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Probabilistic tunnel face stability analysis: A comparison between LEM and LAM

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Abstract. It is a key issue in the tunnel design to evaluate the stability of the excavation face. Two efficient analytical models in the context of the limit equilibrium method (LEM) and the limit analysis method (LAM) are used to carry out the deterministic calculations of the safety factor. The safety factor obtained by these two models agrees well with that provided by the numerical modelling by FLAC 3D, but consuming less time. A simple probabilistic approach based on the Mote-Carlo Simulation technique which can quickly calculate the probability distribution of the safety factor was used to perform the probabilistic analysis on the tunnel face stability. Both the cumulative probabilistic distribution and the probability density function in terms of the safety factor were obtained. The obtained results show the effectiveness of this probabilistic approach in the tunnel design.

Keywords: safety factor; tunnel face; limit equilibrium method; limit analysis method; probabilistic analysis; Monte-Carlo simulation

1. Introduction

The evaluation of the stability of the excavation face is one of the most important aspects in the tunnel design. In shallow tunnels, those for which the depth is relatively small compared to the section dimension, the face instability, when it occurs, involves a soil portion forward to it, up to the surface. To evaluate the face stability, therefore, one has to study the static conditions of the soil portion ahead of it, which can be involved in the destabilization mechanism.

With regard to this relevant static problem, several simplified methods of analysis have been developed in the recent past (Anagnostou and Perazzelli 2015, Lee *et al.* 2004, Pinyol and Alonso 2011, Mollon *et al.* 2013, Chen *et al.* 2019, Khezri *et al.* 2016, Yang *et al.* 2016, Zou and Xia 2017), they are capable of determining the degree of stability of the excavation face (the safety factor). These methods have closed-form solutions or simple numerical solutions, which are based on simplifying assumptions, generally conservative. The advantage of such methods lies in computational speed, more efficient in comparison with numerical modelings (Zhang *et al.* 2020).

Numerical modelings allow a careful study of the state of stresses and strains around the tunnel and, therefore, also ahead of the excavation face (Mazek 2014, Fargnoli *et al.* 2015, Zhang *et al.* 2018a, Zhang *et al.* 2018b). In applications related to the evaluation of the face stability in shallow tunnels, it is necessary to adopt the three-dimensional numerical modeling, also limited to the simulation of one half of the tunnel system, thanks to the existing vertical plane of symmetry. Such modeling requires, however, still today relatively long computation times, since it is necessary to simulate all the excavation and support stages. The results given are, however, accurate since it is able to assess the state of stress and strain around the tunnel and near the face, for the whole soil portion affected by the void creation. By now many computational codes are able to assess backward a safety factor, gradually lowering or increasing the strength characteristics (cohesion and angle of friction, for example) until detecting the collapse of the excavation face. The safety factor in this case is given by the ratio between the real values of the strength parameters of the soil and the reduced values of the strength parameters. Studies related to works in soils are generally characterized by uncertainty of the geotechnical parameters (Phoon and Kulhawy 1999, Baecher and Christian 2005, Oreste 2005, Chok *et al.* 2016, Liu *et al.* 2017). This uncertainty is due to several aspects: the natural variability that these parameters can have in the space (and sometimes also in time); the possible rehashing that soil samples can be subjected during the transportation from the site to the laboratory; the scale effect, always present in the natural formations; the different stress and strain path induced in the soil during laboratory tests and during the

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loading or unloading process that developed actually in the site. To be able to operate in a rational way, the parameters deemed uncertain have to be defined using not only a deterministic parameter, but with a variability interval associated to a confidence level of the estimate. Different hypotheses on the uncertain parameters have to be made and for each assumption the safety factor can be evaluated; it is characterized therefore by an uncertainty assessment and required a probabilistic treatment (GuhaRay and Dilip 2014, Javankhoshdel and Bathurst 2015, Yang and Li 2017, Pandit *et al.* 2018, Leung and Lo 2018, Jin *et al.* 2020, Liu *et al.* 2020). A probabilistic approach to the assessment of the stability of the excavation face requires a very high number of analysis, which cannot be handled by the slow and complex three-dimensional numerical modeling. The simplified methods of analysis, on the contrary, are well suited to a probabilistic treatment, since they are able to develop thousands of evaluations of the degree of safety of the excavation face in a few seconds, reaching the evaluation of the safety factor in probabilistic terms.

