Study of the influence of anthropogenic galleries on the chalk cliff stability at Normandy region (France)

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ABSTRACT: The chalk cliffs are regularly subject to mass collapse phenomena in Normandy region (France). These instabilities represent some problems to manage for local authorities. In some cases, the chalk cliffs contain one or more galleries of anthropogenic origin and hazard assessment should integrate these particular contexts. Numerical modelling was developed in 2022 in order to quantify the influence of galleries on cliff's stability. We studied the behavior of the {cliff + gallery} set according to parameters as the dimensions of galleries, their direction in comparison to the cliff direction (parallel or perpendicular), the superposition of exploited levels, the rock mass discontinuities, the mechanical properties of the overburden layers, etc. A scoring method is presented based on attribution of scores to the main parameters to determine the gallery influence on cliff's stability.

Keywords: Chalk, Cliff, gallery, stability, fracture, collapse, numerical model, distinct element method, plastic, mechanic, scoring.

1 INTRODUCTION

The existing chalk cliffs in Normandy (France) are regularly subject to local instabilities or major collapses. Generally, in a regulatory or decision support framework, the cliff stability is studied on the basis of proven methods described in methodological guides. These guides are supervised and produced by competent scientific institutions, at the request of the French administration (see Cerema & Ineris 2022). Among the sites regularly threatened by stability problems, some have particular configurations, notably the presence of man-made galleries, making their stability study often more complex (see Figure 1).

Currently, cliffs with galleries are often studied by separating the cliff stability diagnosis from the galleries. In practice, the design engineer takes into account the gallery by increasing automatically the hazard level obtained for the cliff. This decision seems sometimes penalizing and overestimating.

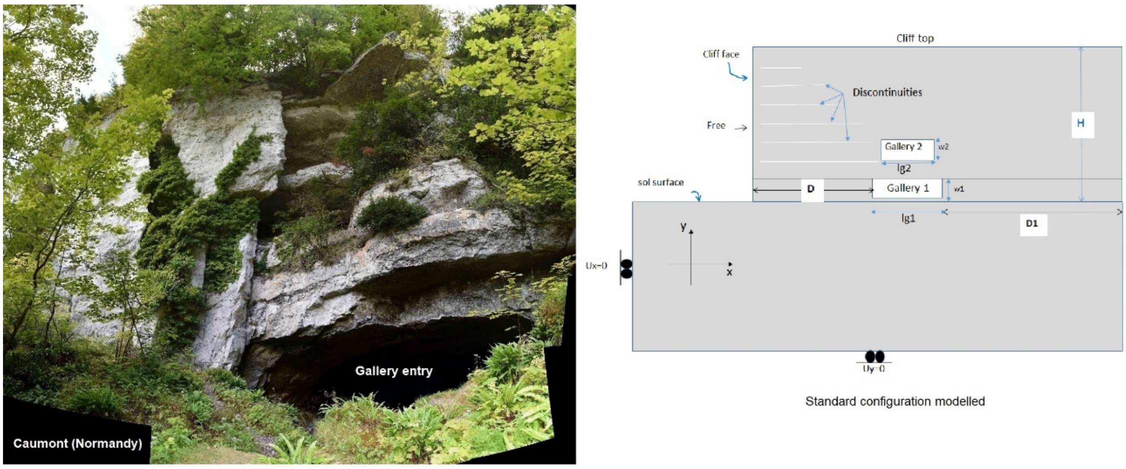

Figure 1. (Left): Example of an excavated cliff site with anthropogenic big galleries located at Caumont (Normandy). (Right): Presentation of the 2D standard geometry modelled.

In this study numerical modelling is used to identify the main parameters involved in the cliff stability and their respective influence. Numerical modelling has to help us to define a practical new assessment method, based on data acquisition about the site, results can be interpreted by geotechnical experts.

The observed in situ excavations could be a troglodyte galleries, large or small underground quarries. Sometimes, they are small galleries excavated probably to search the best chalk quality.

