Resistance Demand against Lateral Spreading at the Embankment Base

Demande de Résistance Contre L'épandage Latéral à la Base de Remblai

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ABSTRACT: A design method for embankments with basal reinforcement has been proposed in this paper. Based on lower bound plasticity theory, equilibrium conditions were satisfied for the stress fields representing variation of stress states within and beneath the embankment. Critical embankment height and the depth of the critical sliding surface are found with an approach specifically developed for embankments, to satisfy both the stability and bearing capacity considerations simultaneously. Once the critical height is found, lateral thrust generated by the embankment loads at the base of the embankment on the embankment side can be calculated by using a stress variation field with the embankment material parameters. A specific merit of the method is providing the capability to calculate lateral thrust action at all the regions separated by the chosen fan of discontinuities. The lateral resistance developed at the base of the embankment, but within the underlying soil is calculated by utilizing the same stress field but inserting the material properties of the underlying soil and stress availabilities at the considered base level. Once the mobilized resistance on the foundation soils side is found, comparing this value by the lateral thrust on the embankment side, the adequacy of the resistance from the foundation soils is evaluated and the required additional resistance to be provided by the reinforcement is directly found.

RÉSUMÉ : Une méthode de conception pour les remblais avec renforcement de base a été proposée dans ce papier. Basée sur la théorie de la plasticité minimale, les conditions d'équilibre ont été satisfaites pour les champs de tension représentant la variation des états de tension à l'intérieur et en dessous du remblai. La hauteur critique de remblai et la profondeur de la surface de glissement critique sont trouvées avec une approche spécifiquement développée pour les remblais, pour satisfaire à la fois les considérations de stabilité et de capacité de charge simultanément. Une fois la hauteur critique a été établit, la poussée latérale générée par le poids de remblais à la base du remblai et sur la côté du remblai ; peut être calculée en utilisant variation de la tension du champ avec les paramètres de matériau de remblai. La valeur particulière du procédé consiste à fournir la capacité pour calculer l'effet de la poussée latérale à toutes les régions séparées par le ventilateur choisi des discontinuités. La résistance latérale développée à la base du remblai, mais dans le sol sous-jacent est calculée en utilisant le même champ de tension mais en insérant les propriétés matérielles du sol sous-jacent avec la disponibilité de stress au niveau de base considéré. Une fois la résistance mobilisée sur le côté des sols de fondation est établi, en comparant cette valeur par la poussé latérale du côté remblai, l'adéquation de la résistance des sols de fondation est évaluée et la résistance additionnelle demandée est fournie directement par le renfort.

KEYWORDS: lower bound plasticity, embankments, limit equilibrium, basal reinforcement, required geotextile strength, soft soils

1 INTRODUCTION

Embankments are usually constructed as parts of transportation networks. Especially when soft soils are encountered as foundation soils, design and construction of an embankment is a difficult work. Consideration of the combined behavior of the embankment and its subsoil is essential to apply a design process which takes care of both the shallow and deep failure risks. This necessity was throughly evaluated in Oser and Cinicioglu (2016), and a new design procedure that is capable of modeling the combined behavior of embankment and its foundation soils was developed. The design method proposed in Oser and Cinicioglu (2016) mainly focuses on possible deep failures that emerge from the weak foundation soils. One of the crucial factors that has a crucial role on the embankment stability is the lateral spreading effect at the base of the embankment. In the paper, the availability of sufficient tensile strength within the embankment material was assumed to divert the focus of the method to deep failures. Now, this study proposes a new method that is mounted on the approach presented in Oser and Cinicioglu (2016) and is capable of controlling both the deep and shallow failures. This is achieved by adding a control mechanism that evaluates the possibility of lateral spreading at the base of the embankment. It is known that lateral spreading action is created within the embankment material and can be resisted by the action of the base shear mobilized on the subsoil side. In case of insufficient frictional resistance at the base on the subsoil side, lateral spreading occurs and may cause rotational failures within the embankment. Failure surfaces may also penetrate into the subsoil and cause deeper failures. Therefore, to provide sufficient resistance against lateral spreading is among the primary design criteria. If design checks indicate insufficient strength against lateral spreading, it is a common practice to place high stiffness geosynthetic reinforcement at the base of embankments.

