Study of collapse occured during the reinforcement work of a vault in a chalk quarry located in the north of Paris (France)

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ABSTRACT: A vault of around ten tons weight collapsed unexpectedly during the reinforcement operations carried out in an old underground chalk quarry, which causes a serious accident. This paper describes the accident circumstances, gives some explanations for the accident, and present a simple 3 dimensional model realized to study the stability of the vault taking into account influence of local discontinuities.

1 INTRODUCTION

In May 2017, a vault weighing about ten tons collapsed unexpectedly during the reinforcement works carried out in an old underground chalk quarry situated about sixty kilometers north of Paris in France. The quarry exploited during the first half of the 20th century by the method of abandoned rooms and pillars. The extracted hard chalk used for the construction of several buildings and monuments of the region.

The exploited layer of chalk is located at a depth of between 15 and 45 m. A mainly chalky roof covered the underground works, and a residual clay-flint formation of varying thickness overhung the chalky cover. The quarry's right-of-way is mostly under a plateau at an average depth of 45 m.

The cover of the quarry is characterized by a singular geological context, due to the presence in the covering of several vertical and horizontal karsts, as well as alteration roots that can reach depths greater than 45 m. The underground works intercept several alteration roots, which are identifiable by their clay material impregnated with numerous blocks of flint of different sizes. These geological objects intercepted at the bottom by the old works of the quarry are sometimes in the origin of a phenomenon of emptying of their filling materials, leading to the appearance of cavities on surface of large diameters (~ 10 m) which may constitute a significant risk to buildings and persons.

Natural subvertical to vertical joints are also present at the site. Some are karstified and filled with clay material. They result sometimes in some problems of stability of the lower part of roof. This is notably the case of the 2017 collapse zone, where two major joints were cutting off the roof, forming a vault weighing about ten tons that had collapsed during the drilling of holes destined for the roof reinforcement system by flat beams

2 GEOLOGICAL AND HYDROGEOLOGICAL CONTEXT

2.1 *Geological context*

At a regional scale, the quarry was excavated in the Coniacian-Santonian chalks of the Upper Cretaceous. Coniacian chalks, which are thick from 30 to 50 m on a regional scale, are described as dolomitic hard chalks, yellowish and pigmented with black dots. Flints are small, in spaced beds, but it is possible to meet at the top of the series flint plates 1 to 4 cm thick. When compact, the Coniacian chalk is a good stone for buildings.

The overlying Santonian chalk presented as a white chalk with much stratification discontinuities. Sometimes chalk is dolomitized at the base and marked by thick benches of small flints. Above, the white chalk becomes soft and the flint, larger, arranged in very close benches. The maximum thickness of Santonian can reach 70 m.

On the upper part of the roof of the quarry, the Coniacian-Santonian chalk would be covered with old alluvium from the Seine (very high alluvium, dated Pliocene), characterized by plates of blunted pebbles, sometimes a few meters thick. A representative geological profile of quarry roof is visible from about 400 m (Fig. 1).

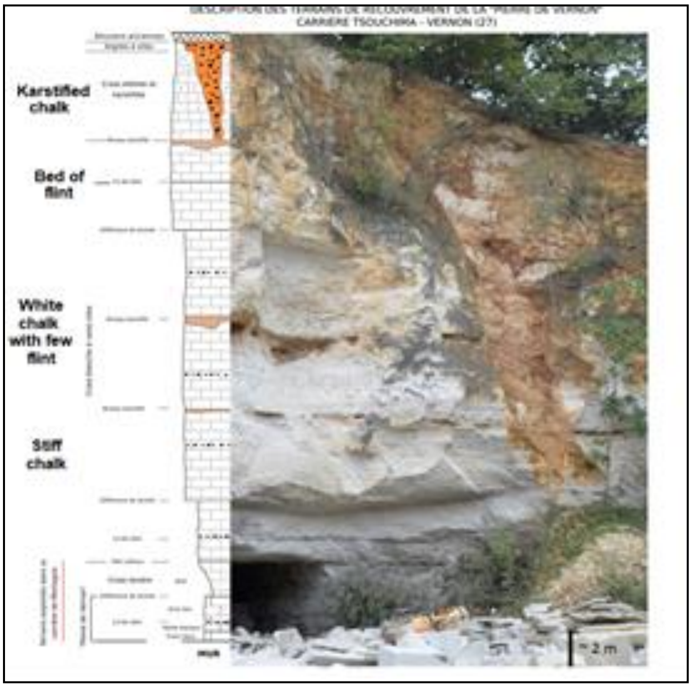

Figure 1. Overburden geology over the quarry (mainly chalked layers).

