

Bearing Capacity of Working Platforms Using Distinct Layout Optimization Method

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Abstract. Bearing capacity of the working platforms from sandy soil resting on NC and OC clays was analyzed using LimitState GEO program. Different failure modes are considered using distinct layout optimization (DLO) method, which forms the upper bound solution of limit state analysis. Different mechanisms of failure were observed as a function of the platform thickness, angle of internal friction of the platform material and undrained shear strength of the subgrade. The distribution of undrained shear strength with depth was also taken into consideration. The typical failure modes were presented. The calculated bearing capacity was compared to analytical solutions and recommendations of BRE. Special attention was paid to the platform resting on soft clay with undrained shear strength lower than 20 kPa, as this case is not covered by these recommendations. The solution obtained with DLO method was compared to bearing capacity calculation using Plaxis and ϕ , c reduction method. Additionally some analysis was performed for a real platform of sandy soil on soft organic clay. Here, the strength and deformation parameters of the platform material and the subgrade were determined with a dilatometer test (DMT). This kind of approach permits to determine both strength and deformation parameters of the platform material and soft subgrade in one test.

Keywords. Limit state, soft soil, undrained shear strength

1. Introduction

The design of working platforms can be considered as a bearing capacity problem of layered soil. The upper layer – platform made up from compacted cohesionless material – is constructed on weak subgrade to permit traffic of heavy machines. The weak subgrade may be generally cohesive or cohesionless. This paper considers the first layer of medium sand and the soft layer from clay. The thickness of the platform, the compactness and strength of the platform material have to assure safe traffic of heavy equipment like drilling or piling rigs, heavy tracks or compactors and the proper execution of piling or soil improvement works.

Different methods exist to estimate bearing capacity of the shallow foundation on such layered soil. The first group is based on analytical methods implemented in BRE 470 or EBGeo (2012) recommendations for contractors of geotechnical works. The second one uses limit state approach. Here, LimitState GEO software was applied to find the kinematically admissible estimation of the subsoil bearing capacity. The

third group of methods addressed in this paper considers the use of Finite Element Model (FEM) Analysis.

2. Geometry and Soil Conditions

2.1. Geometry of the Problem

The present analysis is part of a wider research program concerning the design of working platforms. Here, the attention is focused on the bearing capacity of the platform resting on very soft normally consolidated and overconsolidated subgrade. It is a parametric study with soil parameters assumed using in-situ tests. A typical geometry and load conditions are assumed. The general scheme of the problem is given on Fig. 1. The thickness of the upper cohesionless layer is variable, while the geometry of the weak subgrade is kept unchanged. It is assumed that the track with width of $B=0.7$ m, transmits a uniform load of 77 kPa from tracked plant on caterpillar to the subsoil.

2.2. Soil Parameters

The strength and deformation parameters of the real working platform were estimated using dilatometer test results. Such approach permits both strength (ϕ' , c_u) and deformation soil parameters to be determined in one penetration test. The effective angle of internal friction for the platform material and the undrained shear strength determined for the soft subgrade calculated using the formulae of Marchetti et al. (2001) are given in Fig. 2. The angle of internal friction is estimated in the range from 35° to 42° and the undrained shear strength is from 5 to 16 kPa, which corresponds to very soft to soft clays. The averaged constrained modulus is equal to 40 MPa for the platform material and 2 MPa for the soft subgrade. The soil parameters admitted in the analysis are based on the DMT test results.

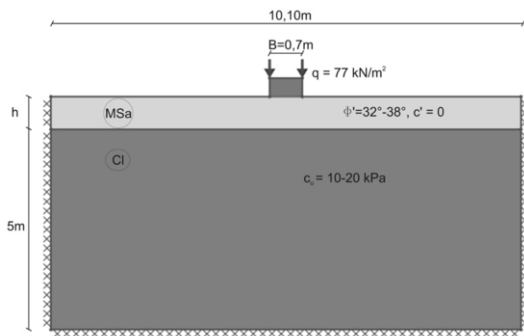


Figure 1. General scheme of the working platform.

