USE OF WOVEN GEOGRIDS UNDER SHALLOW FOUNDATIONS

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Abstract: During the process of selecting foundation solutions it is necessary to determine what load level is bearable by the local soil. In many cases this type of determination includes choice of foundation depth due to the fact that being capacity of the soil may be insufficient to stabilize some types of shallow foundations. However, in some cases this kind of solution is not possible due to factors as cost, space and access. As an alternative approach an application using geogrids as tension distribution elements has been considered to provide improvement in the support capacity of shallow foundations. The main points that must be studied are the resistance parameters like rigidity and deformation. A key issue is how the design can be validated when woven geogrids of high elastic module are used. They need to be able to be placed in layers to resist large loads and ensure rupture by shear stress does not occur. The paper presents a theory that validates this application through a real case study and confirms the calculations methods that are commonly used in shallow foundations on soft soil.

Keywords: bearing capacity, geogrid, polyester, limit equilibrium, soil reinforcement, stability.

INTRODUCTION

During the design period is very important to define the bearing capacity of soil before building a concrete structure with the purpose of choosing the adequate type of foundation. In most cases the foundation designers consider a load bearing capacity of soil trying to conduce a specific work to shallow foundation solution, for obvious reasons as cost, executive velocity and in some cases, technical challenge.

The problem comes when the bearing capacity of soil is not sufficient to propose a shallow foundation. When simulating the conditions of a soil stratum with low bearing capacity to a superficial loading, it is possible to realize ruptures tendencies under critical surfaces of shear strength where the resistance of the soil is insufficient.

There are many kind of method to determine the critical failure surface; however most of theses methods not present much variability of resistance parameters (friction angle, cohesion) what it incapacitates the use of different types of geosynthetic reinforcement. In this paper will present a method developed by Hopkins (1986; 1991), Slepak and Hopkins (1993; 1995a, b), to solve the real problem of shallow foundation under base of high equipment (industrial machine), where the concept of limit equilibrium is used to evaluate a stability of reinforced granular base with geosynthetic. Using this method is possible to apply woven geogrids like reinforcement alternative to shallow foundation and trying to study its behavior considering a elastic-rigid model.

PROPOSED METHODOLOGY

Hopkins Limit Equilibrium Model

The Hopkins limit equilibrium model developed in previous research and used to calculate the factor of safety against failure is a generalized limit equilibrium procedure of slices (Janbu and Bishop Method). The mathematical model has been formulated in such a manner that the factor of safety of a multi-layered flexible soil system may be calculated. The factor of safety may be calculated of a system containing as many as 25 (arbitrarily selected) different soil layers. In the procedure, the potential failure mass is divided into a series of vertical slices; the equilibrium of each slice and the equilibrium of the entire mass is considered. In the approach, the ultimate strengths of the materials in each soil layer are used.

The model developed by Hopkins is used to pavement system where in this paper should be used an adaptation in this method to consider shallow foundation reinforced for woven geogrid.

Basic Assumptions

Fundamental assumptions made in the formulation of the pavement bearing capacity model are as follows:

- A line or thrust line (Bishop 1955) passing the points of action of the interslice forces is known or assumed.
- The materials forming the layers of the pavement of the potentially unstable mass conform to the Terzaghi-Coulomb shear strength formula (Terzaghi 1943).
- For each cross section, the stability problem is treated as two dimensional (plain strain). The shear strength of the soil layers may be expressed in terms of effective stress or total stress (Terzaghi 1943).
- The factor of safety of the cohesive component of strength and the frictional component are equal.
- The factor of safety is the same for all slices. It is expressed as the ratio of the total shear strength available on the shear surface to the total shear strength mobilized to maintain statical equilibrium (Bishop 1954). This assumption implies there is mutual support between adjacent slices. It implies the existence of interslice forces.