The alteration of chalk, especially development of a karstification in the covering, are quite visible on this natural profile. Indeed, the studied site is characterized by the presence of deep alteration roots in the cover, some of which have been intercepted by the mining galleries located at about 45 m depth. This geological singularity is not without consequences on the stability of the quarry, since these roots sometimes drain naturally flint clays, leading to the formation on the surface of craters of large diameters (~ 10 to 12 m) (Fig. 2).

Figure 2. Example of an alteration root intercepted at the bottom, and of the fontis induced in the surface by its emptying

Now a local geological description at the local scale of the exploited layer shows that three levels have been excavated. They are from bottom to top (Fig. 3):

- The ‘Franc-Banc’, located at the base and excavated on about 90 cm thick;
- The 'Petite Hauteur’ or ‘small height', exploited about 40 to 60 cm thick, separated from the ‘Franc-Banc’ by the ‘lit Franc’ or ‘bed Franc’;
- The ‘Gros lien’, exploited about 60 cm thick, separated from the two benches beneath by a bed of flint clearly visible in the quarry.

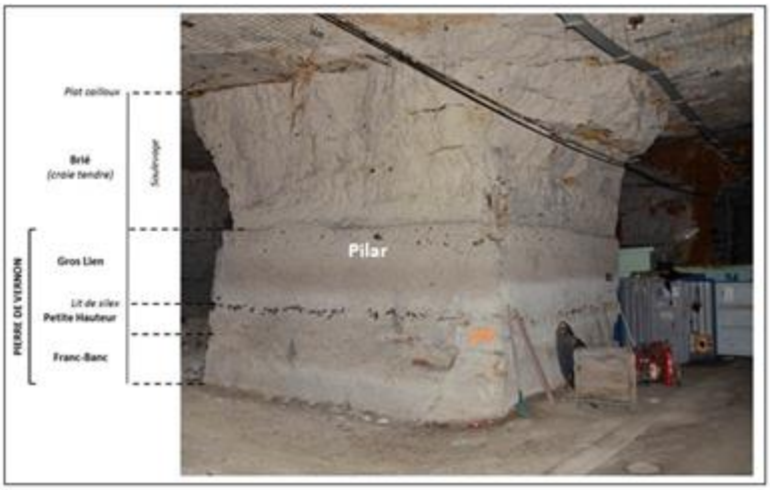

Figure 3. Local geology at a pillar scale

2.2 *Hydrology context*

Chalk represent the main aquifer on the quarry. According to the geological atlas published by the BRGM in the studied area (Fig. 4), the altitude of the roof of the aquifer at the plateau level is between + 30 m and + 40 m NGF (for a medium water level). In other words, between 70 and 80 m depth in relation to the surface perpendicular to the quarry, and between 30 and 50 m deep compared to the level of the bottom of the quarry (overall between +72 m and + 82 m NGF.

This precludes the possibility of a flood of the underground quarry by an increase level of water table.

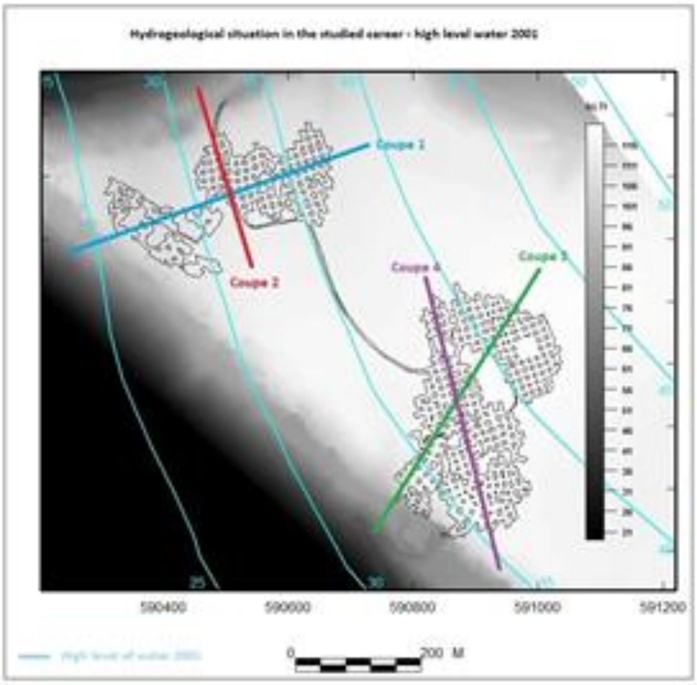

Figure 4. Hydrology situation on the quarry (data from BRGM/ SIGES-SN)

2.3 *Description of fracturation*

The projection on a Schmidt diagrams (bottom hemisphere) of the 158 observed natural fractures (faults or diaclases), highlights three main orientations (three family) which are consistent with the regional ones (Fig. 5).

