in the linear bivariate regression models.

Secondly, we fitted simple bivariate linear regression models describing the evolution of variables to explain Y (number and volume of rock falls) as a function of the potential explanatory variables X (external factors), taken one by one. The purpose of this regression is (Cornillon and Matzner-Lober, 2011):

- to fit a model to explain Y in terms of X;
- to predict the Y values for new values of X.

It could be interesting to observe the relationships between, for example, minimum temperatures and median volume of rock falls over a 10-day period (Figure 6). For each tested relationship, bivariate methods did not appear appropriate because

trigger origins seem complex, with many factors involved. Therefore, other methods need to be used. To identify marine and meteorological conditions conducive or not to rock falls, multivariate analyses are relevant. To identify the triggering factor(s) of rock falls, multivariate analyses cannot define a hierarchy in a combination of agents; this requires an empirical analysis.

Multivariate statistical analyses

In order to answer our first question about marine and meteorological conditions conducive to rock falls, multivariate analyses were performed with the four selected external factors on two populations:

- a first population with 159 10-day periods with rock falls (331) and 109 10-day periods without rock falls was chosen to identify which external factor(s) can discriminate a 10-day period with and without any events. In other words, this is to understand the combination of agents and processes likely or not to trigger rock falls;
- a second population with only 10-day periods (159) with rock falls (331) in order to study precisely the rock falls and their characteristics as a function of the marine and meteorological conditions identified as conducive to rock falls. In other words, because there are only 10-day periods with rock falls, it is possible to identify relationships between combinations of factors and characteristics of rock falls (volume and area of departure).

In detail, the multivariate method used was divided into 3 steps from the rock fall inventory (Figure 7):

1) a PCA was performed to visualize the relationships between the variables and the existence of groups of individuals and groups of variables. This structure highlights the agents *a priori* most relevant to sum up meteorological and marine conditions that

characterize individuals (10-day periods). It is also possible to observe the seasonal distribution of variables and individuals;

2) the second step was a Hierarchical Cluster Analysis (HCA). Using the previous results of the PCA, the variables of individuals (10-day periods) are their PCA coordinates on the first three axes. This step differentiates individuals (10-day periods) as a function of their meteorological and marine agents and thus creates a typology (types of meteorological and marine conditions leading to rock falls). This typology is then used to describe the mean characteristics of meteorological and marine conditions leading to rock falls (average analysis);

3) lastly, the third step was the integration of the geomorphological component of rock falls (volume and departure area) within the 10-day periods. It was performed by the χ^2 test (independence test, p-value coupled with α level of 5 %[1]) to check whether certain types of meteorological and marine conditions preferentially generate many rock falls. By integrating the type to each rock fall (and no longer to 10-day periods), it is possible to know whether certain conditions trigger specific classes of rock fall volume ($V < 200$ m^3, 200 m$^3 \leq V \leq 1{,}400$ m^3, 1,400 m$^3 < V \leq 10{,}000$ m^3, $V > 10{,}000$ m^3) and/or a specific departure area (cliff foot, middle part of the cliff, cliff top, whole cliff face).

Empirical analysis

This exploratory statistical approach (PCA, HCA and χ^2 test) provided major elements of knowledge by identifying the meteorological and marine conditions conducive to rock falls but it was impossible to determine the triggering factors. Indeed, in multivariate analyses, each “factor” variable is represented by a single

[1] The risk of error is 5 % (α).

value that summarizes its behavior over the 10-day period. Thus, the detail of the factor's behavior on each day of the 10 days, which often informs about the triggering factor of the rock fall, remains hidden. To provide this information and answer our second question, we performed an empirical analysis (or human-supervised analysis) on 10-day periods with rock falls (159 cases).

In many fields, such as environmental studies, the use of empirical statements is common and recognized (e.g. in the courts). Empirical methods and the experience of practitioners often yield excellent results in the studies of fluvial geomorphology, ecology, hydrology, and natural hazards. We believe that when statistical studies reach their limits (often due to the nature of the data and the assumptions they imply), experience, observation, common sense and intuition remain valid assessment instruments. Moreover, many statistical methods and spatial analyses need to be human-supervised.

