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Prevention of risk due to karstic cavities detected in a recent motorway in Tunisia using geotextiles

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ABSTRACT: Recently in Tunisia, along the construction of a recent motorway, karstic cavities were localized on a section of about two kilometres. The geotechnical and geological data show that the detected cavities are randomly distributed, and have varied shapes and depths. The hydrogeologic study showed the presence of heavy water activities, which has a high acid concentration. Therefore, strong dissolutions are generated in the gypsum soil that given apparent or no apparent collapses. In order to guard against the risks of accidents that might result from theses cavities, reinforcement of the road bedding layers by underlying geosynthetic materials was considered. The aim of this reinforcement is to limit the surface settlement to permissible value to allow traffic circulation to continue until repairing work on the fill material could be implemented. The technical solution adopted is presented, and the major assumptions used for the design methods are discussed. A particular attention is focused on shape cavities effect for which some numerical tests are carried out leading to conclusions about the geotextile designing.

1 INTRODUCTION

Tunisia, from its geology is a region subjected to the karstic risk. An example of the motorway section provides a very recent illustration. During the construction of the motorway karstic cavities have been observed on a section of about two kilometres. The concessionary "Tunisie-Autoroute" company is associated with CETA (Technical engineering company) for a designing work. "Terrasol-Tunisie" and "Terrasol-France" companies had the responsibility of an expertise of the risk and the study of the convenient solution.

The karstic cavities risk relating to the collapse of blocks from the cavity roof presents a serious safety hazard (Gesualdo A. and al. 2001). These anomalies lead serious problems with respect to the achievement of works, of the perennially of the motorway and the safety of the future users. Two types of anomalies were indexed:

- Collapses related to the presence of karstic cavities, in general from 2 to 3 m in diameter (Fig. 1), but being able to reach in certain cases 4 m to 5 m length by 2 m width (Fig. 2). The collapse phenomenon is complex and very randomly (slowly collapse or collapse of blocks).
- Old chimneys (slowly collapse), filled by argillaceous and marly materials, which testify to the past and evolutionary nature of the karstic phenomenon (Fig. 3).

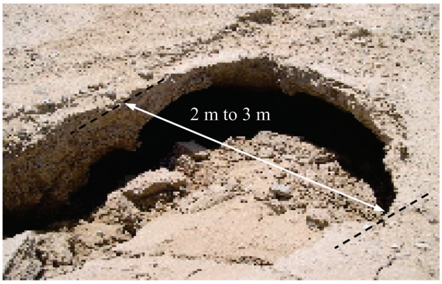

Figure 1. Circular cavities from 2 to 3 m.

In these areas the soil is composed by gypsum of Triassic and marled clay with 30 m thickness, where heavy water activities were developed, which have a high acid concentration that induce the dissolutions of the gypsum and generate the formation of sub soil cavities. The depths and the shapes of cavities already detected are varied. In fact, it is very difficult to detect with the usual method in order to detect all the cavities, in particular, the small cavities at medium or great depths.

Figure 2. Irregular cavities about 4 m × 2 m.

Figure 3. Old chimneys, filled by filling materials.

2 CHOICE OF THE TECHNICAL SOLUTION

The technical solution to be selected for the karstic problems need to take into account the risks incurred in the short and medium term (collapse of the cavities) and long-term (extension of the phenomena of dissolution of the gypsum under the action of seepage waters). Among the solutions which were discussed, we have:

- The use of a concrete slab resting on gypseous base, after filling of the apparent cavities,
- The reinforcement of the embankment by a network of piles if the substratum is intact,
- The filling of the cavities and the use of a geotextile of reinforcement.

The first two alternatives were remote. Indeed, the use of a concrete slab being a rigid structure can mask the formation of the karstic cavities, and does not allow to follow the progression of the phenomenon. With this solution, the collapse of the roadway is probably quick and rather greater and does not constitute a preventive solution. With the reinforcement by a network of piles, one is confronted primarily with a technical problem related to the installation of the piles. Indeed, the lack of the lithological data and complexity of the site make difficult the determination of the zones where the piles can be driven.