Shear Surface Used in Bearing Capacity Analysis

Shear surfaces of various shapes or failure patterns may be assumed in performing bearing capacity analysis. For example, circular and wedge-type shear surfaces may be used. However, basic bearing capacity solutions by Prandtl in 1921 and Reissner in 1924 show that the failure pattern should consist of three distinctive zones as shown in Figure 1. These three zones are identified as zones 1, 2, and 3. Zone 1 is an active Rankine zone. This zone pushes the radial Prandtl Zone 2 sideways and the passive Rankine Zone 3 in an upward direction as shown in Figure 1. The basic Prandtl type failure pattern was assumed in developing the pavement bearing capacity mathematical model. Basic failure patterns and equations for one, homogeneous layer and a multi-layered system are described as follows.

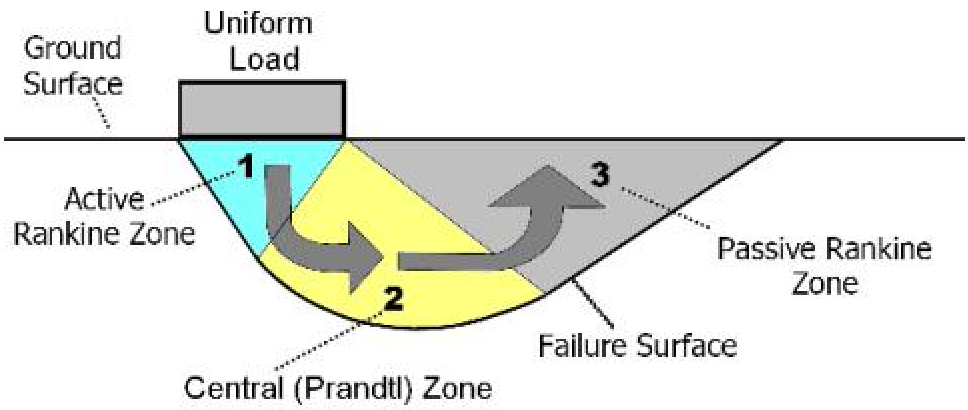

Figure 1. Assumed failure patterns and block movements (Tommy C. Hopkins, Liecheng Sun, and Mikhail Slepak, 2005**).**

When it was assumed a failure surface defined in the figure 1, it was assumed too a condition for a homogeneous layer of material, in other words, the failure surface is within of a foundation soil that is present the same conditions of shear resistance or the same bearing capacity of soil along the depth.

The shear surface assumed in the model analysis for a homogeneous layer of material consists of a lower boundary, identified in Figure 2, as **abcd**. This surface consists of two straight lines, **ab** and **cd**. The portion of the shear surface shown as line **ab** is inclined at an angle, α_1 to the horizontal, or

$$\alpha_1 = 45 + \frac{\phi}{2}, \qquad [1]$$

$$\alpha_2 = 45 - \frac{\phi}{2} \qquad [2]$$

where, ϕ is friction angle of foundation soil.

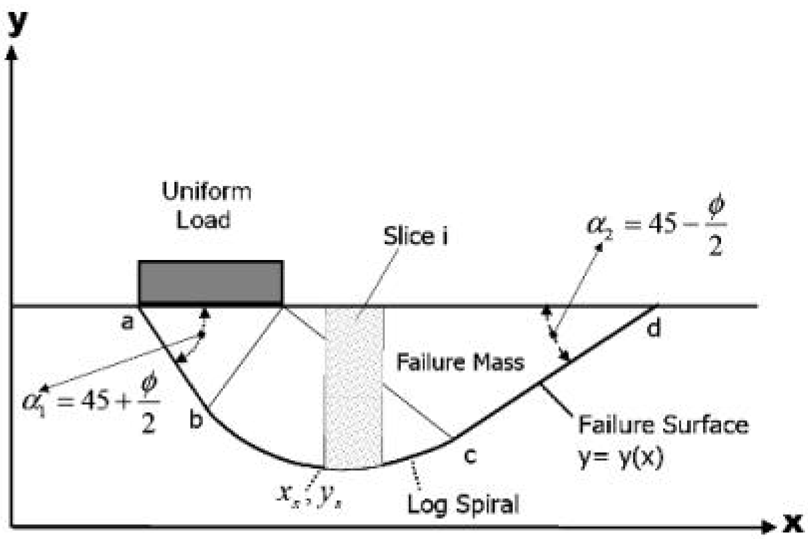

Figure 2. Exit and entry angles for a homogeneous bearing media (Tommy C. Hopkins, Liecheng Sun, and Mikhail Slepak, 2005).

