Impact de digues sur la stabilité des cavités karstiques

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IMPACT DE DIGUES SUR LA STABILITE DES CAVITES KARSTIQUES

IMPACT OF DIKES ON THE STABILITY OF KARSTS

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RÉSUMÉ — L'objectif principal de cette contribution est d'étudier les mécanismes d'interaction entre un fontis et une digue quand elle se trouve dans un environnement karstique. L'inter-influence entre une digue et une cavité dépend, entre autres, de la nature de substratum, de la position de la cavité par rapport à la section transversale de la digue. On cherche à hiérarchiser les différents paramètres géométriques et géomécaniques jouant un rôle dans la stabilité des fontis afin d'améliorer le diagnostic vis-à-vis de l'influence des fontis sur la stabilité de digues. Un modèle analytique mécaniste est utilisé. Nous avons modifié ce modèle afin de tenir compte de la présence de digue. Le modèle modifié tient compte de la géométrie de la digue, la variation du niveau de l'eau lié à la rivière et la variation du niveau d'eau au sein de la digue. Ce modèle a été appliqué aux cas de digues de Val de Loire (Orléans) où la hauteur de terrains de recouvrement correspondant à un sol plutôt peu résistant est faible. Nous avons retenu deux hauteurs : 5 et 10 m. Nous avons calculé la stabilité d'une cavité pour différentes positions par rapport à la digue. Les premiers résultants ont montré que l'instabilité de la cavité karstique pourrait être significativement influencée sous le centre de la digue, notamment pour une profondeur de 5 m. En conséquence, la présence de la digue augmente le risque de fontis d'origine karstique. L'étape suivante du travail concerne les conséquences du fontis sur la stabilité des digues.

ABSTRACT — This paper aims to investigate interaction mechanisms between sinkhole and dike when built over covered karst areas. The influence of sinkholes over the dike stability may depend on the localization of the cavity relatively to the dike. This feature is investigated with analytical method. The aim of this paper is to understand the cavity-dike-cavity interaction mechanisms and to prioritize the geometric and geotechnical parameters for a better evaluation of the risk of dike failure in karst areas. As a result, this study is used to prioritize the location where a sinkhole occurrence is the most probable to occur and damage the dike. The analytical model is based on the mechanical model developed by He et al. (2004).This model considers a simplified shape of the karst cavity which allows taking into account the influence of stresses of overburden and water over its stability. In this paper, a modified analytical model of the karst cavity stability taking into account the dike is developed. More specifically, the model takes into account the dike geometry, the changing of river water level, and the high of water table in the dike. According the in situ-observation and data for Orleans – Val de Loire district (France), two configurations are investigated with an overburden thickness above the cavity equal to 10 and 5 meters. The impact of the cavity position along the dike cross-section is then taken into account and a safety coefficient of the cavity collapse is calculated. Whatever, the model doesn't take the non-linear behavior of soil and dike. The first results of the analytical method show that the instability of the karst cavity could increase significantly under the center of the dike and can affect the stability of dike when it's close to it. The dike increases the risk of the sinkhole. The collapse of the cavity can contribute to the causes of the collapse of a dike.

1. Introduction

Karst refers to a distinctive terrain that evolves through dissolution of the bedrock. It is therefore associated primarily with limestone, but also forms on other carbonates and other soluble rocks (Waltham et al., 2005). Cavities may appear in rock affected by dissolution and cause the subsidence and collapse in upper layers of soils. Sinkhole is considered as a final result when the collapse and propagation of the cavity reaches the surface.

Karsts problems worldwide create huge annual costs that are increased due to insufficient understanding of karsts by engineers (Filipponi and Jeannin, 2008). The presence of a cavity underneath civil engineering structures (especially under hydraulic structures) raises concerns about the safety and stability of these structures. A collapse of hydraulic structure may cause catastrophic, human, financial and environmental losses. This paper focuses on one of the hydraulic structures kinds which is called dikes and sometimes called flood defense embankments or river levee) (International Levee Handbook - Scoping Report, 2010). The river dike (or river levee) is defined as "an embankment whose primary purpose is to furnish flood protection from seasonal high water and which is therefore subject to water loading for periods of only a few days or weeks a year" (U.S. Army Corps of Engineers, 2000).