The approach presented in this study starts by finding the most critical deep failure level within the subsoil and the geometry of the embankment by applying the method by Oser and Cinicioglu (2016). The method can be applied to find the possible heights either when single stage of loading is applied to find the maximum height under short term conditions or the height that can be approached by leaving consolidation periods among the loading stages to make use of the shear strength gain during consolidation periods. Especially, in the case of stage loading, the base shear resistance is not often enough to resist the outward stresses created by the greater embankment heights. At this stage, control of the lateral safety against spreading comes into action.

The outward stresses at the base of the embankment, on the embankment side, is determined by applying a lower bound plasticity approach. A stress fan is created that comparts the base to evaluate the outward stresses caused by lateral spreading action within the embankment. Shear resistance developed on the subsoil side is evaluated by using the same stress fan with the subsoil material properties. The adequacy of the lateral resistance against sliding is tested by comparing total values of these actions which act in opposite directions. A desired value of safety factor against lateral sliding is then introduced into this comparison in order to calculate the required amount of additional tensile strength that will be provided by the basal reinforcement. The last step is to re-calculate the degree of the stabilizing effect of the tensile reinforcement on the overall stability.

2 CONSIDERATION OF OVERALL STABILITY OF THE EMBANKMENT AND SOFT SUBSOILS

In the method by Oser and Cinicioglu (2016), combined behavior of the embankment and subsoils are evaluated by applying a limit equilibrium approach specifically developed for the design of embankments on soft soils. The failure mechanism of the method is a multi-rigid-block mechanism and the stresses in the system are calculated by using the principles of the lower bound plasticity theorem. The method considers only the deep failure case, on the assumption that the inside stability of the embankment will be ensured during construction either by careful compaction or adding tensile inclusions. Milligan and Busbridge (1983) and Han (2015) indicated that, the failure of embankments on soft soils can be controlled by circular or noncircular slip surfaces depending on the thickness of the soft soil layer. Based on this indication, the failure mechanism of the propsed method is mounted on a horizontal slip surface within the soft foundation soils. The critical sliding surface and corresponding ultimate height are found by scanning horizontally through the soft soils and applying the stability analyses of the method. Once, the stress states mobilized at the base of the embankment are found by using the stress fan given in Fig. 1 and applying the approaches of lower bound plasticity theory, the designer is then able to control horizontal, vertical and moment equilibrium conditions. Fig.2 schematizes the considered block mechanism together with the forces and stresses acting on the system.

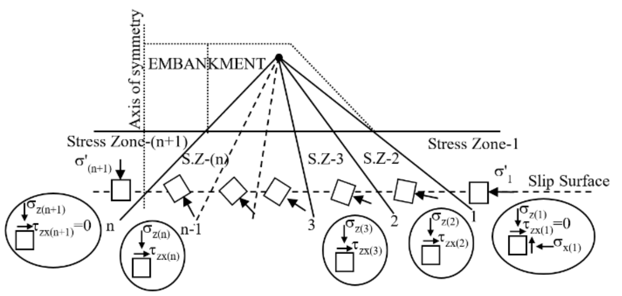

Figure 1. Stress fan and stress-axis rotation beneath the embankment (Oser and Cinicioglu, 2016).

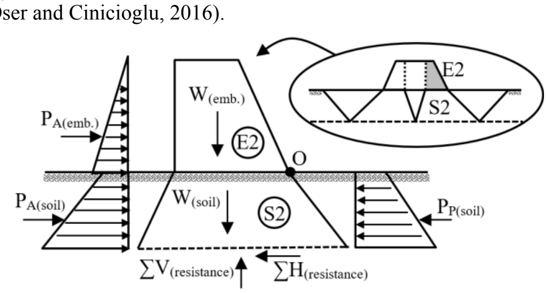

Figure 2. Forces in constituted blocks of the mechanism in the developed limit state method (Oser and Cinicioglu, 2016).

