

NUMERICAL STUDY OF THE STABILITY OF UNDERGROUND CAVITIES IN LILLE METROPOLITAN AREA

Étude numérique de la stabilité des cavités souterraines de Lille Métropole

par Alissar YEHYA (*), Faten RAFEH (*) & Hussein MROUEH (*)

Abstract. – The high concentration of underground cavities, natural or anthropic, in urbanized areas like Lille Metropolis in North France, constitutes a serious problem due to the danger induced on both people and infrastructures, next to the strong constraint implemented in terms of planning and urban development. In this paper, a description of the underground cavities in the region of Lille is followed by the classification of the problematic on two bases; first the degradation of the behavior of the constituent material, chalk; and second the global stability of the underground structure. Afterwards, a stability study of the underground structure is conducted. Eventually, a further plan is proposed depending on the consideration of all the structure non-stabilizing factors and a more adequate law of chalk behavior that includes the effect of all degrading factors.

Résumé. – La présence de cavités souterraines naturelles ou anthropiques pose un problème majeur dans les zones fortement urbanisées comme la métropole Lilloise dans le nord de la France. En effet, ce problème génère un réel danger pour les personnes et les infrastructures et induit une forte contrainte en termes de planification et de développement urbain. Une description des cavités souterraines de région de Lille est présentée puis une classification des problèmes rencontrés est proposée : d'une part la dégradation du comportement mécanique de la craie et d'autre part la stabilité globale de la carrière souterraine. Ensuite, une étude numérique de la stabilité de la structure souterraine a été présentée. Enfin, un futur programme d'études est proposé en considérant d'une part tous les facteurs usuels d'instabilité des constructions et d'autre part une loi de comportement décrivant mieux la dégradation de la craie.

Key words. – underground cavities, chambers and pillars, safety factor, finite element method, nonlinear modeling.

Mots clés. – cavités souterraines, chambres et piliers, facteur de sécurité, méthode des éléments finis, modélisation non linéaire.

I. – INTRODUCTION

Throughout the French territory, the underground abandoned mines and underground cavities cover ten thousand hectares of the area. Since the eighteenth century, quarries were excavated for different purposes. Basically, the aim was the usage, in construction works, of the extracted material which was mostly of limestone, gypsum, Senonian and Turonian chalk, marble, etc. These excavations were accomplished by different exploitation methods (Ineris, 2012).

In the district of Lille, 300 hectares of the above surface are considered under risk where the estimated area of quarries is 120 hectares among which 158 chalk quarries have been identified. Of these, almost 80% were of the type of a chamber and pillars, whereas the rest was distributed among a holts and bottles type and a mixed type that includes both previous exploitation methods (Ville de Lille, 2011). From a hydrogeological point of view, most of the quarries on the territory of Lille South are located above the chalk aquifer but more northerly areas may be occasionally flooded during the rainy season. Among 120 incidents of cavities collapses in the region of Lille, 30 were due to water effect (Ineris, 2012).

II. – OBJECTIVE

The main problem is induced from the instabilities of old underground quarries that lead to its partial or total collapse and thus result in deformations, sometimes reaching huge damages at the surface. Hence, a solution of this problem initiates from setting up a stability study of this underground structure. In the case of the cavities in Lille, this will depend on studying two aspects, the state of chalk material and the behavior of the chamber and pillar system.

Chalk is of a complex behavior due to its sophisticated arrangement and high porosity (Elmo & Stead, 2010). In the conditions of this problem, chalk is exposed to several degrading factors like the climatic change in terms of temperature and humidity variations, the microbial activity, rain effect that induces a hydraulic load at the surface, and leads to increasing the water level inside the cavities which fabricates mechanical and chemical degradation processes of the chalk. Besides, the presence of discontinuities, human external activities, and time and creep effect imply remarkable effects. All these factors, with the complex behavior of chalk must be introduced in an inclusive criterion of chalk behavior. On the other hand, in a chambers and pillars underground structure, the mechanisms of rupture will occur due to collapses initiated either in the pillars,

(*) Laboratoire de Génie Civil et géo-Environnement (LGCgE), Université Lille Nord de France – Polytech'Lille, Université Lille1 - Sciences et Technologies, 59655 Villeneuve d'Ascq cedex, France ; alissar.yehya@gmail.com, faten.rafeh@polytech-lille.fr, hussein.mroueh@polytech-lille.fr

or in the roof. Based on the literature review, this can happen through various aspects as remarked by different researchers in this domain, like the localized rupture and the shear rupture in the pillar or the roof (Watelet, 1996). Also, collapse can occur due to a pillar failure by uniaxial compression or a roof failure by flexure or bending. Besides, buckling of pillars due to breakage of connecting stabilizing bridges in a multi-level cavity, or punching of the overloaded pillars into the weak base may also lead to failure. All these rupture mechanisms have to be considered in such a stability study.