The central issue of the present work is to find a method to assess the influence of a dike over the stability of karst cavities beneath. A mechanical model initially developed in China by He Keqiang et al (2004) is modified to take into account influence of upper dikes and embankments.

2. Sinkhole karsts collapse mechanism

The collapse of karst cavities can take different forms: subsidence, sinkhole, etc. The sinkhole is a brutal failure of the ground above the cavity. There are classically two theories to explain the mechanisms of a brutal karst collapse (Chen, 1988, Thrrap, 1999, Salvati et al, 2002, He Keqiang et al, 2004, Zhao et al, 2011).

The first one is the theory of potential erosion, which proposes that when the water table is lowered due to natural (drought) or human (pumping) factors, the groundwater velocity increases and the hydraulic gradient becomes steeper. Thus the groundwater outwashes and erodes the soil cover (overburden) to form the original hole of a soil cave at the interface between the soluble bedrock and the soil cover.

- If the soil cover is enough thick and has good structure, a natural balanced arch will be formed in the soil cave and the cave will not collapse, if there are no other inducing factors.
- If the soil cover is thin and has poor structure, the soil cave will continue to enlarge until a collapse occurs.

The other one is the vacuum suction erosion theory, which involves relatively airtight confined karsts water. When groundwater suddenly falls by large amplitude and the water table drops below the floor of the soil cover, the groundwater will change from confined to unconfined and a relative vacuum of low air pressure will occur between the water table and the floor of the soil cover.

To evaluate the risk of sinkhole due to karst cavities, He Keqiang et al, 2004 have proposed a mechanical model based on the arch stability. In addition, the study of karsts collapse in Zaozhuang City, China, was carried out using this mechanical model: the results show that the mechanical model agrees with the forming mechanisms and the actual stability situation of the karst cavities.

On the basis of an analysis of the mechanisms and factors that induce karst collapse, combined with the theory of soil-limit equilibrium which is used in the mechanical model of He et al, 2004, this paper establishes mechanical model to evaluate the stability of a karst cavity. In addition, an evaluation of karst cavity underneath the dike of Loire near Orléans city, France, was carried out using the modified mechanical model.

2.1. Mechanical model of He Keqiang et al, 2004

The analytical mechanical model of He Keqiang et al, 2004 provides a theoretical basis for studying the risk of collapse in the presence of dikes. To determine the limit equilibrium height of the soil-hole arch, the following assumptions were made by the authors (figure 1-a):

- Before the original soil hole occurs in the interface between the karsts and the soil cover, the karsts cave has a rectangular shape with a width equal D and height h`.
- The stresses acting on the roof of the karsts cave (see figure 1-b) include the deadweight σ (1) of the cover-layer of soil, the differential atmospheric pressure Δp (2), and the vertical seepage pressure F seepage (3). These three stresses are all distributed rectangular in a vertical direction. To determine the height of the arch, the left part of the arch oa (figure 1-b) was chosen to be analyzed. Supposing that the arch, oa, is acted upon by several forces and it is in a state of equilibrium due to the different stresses. The equilibrium conditions of different forces and moments can then be expressed as follows:

$$(\sum Fx=0,\ \sum Fy=0 \text{ and } \sum Mo=0) \qquad (1)$$

If the arch, oa, is assumed to act upon by several forces and is in a state of balance, the height of the stable arch hmax can be calculated. They considered the arch is kept in an equilibrium state, for that the horizontal force v must be less or equal to the friction caused by the vertical force n at the point a. To guarantee the arch stability in the horizontal direction, the frictional resistance must be greater than the force v supposing that the safety factor of the arch is 2.

