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Research Paper

Accounting for joints effect on the failure mechanisms of shallow underground chalk quarries

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ABSTRACT

Unexploited chalk quarries in North France and its region constitute a risk of damage on both people and constructions. This work aims to study the mechanical behavior of the cavities affected by presence of joints and fractures in the chalk layers. First, an oriented yield criterion based on the theory of multi-mechanisms is developed to account for the presence of double joint sets. Then, a shear strength reduction approach is integrated in this joint model and implemented to study the mechanical stability state of these quarries. This provides some provisions about the effect of joint characterization on strain profiles and failure mechanisms in chalk quarries.

1. Introduction

Urban expansion requires building new constructions and infrastructure in places where geological risks might be high. In North France and its region, the major risk comes out from the presence of shallow underground chalk quarries. Because of the high density of cavities and natural and anthropogenic degradation of chalk, the risk of instabilities and collapses is continuously increasing with time. This, in fact, implements a real danger on both people and constructions at one hand, and induces a strong constraint in terms of planning and urban development on the other hand as stated by Lille Municipality [1]. Consequently, it is always of major interest to urge the study on these underground cavities.

From a safety point of view, these cavities are not only required to avoid ultimate collapse, but also to satisfy limits of a displacement-based criterion. Hence, in order to control the expected circumstances, understanding of instabilities induced by these cavities is quite important. In this aim, observations and measurements of the cavity displacements are necessary to predict the eventual collapses. Nevertheless, numerical modeling of strain and failure mechanisms can provide a complementary approach to understand these phenomena. Knowing that the chalk layers are originally embedded with joints and discontinuities [2], an anisotropic behavior is induced. Anisotropy, whether inherent presented by the embedded joints or provoked by generated fractures, intrinsically affects the strength, and the strain behavior of the chalk rock mass. Especially at shallow depths where stresses are low, the behavior of the chalk rock mass is controlled by sliding along the joints and accumulated shear strains in the discontinuities. Anisotropy may affect the failure mechanisms and thus modify the stability state of underground openings and their surroundings and induce collapses.

Concerning anisotropy, different continuum and discontinuum approaches and numerical models were developed to account for the behavior of jointed rock masses by either implicit or explicit presentation of fractures. For instance, the concept of homogenization of fractured rock media with explicit macroscopic fractures into equivalent continuous media (generally transverse isotropy for one network of joints, orthotropic two networks of joints, etc.) was proposed [3,4]. Singh [3] has presented continuum characterization methods for jointed rock masses and developed expressions to estimate the elastic moduli of the equivalent continuum anisotropic rock mass. Gerrard [4] used an equivalent continuum approach based on the idea of expressing the compliance of an element as the sum of the compliances of the intact rock and that of the individual joint sets. Zienkiewicz et al. [5] have also used the equivalent continuum approach, referred to as a

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multi-laminate model to simulate a discontinuous rock mass. Moreover, Sitharam et al. [6,7], advocated a numerical approach treating the rock mass with equivalent material properties. Another approach based on the explicit consideration of the mechanical behavior of both the matrix and the fractures was proposed by Cai and Horii [8]. This was achieved through a constitutive model that accounts for the effects of density, orientation and connectivity of joints, as well as the properties of the joints themselves. In addition, anisotropic models and/or strength criteria for structurally anisotropic rocks were developed by Duveau et al. [9]. This latter has provided an assessment of representative failure criteria in the framework of modeling the failure behavior of strongly anisotropic geomaterials. Another category of numerical modeling of anisotropic behavior and/or strength of anisotropic rocks is achieved by assuming implicit representation of joint sets [10]. In this case, the rock mass consists of intact material with isotropic linear or nonlinear behavior and weak planes presenting the joints based on the extension of Griffith theory [11,12]. This technique can be considered appropriate for the modeling and analysis of joints effect in fractured rock masses where joints or discontinuities cannot be precisely located. In chalk, this technique can be considered appropriate.

Concerning stability and the associated failure mechanisms, the technique used in this paper is based on the shear strength reduction (SSR) approach and permits the calculation of factor of safety using different numerical procedures. Zienkiewicz [5] showed that the factor of safety could be established by assisting numerical models that apply the strength reduction scheme. Griffiths [11,12] extended this work over a wide range of soil properties and geometries and presented reliable results for slope stability. Shear strength reduction technique employed in different practices by numerical stability study [13] was later improved to consider nonlinear failure criteria by Dawson et al. [14]. The effect of joints was also integrated in the computation of factor of safety [15–18] in order to provide more reliable tools to be encountered in stability engineering problems.