Several parameters could influence the cliff stability: (i) the distance (D) between the galleries and the cliff, (ii) the thickness (H) of the galleries overburden, (iii) the dimensions of the gallery, (iv) the galleries overlapping. The geology of the massif hosting the galleries, or in other terms the mechanical behavior of the formations composing it, are also important (i.e. natural fracturing of the rock mass or thickness of the layers composing the roof, water pressures, etc.)

This study was devoted firstly to the calibration of the model by studying a real case located at Caumont's city (see Figure 1) located in Normandy (France). The cliff was excavated by a big gallery with important dimensions (i.e. about 17 meters width and 5 meters height at the gallery's entry), and it is still currently stable. After calibration, we try to assess the result sensitivity of the model according to the variation of some parameters.

The numerical approach is based on the two dimensional Universal Distinct Element Code developed by Itasca Consultants Company (see Cundall 1971). This method enables to simulate the studied geological environment as an assembly of blocks separated by real discontinuities. In the model the elastic behavior of blocks is defined by Young's modulus (E) and Poisson's ratio (ν) values.

The plastic and post-plastic behavior is governed by tensile strength (Rt), cohesion (C) and friction angle (φ) values. These parameters are generally defined by laboratory tests or from literature review like done it in this work. The mechanical properties of discontinuities are defined in the model by normal (kn) and tangential (ks) stiffnesses to govern the normal and shear elastic deformation of joint. The joint plastic behavior is governed by cohesion (cj) and friction angle (φj). Note that joints mechanical properties values are really difficult to establish and only assumed values were taken into account in all the current numerical models.

The selected dataset for joints is the one allowing to not disturb the initial state of the stresses resulting from a gravity load characterized by vertical and horizontal principle stresses. Values close to the retained ones for these parameters could also work. All the input values are presented in the next chapter, devoted to the mechanical properties introduced in the model.

2 MECHANICAL PROPERTIES OF CHALK

A literature review was carried out to assess the variability of the shear and compressive strength parameter of chalk. The review was performed for both dry or saturated samples from various geographical horizons (see Table 1). Most of the tests concerned cohesion (C) and friction angle (φ) of rock matrix, except for two tests mentioning direct measurements of the compressive strengths (R_c) (see Dessene & Duffaut 1970 and Dessene 1971).

Table 1. Bibliographic synthesis of chalk mechanical data properties.

Chalk location or type	Cohesion (MPa)	φ (°)	Authors
White north chalk	4	28°	Hazebroock (2000)
White chalk saturated and drained	1,5 - 2	27°	Hazebroock (2000)
Chalk from Château Landon (France)	dry: 1,2 saturated: 0,6	28,5° 12,6°	Lafrance (2016)
Chalk from St-Martin-le-Noeud (France)	dry: 2 – 4 saturated: 0,5	29° 42°	Lafrance (2016)
Chalk from Estreux (near Belgium)	dry: 2,5 – 3,4 saturated: 1,5	30-39° 37°	Lafrance (2016)
Chalk from England	0,02 à 0,13	39° - 42°	Bonvallet (2000)
Comparison of 15 chalk	Rc= 2,5 to 27	-	Dessene (1971)
Comparison of chalk from 21 sites samples	Rc dry=5,2 to15,5 Rc saturated=2,4 to 6,4	- -	Dessene & Duffaut (1970)

Thus, for chalks, this review shows a net decrease of their compressive strength and Young's modulus (E) with the increase in water content. These conditions are real for many sites which are located near the sea in Normandy (see Dessene & Duffaut 1970, Hazebroock & Duthoit 2000).

3 CAUMONT'S SITE

Caumont's site represent a cliff about 15 meters high, excavated by a big gallery of 17 meters width, 5 meters height and more than 30 meters long (see Figure 1). Currently, the site entry seems stable and no indice of imminent potential instability was observed. In situ observations performed in the frame of this study enabled us to distinguish that the first roof layer is enough thick (more than 2 meters) and certainly robust. Thus, we assume, in the model, the following properties for chalk: cohesion of 4 MPa, friction angle of 35° and tensile strength of 1.5 MPa (~Rc/10). The properties retained for discontinuities are: kn=2000 MPa/m, ks=1500 MPa/m, Cj=0.1 MPa and φj=20°. These values allow to calibrate the current site observations as explain below.

