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A new embankment construction method through the analysis of possible failure mechanisms in soft soils

Une nouvelle méthode de construction de remblai grâce à l'analyse des mécanismes de défaillance possibles dans les sols meubles

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ABSTRACT: A new method to analyze the failure behavior of embankments on soft soils is proposed in this paper. The proposed method is based on the evaluation of stability considerations applied on a possible mechanism which can be initiated by embankment loading. The developed procedure is applied on a successive set of failure mechanisms that extend towards depth starting from the surface. The envisaged mechanism is made up of concentric half circles starting from the toe of the embankment and spreading towards the deeper soils. By partitioning the circular strips by a slip fan system originating from the center of concentric circles a system of collapse mechanism partitioned to produce finite elements is created. Available stress values at each element are found by applying the rules of the lower bound plasticity solution. Once the stresses and the dimensions of the constructed mechanism are defined stability calculations are made to find the critical depth that will result in failure for any desired embankment height. Moreover safety factors mobilized at lower depths can be calculated.

RÉSUMÉ: Cet article propose une nouvelle méthode concernant l'analyse du comportement à la rupture des remblais sur des sols meubles. Cette méthode proposée est basée sur l'évaluation des études de stabilité appliquées à un mécanisme possible, qui peut être initié par le chargement de remblai. La procédure développée s'applique à un ensemble successif de mécanismes de défaillance qui s'étendent vers la profondeur à partir de la surface. Le mécanisme envisagé est constitué de demi-cercles concentriques partant du pied du remblai et s'étendant vers le profond de sols. De plus, en prenant les bandes circulaires par un système de ventilateur à glissement provenant du centre de cercles concentriques, un système de mécanisme d'effondrement partitionné afin de créer des éléments finis. Les valeurs des contraintes disponibles au niveau de chaque élément ont été déterminés par l'application des règles de la solution de plasticité à la limite inférieure. Une fois que les contraintes et dimensions du mécanisme construit sont définies, les calculs de stabilité sont réalisés pour déterminer la profondeur critique qui entraînera une défaillance pour toute la hauteur de remblai souhaitée. Par ailleurs, les facteurs de sécurité mobilisés à des profondeurs moindres peuvent être calculés.

Keywords: Embankment, failure, limit analysis, limit equilibrium, Cubzac-les-Ponts.

1 INTRODUCTION

Embankments are massive earth structures that are wider and bigger than other conventional structural systems. Differing from the conventional soil-structure interaction problems, a soil-soil interaction problem is created between the embankment and the subjacent layers that are affected by the embankment loads. Especially the presence of soft clays in the foundation stratification constitute major problems for construction due to the soft soils low bearing capacity and great deformation capability. Towards the development of the failure planes in the embankment-foundation soils system, the dominating role is taken by the less rigid constituent. This constituent is usually the soft soils beneath, especially if the embankment is constructed by taking care of necessary precautions to prevent any shallow failure. Even if this is the case, shear planes is initiated inside the weak foundation soils by the action of embankment loads and shearing inside the embankment is incorporated into the weak foundation zones. In this context, it is necessary to envisage an integrated failure mechanism to investigate the combined behavior of embankment and foundation soils (Oser and Cinicioglu, 2017). Moreover the envisaged system should be able to control the internal stability of the system by partitioning the system into smaller zones. This has been achieved by Akbay Arama (2016), Akbay Arama and Cinicioglu (2019), who presented a new method that approaches to the stability of the entire system through the analysis of emerging failure mechanisms starting from the toe towards the centerline. Proposed mechanisms comply with the compatibility condition of the upper bound plasticity theory and also equilibrium condition of the lower bound plasticity theory.

In literature, there are publications applying plasticity theorems in the evaluation of stability conditions of shallow footings and embankments (Chen and Davidson, 1972; Michalowski, 1983; Florkiewicz, 1989; Michalowski, 1992; Michlowski and Shi, 1993; Michalowski 2002; Krabbenhoft, 2005). In these publications upper or lower bound plasticity solutions are used in conjunction either in conjunction with limit equilibrium solutions (Atkinson and Bransby, 1978; Chen, 1975) or finite element calculations (Merifield et al., 1999; Krabbenhoft and Damkilde, 2002). The presented method, however, is based on combined and continuous use of lower bound plasticity solutions together with limit equilibrium approaches applied on emerging mechanisms of failure. As a result, the presented method approaches total stability evaluation through the analyses of local stability considerations.