To use the procedure that describes the shear surface used in Bearing Capacity is necessary to define the shape of the shear surface **abcd** in Figure 2, where the x- and y- coordinates of points **a**, **o**, **b**, **c**, and **d** must be established according to Figure 3. After these points have been defined, the coordinates, x_s (the x-coordinates of the sides of the slices) and y_s (the y-coordinates of the shear surface at the sides of the slices) may be determined. The coordinates of point **a**, x_a, and y_a are assumed. The x- coordinate of point (0, x_o) is assumed and depends on the width of the footing, $C = x_o - x_a$.

The y- coordinate, y_o, is arbitrarily selected, or assumed. The coordinates of point **b**, x_{tn}, y_{tn}, may be defined by first computing the radius, r_1, of the spiral,

$$r_1 = \frac{C \cdot \sin(\alpha_1)}{\sin(\Psi)} \quad [3]$$

where $\psi = 90° - \phi$. Line **ab** is assumed to be tangent to the log spiral curve at point **b**. After determining r_1, the coordinates of point **b** are defined as:

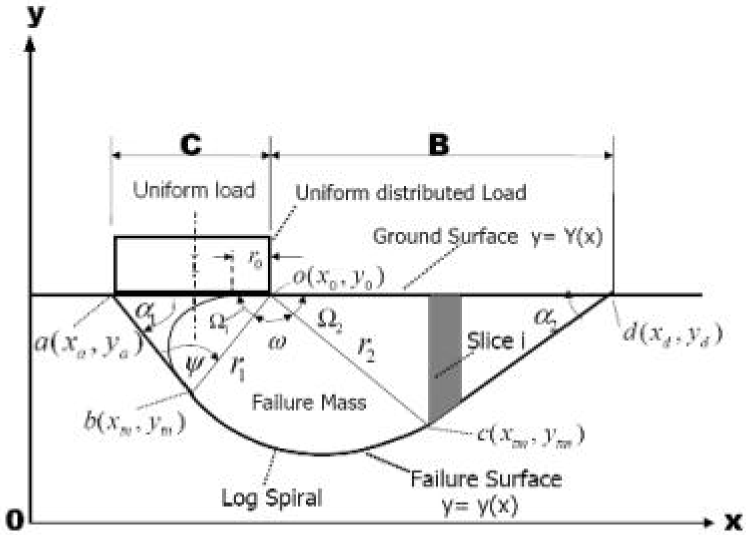

Figure 3. Geometric quantities defining the shape of the shear surface in a homogenous bearing media (Tommy C. Hopkins, Liecheng Sun, and Mikhail Slepak, 2005)**.**

$$x_{tn} = x_o - r_1 \cos \Omega_1 \quad [4]$$

$$y_{tn} = y_o - r_1 \sin \Omega_1 \quad [5]$$

where

$$\Omega_1 = 180 - \alpha_1 - \Psi \quad [6]$$

The initial radius, r_o, of the logarithmic spiral, at the top of the bearing surface (see Figure 3) is defined by the expression:

$$r_o = r_1 \cdot e^{(-\Omega_1 \cdot \tan\phi)} \quad [7]$$

Line **cd** is assumed to be tangent to the logarithmic spiral at point **c**. The coordinates of point c may be defined after the spiral radius, r_2, is determined. This radius is obtained from the expression:

$$r_2 = r_o \cdot e^{(180 - \Omega_2) \cdot \tan\phi} \quad [8]$$

where

$$\Omega_2 = \Psi - \alpha_2 \quad [9]$$

Coordinates of point **c** may now be defined by the following expressions:

$$x_{tm} = x_o + r_2 \cdot \cos(\Omega_2) \quad [10]$$

$$y_{tm} = y_o + r_2 \cdot \sin(\Omega_2) \quad [11]$$

The x-coordinate, x_d, of the point **d** may be determined by first computing the value of r_2 in Equation 8 (Figure 3). After r_2 is determined, the distance B may be calculated using the law of sines, or

