CLIFF COLLAPSE HAZARDS SPATIO-TEMPORAL MODELLING THROUGH GIS : FROM PARAMETERS DETERMINATION TO MULTI-SCALE APPROACH

Anne DUPERRET
EA 2255 LMPG
Université du Havre,
25 rue Philippe Lebon, BP540
76 058 Le Havre cedex, France
anne.duperret@univ-lehavre.fr

Cyrille BERTELLE
EA 4051 LITIS
Université du Havre
25 rue Philippe Lebon, BP540
76 058 Le Havre cedex, France
cyrille.bertelle@univ-lehavre.fr

Pierre LAVILLE
BRGM
Maison de la Géologie
77 rue Claude Bernard
75 005 Paris, France
p.laville@brgm.fr

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ABSTRACT

In this paper, we study the cliff collapses, using observations and in situ measures, along 120 km of the french chalk coastline in Upper-Normandy and Picardy. Cliff collapses occur inconsistently in time and space, in unpredictable way. A european scientific project ROCC (Risk Of Cliff Collapse) has been launched (1999-2002) in order to identify the critical parameters involved, to evaluate their impact and their interaction in mass movements. Cliff collapse process appears as a complex natural system, due to the large amount of parameters able to lead to a collapse. GIS approach has been used to allow an homogeneous cartography of each parameter reported on one layer each one, along a large surface of 120 km long coastline. The computation is decomposed in different steps which consist from the qualitative factors, to quantify them and to normalize them in space. On the basis of field measurements and data analysis, four types of geological information have been added to the GIS model and a first computation of hazard modelling has been proposed to design a collapse hazard sensitivity map, based on a elementary summation of the parameters. We now prospect to introduce a ruled-based systems, dealing with the complexity of the interaction of the local parameters. An interaction network must be defined to represent the spatial and semantic links between local parameters.

1. GEOLOGICAL CONTEXT

Coastal chalk cliffs exposures along each part of the English Channel are composed of nearly vertical cliffs ranging from 20 to 100 m high, with a less or more thin cover of clays-with-flints and a chalk shore platform with a low angle of slope, often covered with sand and/or shingles. The shore platform is made of eroded chalk and is subjected to a semi-diurnal cycle of macrotides, whereas the cliff rocks are submitted to fresh groundwater that infiltrate within the chalk through rainfall (Figure 1).
Coastal chalk cliffs exposed on each part of the English Channel suffer numerous collapses, with mean volumes varying between 10 000 and 100 000 cubic meters per event. Between October 1998 and October 2001, a minimum of 52 collapses have been observed along 120 km of the French chalk coastline located in Upper-Normandy and Picardy, with 28 collapses with volumes greater than 1000 cubic meters. Such collapses occurs inconsistently in time and space and appears to be relatively unpredictable. Little work has been devoted to the analysis of processes responsible for the collapses of the chalk seacliffs, and this led to the European scientific project, ROCC (Risk Of Cliff Collapse) because of the growing hazard to local communities from chalk cliff retreat. The main goal of the ROCC project was to identify the critical parameters leading to chalk coastal cliff collapses, and to evaluate the impact of those parameters and their interaction in such rock mass movements. The main objective was to create maps showing the sensibility of cliffs to erosion (cliff collapse hazard) along the 120 km coastline.

2. CLIFF COLLAPSE PROCESS

The evolution of a cliff from stability toward failure, depends on changes present in the rock mass (lithology, fracture pattern), and processes acting within the rock mass (degree of water saturation, water movement) caused by external agencies of subaerial and marine origin. External agencies lead to :

- the development and opening of fractures (resulting from stress relief, fatigue, wetting and drying, freeze-thaw action),
- the deterioration of the rock material as a result of infiltration of water (resulting in solution, chemical alteration, physical breakdown through freeze-thaw or salt crystallisation),
- substantial geometric changes at the cliff foot (height of shingles and debris accumulation).

The rock mass characteristics such as chalk type, fracture pattern and karstic development may be consider as fixed parameters, only varying in space. Variable parameters such as water saturation of the chalk and water movement in the chalk through fractures and karstic system are closely linked to external agencies, with various delays. External agencies are varying in space and time, with various fitting scales. It is the case of climatological parameters, such as rainfall and temperature (with temporal variations from hours, days, seasons, years and decade) and oceanographic parameters with temporal variations from day to season (for tides and wave action), and variations from year to decade (for sea level variation due to global change).