This empirical analysis (a subjective method of ranking variables) was based on the study of the daily values of sub-aerial and marine factors for each rock fall during 10-day periods in order to identify the triggering factor (most active in frequency or intensity) (Figure 8). After this human-supervised analysis, it was possible to identify rock fall characteristics (volume, departure area) preferentially induced by respective factors.

Results

Multivariate statistical analyses

PCA, HCA and χ^2 test for 10-day periods with and without rock falls (first population)

The first analysis focuses on the structure of meteorological and marine conditions (with the four variables mentioned above) over 10-day periods with rock falls (active

individuals in PCA) and without rock falls (supplementary individuals in PCA) (a total of 268 10-day periods) (Figure 9).

For this population, axes F1 and F2 of the PCA represent 66 % of the total inertia (and 86 % with F3). The highest variable contribution on F1 (35 % of the total information) is the wind (52 % contribution), which opposes temperatures (contribution up to 30 %). Thus, the first axis characterizes wind and temperatures, where negative values represent calm wind and “warm” weather and the inverse for positive values. On the F2 axis (31 % of the total inertia), the tidal coefficient and effective rainfall are the most influential (37 % and 35 %, respectively) and evolve in the same direction. Thus, positive values of the F2 axis mean spring tide and rainy weather (Figure 9). On the F3 axis (21 %), the tidal coefficient and rainfall are located in opposite directions. Due to this distribution on the PCA, the diversity between 10-day periods seems to be explained; first, by wind and temperature and secondly, by rainfall and tidal coefficient.

Furthermore, the distribution of 10-day periods with rock falls is on either side of the variables. Therefore, the triggering of rock falls seems to be more the result of a combination of marine and sub-aerial factors than a single factor and occurs in many combinations (Figure 9). Regarding the temporal distribution between 10-day periods with and without rock falls, seasonality appears. Unsurprisingly, winter (rainy and “cold” weather) is the most favorable season for 10-day periods with rock falls while summer (low wind and “warm” temperatures) is the most favorable season for those without rock falls (Figure 9). Another result provided by the PCA is that “wind” and “temperature” factors differentiate 10-day periods with and without rock falls the most.

The HCA and average analyses (histograms in Figure 10) provide a typology of four classes of meteorological and marine conditions characterizing 10-day periods (in descending order of the number of rock falls) (Figure 10):

1) Type A is characterized by “cold” (temperature mean under 0°C (histogram at the top of Figure 10) thus including freeze/thaw cycles) and dry weather (147 rock falls, 45 % within 100 10-day periods);

2) Type B is characterized by “warm” weather and calm wind (64 rock falls or 19 % within 75 10-day periods);

3) Type C is characterized by high rainfall and high wind (generating swell) (63 rock falls, 19 % within 38 10-day periods);

4) Type D is characterized by spring tide and “warm” weather (the remaining 17 % within 55 10-day periods).

Lastly, the χ^2 test shows a statistically significant link between types of conditions and 10-day periods with and without rock falls (observed distance (13.0) higher than the critical level (7.8) with a p-value of 0.005, so less than α):

- Type C “high rainfall and high wind” (generating swell) has an over-representation of 10-day periods with rock falls (79 % of 10-day periods have rock falls, 21 % of the remaining 10-day periods do not have rock falls);
- Type B “warm weather and calm wind” (corresponding to summer weather) has an over-representation of 10-day periods without rock falls (52 %), so these are conditions conducive to cliff stability.

To go further in the analysis, a second χ^2 test was performed to measure independence between the number of rock falls (0, 1, 2 and more) and types of meteorological and marine conditions. There is a statistically significant link between

these variables (observed distance (18.3) higher than the critical level (12.6) with a p-value of 0.006, so less than α):

- Type C “high rainfall and high wind” has an over-representation of 10-day periods with a minimum of 2 rock falls (47 %, against 21 % for 0 rock fall and 32 % for 1 rock fall) whereas these are under-represented in Type B “warm weather and calm wind” (19 %).

To summarize, in the four types of meteorological and marine conditions identified as responsible (or not) for triggering rock falls, Type C (“high rainfall and high wind”) is the best rock fall trigger over a 10-day period, especially in frequency (2 rock falls or more) whereas Type B, characterized by “warm weather and calm wind”, is the least favorable for the occurrence of rock falls (but they might occur).