$$B = \frac{r_2 \cdot \sin(180 - \Psi)}{\sin \alpha_2} \quad [12]$$

Hence,

$$x_d = x_o + B \quad [13]$$

The y-coordinate, y_d, may be found from the following expression:

$$y_d = y_{tm} + (x_d - x_{tm}) \tan \alpha_2 \quad [14]$$

After the coordinates **a, b, c,** and **d** are defined, the y-coordinate, y_s, of the intersection of the x-coordinate of the side of any given slice **i** and the shear surface may be determined. The potential failure mass is divided into a selected number of slices, n, as shown in Figure 4, or

$$\Delta x = \frac{x_a - x_d}{n}. \quad [15]$$

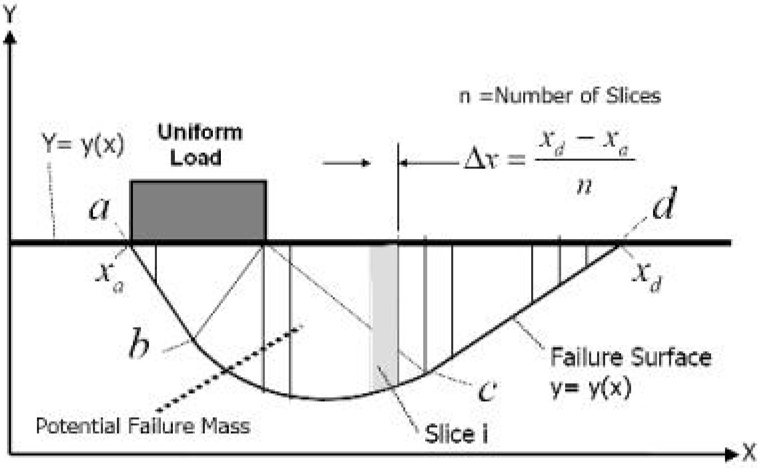

Figure 4. Division of theoretical failure mass into a number of slices and method of computing the width of each slice (Tommy C. Hopkins, Liecheng Sun, and Mikhail Slepak, 2005).

where Δx is equal to the width of each slice. For the x-coordinates, x_s, at the sides of slices that lie between points **a** and **b**, the y-coordinates, y_s, may be computed from the expression:

$$y_s = y_a - (y_{tm} + y_o) \tan \alpha_1 \qquad (x_a < x_i < x_{tn}) \quad [16]$$

Similarly, for the x-coordinates, x_s, at the sides of slices that lie between x_{tm} and x_b, the y-coordinates, y_s, located on the shear surface may be computed from the expression:

$$y_s = y_{tm} - (x_b + x_{tm}) \tan \alpha_2 \qquad (x_{tm} < x_i < x_{tn}) \quad [17]$$

For the x-coordinates at sides of slices that intersect the shear surface between points **b** and **c** (the connecting logarithmic spiral), the corresponding y-coordinates, y_s, cannot be computed straightforwardly since the angle, ω, corresponding to a given x-coordinate of the side of slice i is unknown. The problem may be solved by using an iterative scheme. The iterative scheme is performed by assuming, initially, a value of the angle, ω, and a value of y_{si}. To start the iteration for the first x-coordinate, x_s, which lies between x_{tn} and x_{tm}, the following assumptions are made

$$y_s = y_{tn} \quad [18]$$

and

$$\Omega_n = \Psi_1 . \qquad [19]$$

Iteration is performed on the following expression:

$$\Omega_{(n+1)} = \Omega_n - \frac{(x_o - x_s) - \left[e^{(\Omega_1 \tan\phi)}\right] \cdot r_{ocdot} \cos\Omega_1}{r_o \left[e^{(\Omega_1 \tan\phi)}\right] \left[\sin\Omega_1 - \cos\Omega_1 \cdot \tan\phi\right]} . \qquad [20]$$