- Family F1: with a mean orientation between N110 ° and N115 °. This fracture family is essentially represented by diaclases predominantly vertical or steeply dipping (greater than 75 °). This is a regional orientation, which is found in particular on the chalky cliffs of the coastal coast of the Caux country.
- Family F2: with a mean orientation between N040 ° and N050°. This fracture family is essentially represented by predominantly vertical or steeply diaclases (> 75 ° or 80 °). This is a regional orientation, orthogonal to the previous one (F1).
- Family F3: fracture family only represented by vertical diaclases, which follows a regional orientation and in particular those major tectonic accidents inherited from the basement (Armorican orientation).

Note that the area of the accident is crossed by two diaclases belonging to the F1 family.

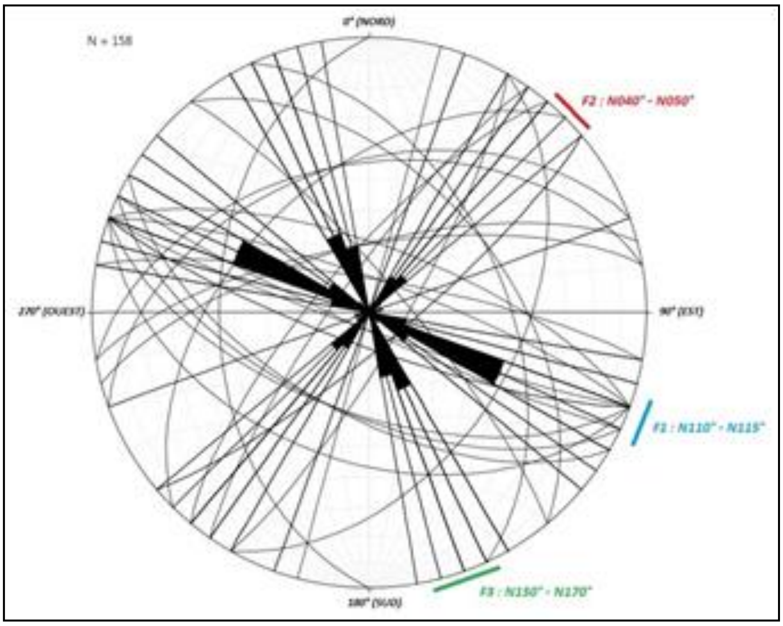

Figure 5. Projection on the Schmidt Diagram (south hemisphere) of the three family fractures observed in the chalk studied quarry.

3 DESCRIPTION OF THE AREA OF THE ACCIDENT

The accident occurred in an area crossed by two subparallel discontinuities. The first limited the crash area to the north, The first limited the crash area to the north, splitting into two fractures on the collapsed zone, creating a first block that had broken off when drilling a dozen holes on the roof (Fig. 6). These latest were intended to receive the bolts that were going to fix the metal beam serving to support the roof. The second discontinuity is located further south of the previous one, about 1.5 m away. It stops a few meters (~5 m) from the firm edge, on a karst cavity closed in height, probably drained of its clay filling material, well before the accident.

The accident zone is located between the P4 and P18 pillars; the zone was weakened by the presence of the two previous discontinuities. The average depth of underground work above the collapsed area would be of the order of 45 m.

The average extraction rate within a zone radius of about 20 meters around the collapsed zone is 85%, calculated using an average length and width of the pillars respectively equal to 6.2 m and 4.6 m, and an average gallery width of 7.8 m. The collapse occurred when drilling holes in the roof, while the latter was weakened by the two discontinuities.

At first sight, the pillars remained intact after the collapse of the vault, and no sign of settlement or occurrence of mechanical fractures were observed on the pillars after the collapse. A block with a mass of about 10 tons, bounded by the two joints, detached from the roof (Fig. 6).