PCA, HCA and χ^2 test for 10-day periods only with rock falls (second population)

For this second population (159 10-day periods), relationships between the variables and the existence of groups of variables are the same as the previous PCA (because 10-day periods without rock falls in the PCA were supplementary individuals).

HCA identifies four types of meteorological and marine conditions for 10-day periods. It is interesting to note that, although “warm weather and calm wind” are identified with the first population as conditions not conducive to rock falls, a group of individuals (10-day periods with rock falls) is always present around these variables (in fourth position, with 56 rock falls within 33 10-day periods) (Figure 11). Thus, rock falls are possible in these summer conditions, when people may stay all day on the beach, near the cliff foot. A χ^2 test was performed on rock falls (no longer 10-day periods) to highlight whether some conditions trigger specific types of rock fall

(volume and departure area). The results are as follows (in descending order of number of rock falls, Figure 11):

1) Type 1 conditions are “cold” (with a mean temperature histogram under 0°C, so numerous freeze/thaw cycles) and dry weather (147 rock falls, 44 % within 65 10-day periods). For these conditions, the χ^2 test highlights that rock falls with volumes less than 200 m^3 are over-represented whereas rock falls with volumes greater than 10,000 m^3 are under-represented (49 % for $V < 200$ m^3, against 27 % for 200 $m^3 \leq V \leq 1{,}400$ m^3, 21 % for 1,400 $m^3 < V \leq 10{,}000$ m^3, 2 % for $V > 10{,}000$ m^3 and 1 % for unknown volume);

2) Type 2, characterized by high rainfall and high wind (70 rock falls or 21 % within 31 10-day periods), has an over-representation of rock falls with a departure area of the whole cliff face (56 % of cases, against 21 % for cliff foot, 13 % for foot and middle part of the cliff, 3 % for middle part of the cliff and 7 % for cliff top). This type of conditions has a high proportion of rock falls greater than 10,000 m^3 with 9 % of cases (whereas these massive rock falls represent only 5 % of the total number of rock falls in the ESTRAN inventory);

3) Type 3 is characterized by a spring tide and “warm” weather (57 rock falls, or 17 % within 30 10-day periods). This type has an over-representation of rock falls with a fallen volume between 1,400 and 10,000 m^3 (35 % of cases, against 32 % for $V < 200$ m^3, 24 % for 200 $m^3 \leq V \leq 1{,}400$ m^3, 9 % for $V > 10{,}000$ m^3);

4) Type 4, the rarest, is characterized by “warm” weather and calm wind conditions (the remaining 17 % within 33 10-day periods). This type has an over-representation of (1) cliff foot rock falls (45 % of cases, against 28 % for the whole cliff face, 23 % for foot and middle part of the cliff, 2 % for cliff top and 2 % for unknown volume), and (2) rock fall volume between 200 and 1,400 m^3 (45 % of cases, against 29 % for $V < 200$

m^3, 20 % for 1,400 $m^3 < V \leq 10{,}000$ m^3, 3 % $V > 10{,}000$ m^3 and 3 % for unknown volume).

Therefore, from this second population, we have complementary information about conditions likely to trigger rock falls. “Cold (freezing) and dry weather” conditions (Type 1) generate many rock falls, usually small in volume (less than 200 m^3) without a specific departure area. In contrast, “high wind and high rainfall” conditions (Type 2) are more conducive to massive rock falls (more than 10,000 m^3) from the whole cliff face. “Warm weather and calm wind” (Type 4) generate rock falls of modest size (200 to 1,400 m^3) mainly coming from the cliff foot. More surprisingly, “spring tide and warm weather” conditions (Type 3) seem to be responsible for large rock falls (from 1,400 to 10,000 m^3).