In order to satisfy the equilibrium of the overall block system, the conditions given by Eqs. (1)-(2) should be met.

$$\sum F_{SLIDING} \leq \sum F_{RESISTANCE} \text{ (Horizonral eq.)} \quad (1)$$

$$\sum W \leq \sum V_{RESISTANCE} \text{ (Vertical eq.)} \quad (2)$$

Sliding and resisting forces defined in Eqs. (1)-(2) can be given as in Eqs. (3)-(5).

$$\sum F_{SLIDING} = P_{A(EMB)} + P_{A(SOIL)} \quad (3)$$

$$\sum F_{RESISTANCE} = P_{P(SOIL)} + \sum H_{RESISTANCE} \quad (4)$$

$$\sum W = W_{(EMB)} + W_{(SOIL)} \quad (5)$$

where $\sum V_{resistance}$ and $\sum H_{resistance}$ represent total vertical and horizontal resisting forces that were calculated by the application of lower bound plasticity theorem on the stress zones created between the passive and active zones as shown in Fig.1. These resisting forces are calculated as expressed in eqs. (6)-(7) based on normal and shear stresses on the slip surfaces found by considering the stress axis rotation starting from the active side towards the passive side to find the stresses on the embankment side and in the opposite direction that is from the passive side towards active side on the subsoils side.

$$\sum H_{RESISTANCE} = \sum_{i=2}^{n}\left(\tau_{zx(i)} \cdot Y_{i-1}\right) \quad (6)$$

$$\sum V_{RESISTANCE} = \sum_{i=2}^{n}\left(\sigma_{z(i)} \cdot Y_{i-1}\right) \quad (7)$$

Critical embankment height that satisfies all the forces and moment equilibrium conditions ($P_{A(emb.)}$, $P_{A(soil)}$ and $W_{(emb.)}$) in Fig.2 is determined as limit embankment height ($H_{L(EMBANKMENT)}$). If the desired embankment height is greater that that could be provided at one stage stage loading technique is used. In case of stage loading, the above procedure is used repeatedly between the consolidation stages to find the incremental heights that could be applied under undrained conditions during construction stages and strength gain during consolidation stages are found by constructing stress paths to follow the stress variation all through the construction and consolidation stages. The method is explained thoroughly in Oser and Cinicioglu (2016).

3 SAFETY AGAINST LATERAL SPREADING

Apart from satisfying the overall stability as explained in section 2, the provision of sufficient safety against lateral spreading at the base level of the embankment is among the crucial concerns in embankment design on soft soils. As mentioned in Chai and Zhu (2002), tendency of lateral spreading increases the shear stresses acting outwardly at the ground level, decreases the bearing capacity and increases the lateral displacements in the soft soil.

The method proposed in this paper is based on a comparison of the outward stresses calculated at the base using the embankment material properties against the shearing resistance mobilized in the foundation soil. The variation of these stresses and the stress rotation effect along the base is accounted for by using the partitioning of the stress fan applied. The mechanism of the method is different from the applications that calculate outward stresses only as a result of the lateral active earth thrust mobilized within the embankment as if there is a hypothetical retaining wall along the shoulder of the embankment. The method proposed in this paper calculates the outward stresses as a component of the collapse mechanism mobilized at the surface and resulted from the combined behavior of the embankment and foundation soils as schematized in Fig. 3.

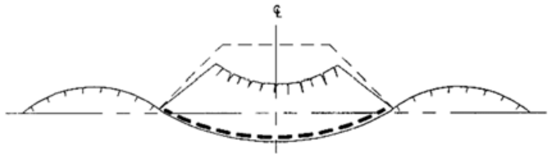

Figure 3. Settlement of soft subsoil under embankment loads (Holtz et al. 1998)

In accordance with the settling action of the embankment material by sagging into deformed clayey subsoil, the outward stresses can be calculated at any horizontal level as a result of the action of the active wedge constituted within the embankment material as seen in Fig. 4. The stress state at the base level along the symmetrical line corresponds to principal stresses on the vertical and horizontal axis but stress axis rotation occurs towards the embankment toes. As a result of this action, outward shear stresses are created and can be calculated by using the approach given in Oser and Cinicioglu (2016). In the application of this approach a stress fan is created and the stress state at the centerline of the active wedge in the middle of the embankment is transferred towards the toes by applying the principles of the lower bound plasticity theory.

The resisting shear stresses are created by the action of the passive wedge outside the embankment toes. Using the same approach, resisting shear stresses are calculated starting from the passive stress state mobilized within the subsoil. The stress values are found by using subsoil material properties and the depth from the surface. As seen in Fig. 3, as the weak subsoil is loaded, some settlement inevitably occurs and the embankment penetrates into the weak subsoil to some extent, therefore passive resistance is created at the level of penetration. This depth level can be taken as the level of passive resistance that will be developed and then these stress states are transferred towards the active side to find the resisting shear stresses. In some cases, some surface stripping can be made purposely to carry the base level inside the subsoil. Based on these considerations the base level is chosen.