This paper aims to study the effect of joints on the behavior of underground cavities excavated at shallow depths in jointed chalk layers. Based on the geological inspections performed [1], geometry characteristics and ground properties are defined and numerical models of the excavation are simulated. Two main issues are considered in the numerical analysis: (i) a nonlinear constitutive law used to account for the effect of joints on the chalk behavior is developed based on the theory of multi-mechanisms for plastic strains by Koiter [19,20], (ii) an algorithm to compute a strength reduction factor based on the conventional shear strength reduction (SSR) method [5] is provided and implemented in the numerical analysis of the excavation. By this, strain and failure mechanisms are simulated and the influence of joints on the ultimate resistance and deformational behavior of the underground cavities are analyzed.

2. Numerical modeling of a chalk cavity

2.1. Geometry and ground properties

The geometry of underground quarries depends on the diversity of exploitation methods used. The most frequent discovered in North France and its region, are known by ‘holts or bottles’ and ‘room and pillar’. This latter represents the majority of the cases [21,22], and is the concern in this study (Fig. 1). Consequently, dealing with cavities excavated by the method of rooms and pillars, a wide range of geometric parameters can be incorporated. Variation in dimensions of both pillar and roof is expected to produce a considerable influence on their deformability and strength. Nevertheless, the aim in this work is to focus merely on the effect

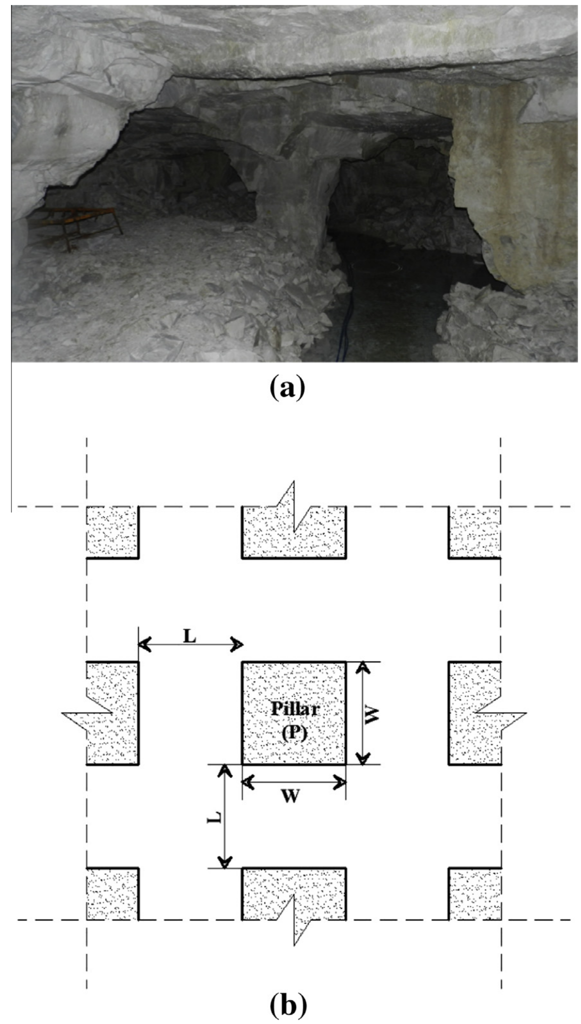

Fig. 1. (a) Underground quarry in Hellemes-North France (Lille Municipality, 2013), (b) top section of the room and pillar quarry.

of joints. Therefore, a particular case of geometry chosen from cases in North France [21,22], is considered in the numerical modeling of the excavation which is detailed later. The pillar of jointed chalk is of width $W = 6$ m and height $h = 3$ m, the void room is of clear span $L = 6$ m, covered by $H(\text{chalk}) = 7$ m of jointed chalk at the roof and above them silt with $H(\text{silt}) = 3$ m (Fig. 12(b)).

Ground properties are inspired from experiments carried out on chalk samples taken from the quarries excavated in North France and its region [23–25]. A summary of these properties used in the numerical modeling is provided (Table 1).

The chalk continuum constitutes of intact chalk represented by the matrix and two symmetric embedded joint sets defined as weak planes [21,22]. Same elastic properties are defined to assess the stress state in the element including the matrix and the joints. The irreversible strains in the matrix and in the joint sets are simulated by considering several failure criteria in the framework. In

Table 1
Mechanical properties of chalk including matrix and joints, and silt.

		Young modulus (MPa)	Poisson ratio	Cohesion (kPa)	Friction angle (°)	Dilation angle (°)
Chalk	Matrix	250	0.3	200	30	5
	Joints			20	30	5
Silt		10	0.3	10	30	5