Empirical analysis

The empirical analysis confirms and adds to the multivariate analyses. With this subjective method of variable ranking, triggering factors are identified:

1) effective rainfall seems to be involved in 56 % of the number of rock falls and 72 % of the total fallen volume. Of these 185 rock falls probably due to rainfall, 79 cases come from the whole cliff face (43 %) and 34 % are between 200 and 1,400 m^3. As a proportion of the 331 rock falls in the inventory, the characteristics of the 185 rock falls triggered by rainfall are mostly: (1) between 200 and 1,400 m^3 or over 10,000 m^3 (64 % and 56 % of the ESTRAN database, respectively), (2) from the whole cliff face (59 %) (Figure 12);

2) freeze/thaw cycles seem to be involved in 19 % of the number of rock falls and 10 % of the fallen volume. These rock falls are mostly from the whole cliff face (22 cases, 34 %) or the cliff foot (16 cases, 25 %) and smaller than 200 m^3 (45 %).

However, as a proportion of the 331 rock falls in the database, the characteristics of rock falls triggered by freeze/thaw cycles are mainly: (1) smaller than 200 m^3 (23 % of the inventory), (2) from the cliff top (50 %) or cliff foot (16 %) (area where chalk is preferentially saturated in water by runoff or infiltration) (Figure 12);

3) the next factor is marine roughness, a combination of spring tide (coefficient more than or equal to 85[2]) and high wind (more than 8 m/s) that generates marine actions at the cliff foot, with 15 % of the number of rock falls and 9 % of the fallen volume. These rock falls are mostly from the whole cliff face (20 cases, 31 %) or unsurprisingly from cliff foot (17 cases, 27 %) and smaller than 200 m^3 (42 %). As a proportion of the 331 rock falls in the inventory, the characteristics of rock falls triggered by marine roughness are mainly: (1) smaller than 200 m^3 (17 %), (2) from the foot/middle part of the cliff (20 %) or the foot cliff (17 %) (Figure 12). This factor needs complementary studies, as its influence is difficult to quantify due to rock falls of small volume being quickly removed during a turbulent marine period (and that could be missed by the ESTRAN organization).

Nevertheless, these identified triggering factors rarely act alone. Only 49 rock falls (15 %) seem to be triggered by a single factor. These few cases occurred with only one predominant parameter (while other marine and sub-aerial factors were of low frequency or intensity). The vast majority of rock falls is due to a combination of the triggering factors mentioned above (very common in mid-latitudes). This is the case during unsettled weather (rainfall, marine roughness), which occurs approximately 2/3 of the year along the Normandy coast (sometimes with freeze/thaw cycles). Consequently, it is more appropriate to identify three types of weather leading to the triggering of rock falls: periods of high effective rainfall over a 10-day period, periods

[2] With this value of 85, we are sure that the tide affects the foot of the cliff along the coastline studied.

of freeze/thaw cycles, types of weather characterized by atmospheric disturbance involving heavy rainfall and high wind (thus high waves).

Discussion

The ESTRAN database is unique and significant because of the weekly frequency of surveys (which track small and large rock falls), the precise dating of rock falls, the length of the coastline surveyed (37.5 km) and the duration of 7 years. There are other inventories of this coastal section (e.g. Duperret et al., 2004; Dewez et al., 2013) but a comparison of results is difficult. Their spatial and temporal representativeness are limited. For example, the inventory of Dewez et al. (2013) was carried out on 750 m and for 2.5 years. Dating of rock falls remains limited: of the order of the month to the season for Duperret et al. (2004). However, the types of favorable conditions for triggering rock falls can sometimes tend towards the same conclusions for massive rock falls, which are often linked to specific meteorological conditions. For example, Duperret et al. (2004) show two types of triggering meteorological conditions: heavy rainfall and sudden rainfall during dry periods. However, these authors point out that their results are questionable because of the small number of cases (55 including only 4 precisely dated).

This participation in the scientific debate about determining the factors and processes likely to trigger rock falls is based on an exploratory statistical approach and an empirical analysis. These two methods are complementary. Whereas the statistical one provides the types of combination of meteorological and marine factors conducive or not to rock falls, the empirical one determines the triggering factor for each rock fall. Each of these approaches gives information about the modalities of retreat (rock fall departure area and volume). The statistical analyses underline that

“cold and dry weather” and “high rainfall and high wind” are the best conditions for triggering rock falls. The empirical analysis identifies effective rainfall as the most important triggering factor. It seems to generate the majority of both rock falls (56 %) and fallen volume (72 %). It is followed by freeze/thaw cycles and marine roughness. However, this subjective ranking of the triggering factors should be weighted in terms of the frequency of their occurrence per year. Whereas rainfall occurs about 130 days a year, freeze/thaw cycles are much less frequent: about 26 times a year over the seven years observed (with 183 registered cases). Based on these results, freeze/thaw cycles seem to be more “efficient” than rainfall, because when they occur, rock falls are nearly always observed.