In this paper, initial results of the related work are presented. The main is to focus on the effect of geometric parameters of the structure. The simulations are carried out on a PLAXIS 2D finite element code considering an elastic perfectly plastic behavior for the chalk (Yehya, 2012). Knowing that, this is not the perfect behavior for the chalk in our case, more adequate elastoplastic and elastic-viscoplastic models will be considered in the future work. This will be accompanied with taking into account the effect of different natural factors (water, time, etc) and anthropic factors (human activities, etc) on the chalk itself, as well as on the structure.

III.— DESCRIPTION OF THE NUMERICAL MODEL

This model represents a predefined case of a chamber and pillars cavity. It is implemented as a continuum model using PLAXIS 2D finite element method, where the rock and soil follow Mohr-Coulomb failure criteria. Two types of models are adopted. The first model takes the section of one pillar resting between two chambers. It focuses on the behavior of a single pillar under the applied conditions. The second model represents a multi-pillar system taking the section of mid to mid chamber due to symmetry. This is assigned to study the combined deformation behavior between the roof and the pillars. According to the section of the models, a range of dimensions is considered depending on the INERIS reports for the cavities in Lille and the region (Ineris, 2012). Width of pillar W ranges from 2m to 8m, span of chamber L is from 3m to 6m, thickness of roof h varies between 5m and 7m, height of the ceiling H is 2.5m, the clayey sand cover layer is 3m height, and rock fill material on floor is 1.5m height (Fig.1). The values of the mechanical properties of the materials used in the adopted models are listed (Tabl. 1).

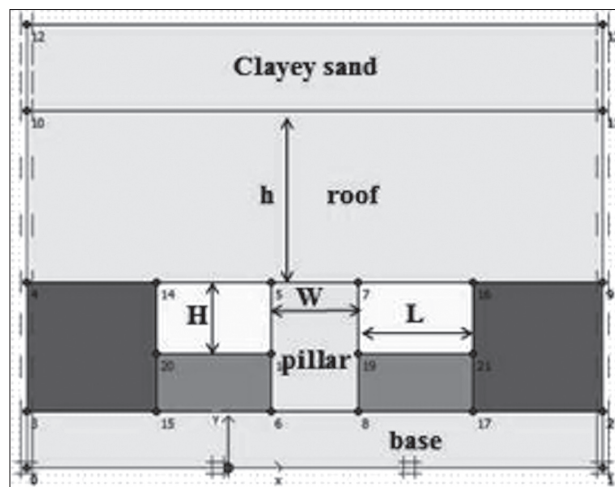


Fig. 1.—Section of the model implemented on Plaxis 2D.

Fig. 1.—Section du modèle mis en œuvre sur Plaxis 2D

Mechanical Properties	Elastic Modulus (KN/m ²)	Cohesion (KN/m ²)	Angle of friction	Dilatancy angle	Density (KN/m ³)
Rock	1.5E+07	100	30	30	21
Clayey sand	1.0E+05	24	30	30	19
Fill material	1.5E+07	10	25	25	21

Tabl. 1.—Materials mechanical properties.

Tabl. 1.—Propriétés mécaniques des matériaux.

IV.— ANALYSIS OF THE IMPLEMENTED MODELS

For the single-pillar model, a compression failure occurs in the pillar as its strength decreases with the increase of the applied load. A depression on the surface is observed due to the shortening of the pillar under excessive loading. For the different ranges of dimensions, the factor of safety FS that is defined as the ratio of the pillar strength to the load applied on the pillar. In the study of pillars and chambers cavities, the stability is referred to a classification of the factors of safety into three categories: $FS < 1$ means failure; $1 < FS < 1.4$ indicates an unstable situation (prone to degradation); and $FS > 1.4$ refers to a stable state (Lunder & Pakalnis, 1997). In the study of the pillar strength, different authors have worked on the effect of width to height ratio in chambers and pillars quarries (Martin & Maybee, 2000; Salamon & Munro, 1967). In this work, the width to height ratio is considered for the stability study of chalk pillars existing in the room and pillars quarries in the region of Lille in North France. FS increases as the width W of the pillar increases since its strength increases. On the other hand, as the span L of the chamber increases, an increase in the distribution of the applied load occurs and hence FS decreases. FS decreases slightly as roof height h increases. The rigidity of the roof is high in all simulations. Moreover, the curves of higher L have higher slopes since as L increases the applied load increases, and hence there will be more effect of W/h that resembles the strength. In addition, for the high values of W/h high strength is observed which indicates higher ability to resist higher loads is observed. Therefore, the effect of the increase in span L will be less and that can be seen from the curve; they start to converge and become closer for high values of W/h (Fig. 2 A-B).

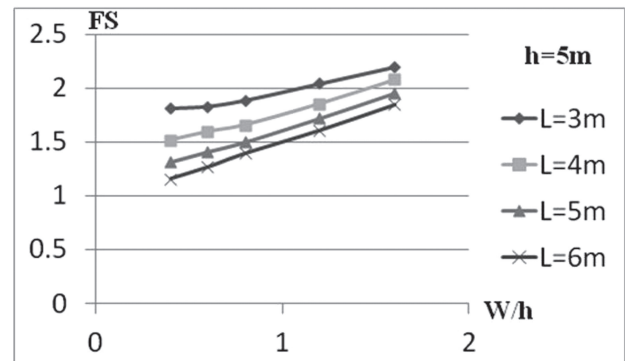


Fig. 2-A.—The variation of FS (Factor of Safety) with respect to W/h (Width to height ratio) for different values of L (Span Length) for $h=5m$, in Model 1.