The envisaged mechanism is made up of concentric half circles starting from the toe of the embankment and spreading towards the deeper soils. By partitioning the circular strips by a slip fan system originating from the center of concentric circles a system of collapse mechanism is created. Although this paper does not employ a finite elements method, a mesh of finite elements is constituted by the partitioning of concentric circles with slip fans. Available stress values at each element are found by applying the rules of the lower bound plasticity solution. Once the stresses and the dimensions of the constructed mechanism are defined stability calculations are made to find the critical depth that will result in failure for any desired embankment height. Moreover safety factors mobilized at lower depths can be calculated. Depending on this finding embankment construction procedure can be arranged either by allowing local failures at shallow depths and then facilitating the strength gain in the succeeding stages in the forthcoming loading stages if the construction is continued by applying stage construction technique or alternatively some soil improvement methods can be applied to strengthen the zone above the critical depth (Akbay Arama and Cinicioglu, 2014; Akbay Arama et al., 2018). In the context of this paper only a well-instrumented test embankment called

Cubzac-les-Ponts with a known height and failure depth is used to make comparison with the proposed new method by finding the depth of collapse. The results verified the applicability of the method presented in this paper.

2 MATERIAL AND METHOD

The method given in this paper is presented through its application on a well-documented case history of Cubzac-Les-Ponts. The method works well to scrutinize the critical depths which may give rise to failure under an embankment of a specific height. In the opposite direction the method can also be used to find the ultimate height of an embankment that can be built over weak soils. As undrained conditions prevail during construction, the solutions in this paper is based on undrained behavior. The details of the method are given in the following sections.

2.1 Cubzac-les-Ponts B test embankment

The geometrical and geotechnical properties of the Cubzac-Les-Ponts test embankment B are given in Fig.1. The Cubzac-les-Ponts test embankments were built in 1972 by the Ponts et Chaussèes Laboratory of France in an area 30 km north of the city of Bordeaux. The purpose of the construction of the embankments is to determine the behavior of the earth fill embankments on soft soils. For this purpose four trial embankments were built. Among these, embankment B was adopted as the example of this paper to work on. It was built to a height of 2.3 meters with a maximum safety of 1.5 against failure. The widths of the base and the platform of the embankment are 62.5 meters and 24 meters respectively. Construction of B was completed in 7 days with five stages implying that the drainage conditions can be considered as undrained. Embankment B is made up of coarse gravel with a friction angle of 35° and a unit weight of 21 kN/m^3. The foundation profile is consisted of 2.0 meters thick crust layer followed by a soft clay layer of 7.0 meters. Under the soft clay layer there exists a gravel layer underlain by the limestone at the bottom. The ground water level is 1.0 meter from the ground surface. The geotechnical and geometrical properties of the embankment and foundation soils are given in Figure 2. As the height attained in case of Cubzac-Les-Ponts test embankment B was 2.3 meters with a safety factor of 1.5, the corresponding ultimate height would be approximately 3.45 meters.

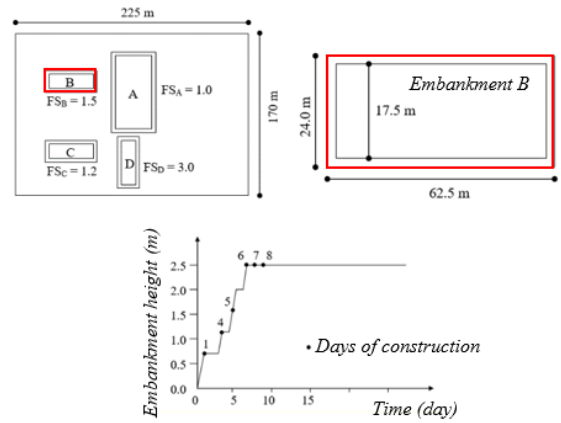

Figure 1. The location plan of test embankments, geometrical dimensions and construction process of embankment B

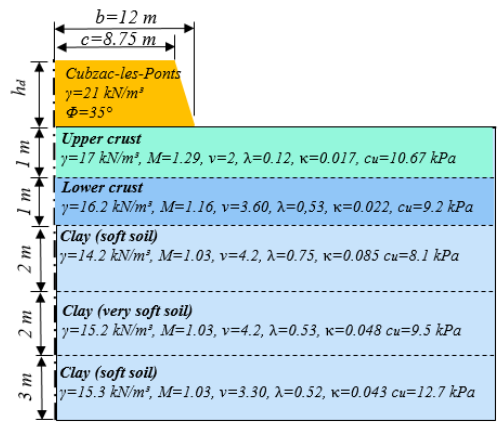

Figure 2. Geotechnical and geometrical properties of the embankment B.