Two interesting simplified design methods have recently been developed to analyze the stability of the soil face in shallow tunnels (Oreste and Dias 2012, Dias and Oreste 2013, Mollon *et al.* 2011). The first is based on the limit equilibrium method and allows determining the safety factor of the face as the ratio of resisting and destabilizing forces acting on the sliding surfaces of a 3d block ahead the excavation face. The second is the spatial discretization technique; it refers to a 3D rotational failure mechanisms for a circular tunnel face and the rate of work done by external forces is compared with the energy dissipation in the system, considering an upper-bound solution.

In this work this two simplified design methods for the tunnel face stability analysis are firstly discussed in detail. These methods then were compared with a numerical modeling developed with a three-dimensional finite difference calculation code. Subsequently, the simplified methods have been used in the context of a probabilistic approach, applied to a specific case of a shallow tunnel carried out in soils, using the Monte-Carlo procedure. After having extracted random values of the uncertain parameters, the safety factors of the excavation face were calculated using the simplified methods and these results were treated in order to obtain their probabilistic distributions. The average values, the standard deviations and the variability intervals of the safety factors, with the associated probability of collapse were obtained.

The results were compared and discussed, in order to obtain considerations relevant to the evaluation of the stability of the excavation face in the presence of soil uncertain parameters, which influence the static problem under consideration.

2. Analytical methods to evaluate the face stability

2.1 Limit equilibrium method

A simple method to evaluate the safety factor is based on the limit equilibrium method (LEM) applied to a three-dimensional soil block (block 1 in Fig. 1) ahead of the excavation face (Oreste and Dias 2012, Dias and Oreste 2013). This method allows determining the safety factor of the face as the ratio of the resisting and destabilizing forces acting on the sliding surfaces of the block. Referring to half of the block 1 for symmetry reasons, one obtains:

$$F_{s,\vartheta} = \frac{F_{st}}{F_{inst}} \tag{1}$$

where F_{st} denotes the resisting forces acting on the sliding surfaces,

$$F_{st} = \left[c \cdot \left(\frac{B/2}{\cos\varepsilon} \cdot \frac{H \cdot \cot\vartheta \cdot \cos\varepsilon}{2 \cdot \cos\chi} \right) + \left(\frac{W_1}{2} + \frac{V}{2} \right) \cdot \cos\chi \cdot \tan\varphi \right] + \left[c \cdot \left(\frac{\frac{B}{2} \cdot H \cdot \cot\vartheta}{2} \right) + \frac{V}{2} \cdot \tan\varphi \right] \cdot \cos\vartheta \tag{2}$$

W_1: weight of the entire block 1 (see Fig. 1);
V: total vertical force that block 2 transmits to block 1:

$$V = 2 \cdot (\gamma \cdot h_c) \cdot \left[\frac{\left(\frac{B}{2} \cdot H \cdot \cot\vartheta \right)}{2} \right] - 2 \cdot h_c \cdot \left[\left(\frac{B}{2} \right) \cdot \left(1 + \frac{1}{\cos\varepsilon} \right) \right] \cdot \left(c + \gamma \cdot \frac{h_c}{2} \cdot k_0 \cdot \tan\varphi \right) \tag{3}$$

B and H: width and height of the tunnel;
h_c: depth of the tunnel roof from the surface;
c and φ: soil cohesion and friction angle;
γ: specific weight of the soil;
F_{inst} denotes the destabilizing forces acting on the sliding surfaces:

$$F_{inst} = \left(\frac{W_1}{2} + \frac{V}{2} \right) \cdot \sin\vartheta \tag{4}$$

k_0: coefficient of lateral stresses;
ε and χ: geometrical angles evaluated as follows:

$$\varepsilon = \arctan\left(\frac{H \cdot \cot\vartheta}{B/2} \right) \qquad \chi = \arctan\left(\frac{\tan\vartheta}{\cos\varepsilon} \right) \tag{5}$$