$$2t=v=n.fk \qquad (2)$$

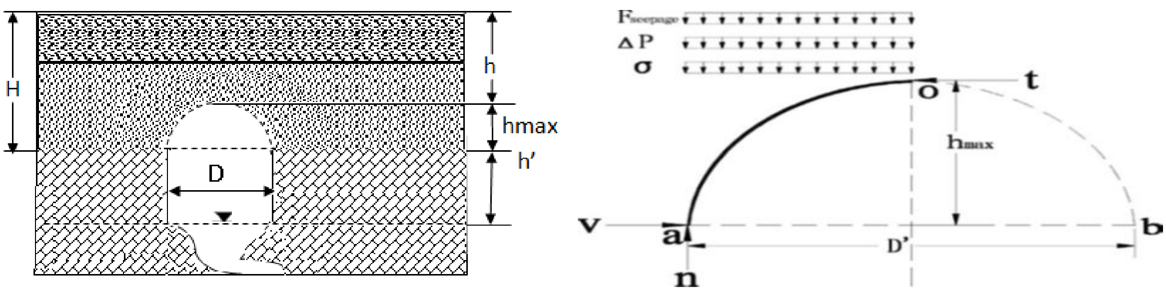

Figure 1. (a)Original karsts cave and equilibrium arc of the soil hole. Where hmax refers to the height of the pressure arch above the cave ceiling, which is the limit equilibrium height of a soil-hole arch; and H is the thickness of cover-layer soil (one layer or more) (He Keqiang et al, 2004). (b) Mechanical condition of the pressure arc (He Keqiang et al, 2004)

Where: fk is the coefficient of friction of the cover-layer soil (equal to tangent of internal friction angle). From equations 1 and 2:

$$hmax=\frac{D'}{2fk} \qquad (3)$$

The authors considered that the sidewall of the karst cave is stable and the failure of the arch cavity can only take place in the cover-layer of soil. Therefore, the span of the pressure arch D', is roughly equal to the span of the karst cave D. In addition, because the karst cave is in three dimensions with a circular plane, Eq. (3), which is in two dimensions, should be corrected by adding an experimental coefficient. For a solid cave with a circular plane, the experimental coefficient is chosen to be 0.828 according to Chen Guoliang, 1994 (cf. He Keqiang et al, 2004).

$$hmax=0.828\frac{D'}{2fk} \qquad (4)$$

If assumed that the arch collapse, because excessive compressive stresses for example, the strength may be investigated by considering the whole stability of the soil cylinder above the cave.

For this, they considered the four following forces (Fc):

(1) The deadweight of the soil column (Gsoil in eq. 5).

(2) The deadweight of rainwater (Grain in eq. 6).

(3) The seepage force (Fseepage in eq. 7) (see fig.2).

$$\mathbf{Gsoil} = \gamma.\frac{\pi D^2}{4} h \quad (5)$$

$$\mathbf{Grain} = \gamma_W.\frac{\pi D^2}{4} h0 \quad (6)$$

$$F_{seepage} = \frac{\pi D^2 (h0 + h)}{4}\gamma_W + \frac{3\pi D^2 V^2}{16dg}\gamma_W h \quad (7)$$

Where, d is the average grain diameter of soil (mm), h0 is the level of karst groundwater (which is considered equals to the level of rainwater on the ground surface) and V is the seepage flow velocity (m/s).

(4) The differential atmospheric pressure Δp (differential pressure between the atmospheric pressure and the relative low pressure in the soil cave) is difficult to assess, experimental values are needed to establish the model. According to the measurements of Chen Guoliang, 1994, the maximum value of differential atmospheric pressure is less than 50 kPa. They considered the lateral force due to the friction (φ) and the cohesion (c) is the force of resistance (f):

$$f = \pi D\left(\frac{K\gamma D^2}{2}\tan\varphi + ch\right) \quad (8)$$

Where K is the lateral compressive coefficient of soil.