When

$$\left\| \left[(x_o - x_s) - \left\{e^{\Omega_n \tan\phi}\right\} \cdot r_o \cos\Omega_n\right] \right| \leq \Delta, \qquad [21]$$

Where Δ a selected value, then

$$\Omega_{(n+1)} \approx \Omega_n , \qquad [22]$$

and the correct angle, ω, is found that corresponds to the x-coordinate of slice i. A selected value of 0.0001 is used for Δ in the bearing capacity computer program. The y-coordinate, y_s, may be computed from the following expression:

$$y_s = y_o - \left[r_o e^{(\Omega_{n+1} \tan\phi)}\right] \sin\Omega_{n+1} . \qquad [23]$$

For each x-coordinate of the side of each slice that lies between the x-coordinates, x_{tn} and x_{tm}, the iterative scheme is repeated so that corresponding y-coordinates, y_s, may be determined. Convergence is very rapid using this scheme.

Wayne Method et al.

Wayne et al. (1998) propose to use a filling soil on a geosynthetic reinforcement when this reinforcement is positioned on the soft soil and the failure occur by puncture load, where ultimate bearing capacity of soil is computed from the expression

Rectangular loading condition

$$q_{ult} = c.N_c + \left[2.c_a + \gamma.H\left(1 + \frac{2.D}{H}\right).\frac{K_p.\tan\alpha}{B}\right].\frac{H.(B+L)}{B.L} + \gamma.H + 2.T.\frac{B+L}{B.L} \qquad [24]$$

Infinite loading condition

$$q_{ult} = c.N_c + \left[2.c_a + \gamma.H\left(1 + \frac{2.D}{H}\right).\frac{K_p.\tan\alpha}{B}\right].\frac{H}{B} + \gamma.H + .\frac{2.T}{B} \qquad [25]$$

where,

c is soft soil cohesion, N_c is adopted 5.14 when it use synthetic reinforcement, ca is cohesion of filling soil, α is 2/3 of friction internal angle of filling soil, γ is bulk unit weight to filling soil, K_p is passive thrust coefficient, H is filling soil height, D is depth of shallow foundation, T is Tensile Strength of reinforcement.

CASE STUDY

The following real case study reinforces the necessity for the application of reinforcement under shallow foundation. This study focuses on the application of geogrid reinforcement under shallow foundation for high equipment to industrial building located in São Paulo, Brazil, that originally needed some alternative to better the foundation soil. For this work it was used the following design information:

Filling soil parameters

γ_a = 18 kN/m³
ϕ_a = 40 degrees
H = 0.30m

Uniform load on surface (high equipment)

Q = 60 kPa

(base width of equipment) B = 2.00m

Foundation soil parameters

γ_f = 18 kN/m³

ϕ_f = 0 degrees

c = 15kPa

The Ultimate Bearing Capacity required stabilizing the soil foundation to receive the base of high equipment should be bigger than 100kPa.

Geogrid reinforcement properties

For this work was used a woven high strength geogrid composed of high tenacity, multifilament polyester yarns woven in tension and PVC coated to form a stable fabric. This geogrid was considered ideal for that application where its mechanical properties have been tested in accordance to published standards, and it presented in Table 1.

Table 1. Reinforcement material properties.

Mechanical properties				
MD – Tensile Strength (Ultimate)	T_{ultlMD}	kN/m	ASTM D6637	60.00
XD – Tensile Strength (Ultimate)	T_{ulttXD}	kN/m	ASTM D6637	30.00
MD – Ultimate Strain at failure	ε	%	ASTM D6637	12.00
Tensile strength at 2% strain	$T_{2\%}$	kN/m	ASTM D6637	12.00
Tensile strength at 5% strain	$T_{5\%}$	kN/m	ASTM D6637	18.00
CREEP reduction factor	RF_{CR}		ASTM 5262	1.65
Long Term Design Strength		kN/m	ASTM 5262	36.36

Calculation Development

Considering log spiral determination to bearing capacity analysis is possible to obtain the ultimate resistance of geogrid considering its reduction factors. Respecting the terms imposed for a homogeneous soil and considering the zones of active, passive and log spiral curve, is possible to determine the form of the surface of critical failure (Figure 3).