The third solution considered seems the most adapted to this problem. Indeed, the treatment of the cavities by injection of filling materials makes it possible to slow down their evolution. Moreover, the use of a geosynthetic, positioned at the base of the embankment, makes possible to detect presence of a cavity, due to the vertical movements obtained at the surface, and on the other hand to limit the surface settlement to permissible values allowing traffic circulation until repairing works can be carried out. For this project, the purpose of the designing method is to obtain in serviceability limit state a maximal surface settlement of 0.10 m for diameters of cavities of 2 m (maximal strain acting on the geosynthetic less than 5 %).

3 REINFORCEMENT BY GEOSYNTHETIC

3.1 *The technical solution chosen*

The technical and economical solution chosen for the reinforcement of the road embankment is a non woven geotextile armed in the traffic direction with polyester high tenacity fibres (reinforcement is needed to support the required tensile force).This choice owing to the qualities of this type of geotextile as easy and quick to install and guarantees the anchorage to be parallel to the road (no need to make transverse anchorage). The embankment, carried out above the geosynthetic sheet, is constituted by a layer of granular material of 0.8 m height. The thickness of the pavement road layer is about 0.35 m.

3.2 *The usual analytical design methods*

Two analytical design methods are commonly used in Europe: the British Standard (BS8006 1995) and the French method (Villard et al. 2002) based on numerical and experimental results of the full-scale experimental program RAFAEL (Villard et al. 2000). The major difference between the two methods leads on the assumption of the collapse area over the cavity. This area is assumed to be trunconical for the BS8006 method and to be cylindrical for the RAFAEL method. Another difference is the use for the RAFAEL method of an expansion coefficient characteristic of the dilatance capacity of the fill embankment. These two assumptions lead, in some cases, to very different design results. We note: H the thickness of the granular embankment (H = 0.8 m), D the diameter of the cavity, f the vertical maximal displacement of the reinforced geotextile on the axis of the cavity, s the settlement at the surface embankment, C_e, ϕ and γ, respectively the expansion coefficient, the friction angle and the dry density of the granular fill material ($\phi = 30°$ and $\gamma = 20$ kN/m^3), p the live load at the surface due to the weight of the pavement road layer and to the dynamic traffic load (p = 29 kN/m), q the vertical stress applied on the reinforced geotextile, ε_{max} and T_{max} the maximal strain and the maximal tensile force acting on the reinforced geotextile, and K_a the active earth pressure coefficient. The equations used by the RAFAEL method are:

$$q = \frac{D\,\gamma}{4\,K_a\,\tan\phi}\left(1 - e^{-K_a \tan\phi\, 4\,H/D}\right) + p e^{-K_a \tan\phi\, 4\,H/D} \qquad (1)$$

$$T_{max} = \frac{q\,D}{2}\sqrt{1 + \frac{1}{6\,\varepsilon_{max}}} = J\,\varepsilon_{max} \tag{2}$$

$$\varepsilon_{max} = \frac{8}{3}\left(\frac{f}{D}\right)^2 \tag{3}$$

$$s = f - 2H\,(C_e - 1) \tag{4}$$

$$K_a = (1 - \sin\phi)/(1 + \sin\phi) \tag{5}$$

The equations used by the BS8006 method are for one direction of reinforcement and in serviceability limit state:

$$q = \gamma\,H + p \tag{6}$$

$$T_{max} = \frac{q\,D}{2}\sqrt{1 + \frac{1}{6\,\varepsilon_{max}}} = J\,\varepsilon_{max} \tag{7}$$