Contrary to what is often stated in the scientific literature, marine roughness does not appear to be only a transport and debris removal agent. This is the third factor explaining the triggering of rock falls. Unsurprisingly, marine roughness seems particularly effective at the cliff base, involving rock falls of small volume (but can cause mass movements affecting the whole cliff face). This result is consistent with fine quantitative results obtained by terrestrial laser surveys carried out along this coastline (Letortu et al., in press, accepted).

However, in many cases, the triggering of rock falls seems to be the result of a combination of factors. The most common combination (56 rock falls out of 331) is marine roughness (linked to wind speed and during spring high tide) and high effective rainfall (instantaneous or cumulative). This corresponds to the very common types of disturbed weather in mid-latitudes, which dominate for approximately 2/3 of the year. Low pressure with two fronts crosses the English Channel and generates high rainfall in Normandy and a marine roughness conducive to triggering rock falls. If this type of weather is followed by a period of freeze/thaw cycles, cliff weathering and

cliff retreat will reach their peak. However, is this due to the inaccuracy of the rock fall dating (often around a 10-day period)? To go beyond this limit, we collected 74 correctly-dated rock falls from the local press and carried out the statistical and empirical analyses. Even if rock fall is dated to the day, the process of identifying the triggering factor(s) remains complex. High rainfall plays a role but is also combined with the other factors.

This work confirms that identifying triggering factors is complex because the evolution of environments is not linear and not limited to direct causal relationships. The “purge” effect, relays or combinations of processes and/or hysteresis phenomena (which we tried to integrate by using a mobile 10-day period) complicate the analysis of relationships. In addition, cliffs inherit past environmental changes (Trenhaile, 2002) i.e. they are influenced by the size and location of previous rock falls (the “purge” effect). The purge effect means that a cliff face has been recently affected by a fall, called here a “purge”. The cliff face is “new”, so it must not be affected by another fall soon because it has to be “prepared” by preparatory processes for a certain time to be ready to fall. So, cliff retreat is a process with a “memory” (Lee et al., 2001). Whatever our understanding of current processes and their impacts, the evolution of the cliff is partially based on the long-term degradation of the rock (Griggs and Trenhaile, 1994; Swenson et al., 2006; Lim et al., 2011).

Moreover, the dichotomy between weathering factors and triggering ones is not always obvious. This determination is complex because the relationships between the factors are non-linear. Several reasons may explain this:

1) the transition state between weathering and triggering factors can be inappropriate for common statistical methods (e.g. the presence of discretized data). It could be

more relevant to study these factors using fuzzy logic. This is why we tried to incorporate temporal flexibility by working over mobile 10-day periods;

2) the triggering factor may be random. If the material is ready to fall, any factors, whatever their intensity, are likely to generate a rock fall;

3) conversely, the factors identified as triggering (under certain conditions) may occur without generating any departures of material due to a previous “purge” effect. The material expected to fall is already on the ground. In other words, factors that can be triggering are repeated but with no rock falls. They participate, like others, in lowering the stability margin of the cliff to a critical value. In this case, the agents and processes are just preparatory.

There is also the question of the time required to determine the triggering factors. Is the 10-day period sufficient? Should the analysis period be increased when meteorological and marine conditions are not dynamic in the 9 days preceding the rock fall? This is the case of the collapse of 08/26/2001 (correctly-dated rock fall from the local press) where no increase in the intensity or frequency of triggering agents occurred (*a priori*) during the 10-day period, while on 08/02/2001 rainfall greater than 26 mm was recorded. Are these phenomena related? Are there other explanatory factors (e.g. micro-earthquakes), processes such as hydroclasty, or decaying? Are there hysteresis phenomena over intervals of several weeks? Lengthening the observation period of agents and processes responsible for triggering rock falls would make determining the contribution of each factor more complex, because of their multiple occurrences over this longer time period.