Fig. 2-A.—Variation de FS (Facteur de Sécurité) par rapport à W/h (Rapport largeur sur hauteur) pour différentes valeurs de L (Longueur de Portée) pour $h=5m$, de Model 1.

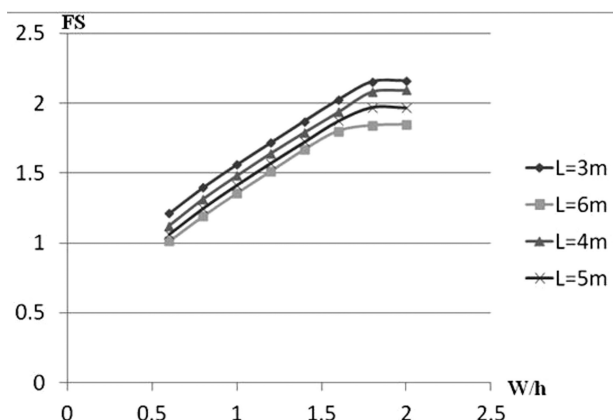


Fig. 2-B. — The variation of FS (Factor of Safety) with respect to W/h (Width to height ratio) for different values of L (Span Length) for h=7m, in Model 1.

Fig. 2-B.—Variation de FS (Facteur de Sécurité) par rapport à W/h (Rapport largeur sur hauteur) pour différentes valeurs de L (Longueur de Portée) pour h=7m, de Model 1.

In the multi-pillar model, 2 mechanisms of failure are observed. For small values of W/h (<1.6), and under a low confining pressure, the rupture is initiated by a brittle failure in the pillar. No span deflection or depression at the surface is observed, so the collapse of the roof is directly followed without any previous alert. On the other hand, for high W/h (>1.6) and under a high confining effect on the core of the pillar, deformation starts in the roof with a ductile behavior of pillar (Fig. 3).

According to the factor of safety, as W/h increases the strength of the pillar increases and hence the stability factor FS increases for W/h<1.6, since in this range the rupture occurs in the pillar. For W/h>1.6, FS becomes stable and independent of the W/h increase (Fig. 3). In fact, this is because for W/h>1.6, rupture occurs in the roof (upward progression) and the width of the pillar and its strength will no more affect the stability. Also, it is noticed that for $W \leq L/3$, we always have pillar failure. For $L/3 < W < 2L$, a slight effect of L on FS is observed, and the effect of width of pillar is more obvious. For $W \geq 2L$, unlike W, has a higher effect on FS. In this case, the span will become the critical dimension that affects failure. By this distribution, it is possible to include all the existing cases even when there might not be a constant L/H ratio presented for certain pillar and chamber cavities.

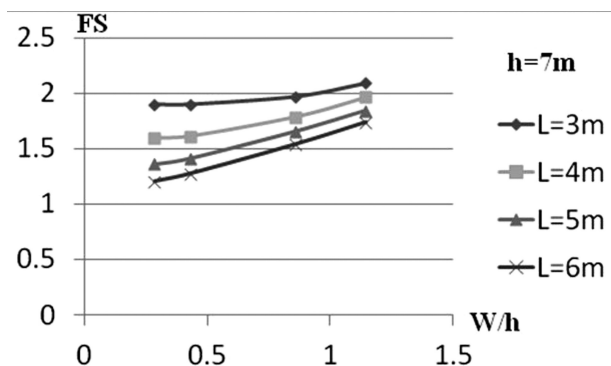


Fig. 3. — The variation of FS (Factor of Safety) with respect to W/h (Width to height ratio) for different values of L (Span Length), in Model 2.

Fig. 3.—Variation de FS (Facteur de Sécurité) par rapport à W/h (Rapport largeur sur hauteur) pour différentes valeurs de L (Longueur de Portée), de Model 2.

V.— CONCLUSION

Nowadays, the phenomenon of collapses of underground cavities, regarding all the encountered damages and losses, is considered one of the seriously existing natural hazards. Accordingly, an inclusive stability study of these quarries is highly recommended. This has to be implemented on two levels: the level of the material itself by considering all the natural and anthropic factors that affect the properties and behavior of the chalk through a refined law of failure; and the level of the structure by considering the various mechanisms of rupture. For the meantime, our aim is restricted to studying the stability of the structure based on its geometry variations, considering an elastic-perfectly plastic model for the behavior of chalk. Whereas, future work aims to introduce all the weakening effects into the model with a chalk law of behavior that is more consistent with its complex behavior than Mohr-Coulomb, and using a numerical method which properly represents this problem without the restrictions of finite element method and PLAXIS 2D.

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