$$\varepsilon_{max} = \frac{8}{3}\left(\frac{f}{D}\right)^2 \tag{8}$$

$$s = f\Big/\left(1 + \frac{2H}{D\tan\phi}\right)^2 \tag{9}$$

3.3 *The expectation of the surface settlement*

The criterion commonly used for the design method is the surface settlement which must be sufficiently weak to allow the traffic circulation until repairing work on the fill material could be carried out. One of the difficulties met wile designing this type of structure is related to the choice of some parameters, for example, the diameter of the cavities. In this case, it is advisable to consider an average diameter of cavity of which the probability of appearance is greater, which is in practice not very easy taking into account the difficulties encountered to locate the cavities whose form is in addition complex. Another parameter is the choice of the design method. To evaluate the influence on the surface settlement of different assumptions, some calculations were carried out, the ones by using BS8006 method, the others using the RAFAEL method. For the latter, four values for the expansion coefficient C_e were chosen. This parameter has a great influence on the dimensioning while being very difficult to evaluate (especially for re-compaction under traffic which must reduce C_e). It is admitted that for usual filling materials the value of C_e should not exceed 1.15. With the assumption of an expansion coefficient equal to one, the surface settlement for the RAFAEL method is equal to the maximal vertical displacement of the geotextile sheet. The results of calculations are deferred in tables 1, 2 and 3 for three values of the diameter of the cavities (D = 2 m, D = 3 m and D = 4 m).

From the results obtained we can note that the design methods used give closed results for the maximal strain and maximal tensile force on the geosynthetic. On the other hand, the surface settlement is rather different, in particular in the case of D = 3 m or D = 4 m. For cavities of 2 m diameters the surface criterion s/D of 5 % is obtained both with the BS8006 and RAFAEL method (C_e = 1.1). In these cases, the maximal strains of the geosynthetic are around 5 % that leads to the required characteristics of the geosynthetic. For the two dimensioning methods, the rigidity of the pavement road layer is not considered. One can expect in reality lower surface settlements than those calculated.

Table 1. Results of analytical methods (D = 2 m).

Analytical Method	BS8006	RAFAEL C_e = 1	RAFAEL C_e = 1.05	RAFAEL C_e = 1.1	RAFAEL C_e = 1.15
D (m)	2	2	2	2	2
s (m)	0.053	0.274	0.194	0.114	0.034
f (m)	0.3	0.274	0.274	0.274	0.274
T_{max} (kN/m)	87.4	72.9	72.9	72.9	72.9
ε_{max} (%)	6.02	5.02	5.02	5.02	5.02
s/D (%)	2.64	13.7	9.72	5.72	1.72

Table 2. Results of analytical methods (D = 3 m).

Analytical Method	BS8006	RAFAEL C_e = 1	RAFAEL C_e = 1.05	RAFAEL C_e = 1.1	RAFAEL C_e = 1.15
D (m)	3	3	3	3	3
s (m)	0.141	0.492	0.412	0.332	0.252
f (m)	0.523	0.492	0.492	0.492	0.492
T_{max} (kN/m)	117.9	104.1	104.1	104.1	104.1
ε_{max} (%)	8.12	7.17	7.17	7.17	7.17
s/D (%)	4.71	16.4	13.7	11	8.4

Table 3. Results of analytical methods (D = 4 m).

Analytical Method	BS8006	RAFAEL C_e = 1	RAFAEL C_e = 1.05	RAFAEL C_e = 1.1	RAFAEL C_e = 1.15
D (m)	4	4	4	4	4
s (m)	0.271	0.742	0.662	0.582	0.502
f (m)	0.778	0.742	0.742	0.742	0.742
T_{max} (kN/m)	146.5	133.2	133.2	133.2	133.2
ε_{max} (%)	10.09	9.17	9.17	9.17	9.17
s/D (%)	6.79	18.55	16.5	14.5	12.5

3.4 *The influence of the shape of cavities*

A finite element model allowing the modelling of the fibrous nature of the geotextile was used in order to take into account different shapes and orientation of the cavities (circular and rectangular) and different types of reinforcement (reinforcement in the longitudinal direction and reinforcement in two perpendicular directions) (Fig. 4). The diameter of the circular cavities is 2 m and the size of the rectangular cavities is 2 m × 4 m. For the numerical simulations the geosynthetic is assumed to be a non-woven geotextile (J = 25 kN/m) reinforced in one (J = 1440 kN/m) or two perpendicular directions (J = 720 kN/m in each direction). Vertical forces are applied on the geosynthetic in order to simulate a uniform vertical load of 45 kN/m^2. The results obtained (sag and tensile forces in reinforced directions) are presented in table 4 and in figures 5 and 6.