Figure 2 shows the cross section of the collapse of a column of soil above the arch of the cavity and also the main forces, which affect the stability of the cavity arch. For calculation of the factor of safety of sinkhole stability, they equated between the pressure forces of collapse (Fc) and the pressure force of resistance (Fac)):

$$Fac = \frac{4}{D}\left(\frac{K\gamma h^2}{2}\tan\varphi + ch\right) \quad (9)$$

$$Fc = \gamma h + \gamma_W h_0 + (h_0 + h)\gamma_W + \frac{3V^2}{4dg}\gamma_W h + \Delta P \quad (10)$$

Therefore, the safety factor can be defined as:

$$F.S = \frac{Fac}{Fc} = \frac{\frac{4}{D}\left(\frac{K\gamma h^2}{2}\tan\varphi + ch\right)}{\gamma h + \gamma_W h_0 + (h_0 + h)\gamma_W + \frac{3V^2}{4dg}\gamma_W h + \Delta P} \quad (11)$$

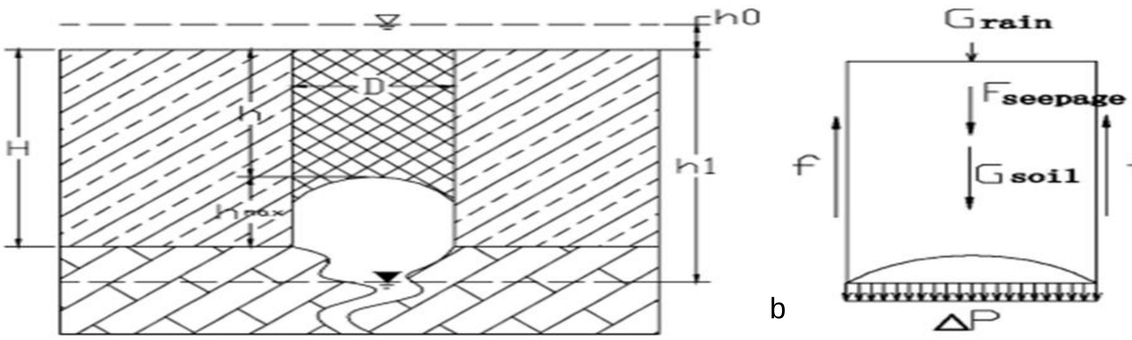

Figure 2. (a) Cross section of the karsts collapse column, (b) Mechanical analysis of the karsts collapse column (He Keqiang et al, 2004).

2.2. Dike effect and the modification

Before presenting the modification of the previous mechanical model, we show here a typical cross section of a Loire dike (levee) near the city of Orléans (France) that was taken as a case study (see figure 3). The section presents different periods of the construction and the reinforcement of the dike. The typical dimensions of the dike are: height of dike is 7 m and the slope in water and land sides is 1V/2H. The karstic limestone under the gravel and sandy alluvium soil can contain cavities. Previous equations are modified by adding the effect of dike weight and the changing of water table in it. The same pressure force of anti-collapse, Fac, is considered (eq. 9). The collapse force is changed by neglecting the part of seepage velocity because it could be considered very small and by considering the additional weight of the dike and the flood. Four situations according the level of water in upstream and the position of the cavity are considered (see figure 4). So, we can rewrite collapse pressure force (Fc) as follows:

$$Fc\left(flood, \frac{u}{s}\right) = \gamma(h + hy) + \gamma_W(h + hd) + \mathbf{\Delta}P \quad (12)$$

$$Fc\left(flood, \frac{d}{s}\right) = \gamma(h + hy) + \gamma_W(h + yph) + \mathbf{\Delta}P \quad (13)$$

$$Fc(normal) = \gamma(\boldsymbol{h} + \boldsymbol{h}y) + \gamma_W(\boldsymbol{h}) + \mathbf{\Delta}P \quad (14)$$

$$Fc(dry) = \gamma(\boldsymbol{h} + \boldsymbol{h}y) + \mathbf{\Delta}P \quad (15)$$