Analytically it obtain critical surface and using the MacStars® 2000 program it is possible to check the stability of reinforced soils (figure 5 and 6). The result obtained from MacStars® 2000 (Figure 5 and 6) showed an improvement of 62% in the support capacity of this soil through analytical failure surface.

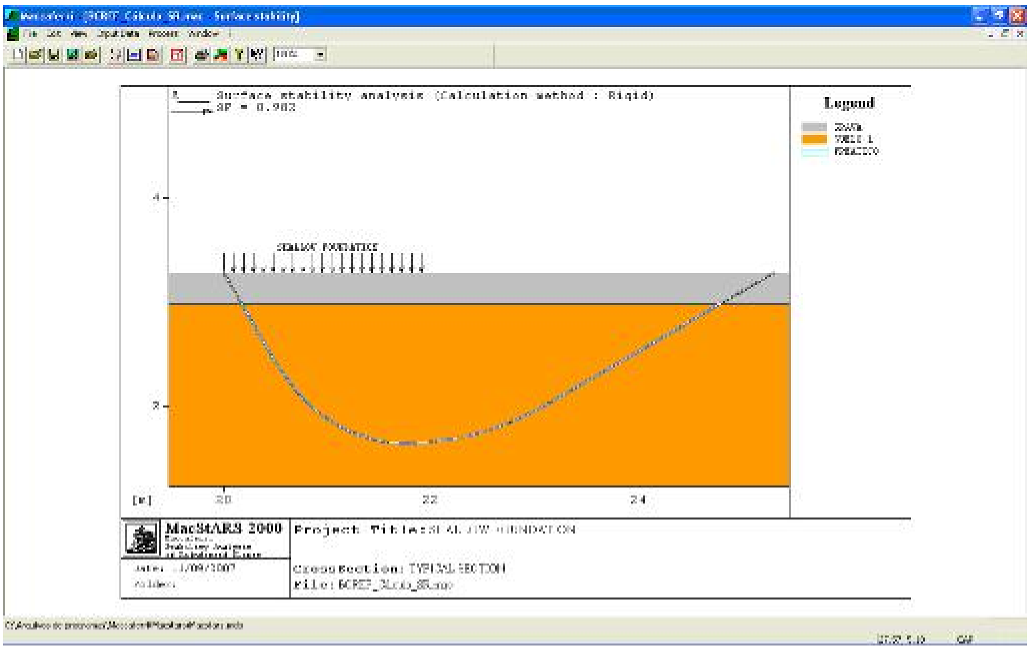

Figure 5. Safety factor of 0.982 obtained from MacStars® 2000 without reinforcement.