The safety factor in Eq. (1) is a function of the angle ϑ, which is not a priori known. The minimum of the safety factor varying *F*s is evaluated with respect to the angle ϑ and this value represents the safety factor of the face:

$$F_s = \min\left[F_{s,\vartheta} \right]_{\vartheta = 0 \div 90^\circ} \tag{6}$$

The geometry of the tunnel has a rectangular shape in the LEM model; it is characterized by a width B and a height H, which is generally an approximation of the actual section of the gallery. The shape of the potentially unstable block (block 1) in correspondence of the face is triangular. The circle passing through the three vertices of this triangular section has a radius R equal to:

$$R = \frac{B^2}{8 \cdot H} + \frac{H}{2} \tag{7}$$

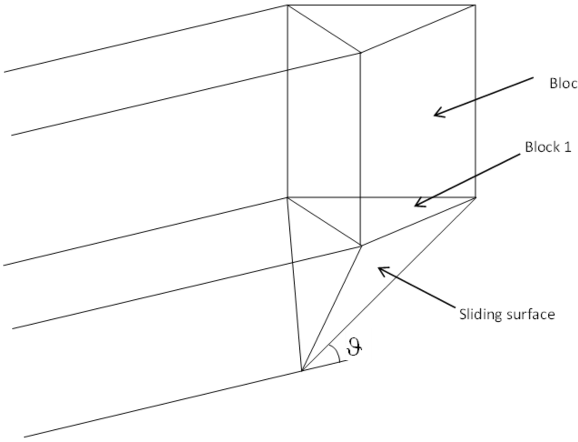

Fig. 1 The geometry of the used LEM model ahead the excavation face of the tunnel (Oreste and Dias 2012)

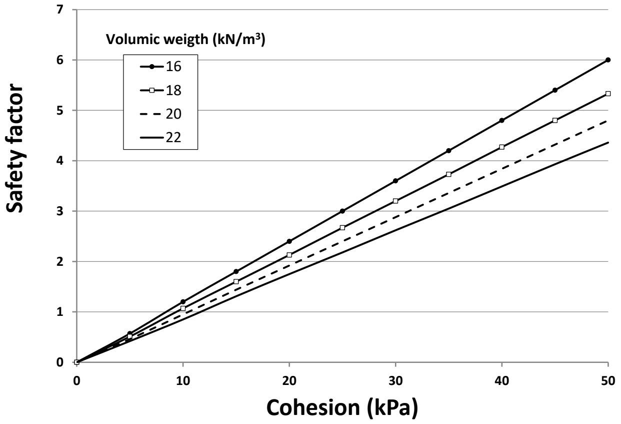

Fig. 2 Evolution of the safety factor of the excavation face, varying the cohesion and for different soil unit weights

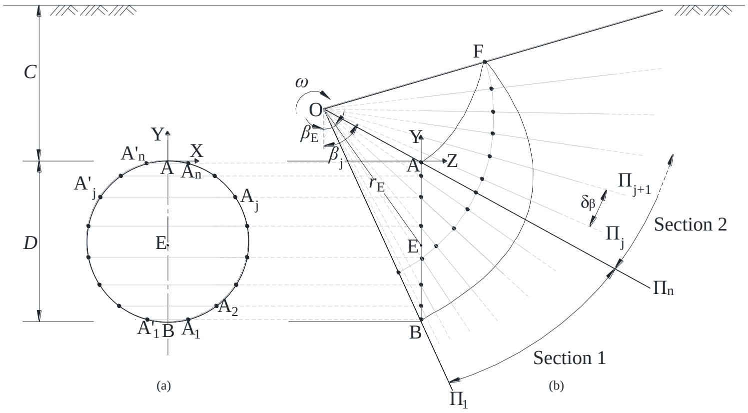

Fig. 3 Discretization technique for the rotational collapse mechanism of a tunnel face (Mollon *et al.* 2011)

Furthermore, in the case of a square section, the inscribed circle has a radius equal to the side length of the square.

It is possible, therefore, to detect the equivalence between the considered rectangular or square section of the tunnel and a circular section of radius R, according to Eq. (7) or considering the inscribed circle.