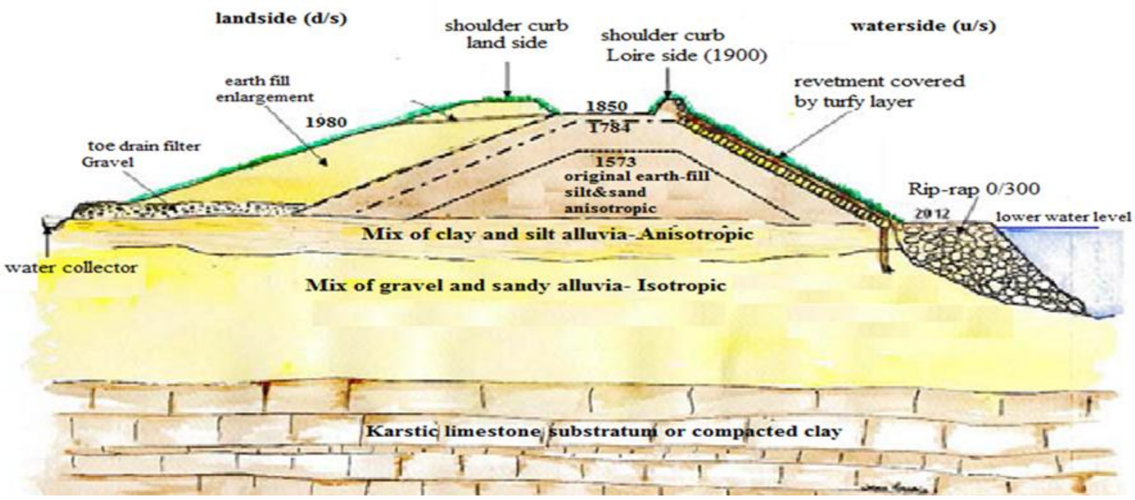

Figure 3.Typical cross section of a Loire levee nowadays (courtesy Jean Maurin) (International Levee Handbook, 2012)

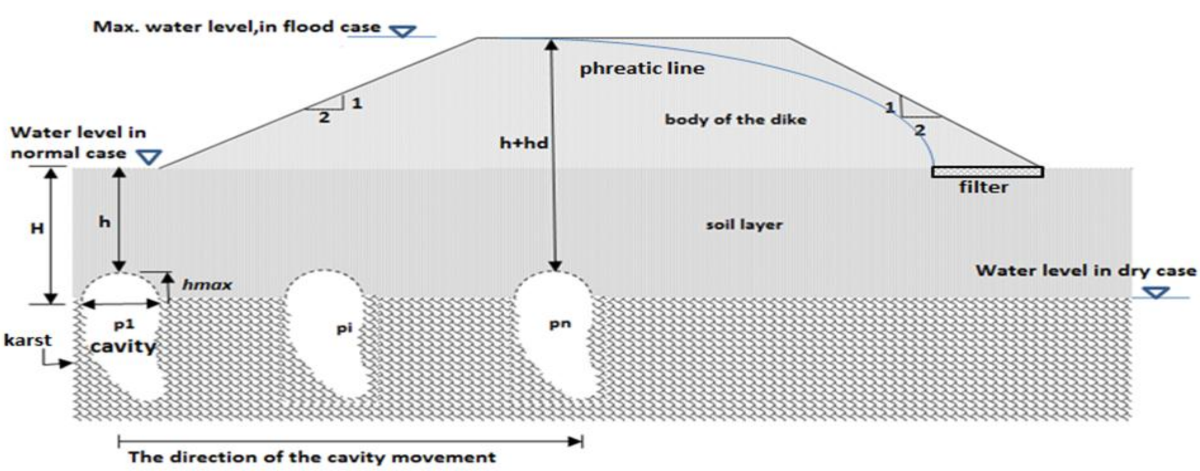

Figure 4. Different positions of sinkhole (horizontally from position p1 to position pn = 14 m)

Where:

Fc (flood, u/s) is the collapse pressure force for the dike saturated part in upstream (horizontally from bottom of the dike to its top) in the case of floods, assuming the level of water river equals to the top of the dike,

Fc (flood, d/s) is the collapse pressure force for dike semi-saturated and dry parts in downstream (horizontally from top of the dike to its bottom) in the case of floods, assuming the level of water river equals to the top of the dike and taking into account the height of the phreatic line through the dike,

Fc (normal) is the collapse pressure force in normal case when the level of river water equals to the level of the bottom dike,

Fc (dry) is the collapse pressure force in dry case when the level of river water underneath soil (alluvial) level, hy is the height of the dike part over the cavity and yph is the height of phreatic line over the cavity. Hd is maximum height of dike (for typical dike is equal to 7 m).