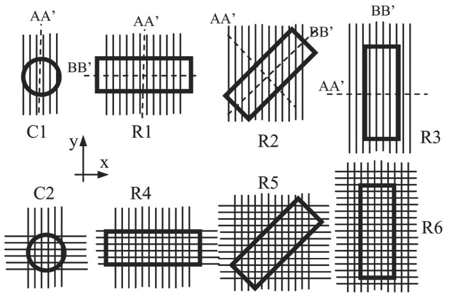

Figure 4. Geometries of cavity and reinforcement studied.

Table 4. Results of numerical approach.

Case	f (m)	Ty_{max} (kNm)	Tx_{max} (kNm)	Transverse Anchorage
C1	0.291	84.99	0.87	No
R1	0.293	85.73	1.87	No
R2	0.459	102.13	0.64	No
R3	0.733	140.71	3.65	No
C2	0.298	48.77	48.77	Yes
R4	0.370	71.10	44.75	Yes
R5	0.454	53.27	53.27	Yes
R6	0.370	44.75	71.10	Yes

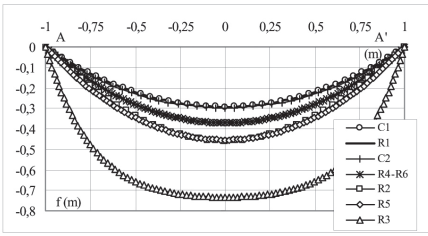

Figure 5. Vertical displacements of the sheet in section AA′.

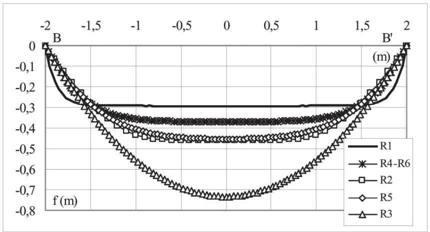

Figure 6. Vertical displacements of the sheet in section BB′.

The whole results obtained show the great influence of the shape of the cavities (the maximal vertical displacements of the geosynthetic sheet are comprised between 0.291 m for case C1 to 0.733 m for case R3). We can note that the vertical displacements obtained in the cases C1, R1 and C2 are very similar. R1 give better results than R4 but R3 give worse result than R6. In fact, in the cases of one direction of reinforcement, the size of the cavity needed for the design is the length of the fibre reinforcement over the cavity. In this case, the numerical and analytical results, based on similar assumptions (2D and uniform vertical load), are in good agreement (comparison between C1, R1 and table 1, and comparison between R3 and table 3). Reinforcement in two perpendicular directions may be useful with dissymmetrical cavities (R2 similar to R5, R6 better than R3 but R4 worse than R1). Note that this technical option needs to be carried out with a transverse anchorage, and that analytical formulations cannot be used easily.

4 CONCLUSIONS

The randomness and unforeseeable karstic mechanisms are at the origin of the difficulties encountered to find an efficient solution of reinforcement of road embankment. A preventive solution with reinforced geotextile was carried out to minimize the risks due to collapse being able to occur. The design of this type of structure is taking into account strong uncertainties about the shape and the diameter of the cavities problematic. Indeed, as numerical simulation carried out shows, these parameters have a great influence on the designing. For this type of problems, it is necessary to keep in mind that the solution of reinforcement proposed is temporary and that it makes it possible to avoid dramatically accident in other circumstances. The reinforced solution was really applied and the traffic on the motorway has been beginning in February 2006. The chosen geosynthetic is constituted from a reinforced non woven geotextile and have the following main properties: the maximum average tensile is 260 kN/m corresponding to 8% of strain (J # 3200 kN/m).

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