A simplified method of analysis as that described above, is capable of developing numerous calculations in short times considering variability intervals of the main parameters that are deemed of uncertain evaluation. By way of example, for the case of a tunnel having a square section (B = H = 6 m), with a cover $h_c = 9$ m, a soil friction angle $\vartheta=35°$ and a coefficient k_0 equal to unity, the results in terms of the safety factor of the face of Fig. 2 were obtained using the method described above. This graph is able to show the trend of the safety factor within intervals of variability of the cohesion and the specific weight. These results make it possible to identify which parameter (or what parameters) in the specific problem has a greater influence on the safety factor and possibly deepen the geotechnical investigations to arrive at a more precise assessment of that particular parameter (or of those parameters).

In the reported study in all the considered cases the vertical force V transmitted from the block 2 to the block 1 is equal to zero (V=0). This is the reason why the safety factor has a linear trend with reference to the cohesion.

2.2 Limit analysis method

Another interesting simplified analysis method is the spatial discretization technique developed by Mollon *et al.* (2011). It aims to generate a 3D rotational failure mechanism with respect to the passive and active cases for a circular tunnel face. The 3D rotational failure mechanism reported by Mollon *et al.* (2011) has two significant characteristics: include the whole tunnel face and are consistent with the soil rotational movement observed in experiments. This rotational collapse mechanism by Mollon *et al.* (2011) has been proven to yield the best upper-bound solutions. This classical failure mechanism inspires a series of extended work (Ibrahim *et al.* 2015, Pan and Dias 2015, 2016, 2017, Senent and Jimenez 2015).

A circular tunnel of diameter D with buried depth C is plotted in Fig. 3. The whole failure mechanism rotates around a horizontal axis passing through point O with an angular velocity ω. For any point of the failure mechanism, the velocity is equal to the product of the angular velocity and the distance between the rotating center and the point under consideration. The discretization mainly includes two parts of the failure mechanism. The tunnel face is discretized by $2n$ points, A_1, A_2,…, A_n and the corresponding symmetrical points A'_1, A'_2,…, A'_n, and the Section 2 is discretized by several radial planes, $\prod_j$, separated by an angle of δ_β, as seen in Fig. 3. The precision of the generation of the failure mechanism is controlled by these two discretization parameters, n and δ_β. It is easily to understand that the finer the discretization parameters, the more accurate the failure mechanism. In the following numerical computation, the two discretization parameters are taken to be n=200 and δ_β=0.5°. The geometry of the failure mechanism is determined by two dimensionless parameters β_E and r_E/D.

Based on the upper-bound method, a necessary condition for the tunnel face to be safe is given by (Chen 1975, Michalowski and Nadukuru 2013):

$$W_D \geq W_E \tag{8}$$

where W_e is the rate of work done by external forces and W_D is the energy dissipation (or the resisting work rate) in the system.

In the present analysis of a tunnel, the external forces under consideration only refer to the gravity with the assumptions that no ground surcharge and no water exist. The work rate of external forces can be obtained by a simple summation of the rate of external work on each volume element:

$$W_E = \gamma \sum RV \sin\beta \tag{9}$$

The internal energy dissipation (the resisting work rate) occurs in the soil masses and also along the reinforcements (like the soil nails and umbrella pipes, which are not considered in this contribution). Thus the total internal energy dissipation is the sum of dissipation on each triangular facet:

$$W_D = \mathrm{c} \cos\varphi \sum RS \tag{10}$$

where R, V, β, and S are explained in detail in Mollon *et al.* (2011).

Since Eq. (8) is necessary for the face stability, an upper-bound estimate of the safety factor of the tunnel face can be given by (Anthoine 1989, Saada *et al.* 2012):

$$F_S = \frac{W_D}{W_E} \tag{11}$$

when the total internal energy dissipation is positive. The defined safety factor exhibits the following properties: F_s<1 for an unstable tunnel face; F_s=1 is the limit state; F_s>1 the necessary condition for a safe tunnel face. The upper-bound safety factor is obtained by minimizing Eq. (11) with respect to the two variables, r_E/D and θ_E.

3. Comparison between simplified and numerical methods

The following reference case is analyzed by two simplified methods (the LEM and the LAM models): a circular tunnel of diameter of 6m excavated in a soil with the geotechnical characteristics reported in Table 1. The overburden h_c is equal to 9 m and the k_0 coefficient is equal to 1.