For all numerical simulations, the initial field of in situ stresses is defined by gravity loading. Then the model is solicited by excavating the gallery in successive steps of 2 meters each one, up to reach width of 16 meters. After, the pitch of excavation of the gallery is reduced to 1 meter. According to the excavated width of the gallery, we analyzed the evolution of some parameters like stresses, displacements, plastic zones (zones in which the Mohr-Coulomb criterion is reached and exceeded), or fractures shear zones. At the end of each step, the equilibrium state reached is checked by the evolution of the unbalanced forces which must converge to a small value close to 0.

When the gallery width is equal to 17 meters, we observe that no plastic zone appears in the roof at this stage. In other words no cracks initiation in the roof was numerically simulated (see Figure 2 -a). A tensile stress has developed with lower but close values to the tensile strength of 1.5 MPa. The maximal computed tensile stresses are equal to 1.43 MPa, and are located in the middle part of the lower layer of the roof and on the edges of the gallery. Indeed these zones corresponds to the location of high flexion deformation which are induced by excavation. When the gallery width is increased by excavating 1 meter more, a plastic zone appears in the lower layer of the floor. The roof is cracked in more than half of its total thick, which could lead to its collapse. The propagation of the collapse to the entire roof is probably not excluded (see Figure 2-b). The latter assumption was investigated in a sensitivity study. It was carried out to assess how the collapsed areas could propagate towards the upper roof (see below). Thus cracks could develop in the roof which could lead to a cliff collapse.

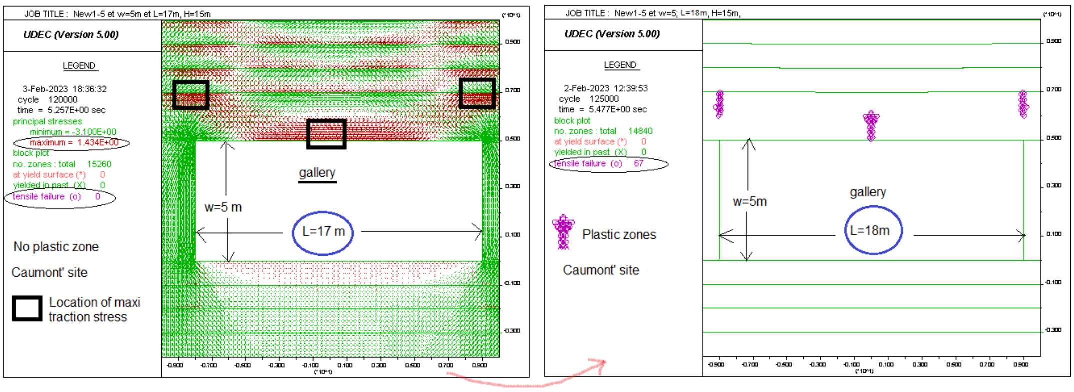

Figure 2. Results obtained for the Caumont' site in Normandy – calibration model (a: left; b: right).

The model also shows that an increase of the lower roof's layer thickness (5 meters) can lead to a stable state in spite of the tensile strength decrease of chalk (0,8 MPa). These results testify to the complexity of the problem and provide evidence that two different sets of parameters could lead to the same final state of the edifice (stable or instable).

Subsequently in this study, we multiply the scenarios by studying different values for each parameter. For these cases, lower mechanical than those retained for the Caumont's site were assumed. The aim was to study the others observed configurations elsewhere characterized by lower resistances of chalk and with gallery's dimensions smaller than those of the Caumont's case. Only a synthesis of some results is given hereafter (see table 2). We modelled gallery with maximum width of 6 meters, and a height equal to 2 meters. Most of visited galleries have a small dimensions than those assumed here. Also cliff is modelled as a superimposed horizontal layers of 1 meter thick and galleries are perpendicular (⊥) or parallel (//) to the cliff face.

When we try to model parallel gallery to cliff, we simply reduce the distance D between galleries to a small value close to 1 or 2 meters according to the studied configuration (see Figure 1).

We present in table 2 a synthesis of some modeled scenarios and stability conditions in terms of maximum gallery's width before cracks formations. Only a short description of the main results is presented hereafter.