This statistical approach and the empirical one are based on the analysis of external conditions, but it is also essential to take internal factors into account (rock mechanics, micro- and macro-cracking). Whereas, at first sight, the Upper Normandy

coastal chalk cliffs appear homogeneous in lithology, on a fine scale there are many differences (Mortimore et al., 2004; Lasseur, 2007). These limitations of this work must be taken into account in future developments to improve our results. For example, it would be interesting to focus on a type of chalk lithology (e.g. Santonian stage) with a specific departure area of rock falls. This will become possible when the database has been enriched with new inventory years. Furthermore, data of meteorological and marine parameters need to be on a finer temporal and spatial scale. Thus, determining the agents and processes responsible for triggering rock falls remains difficult due to the limited number of cases observed (especially precisely dated) and a lack of knowledge of the internal parameters in chalk cliffs and of meteorological and marine parameters on fine temporal and spatial scales.

Conclusions

The originality of this paper is the analysis of a large inventory of 331 rock falls (date, geomorphological features) in Upper Normandy using multivariate statistical analyses (PCA, HCA) and empirical analysis. The results, deduced directly from these analyses, highlight innovative information about the conditions leading to rock falls and triggering factors:

1) the frequency of rock falls is linked to meteorological and marine conditions: unsurprisingly, high rainfall and high wind (winter weather with marine roughness) are the most favorable conditions for 10-day periods with many rock falls (2 or more) while warm weather and calm wind (summer weather) are the most favorable conditions for 10-day periods without rock falls (but rock falls might occur).

2) the volume of rock falls depends on triggering factors: freeze/thaw cycles are mainly responsible for debris falls (volume less than 200 m^3) whereas high rainfall

triggers preferentially more massive rock falls (between 200 and 1,400 m^3 or more than 10,000 m^3). Marine roughness seems to trigger rock falls of small volume (less than 200 m^3) in particular.

3) the cliff face location of rock falls is due to triggering factors: high rainfall mainly triggers rock falls coming from the whole cliff face while freeze/thaw cycles trigger rock falls coming from the top and foot of the cliff face. Unsurprisingly, marine roughness seems particularly effective at the cliff base.

Some difficulties remain in quantifying the proportion of marine and sub-aerial factors because of problems of combinations of factors (very common in mid-latitudes) or the relay of factors (85 % of 331 cases) and probably hysteresis phenomena. In view of these various findings, it is still presumptuous to predict the location and time of triggering of rock falls. However, the approaches adopted (statistical and naturalistic) and the observations made in this study are from an original inventory, and constitute a real starting point for the prediction and prevention of the hazard of rock falls in Upper Normandy.

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Dieppe (1971-2000)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Maximum temperatures (°C)	7.2	7.7	9.9	11.5	14.9	17.2	19.5	20.3	18.5	15.2	10.7	8.2	13.4
Mean temperatures (°C)	4.9	5.0	7.0	8.5	11.8	14.2	16.4	16.9	15.0	12.0	8.1	5.9	10.5
Minimum temperatures (°C)	2.5	2.3	4.1	5.4	8.6	11.3	13.4	13.5	11.5	8.8	5.5	3.6	7.5
Mean number of days with minimum temperatures <= 0°C	7.7	8.3	3.8	1.3	-	-	-	-	-	0.3	3.4	7	31.8
Mean number of days with minimum temperatures <= -5°C	2.2	1.4	0.3	-	-	-	-	-	-	-	0.2	0.8	4.9
Mean number of days with minimum temperatures <= -10°C	0.4	0.2	-	-	-	-	-	-	-	-		0.0	0.6
Maximum daily height of rainfall	29.5	38.5	32.0	27.0	52.5	40.6	58.5	100.8	56.1	77.5	46.1	42.0	-
Height of rainfall (mean in mm)	64.0	51.8	57.6	56.7	59.2	58.6	53.3	50.6	80.4	90.8	93.8	87.4	-
Mean number of days with rainfall >= 1 mm	11.7	9.9	11.9	10.3	10.3	9.6	8.3	8.5	10.8	11.4	13.8	13.2	129.6
Mean number of days with rainfall >= 5 mm	4.6	3.5	3.8	4.2	4.1	4.0	3.1	3.5	5.6	5.8	6.8	6.3	55.3
Mean number of days with rainfall >= 10 mm	1.7	1.1	1.1	1.3	1.5	1.5	1.6	1.2	2.5	2.9	3.4	2.8	22.5
Mean number of days with gust >= 16 m/s	13.6	10.4	11.3	9.0	6.7	5.6	5.1	-	7.9	10.5	10.9	11.8	102.8
Mean number of days with gust >= 28 m/s	1.2	1.4	0.7	0.3	0.1	-	0.2	-	0.2	0.7	0.5	1.4	6.7