Table 1 The geotechnical parameters of the soil in the studied reference case

Cohesion, c (kPa)	35
Friction Angle, φ (degree)	35
Unit Weight, γ (kN/m^3)	19

Table 2 Ground parameters considered in the 3D numerical model

Young's modulus, E (MPa)	300
Poisson's ratio, v	0.3
Dilatancy Angle, ψ (degree)	0

Table 3 Obtained safety factors by FLAC 3D numerical method and by LEM and LAM analytical methods

	FLAC 3D	LAM	LEM
Circular section (R=3 m)	3.98	3.99	-
Square section (6x6 m^2)	-	-	3.81

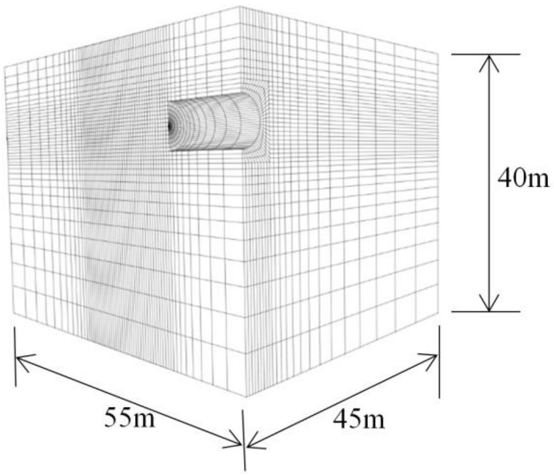

Fig. 4 The 3D numerical model of a circular tunnel in the considered reference case

This section presents a comparison of safety factors obtained by the 3D finite difference software FLAC 3D and by the two presented analytical methods for the considered reference case (see section 2). The numerical analysis is performed considering a radius of 3 m (inscribed circle in the square section 6 m x 6 m). Fig. 4 presents a view of the numerical model for a circular section: 56,000 zones and a total of 60,000 nodes were used in the model. The size of the numerical model is taken as 45 m in the transversal direction, 55 m in the longitudinal direction, and 40 m in the vertical direction; the size is large enough to eliminate the influence of boundary on the stress and strain state of the ground. The grid in the vicinity of the tunnel face is densified as the stress and strain concentration occurs at this zone during the construction of the tunnel. Due to the symmetry of the problem on the vertical plane through the tunnel axis, only a half of the physical domain was considered in the model.

In the numerical model, a linear elastic-perfectly plastic constitutive model based and the Mohr-Coulomb strength criterion were assigned to the soil masses. The parameters used are shown in Table 2. The tunnel concrete lining was modelled with shell structural elements with the Young's modulus of 40 GPa, the Poisson's ratio of 0.2 m and thickness of 0.22 m. The automatic search for the safety factor by the strength reduction technique in FLAC 3D was adopted.

Table 3 lists the safety factors calculated by FLAC 3D numerical method, limit analysis (LAM) and limit equilibrium (LEM) methods. It is shown that the safety factors calculated by the LAM and LEM agree well with that provided by the FLAC 3D, which means that both the LAM model and the LEM model are effective approaches to assess the safety factor of the tunnel face. In fact, this LAM model has been validated by Mollon *et al.* (2011) and Ibrahim *et al.* (2015) to compute the required face pressure and this LEM model has been verified by Oreste and Dias (2012) to evaluate the safety factor of a reinforced tunnel face. It should be noticed that the LAM which has a strict theoretical basis with respect to the LEM theory gives a rigorous upper-bound estimate. This remark is consistent with the observation in Table 3. Besides, it is of interest to point out that both the LAM and LEM models are more efficient than the numerical modelling with FLAC 3D. For example, these two analytical models cost about one minute for one safety factor calculation on an Intel Xeon CPU E5-1620 3.5GHz PC, but it takes about one half hours for the numerical modelling.