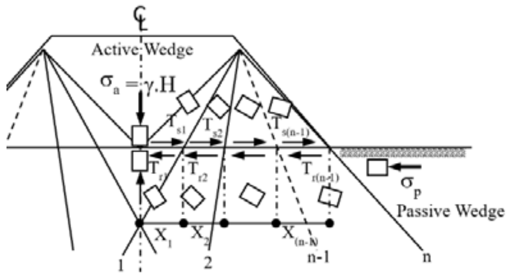

Figure 4. Fan of discontinuities for sliding forces and resisting forces due at a depth near to surface level

The lateral outward stresses and resisting shear stresses are calculated by Eqs. (8)-(9).

$$\sum F_{spreading} = \sum_{i=1}^{n-1} \left(T_{s(i)} \cdot X_i \right) \quad (8)$$

$$\sum F_{resistance} = \sum_{i=1}^{n-1} \left(T_{r(i)} \cdot X_i \right) \quad (9)$$

Factor of safety against lateral spreading is found by proportioning ($\sum F_{resistance}$) to ($\sum F_{spreading}$) as shown in eq. (10).

$$FS_{lateral\ spreading} = \frac{\sum F_{resistance}}{\sum F_{spreading}} \quad (10)$$

As a result of the comparison of outward stresses against resisting shear stresses a certain value of safety factor which can take care of both lateral spreading and horizontal force equilibrium conditions (evaluated by considering the overall stability) should be provided. The resistance against lateral spreading should also be sufficient against the lateral thrust created by the height achieved by undrained loading and also the greater heights that will be achieved by the application of stage loading technique. If the available resistance forces are not adequate the required amount of additional strength is found by eq. (11).

$$FS_{lateral\ spreading} = \frac{\sum F_{resistance} + F_{reinforcement}}{F_{spreading}} \quad (11)$$

The additional strength provided by the geotextile reinforcement at the base level also helps to improve the overall horizontal stability condition the components of which are shown in Fig.5. Eq. (12) gives the additional horizontal resisting force effect and the factor of safety for the overall stability condition can be calculated by Eq. (13).

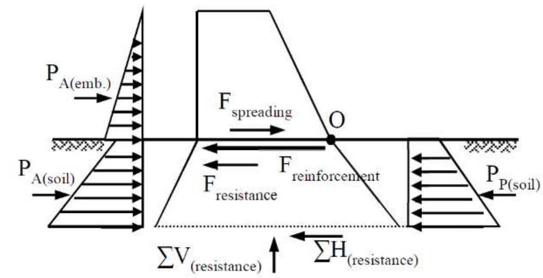

Figure 5. Reinforcement at the base level of embankment against lateral spreading effect

$$F_{rein.(additional)} = F_{resist.} + F_{rein.} - F_{spreading} \quad (12)$$

$$FS_{emb.} = \frac{P_{P(soil)} + \sum H_{resistance} + F_{rein(add.)}}{P_{A(soil)} + P_{A(emb.)}} \quad (13)$$

4 APPLICATION OF THE METHOD

A sample calculation by following the procedure in the context of the newly developed method proposed in this paper is made to test the applicability of the method. A typical soil profile consisting soft clay layers and the related parameters used for this purpose are given in Table 1. Ground water level is taken as 1.0 meter below the ground surface.

Table 1. Geometrical cross section and subsoil material properties of embankment

Soil	Depth (m)	γsat (kN/m3)	σ'v (kN/m2)	ϕ' (°)	cu (kN/m2)
Embankment	-	21.0	-	25.0	-
Clay crust	0 – 1	17.0	8.5	22.0	-
Over cons. clay	1 – 2	16.2	20.1	29.9	11.3
Very soft clay1	2 – 4	14.2	27.4	26.0	10.0
Very soft clay2	4 – 6	15.2	36.8	26.0	11.6
Soft clay	6 – 9	15.3	50.0	26.0	15.6

4.1 *Limit heights of embankment under drained and undrained loading conditions*

Limiting lower bound embankment heights and corresponding critical depths of failure surfaces are found using the properties given in Table 1, both for undrained and drained cases, for the first step of calculations using the method by Oser and Cinicioglu (2016). The results are tabulated in Tables 2.