3. GIS APPROACH

Cliff collapse process appears as a complex natural system, due to the large amount of parameters able to lead to a collapse. GIS approach has been used to allow an homogeneous cartography of each parameter reported on one layer each one, along a large surface of 120 km long. GIS has been also used to perform various combinations between each parameters to obtain various degrees of hazard.
The coastline location has been identified on the IGN topographic cartography basis at 1/25 000 (MNT IGN©1992, as a raster). Each GIS layer is dedicated to one parameter. The most simplified method to attribute a level to each parameter is to evaluate the minimal and maximal value of the parameter within a fixed geographic framework. The operator attribute the level zero for the minimal value and the value 100 for the maximal value. Then, each parameter (with various original units) may be reported on a layer with percents as a value of the parameter intensity ; moreover parameters may be combined easily together on the same geographic framework. The report of each parameter has been realised on a coastal strip located at the top of the cliff (drawn from a 50 m wide dilatation each part from the coastline). For each parameter, various strip sections (polygons) are defined as a function of the parameter value.
The GIS framework is usefull for the spatial correlations of various parameters and to combine several models to represent an hazard level.

4. PARAMETERS DEFINITIONS

Georeferenced data produced by IGN have been used to build the GIS basis through Mapinfo® software. The various layers of the GIS are composed of parameters all varying in space, but non-variable or variable in time. Non-variable parameters in time are the geographic information (coastline location, cliff height) and the geologic information (chalk lithostratigraphic succession, fracturation). Variable parameters in time are the hydrogeologic and the oceanographic informations. Unfortunatly, oceanographic parameters have not been considered in this study. The cliff collapses occurrence results from the intercation of all these parameters, but we may consider that the observed location of past cliff collapses is a non variable parameter in time.

4.1 Coastline location and cliff height

One layer is dedicated to the spatial location of the coastline (precisely defined at the top of the cliff) to build a 100 m wide strip.
A second layer is dedicated to the cliff altitude and has been used to select various height sections (as polygons) within the strip, with 10 m intervals, varying from 5 to 100m height. These layers have been deduced from the 1/25 000ème IGN topographic map (not shown in this study).

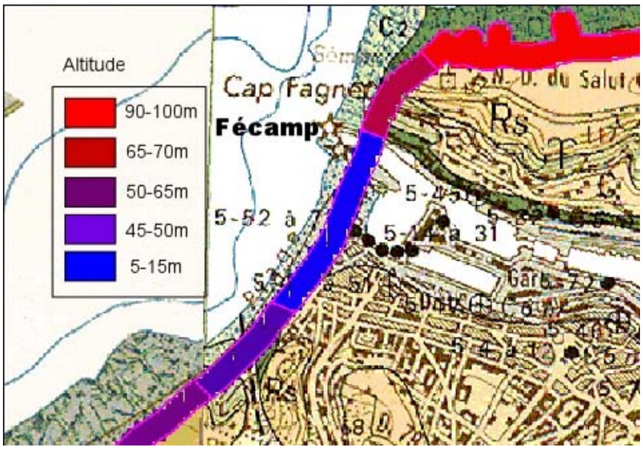


Figure 1 : Geological map (© BRGM) as raster around Fécamp and the strip indicative of the cliff altitude

4.2 Past cliff collapses occurrence

During the ROCC project, regular field surveys performed during october 1998 and december 2001 allowed to report a minimal value of cliff collapses. For each reported collapse, the location and date of occurrence were reported and the volume of the deposit were measured (Duperret et al., 2004). Such data have been reported on a layer in the GIS, as recent collapses parameter.

4.3 Chalk lithostratigraphy

As defined in UK (Mortimore, 1983), chalk type units are defined on the basis of a lithostratigraphic concept and are more representative of the geotechnical properties of the chalk than the stratigraphic scale traditionaly used in France (Mortimore, 2001 ; Duperret et al., 2004).
The Chalk lithostratigraphy layer is composed of six chalk units of various characteristics detailed below :

(1) Cenomanian craie de rouen is a nodular chalk with numerous flint bands in Upper-Normandy. Unit (1a) is defined between Antifer and Fécamp headlands, (1b) is defined north of Fécamp and (1c) south of Antifer.
(2) the Holywell nodular chalk is a nodular and massive chalk, with few flint bands, which contains many flaser marls and abundant Mytiloides shell debris layers, with open crossed fractures north of Fécamp (2a) and closed crossed fractures southward (2b)
(3) the New Pit chalk formation contains numerous flint bands in cliffs south of Fécamp (3a) but is flintless northwards at St Martin-plage, north of Fécamp (3b),
(4) The Lewes Nodular Chalk is a yellowish coarse chalk, including soft, marly bands and nodular hardgrounds, with regular flint layers. The Lewes Nodular Chalk formation contains dolomitic layers to the south of Fécamp (4a) which are absent northward (4b),
(5) The Seaford Chalk Formation is a homogeneous white chalk with conspicuous bands of large flints, with large collapses, north of Fécamp (5a) and small collapses southward (5b)
(6) The Newhaven Chalk Formation is a marly chalk with numerous marl seams and regular but few flint bands.