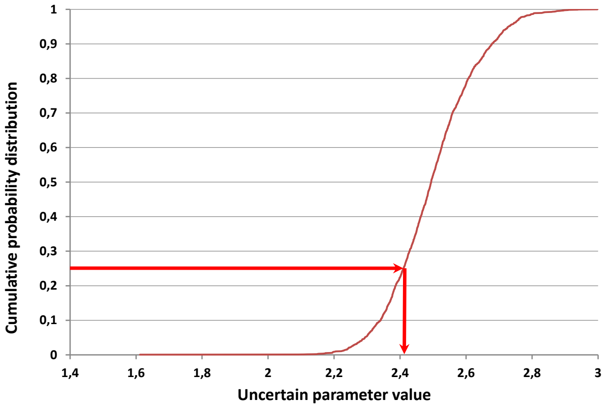

Fig. 5 A typical cumulative probability distributions of a uncertain parameter

4. Probabilistic approach using the Monte-Carlo method

If the parameters that characterize the soil properties under consideration are certain, a deterministic approach is generally adopted. In this case, the safety factor (a single value) is calculated from the available datum.

When, on the contrary, the knowledge of some or all of the geotechnical parameters of soils has a significant degree of uncertainty, it is possible to perform analyses in the probabilistic field, abandoning the traditional deterministic approach. If the independence between the various uncertain parameters can be assumed, it is possible to proceed using the Monte-Carlo method in the following way:

1. For each uncertain parameter a function of the probability density is defined, on the basis of the estimated average and standard deviation values, with a preliminary hypothesis on the type of distribution adherent to each parameter;

2. By integrating the probability density function, the function of the cumulative probability of each uncertain parameter is determined ;

3. Subsequent extractions of random vectors of the uncertain parameters are carried out (each vector is the set of values of the uncertain parameters belonging to a single extraction); within a single extraction a random number (between 0 and 1) is extracted for each uncertain parameter; each random number allows to obtain the value of the uncertain parameter through its cumulative probability function (Fig. 5);

4. Then, a value of the safety factor can be associated to each random vector of uncertain parameters; the safety factor is obtained by a calculation assuming as input data the values of the uncertain parameters in the considered

random vector;

5. The extraction of a random vector of uncertain parameters and the related calculation of the associated safety factor is repeated several times, until the stabilization of the sample of the safety factors is obtained; the stabilization is assessed through the common statistical methods;

6. The set of safety factors thus obtained is used to determine a cumulative probability distribution of the safety factor; such distribution is able to indicate the probability that the safety factor can be actually lower than a specific value.

Fig. 5 presents a typical trend of the cumulative probability function of a parameter of the problem. This trend is typically obtained from the distribution of the probability density through integration.

5. The effect of the geotechnical parameters uncertainty

The probabilistic analysis described in Section 4 has been developed with the LEM (Eqs. (1)-(6)) and LAM (Eqs. (8)-(11)) methods for the reference case study. The mean mechanical characteristics of the soil are those reported in Table 1. A normal probability distribution for the three main physical and mechanical parameters of the soil (cohesion, friction angle, specific weight) was assumed. For each of them was assumed a mean estimate $\bar{x}$ equal to the values of Table 1 and a standard deviation σ calculated assuming that a probability of 99 % exists that the true value falls in the interval between $0.9 \cdot \bar{x}$ and $1.1 \cdot \bar{x}$. The standard deviation σ is in this case calculated on the basis of the following equation:

$$\sigma = \frac{0.1 \cdot \bar{x}}{2.58} \quad (12)$$

The Monte-Carlo procedure produced the extraction of 10000 random vectors of the three uncertain parameters; for each of them the safety factor was calculated by using the LEM and the LAM method. The sample of the 10000 safety factor values was ordered to have the cumulative probabilistic distributions shown in Fig. 6. The obtained average value $\bar{x}$ is equal to 3.81 (LEM) and 3.99 (LAM); the standard deviation σ is equal to 0.19 (LEM) and 0.27 (LAM). From these values it was possible to obtain the probability density distribution of the safety factor (Fig. 7). Assuming a normal distribution of the probability density of the safety factor, an interval of the safety factor between 3.31 and 4.31 (LEM), 3.28 and 4.70 (LAM) associated to a confidence level of 99% was obtained by the calculation; it means that in the range of 3.81 (1±0.13) (LEM), or 3.99(1±0.1732) (LAM) a 99% probability exists that the true value falls within it.