3. Evaluation of karst cavities stability under the typical Loire dike near Orléans

The Loire dikes are old linear earthen structures built over time to protect Loire flood plains from flood damages (International Levee handbook, 2012). In the Val d'Orléans area, more than 63,000 people live in the zones threatened by a major flood of the Loire, protected behind 40 km of levees. In case of breach in one of these levees, 11,000 people would be threatened directly (Maurin et al, 2012). The modified mechanical model was applied to evaluate the stability of karsts cavity in the alluvial layer underneath a typical Loire dike in Orléans city (France). For evaluation the dike impact on the stability of the cavity and for comparison between the results, we assume the following reference values for alluvium soil (FILLIAT,1981): the height of cover layer (H) =5 m; the cohesion (c) =20 kPa and the internal friction angle (Φ) =30°. The values of H and D are based on database of Loire dike in Orléans (Mathon, 2011). It is important to note that we considered that the properties of the dike and the soil beneath it are the same and homogeneous.

A sensitivity study was carried out basing on the data collected during large period (Gombert et al. 2014) , with a thickness of soil layer above the karsts layer (H) equals to 5 m or 10 m. The cavity position varies with respect to the geometry of the dike for deferent width of cavity D (from 1 to 5 m).

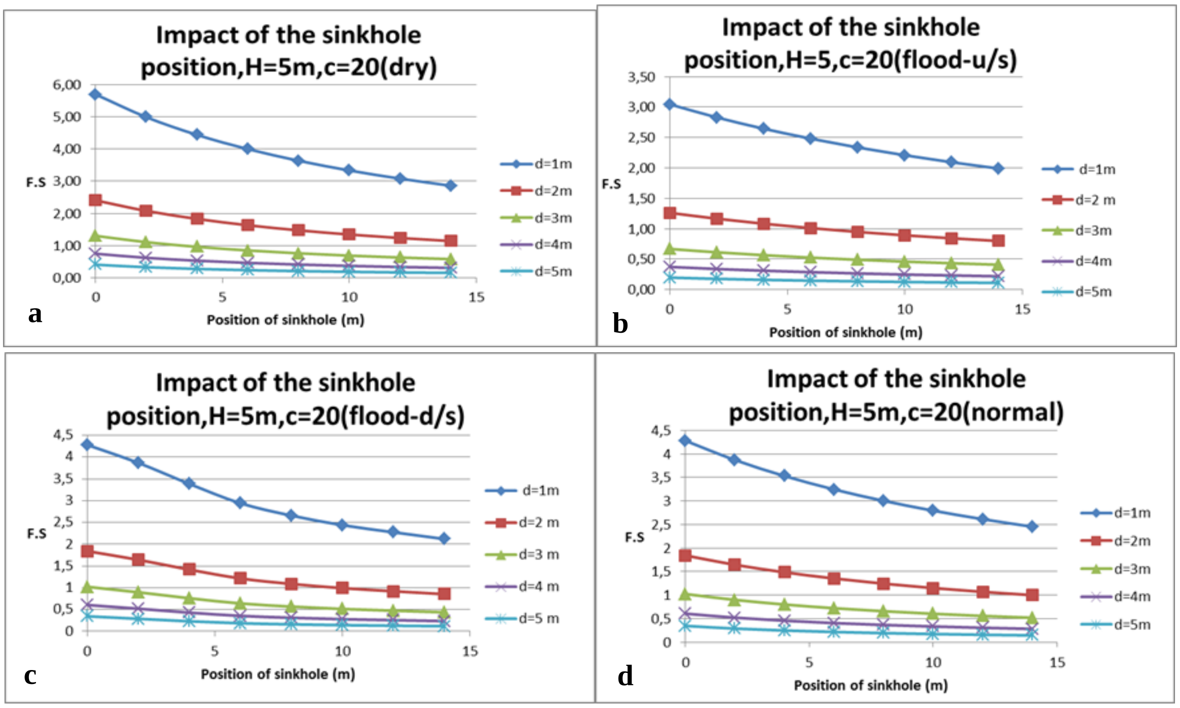

Figure 5. Relation between the position of cavity with respect to the dike and the safety factor. a- dry case (water level below of alluvial layer), b- flood case for the