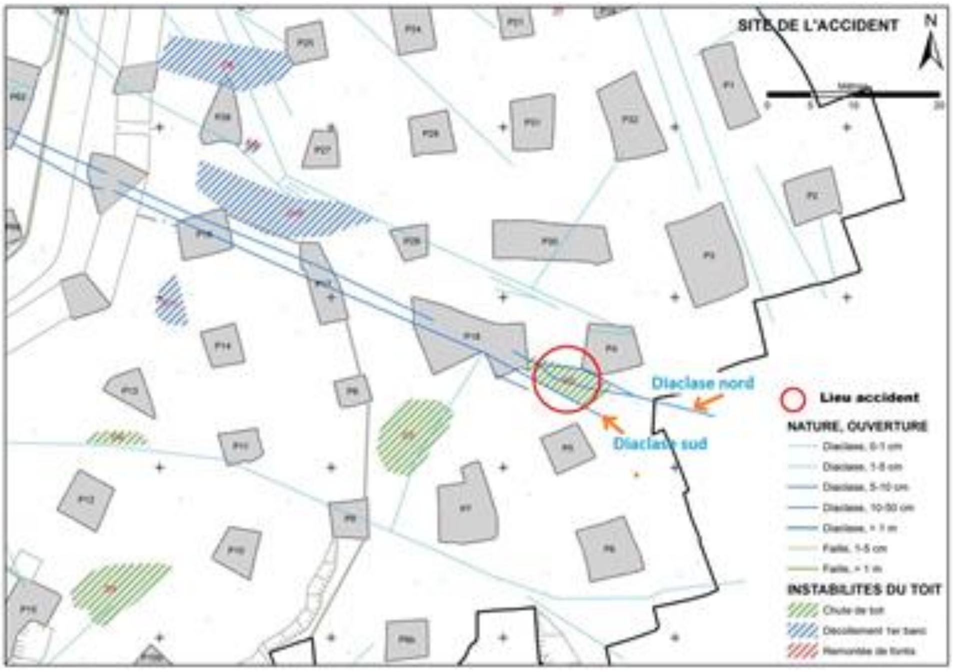

Figure 6. Situation of underground work near the collapsed zone.

4 ANALYSIS OF THE COLLAPSE

4.1 *Hypothesis*

We have retained for chalk the mechanical properties summarized below. These values were obtained in laboratory from measurements realized on chalk samples coming from another nearby quarry, also located north of the Paris Basin, which had exploited the same chalk. The value of the tensile strength (R_t) has been assumed to be of the order of R_c / 10, where R_c is the simple compressive strength.

Thereafter, we retain for chalk a density value of 2100 kg/m^3, a Young modulo of 20000 MPa, Poisson ratio equal to 0.3, a simple compressive strength (R_c) of 38 MPa, an elastic strength (R_E) equal to 11.5 MPa and traction strength (R_t) of 3.8 MPa.

4.2 *Analysis of the event*

For pillars that are within a radius of about 30 meters around the collapsed area, we assume the tributary area method to assess the average vertical stress (σ_v) supported by the pillars. The calculated value is in the order of 6.3 MPa, considering an average extraction rate of 85% and a maximum depth of 45 m. This value could be considered as close to the maximum vertical stress. Therefore, it would lead to a long-term safety factor (Fs) which would be of the order of 1.8 for the pillars in this area. This safety factor value is obtained by admitting a long-term value of strength equal to R_E, and F_S is being estimated by the ratio R_E / σ_v.

Consequently, the long-term mechanical stability of the pillars could be guaranteed. This result was verified by the in situ observations made immediately after the collapse of the roof, which

confirm the absence of settlement or punching of the pillars, which could have weakened the roof, and thus favoring its rupture. The pillars are staying in a good mechanical state.
The roof probably weakened by the two subparallel fractures, which predisposed it strongly to a long-term break. In this case, drilling of the holes would be an aggravating circumstance, having probably accelerated the fall of the vault in the zone delimited by the previous two fractures. The vibrations induced by the drilling of holes would probably have weakened the balance of the blocks within the roof, causing finally the fall of the blocks, which composed mainly the vault. The latter were also quite heavy (~ 10 tons) to overcome the natural cohesion of the vault.
The latest explanations are still intuitive, difficult to prove without the help of heavy and sophisticated calculations means. Indeed, only numerical models which enable us to simulate the influence of dynamic solicitations on roof stability, and which take into account fractures, could help to verify these hypotheses.

We have modeled this case by carrying out simplifying hypotheses; the objective being to demonstrate the interest of a discontinuous medium approach to study vault stability. We assumed that the drilling of the first two rows of holes on the roof prior to the collapse of the vault resulted in a reduction in lateral containment, leading to a horizontal stress drop. The precarious balance between the weight of the vault and the friction within the two discontinuities had finally broken off and the vault collapsed (Fig. 7). Note that only a dynamic model could help us to demonstrate this phenomenon. This latest will be the subject of another study, which will carried out in another frame.

Figure 7. Simulation of the vault collapse induced by a decrease of cohesion and friction parameters.