Source of data: Meteo-France

Table I: Meteorological data in Dieppe (Meteo-France, 1971-2000)

Rock fall date	Rock fall number	Town	Coordinate x (RGF93-L93)	Coordinate y (RGF93-L93)	Volume (m^3)	Departure area of rock fall
02/06/02	1	Varengeville	556,948	6,981,584	1,372	cliff foot
02/18/02	2	Varengeville	554,542	6,981,917	942	whole cliff face
02/18/02	3	Varengeville	554,661	6,981,894	20,100	whole cliff face
02/23/02	4	Dieppe	559,928	6,982,139	92	whole cliff face
03/04/02	5	Sainte-Marguerite	553,865	6,981,975	92	whole cliff face
03/04/02	6	Sainte-Marguerite	554,030	6,981,961	976	whole cliff face
03/25/02	7	Varengeville	555,028	6,981,826	1,508	whole cliff face
⋮	⋮	⋮	⋮	⋮	⋮	⋮
12/14/09	325	Varengeville	555,344	6,981,751	93	cliff foot
12/22/09	326	Sainte-Marguerite	553,626	6,982,019	202	whole cliff face
12/22/09	327	Sainte-Marguerite	553,683	6,982,013	1,581	whole cliff face
12/22/09	328	Varengeville	554,798	6,981,867	448	whole cliff face
12/22/09	329	Varengeville	555,137	6,981,789	478	whole cliff face
12/22/09	330	Varengeville	555,157	6,981,785	259	cliff foot
12/23/09	331	Dieppe	563,951	6,983,619	31	cliff foot

Table II: Extract of enriched inventory (volume, departure area of rock fall) used for the next analyses

Figure 1: Presentation of the studied area (from Veules-les-Roses to Le Treport) showing a cross-section with lithostratigraphy

Figure 2: Example of a rock fall (then a slide of tertiary strata) on the west side of Dieppe that threatens urbanization (18/12/2012, *Les informations Dieppoises*)

Figure 3: Rock fall inventory (A: index card made by the ESTRAN organization for rock fall n°123; B: spatial distribution of rock falls; C: temporal distribution of rock falls)

Figure 4: Rock fall distribution (number and frequency) as a function of volume (A: total distribution of the number of rock falls as a function of fallen volume; B: thresholds observed to distinguish classes of volume as a function of rock fall frequency)

Figure 5: Descriptive statistics of variables “factor” and “rock fall” over a 10-day period

Figure 6: Bivariate regression between minimal temperatures and median fallen volume over a 10-day period

Figure 7: Method of multivariate statistical analyses (with 3 steps)

Figure 8: Method of empirical analysis with the example of the rock fall of 02/08/02

Figure 9: PCA for 10-day periods with and without rock falls (distribution of variables in insert) and seasonal distribution

Figure 10: Results of the typology (4 types deduced by the HCA) and their meteorological and marine conditions per type (average analysis with histograms on the right), superimposed on the PCA (previously performed on the 268 10-day periods with and without rock falls)

Figure 11: Results of the typology (4 types deduced by the HCA) and their meteorological and marine conditions per type (average analysis with histograms on

the right), superimposed on the PCA (previously performed on the 159 10-day periods with rock falls)

Figure 12: Results from the empirical analysis with the first three triggering factors (histograms of number of rock falls, sector diagrams of distribution of rock falls per class of volume, and geomorphological specificities of rock fall per triggering factor)