Starting from the values of $\bar{x}$ and of the safety factor sample, an even more interesting result is to identify the value of the safety factor associated with a minimal probability (for example 2 ‰) that the real value could be below it. In this case the safety factor $F_{s,2‰}$ (linked to a cumulative probability of 2 ‰, $F_{s,2‰} = \bar{x} - 2.88\sigma$) is equal to: 3.27 (LEM), and 3.38 (LAM).

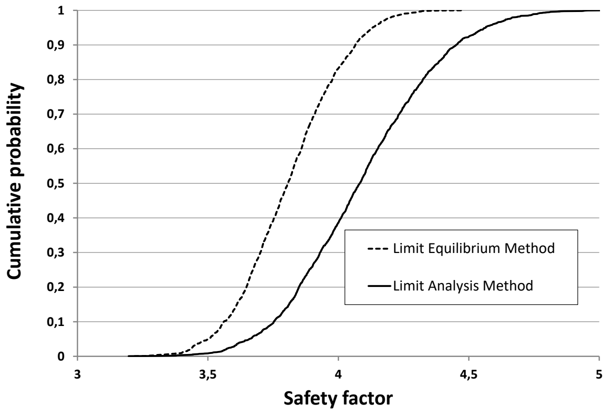

Fig. 6 Cumulative probability distributions of the safety factors obtained by the probabilistic procedure

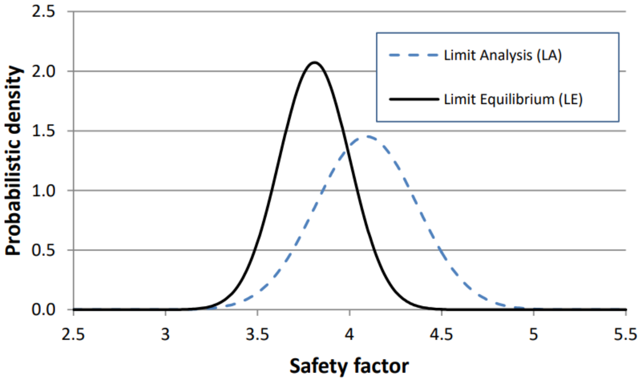

Fig. 7 Probability density curves of the safety factors obtained by the probabilistic procedure using LAM and LEM methods for the studied case

The mean value of the PDF provided by the LAM is bigger than that of the PDF given by the LEM. This is not surprising because that the LAM lead to a rigorous upper-bound solution. Besides, these two mean values of the safety factor are close to the corresponding deterministic results listed in the Table 3.

The LEM method provides results in good agreement with the LAM method. The LAM and the LEM have some effects on the final PDF in terms of safety factors. The variability range of the safety factors for the LEM is slightly smaller than the one obtained by LAM, assuming the same level of confidence in the probabilistic analysis. Even though the LAM is based on a stricter theoretical basis than the LEM, the LAM can also give good results.

6. Conclusions

The evaluation of the stability of the excavation face is a key aspect in the tunnel design, because it is necessary to understand if the face reinforcement is required or not during the construction of the tunnel. In shallow tunnels, the stability of the excavation face is evaluated by analytical methods (such as LEM and LAM methods, presented in this work) or with three-dimensional numerical methods; these last require preparation times of the model and calculation times much longer than the analytical methods.

In the geotechnical field often the mechanical parameters of the soil are not certain, also because of the natural variability that occurs in space. For this reason it is useful and necessary to conduct probabilistic evaluations and not simple deterministic ones. The probabilistic studies typically refer to the Monte-Carlo method and require a large number of calculations. For this reason the three-dimensional numerical modeling is not suitable for this approach and the fast analytical methods need to be used.

In this paper, after having presented two analytical methods for evaluating the safety factor of the excavation face in shallow tunnels, the results obtained for a case study were successfully compared in the deterministic approach with the results of a three-dimensional numerical modeling, Then, starting from the probability distribution of some uncertain geotechnical parameters of the soil, a new and simple probabilistic approach, able to quickly calculate the probability distribution of the safety factor, was illustrated.

Using the LAM and LEM methods, the probabilistic approach has been applied to the considered case study, demonstrating the utility and effectiveness of this approach in the tunnel design sector.

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