cavity underneath upstream dike side, c- flood case for the cavity underneath downstream dike side, and d- normal case (water level at the bottom of the dike).

4. Results analysis

The stability of the cavity is considered when the safety factor is greater than 1. We compare the number of the stable configurations. The figure 5 shows the factor of safety of previous cases when alluvial layer equal 5 m and with different width of the cavity (from 1 m to 5 m) in eight different positions underneath the dike (from p1=0 to pn= 14 m). We can note, in the dry case (figure 5 a), that 45% of the 40 cases are safe (safety factor > 1) while, in the flood case (figure 5 b) only 30% of cases are safe. The flood case for cavity in downstream dike side (figure 5 c) is more stable than the previous case of upstream dike side with 35% of safe cases while the normal case (figure 5 d) has 37.5% of cases are safe.

The results of figure 5 show that the increasing of the water level leads to decrease the cavity stability, in other word, the water level in upstream side of the dike adversely affect the stability of cavity.

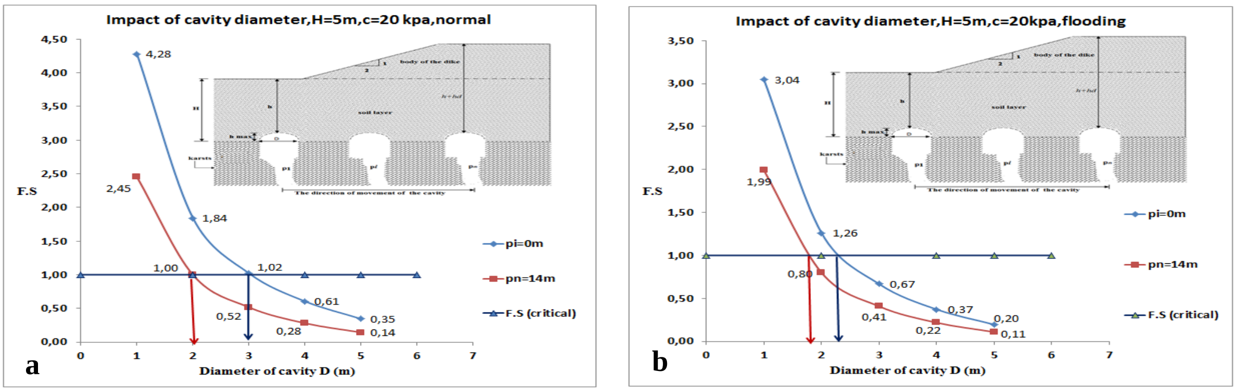

Figure 6. Effect of cavity diameter on its stability in deferent positions. a- in normal case. b- in case of flooding.

5. Conclusion

The stability of karst cavity was carried out taking into account the existing of the dike. The work presented herein is based on an analytical approach. The modification of the model concerns the introducing of the vertical load due to the dike. The application of the mechanical model helps us to get a simple method to evaluate the impact of a cavity on the dike stability. The model is applied on the configuration of Orléans dikes. The values of different parameters were based on collected data.

According to the results, the risk of the cavity collapse can be increased significantly by the effect of dike. The collapse could occur in the flood season for a cavity diameter roughly equal to 2 m and a cavity located underneath the maximum height of the dike.

The analytical model is sample method but some phenomena cannot be considered mainly the non-linear behavior of terrain. The first results need an improvement to take into account different complex phenomena associated to flooding and soil erosion, numerical modeling will be carried out for better understanding of dike-cavity interaction.

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