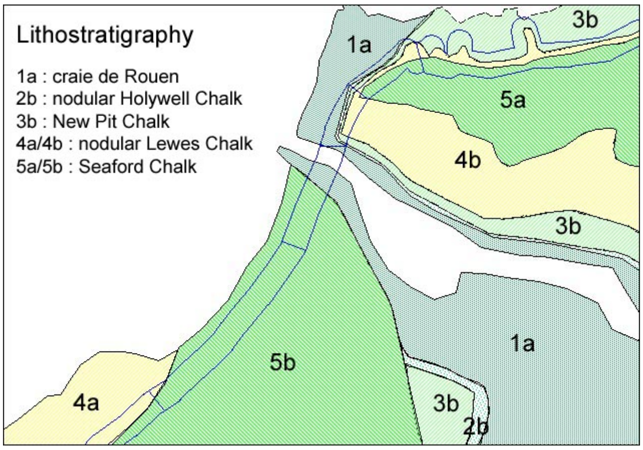


Figure 2 : chalk lithostratigraphy map, around Fécamp.

Chalk rocks present various degrees of physical properties, particularly density and porosity. The standart strength categories used to describe rocks for engineering purposes could not be applied readily to chalk, due to the variations in physical properties even within a single block of intact chalk.

Even if each chalk unit is well defined, a direct comparison of each chalk units is not realistic. Moreover, some types of chalk retain water at saturation level while others gain and lose water more readily, changing drastically their physical properties.

The lithostratigraphic indice has thus been determined by a direct correlation between each vertical lithological succession on the cliff face and the estimated volumetric mass able to collapse. Each chalk unit formation overlay an older one. On the cliff face, various chalk successions may appears, depending on the height of the cliff and the thickness of each chalk units (Fig. 3). From field works, chalk units succession have been recognized on the cliff face outcrops, conducting to the definition of twenty four vertical successions of chalk units (Mortimore, 2001, Duperret et al., 2004).

As examples : five chalk units outcrop on a vertical section at Fécamp (1a/2b/3b/5b/5a) whereas one chalk unit outcrops at Dieppe (6). Cliff collapses volumes have been estimated for each event observed in the field in France and UK. The involved volumes are varying from 1 to 100 000 m^3 (Mortimore et al., 2004). Seven volumic classes have been defined and each volumic class has been attributed to the corresponding lithostratigraphic sequence. On the basis of involved volumes during a collapse, a percent scale has been established for each lithostratigraphic sequence. The maximum influence has been established for the sequence 1a/2b/3b/4b/5a (at Fécamp) and sequence 4b/5a (100%), with collapses of mean volumes reaching 55 000m^3 and the minimum influence is established for the sequence 1b/2b (0%), with no reported collapse. The six other intermediates classes are based on a logarithmic scale and defined at 99%, 84%, 78%, 58%, 42% and 35%, with involved collapsed mean volumes of 50 000 m^3, 10 000 m^3, 5000 m^3, 500 m^3 and 100 m^3, 50 m^3 respectively.

4.4 Fracturation

On the basis of the observations in the field, a preliminary hypothesis was suggested that fractures embedded within the chalk cliffs could influence cliff collapse. About 2000 fracture orientation measurements were collected on 34 investigations sites regularly spaced along the 120 km long coastline. Fracture analysis were completed and homogenised on a systematic analysis of the cliff face from a continuous set of oblic aerial photography of the cliff face, realised in 1986. The correlation between field data and continuous aerial photography acquisition has been used to define two major layers dedicated to fracture occurrence (Genter et al., 2004).