With a perpendicular gallery (model with large values for D and D1), for a moderately stiff chalk (compressive strength close to 3.5 MPa and tensile strength equal to 0.4 MPa), results indicate a stability of the edifice {cliff + gallery} while gallery's width is less than 6 meters (see table 2 - N°4 and N°5). An increase to 20 m of height cliff leads to potential instability and cracks' development in the middle of the roof when gallery's width exceeds 3 meters in the model (see Figure 3-a).

The same previous model geometry and mechanical properties were used to study the effect of two overlapped galleries excavated in two different levels (see table 2, N°9). Results showed stable state when galleries are lower than 2 or 3 meters wide for the low level and close 2 meters wide for the highest one. No cracks were observed (cf. Figure 3-b).

For a parallel gallery, the effect of distance D was studied with D equal to 1 or 2 meters. When D is equal to 2 meters, with gallery's width lower than 4 meters, stability is obtained and no cracks (or plastic zones) were observed (see Figure 3-c). If we assume a D value equal to 1 meter, an instability of the roof and cracks appear (see Figure 3-c).

Finally, the effect of a major fracture, defined as an open discontinuity without filling material (no cohesion between its two planes), was taking into account in different numerical simulations. This state could be generated by frequent water circulations combined with seasonal weather variations, etc., leading to alteration of pre-existing geological discontinuities. As shown in the Figure 3-d, the edifice is potentially instable and cracks were simulated in the gallery when a small width is excavated for the gallery (~ 2 meters in the modelled case). Presence of such a major discontinuity could be considered as unfavorable factor for the stability of the set {cliff + gallery}.

Table 2. Synthesis of examples of performed scenarios.

N°	⊥ or //	Brief Model parameters Description	Result	Comment
1	⊥	w=5m;H=15m;Rt=1.5MPa; e=2m;	Stable while lg≤17m	Caumont's case
2	⊥	w=5m;H=15m;Rt=0,8MPa; e=5m	Stable while lg≤17m	Importance of e
3	⊥	w=2m;H=15m;Rt=0.4MPa; e=1m	Stable while lg≤6m	Low Rc
4	⊥	w=3m;H=15m;Rt=0.4MPa; e=1m	Stable while lg≤6m	Gallery height
5	⊥	w=2m;H=20m;Rt=0.4MPa; e=1m	Stable while lg≤3m	Influence of H
6	//	w=2m;H=15m;Rt=0.4MPa; e=1m; D=2m	Stable while lg≤4m	2 m width Pillar
7	//	w=2m;H=15m;Rt=0.4MPa; e=1m; D=1m	Stable while lg≤2m	Influence of D
8	//	w=2m;H=15m;Rt=0.4MPa; e=1m; D=2m;	Stable while lg≤1m	Open fracture
9	⊥	w=2m; Rt=0.4MPa; gallery superimposed, e=1m, H=15m, 20m	Stable while lg≤3m	for 2 galleries

PZ*= Plastic Zone; ⊥ = perpendicular to gallery; //= parallel to gallery.