We made a simple tridimensional geometry for the model representing the local collapsed zone with the real mean local dimensions of pillars and galleries. In the same time, we simplify the shape of the pillars (see Fig. 7).
We also take into account only two pillars separated by rooms, and we assume a fixed (displacement equal to 0) boundary conditions for both horizontal faces and for the bottom face of the model. A free condition was applied in the upper face of the model.

In the first step, a stress tensor (equivalent to the initial in situ stresses corresponding to gravity effect) was applied in the 3D model before excavating the galleries.
The second step of modelling was devoted to the excavation of galleries, and the simulation of a decrease of joints mechanical properties done in the next step.

The two figures 7 and 8 shown the results obtained by the model.

As shown in these two Figures, the reduction of the mechanical properties (cohesion and angle of friction) of the two discontinuities inevitably leads to the rupture of the vault. We can see that the bloc dropped from the roof when the weight overcome the cohesion.

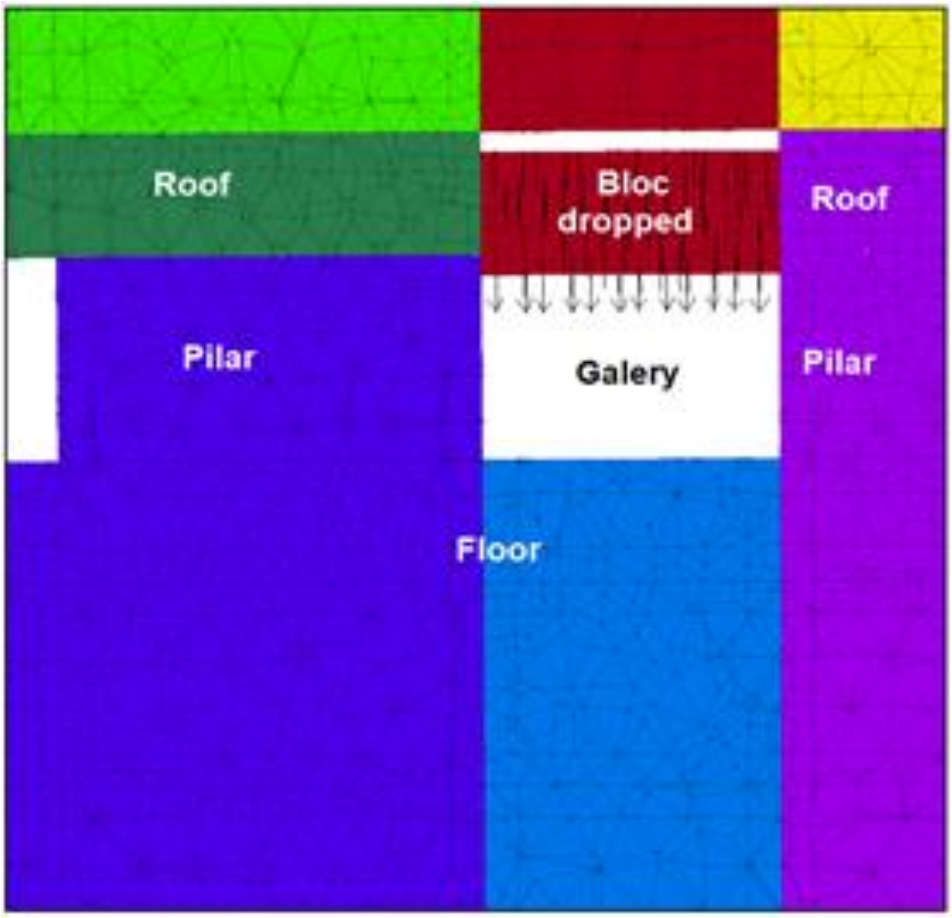

Figure 8. Simulation of the vault collapse induced by a decrease of cohesion and friction parameters (vertical cross section).

5 CONCUSION

The collapse that occurred in May 2017 in the chalk quarry located in north of Paris, exploited by rooms and pillar method, had occurred in a vault weakened by the presence of two fractures. Drilling of the holes in the roof was probably precipitated the collapse, by causing a slight relaxation of the roof. So that, the vibrations induced during drilling were an aggravating factor.

A simple three-dimensional model, limited to the local zone of collapse, and explicitly taking into account the presence of the two discontinuities. This model allowed verify the influence of the reduction of the cohesion of the massif on the stability of the vault, which guaranteed by the horizontal containment stress. We assume that the drilling of the holes in the roof induced probably a decrease of containment stress. The effect of vibration due to drilling is an aggravating circumstance.

The actual influence of vibrations induced by drillings will be studied further in the frame of another study, which is currently in progress.

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