2.2 *Application of the proposed method*

The proposed design method consists of integrated use of plasticity theory and limit equilibrium method. The envisaged failure mechanism emerges by formation of circular shear planes originating from the toe and extending towards the centerline. The method is based on evaluation of the stability of the wedges constituted by a circular shear plane at the considered depth and the two edge slip lines of the slip fan that partitions the considered circular shear plane. In this way the depths and the widths of the wedges increase as the level of the considered depth increases. At the end, when the shear planes reach to the centerline axis from both sides in case of symmetrical embankments, the entire volume of foundation soils affected by embankment loads are scanned through in terms of local and total stability. The emerging failure surfaces mounting up to a total collapse mechanism is shown in Fig. 3.

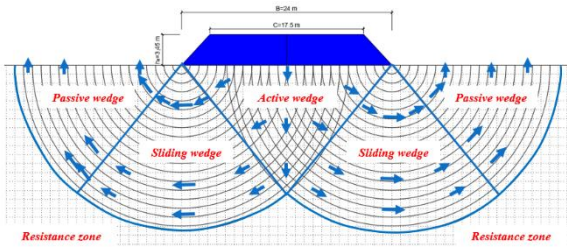

Figure 3. The general failure mechanism drawn for the proposed method

As seen in the figure, ultimate total collapse mechanism resembles bearing capacity failure mechanism of shallow foundations. However, differing from the general bearing capacity failure, this method mainly focuses on the local stability and scans the emerging wedges in terms of internal stability. Fig. 4 demonstrates the two slip fan system used in this method to take care of dual stress axis rotation effect both on the stresses acting on the edge slip lines of the sliding wedge and also through the circular slip plane inside the foundation soils.

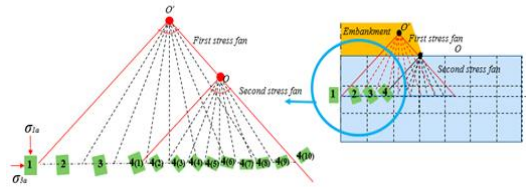

Figure 4.Dual stress rotation effect considered by two slip fans.

The sliding wedges emerging through the increasing depths are shown in Fig. 5. It can be identified in the figure that as the depth increases the size of the shearing wedge and thus the foundation area affected by the shearing increases. Thus, the evaluations at the small depths belong to local shearing behavior.

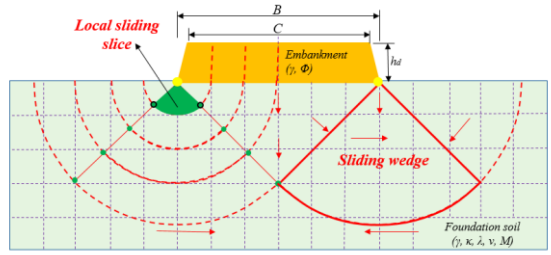

Figure 5. Development of local sliding mechanisms

A representative sliding wedge is detailed in Fig. 6 together with the stress system acting on it.

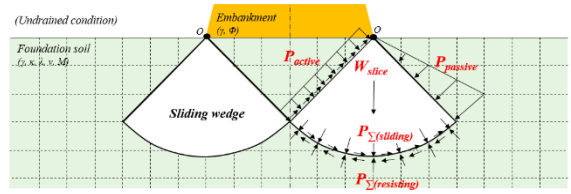

Figure 6. A representative sliding wedge

The shearing stresses created by the active forces are resisted by the resisting stresses created by the passive forces and these both types of stresses act along the circular sliding plane in directions opposite to each other. The net effect of these opposing forces implies the way of the behavior either towards failure or safety. Calculated stress values are inserted into the wedge mechanism

that is used for the evaluation of the local stability as seen in Fig. 6.

3 RESULTS

The sample calculations made for the Cubzac-Les-Ponts case started with a depth of 1.0 meter for the first sliding wedge. Of course, the frequency of the depths and thus the fineness of the mesh attained changes according to the requirements of the level of sensitivity.