As seen in Table 2, under undrained conditions, the height of embankment that can be built is 3.0 metres with a factor of safety of unity. If stage loading is applied it is possible to increase this height to 7.2 meters for drained conditions. These values are found by satisfying all the equilibrium conditions of vertical, horizontal and moment equilibrium, however, lateral spreading risk at the base of the embankment has not been included into this scheme of calculations.

Table 2. Limit embankment heights for various slip surface depths under undrained/drained loading conditions

Slip Surface	Embankment Height (m). (undrained / drained)	
Depth	Horizontal Equilibrium	Vertical Equilibrium
3	3.15 / 9.55	4.30 / **7.20****
4	3.10 / 10.45	6.70 / 9.60
5	**3.00*** / 11.50	9.35 / 12.80
6	3.25 / 12.55	14.30 / 16.65
7	3.25 / 13.65	19.45 / 21.40

* limit embankment height for undrained loading

** limit embankment height for drained loading

4.2 *Safety of embankment against lateral spreading*

In this section, following the procedure proposed in this paper and using the greater height found for drained conditions the risk of lateral spreading is tested and calculations to provide the necessary amount of additional strength is carried out.

In order to carry out the necessary calculations by using the principles of lower bound plasticity theory, the failure surface is chosen as a horizontal surface near the base level of the embankment (50cm in the presented calculation). Related calculations are done on the embankment side using the embankment material properties to find the variation of outward lateral stresses along the base level and on the subsoil side using subsoil material properties to find the variation of resisting shear stresses. Drained properties were chosen for the embankment material as it is granular and for the dry crust layer as it lies above the ground water level. In addition to these, as long term behavior corresponds to the maximum possible height drained properties were also chosen for the soil layers below the ground water level. Summing up the values of outward and resisting stresses at the base of the 7.2 meters high embankment the forces acting at the base are found as, $F_{spreading} = 214.6\ kN$ and $F_{resistance} = 92.5\ kN$. These values give a safety factor of 0.43 against lateral spreading, which indicates that, failure will inevitably occur by the initiation of a separation effect emerging from the base level towards both to the embankment side and to the foundation soils.

In order to guarantee the safety against lateral spreading additional tensile strength should be provided by using a tesile reinforcement. The required amount of additional strength is found by adopting a desired safety factor which was chosen as 1.5 for the sample case given here which gave the necessary amount of additional strength as 230 kN as given in the calculations below.

$$1.5 = \frac{92.5 + F_{reinforcement}}{214.6}$$

$$F_{reinforcement} = 230\ \ kN$$

4.3 *Effect of reinforcement on the stability of embankment-subsoil system*

As the last step of the design procedure, the stabilizing effect of the reinforcement on the overall stability is tested. The forces acting at the base of the 3 meters high embankment with basal reinforcement are; $F_{resistance} = 92.5\ kN$, $F_{spreading} = 96.0\ kN$, $F_{reinforcement} = 230\ kN$ which give a safety factor of $FS_{lateral\ spreading} = 3.36$, against lateral spreading.

The effect of the additional strength provided by the reinforcement on the overall horizontal stability of the 3.0 meters high embankment for which the sliding surface lies at 5.0 meters depth is found by comparing the available horizontal forces. These are calculated as; $P_{A(emb.)} = 3.4\ kN$, $P_{A(soil)} = 387.8\ kN$, $P_{P(soil)} = 293.6\ kN$ and $\sum H_{resistance} = 132.4\ kN$.

As a result, the safety factor found for horizontal overall stability increases to 1.45 compared to the value of 1.0 which controlled the overall stability and thus defined the critical height for the undrained case without basal reinforcement.

5 CONCLUSION

In this paper, a new design method for embankments with basal reinforcement is proposed. The basic property of the proposed method is to control the degree of adequacy of the lateral resistance against outward spreading at the base and calculate the necessary additional tensile strength to be provided to develop a desired safety level against lateral spreading action. Moreover, this newly introduced method is attached with the recently proposed mehod by Oser and Cinicioglu (2016).

By this attachment, the method gained the capacity to carry out the complete set of calculations that control all conditions of the overall stability consideration for the combined embankment - foundation soils system together with a special focus on the lateral spreading control.

The method is basically a limit equilibrium method developed by applying the principles of lower bound plasticity theory. The procedure of the method is rational and simple as can be seen in the simple set of calculations provided in the paper to test the applicability.

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