i) Transverse fracturation indice

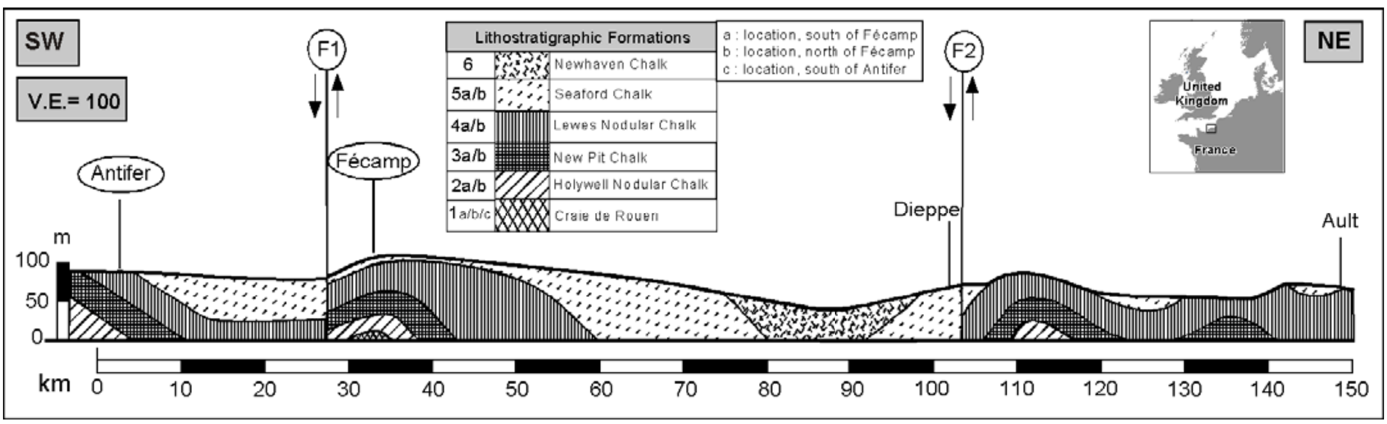
The total number of fractures that appear on the cliff face represents in fact the number of transverse fractures to the cliff face. From this numbering, various sections of fracture density have been defined. The total number of fractures reported on a complete area of the cliff face vary from zero to 396 per square meter, which is equivalent to a scale of fracture density varying from zero to 0.17 and a mean space between fractures varying from zero to 95.5. An indice of transverse fractures has been calculated from these data, varying from zero to 100% and has been used to define 63 sections of various length on the strip, with various degrees of transverse fracturation.

ii) Parallel fracturation indice

A second layer has been dedicated to fracture data parallel to the cliff face. Such data have been detected on aerial photographs on the naked beach platform, where fractures set

appears easily. Calculations have been realised on a density fracturation scale with four levelsreported in percent in the GIS.

Figure 3 : vertical cross section of the various chalk lithostratigraphic sequence on the cliff face



4.5 Hydrogeology

Experiments on chalk rocks show that hydration produces a marked decrease of the chalk strength, which varies depending on the chalk type. When chalk samples are submitted to a progressive water wetting, a fall of strength occurs. The decrease of the UCS strength is between 20 and 50% of the dry strength of chalk and this reduction begins with very low values of water content within the chalk (Duperret et al., 2005). Chalk rocks formations are said to exhibit a dual porosity/permeability. In a classic dual-porosity aquifer the matrix pores provide storage and fissures provide the permeable pathways for flow. At large scale, the chalk aquifer presents a behaviour of a porous system, with low flow and at small scale, the chalk aquifer presents a behaviour of fissural system with high flows.

At large scale, the water content of the chalk varies with fluctuations of groundwater level, submitted to rainfall inputs. The magnitude of the water table fluctuations in Upper Normandy is generally inversely proportional to the degree of fissuring (i.e. low permeability areas with less fractures have high water table fluctuations) (Crampon et al., 1993). Hydrogeology data have been summarized on three layers in the GIS (Caudron et al., 2001).

i) Water table level

Data have been deduced from the hydrogeological map at 1/100 000 edited by BRGM. Original data was compiled from various available piezometric data in upper eptembe, that were acquired at various step of space and time. Even if this information is unprecise, it is able to give some interesting trends concerning the water table location in depth. Four classes of water table have been defined as a function of chalk imbibition thickness near the coastline : (0) zero for suspended valleys, (1) low imbibition thickness (lower than 5 m), (2) moderate imbibition thickness (around 10 m), (3) high imbibition thickness (higher than 10 m), (4) very high imbibition thickness (coastal area covered by impervious tertiary cover). The water table indice is ranging from 2.5 to 100 %, with the lowest water table effect for the class (1) and the highest water table effect for the class (4).

ii) Coastal piezometric slope

Like water table layer, the coastal piezometric slope has been directly deduced from the hydrogeological map at 1/100 000. The degree of coastal piezometric slope gives an indication of the hydric flow, from the aquifer to the coastline. Five classes have been defined, with a piezometric slope ranging from 0, lower than 5 $‰_{o,}$ between 5 and 10 $‰_o$, between 10 and 20 $‰_o$, between 20 and 40 $‰_o$, and higher than 40 $‰_o$. The higher the slope is, the higher hydric flow is, the higher the influence to collapse is.