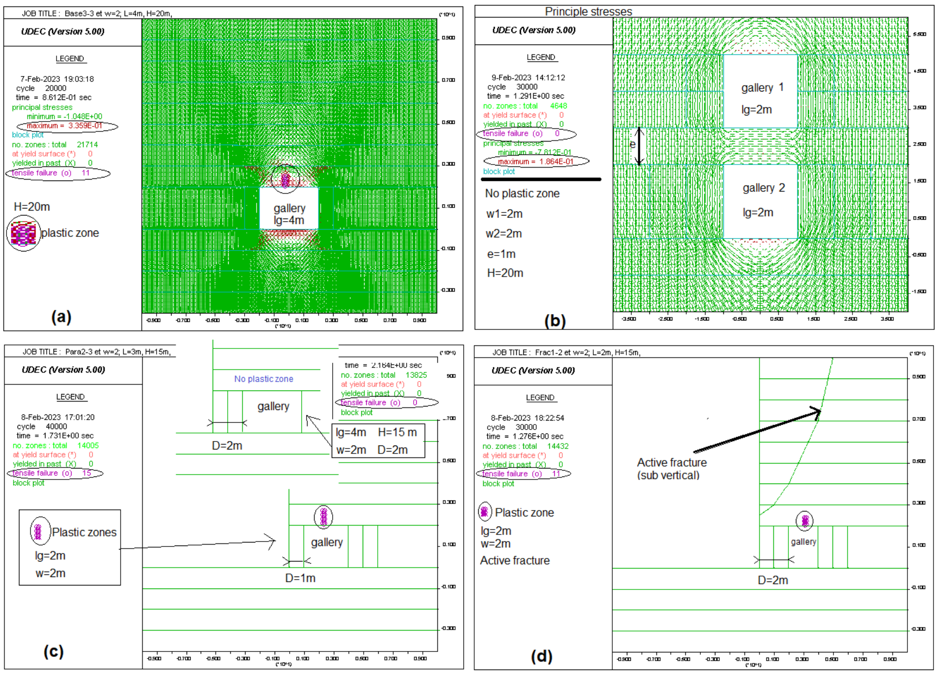

Figure 3. Model results obtained for different hypothesis: (a Cliff height equal to 20m, (b) Superimposed galleries, (c) Gallery located 1 or 2 m from cliff, (d) Effect of an active discontinuity on the cliff stability.

4 SYNTHESIS AND CONCLUSION

The Caumont calibration model was helpful to determine a set of parameters values in agreement with the current observed stable state. The sensitivity studies enable to assess the influence of parameters like chalk mechanical strengths, geometry of gallery and cliff, presence of active major open discontinuity, etc.

As shown by the model results, it seems true that a highly resistant and stiff chalk could generally be sufficient to reduce significantly, or probably to cancel, the potential influence of gallery in the cliff's stability. Otherwise, the cliff's stability will also depend of others parameters, like for example the thickness of chalk layers, major fracture, etc.

The previous analyses confirm also that the stability of {cliff/gallery} edifices depends of set of parameters which values could vary from one set to the other. Several other simulations, not described in the current paper, were made in order to assess the parameters contribution to stability: very favorable, moderately favorable or unfavorable (see Figure 4). An empiric cumulative score is obtained for a studied site and is compared to the mean score equal to 70 points. When the cumulative score assigned to a site is much higher than 70 points, the contribution of gallery to the cliff stability could be considered as negligible. If the score is much lower than 70 points, presence of the gallery could potentially influence the cliff stability and the hazard level retained on the cliff should be upgraded. A score value close to 70 points needs more investigations to better precise one or more parameters of the studied site. The current scoring method could be improved later by using a multi criterion analysis method to better define set thresholds for classes.

This proposal will be useful in the study of cliff with excavated gallery. It offers the possibility to take into account the influence of gallery in an objective way instead of an upgrade of the hazard level which is not always justified.

Paramètre	Value by classe	Very favorable	Moderately favorable	Unfavorable
Tensile strenght (Rt)	> 3 Mpa	40	-	-
	[1, 3] Mpa	-	20	-
	< 1 MPa	-	-	1
Lower layer thick of gallery's roof	Thick ≥ 2 m	25	-	-
	1 m ≤ Thick < 2 m	-	10	-
	Thick < 1 m	-	-	1
Cliff Height (H)	H ≤ 10 m	20	-	-
	10 < H ≤ 25 m	-	10	-
	H > 25 m	-	-	1
Galerry width (Lg)	Lg ≤ 2m	10	-	-
	2 < Lg < 4 m	-	5	-
	Lg ≥ 4 m	-	-	1
Gallery Height (w)	w < 2 m	10	-	-
	2 < w < 4 m	-	5	-
	w ≥ 4 m	-	-	1
Gallery Parallel to cliff	No	10		
	Yes and D ≥ 2 m		5	
	Yes and D < 2 m			1
Discontinuitie/ Fracture (F)	No visible F	15		
	No active (F)	-	10	-
	Active (F)	-	-	1
Presence of galleries Superimposed	No	10	-	-
	Yès but layer thick between ≥≥ 2m	-	5	-
	Yès with layer thick < 2 m	-	-	1
Cumulate score		**140**	**70**	**8**

Figure 4. Empirical notation for the main parameters contributing to the {cliff/gallery} set stability.

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