A stress fan with a fan angle of 80° and nine discontinuity planes is applied in the sample calculation. The total amount of angular rotation of stress axis from the active side to the passive side is 90°. Fan angle (θf), in terms of the number of slip fans can be calculated by eq. 1. In this equation n denotes the number of discontinuities and Δθ represents the angle of total stress axis rotation.

$$\theta_f = \left[\frac{n-1}{n}\right].\Delta\theta == \left[\frac{9-1}{9}\right].90° = 80° \quad (1)$$

The variation in stress states that are transferred through nine discontinuity planes can be calculated by eqn. 2.

$$\Delta s = n.(2.c_u.\sin\delta\theta) = 9(2c_u \sin 10°) \quad (2)$$

All the stress conditions and stress axes rotations throughout a given horizontal plane (z_1=1 m) in Figure 4 can be calculated by the use of Mohr circles and Equation 2.

Using the calculated stress values, acting stresses states can be inserted to the wedge system shown in Figure 7.

Limit equilibrium theorem is used at this stage of the application of the proposed method. The static equilibrium of the stresses on each local failure slice is based on the equilibrium of forces in the vertical and horizontal directions and the moment equilibrium of the system with respect to the toe. Equilibrium condition (FoS=1) is thus controlled at all the considered depths.

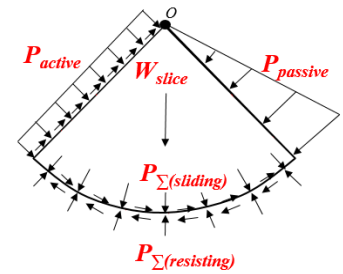

Figure 7. The stresses and forces acting on the first local failure slice

The sliding wedge that extends to the depth of 1.0 meter, the vertical equilibrium consideration gives a safety factor of 3.54, the horizontal equilibrium of the forces gives 1.43 and the moment equilibrium 1.25. The minimum factor of safety value is encountered via moment equilibrium, but it is still greater than 1.0 and it can be concluded that the depth of 1.0 meter is not the failure depth. For the purpose of finding the critical depth that will initiate failure or to find the safety levels of the slip lines at greater depths, the analyses are repeated for all the considered depths. Table 1 gives selected levels of analysis carried out.

Table 1. Results of analysis

Depth (m)	Horizontal equilibrium of forces	Vertical equilibrium of forces	Moment equilibrium
1	1.43	3.54	1.25
2	1.10	1.52	1.16
2.1	0.76	0.74	0.83
3.05	1.01	1.22	1.10

Scanning through the safety factors resulted from the application of equilibrium equations and given in Table 1, the depths that carry the risk of iniating failure fall between 2.1 to 3.05 meters. The finding is perfectly reasonable, as 2.1 meters is the depth corresponding to the top level of the soft clay layer that is directly beneath the bottom of the crust layer and 3.05 m is the middepth of the weakest clay layer. This finding has also been supported by the arguments of the researchers

who worked on the stability problem of the same case (Mieussens et al., 1974; Bolondeau et al., 1977; Wood, 1990; Oztoprak, 2002, Oztoprak and Cinicioglu, 2005; Oser and Cinicioglu, 2016).

4 CONCLUSIONS

In this paper, a new design method is proposed for the embankments constructed on soft soils and applied to a well-instrumented test embankment called Cubzac-les-Ponts B (Akbay Arama, 2016). A distinct property of the method is its ability to investigate the stability with an approach scanning through the possible local mechanisms towards the general. Thus, both local and total stability considerations can be taken into account. Moreover stress variation due to the stress axis rotation along the possible sliding surfaces are calculated and with this property, the presented approach is based upon the fundamental stress behavior.

The aim of the method is either to find the critical depths that have a potential to give rise to development of a failure mechanism or in the opposite way, to find the maximum height of an embankment over a possible sliding surface indicating that, the method could work in both ways.

As stress values are also calculated, the method can also be used in conjunction with stage construction technique provided that the stress variation during consolidation periods are also calculated in the course of the application of the method.

The method is founded on a sound theoretical basis by using lower bound plasticity theorem for the solutions and the failure mechanism developed to solve the stability consideration is compatible with upper bound theory.

The method is also applied on a well documented case history; Cubzac-les-Ponts test embankment B in the sample solution provided in this paper and the results indicated the effectiveness and the validity of the method.

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