iii) Coastal springs occurrence

Coastal springs locations reveal mainly the occurrence of fissural and/or karstic system in the chalk. These data have been collected in the field during eptember-october 1999 (fall 1999). Three classes have been defined depending of the springs flow and the spring density on a coastal section : (1) no coastal springs or coastal springs with low flow (lower than 10 l/s) and low linear density, (2) coastal springs with low flow (lower than 10 l/s) and high linear density or coastal springs with mean flow (between 10 and 100 l/s) and low linear density, (3) coastal springs with mean flow (between 10 and 100 l/s) or coastal springs with high flow (higher than 100 l/s). As a first approximation, the higher the flow and density are, the higher the karstic system is developed, and the higher the fissural flow transit is.

5. HAZARD MODELLING

5.1 Arithmetic combination

Based on the GIS model, a first computation of hazard modelling is proposed. The goal is to design a collapse hazard sensitivity map. The computation is decomposed in different steps which consist from the qualitative factors, to quantify them and to normalize them in space. The computation is based on a elementary summation of the parameters. The resulting sum in each coastal strip must be considered as a potential level of low to high degree of collapse hazard, based on a percent deduced from all parameters. A part of the resulting GIS is presented in the figure 4. Nevertheless, a confrontation with models and observations needs to be performed to introduce weighting in association with the pertinent parameters.

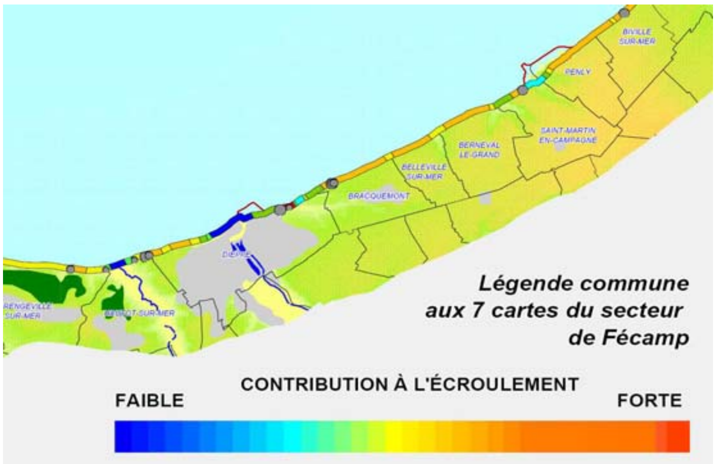


Figure 4 : Detail of the hazard sensitivity map deduced from arithmetic combination between each parameters

5.2 Multi-scale rule-based qualitative system

We now prospect to introduce a ruled-based systems, dealing with the complexity of the interaction of the local parameters. A process modeling allows to describe the alea estimation from complex interaction between geological structure, external agencies and hydrodynamic phenomena. The process modeling is described on Figure 5 where transitions are activate by physical qualitative modeling rules (Kuipers, 1986). During some specific external agencies (rainfall, temperature, ...), some links will be activated and dynamically propagate the phenomenon through the rules-based process which finally give in/output of the cliff collapse hazard. The resulting collapse hazard can be considered as a kind of emergent computation. This process concerns a local description and the multi-scale approach consists to change the level of description and to represent each local process as a compartment. The compartments are linked by spatial transfers that correspond to pressure variation and water displacement along the fracture network as represented by the figure 5. The implementation of the whole method is in progress.

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ANNE DUPERRET is maitre de conférences in earth sciences at Le Havre University since 10 years. She is working on coastal erosion processes. She has a large experience on coastal chalk cliff instabilities, due to field works in collaboration with French Geological Survey (BRGM) and Brighton University (UK) on coastal chalk cliffs from France and United Kingdom.

CYRILLE BERTELLE is professor in computer science in Le Havre University and develops research activities in complex systems modeling. His current activities concerns self-organization processes formalization within various applications: ecosystems and natural systems, decision making modeling based on GIS models, emotional modeling for decision making. He is one of the co-directors of a research laboratories amalgamation which promotes the Sciences and Technologies in Information and Communication over the Haute-Normandie in France.

PIERRE LAVILLE is geologist at BRGM (French Geological Survey). He has been director of the regional geologic survey at Reims and is now responsible of the professionnal learning, the use and the management of BRGM geological database at Paris. He is a specialist of GIS system dedicated to earth sciences problems.

Figure 5 : conceptuel process modelling by multi-scale rule-based qualitative system