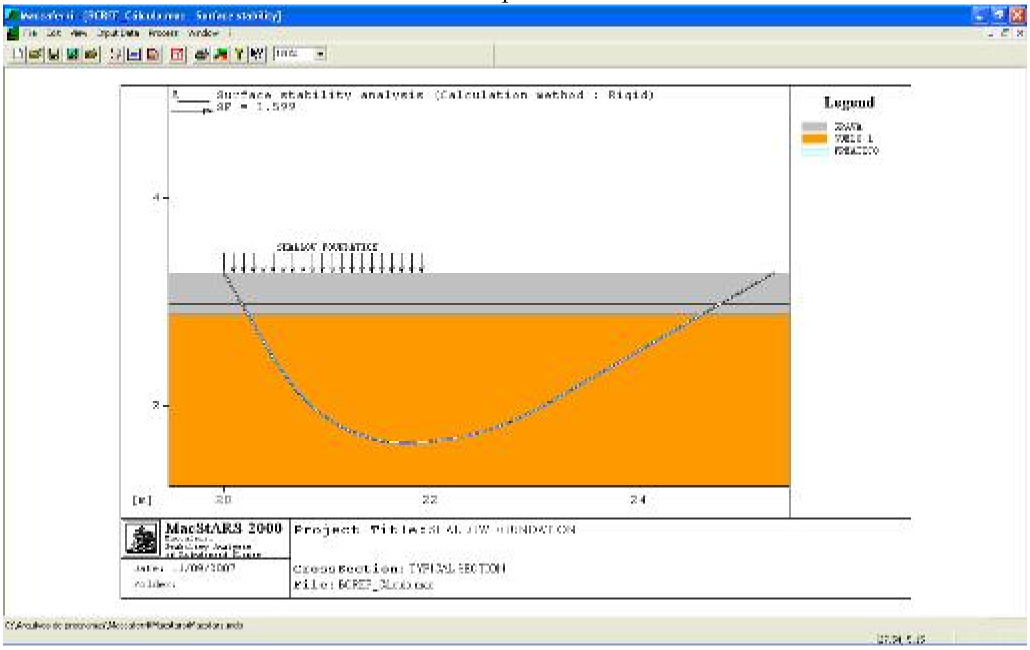

Figure 6. Safety factor of 1.692 obtained from MacStars® 2000 with reinforcement.

Now considering the Wayne Method and using the design information and geogrid reinforcement properties, and applying equation 25 to infinite loading condition, it can obtain the following results:

$$q_{ult} = c.N_c + \left[2.c_a + \gamma.H\left(1+\frac{2.D}{H}\right).\frac{K_p.\tan\alpha}{B}\right].\frac{H}{B} + \gamma.H + .\frac{2.T}{B} = 114.06 \text{ kPa}$$

This result represents a superior value to ultimate bearing capacity required to stabilize the foundation of high equipment.

CONCLUSION

The inclusion of woven geogrid reinforcement under a shallow used a calculation process that is not usual. As there is not a specifically method to calculate this type of application by geogrids, this paper has brought a suggestion that relates the geogrid mechanical characteristic with particular characteristic of shallow foundation and bearing capacity analysis considering the three levels to sliding surface, active zone, log spiral curve and passive zone.

Polyester geogrid presents its best performance to high deformation or long term strength when used in, for example, reinforced embankment over soft soils. However, the results obtained in this work show that is possible to use a woven geogrid under concrete floor (high tenacity polyester geogrid), since that is considered its characteristics strength to low deformation or short term strength when consider a uniform load on ground level.

The model proposed by Hopkins, which are based on limit equilibrium and are operated together, can be used to analyze the bearing capacity, or stability, of early construction of loads on a homogeneous layer of base aggregate material and subgrade of soft soil. In this case considering shallow foundation is necessary to consider initial mobilization of geogrid strength before receives the concrete floor or rigid element, in other words, during the construction soil operation the geogrid must be working.

The difference between methods should be done for a correct interpretation. Wayne’s Method considers a capacity of last load for a reinforcement soil with geosynthetic, while Hopkins’s Method considers a factor safety according to the search of the surface of critical failure. Understand the load capacity of the soil according to Wayne’s Method looks simple, however that method specifies the placement of a reinforcement to a certain depth without taking in account which the maximum length under the shallow foundation should be adopted, that the makes useful when it needs to know, like initial parameter, which the load bearing capacity of soil reached with the reinforcement, however limited when they introduce wide foundations, as the presented in this paper. Already Hopkins’s Method complements the one of Wayne, once that when establishing a failure surface also criticizes establishes which the area that will be asked under the foundation. Regarding the safety factor obtained by traditional methods according to of analyzes of slope stability as Janbu or Bishop, just makes that attractive method in terms of manipulation of the safety factor adopted by the geosynthetic material and by softwares of slope stability analysis diversity existing nowadays.

The results reported in this paper suggests that assumptions regarding the geostatic case, where it possible to use the repose earth thrust distribution on geogrid reinforcement, and this consideration is passive to numerical analysis to confirm it, mostly because it has not evaluated the geotextile behavior. The geotextile was considered like separation membrane whose work is keeping the thickness of base aggregate and sufficient bearing capacity to equipment traffic.

Despite empiric considerations the polyester geogrid has presented excellent results, exactly as it was designed.

Acknowledgements: The authors wish to extend special thanks to Maccaferri America Latina, Prof. Eng. Benedito de S. Bueno, Mr. Jim Walker and their families.

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