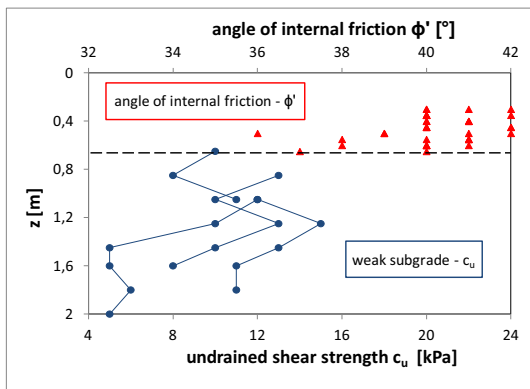


Figure 2. DMT test results in the platform and the subgrade.

Taking into account the estimated undrained shear strength of the subsoil (Fig. 2) four different distributions of c_u were analyzed in this study (Fig. 3). Two constant distributions of c_u

with depth were assumed with c_u equal to 10 and 20 kPa. Additionally, two other models of undrained shear strength distributions with depth were used. The first one considers the shear strength increasing with depth at 2 kPa/m and the second one is described with c_u decreasing with depth at 2 kPa/m. The undrained shear strength increasing with depth is typical for normally consolidated soils, other distributions of c_u correspond to overconsolidated soft soils.

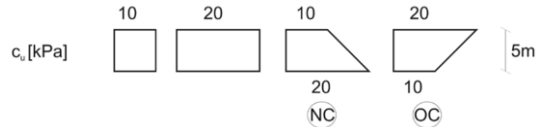


Figure 3. Undrained shear strength distribution in weak subgrade.

3. Description of the Calculation Methods Used

The design calculation described in BRE 470 guide is based on the analysis developed by Meyerhof (1974) for a footing punching through a strong platform material overlying a weak subgrade. The analysis based on punching failure represents a major simplification of the actual field situation and is semi-empirical in character. According to BRE 470 it is possible to calculate the necessary platform thickness for a given load, foundation shape and shear strength parameters of the platform (ϕ') and the soft subgrade (c_u). It is also possible to check the platform thickness when geosynthetic reinforcement is introduced under the platform layer. The use of recommendations is restrained to the soft subsoil with c_u equal at least 20 kPa. Thus BRE 470 recommendations cannot be applied to very soft subsoil.

Kinematically admissible solution of bearing capacity can be determined using LimitState GEO program. It estimates the ultimate limit state (ULS) using the computational limit analysis technique - Discontinuity Layout Optimization (DLO). The optimization procedure is implemented to identify the critical slip surface when the failure occurs. The patterns of rigid sliding blocks in plane strain condition together with inter-block forces are obtained. The calculated bearing capacity is a

kinematically admissible solution and forms the upper bound of the limit state. Two different approaches are possible. When “Factor on load” approach is used the load at failure is obtained, so it is possible to calculate the margin of safety concerning the applied load. If “Factor on strength” approach is chosen the strength parameters, i.e. $\text{tg}(\phi')$ and c' or c_u , are divided by a certain factor up to failure. In this way one can get a margin of safety concerning the effective or total strength parameters of the subsoil. The software allows applying the partial coefficients concerning both actions and strength parameters in order to meet the requirements of calculations according to EC-7. In the present analysis all partial coefficients concerning actions and strength parameters were assumed equal to 1. This is the principal method used in this paper to determine the bearing capacity of the working platform.

Bearing capacity of shallow foundation can be also calculated using FEM program like PLAXIS, Białek (2013). Then ϕ , c reduction procedure is applied and the margin of safety concerning the soil strength parameters can be established, Vermeer (2002).

In all three methods the analyses were made assuming strip foundation and plane strain conditions. The Mohr-Coulomb model was used to describe soil failure criterion. The platform material was considered as drained and weak subgrade was assumed as undrained. The contact area between caterpillar and working platform was characterised by the boundary element having zero thickness and geotechnical parameters reduced by 50% .

4. Calculations

4.1. Results obtained with DLO

The calculations were performed using “Factor on load” and “Factor on strength” approaches. In the first step the values of internal friction angle for platform material in the range from 32° to 38° and $c_u=20$ kPa were assumed.

The kinematic mechanisms of failure and calculated factors on load are given on Fig. 4 and 5 for $\phi'=35^\circ$ and different relative thickness of the platform. The punching failure mechanism

observed in Fig. 4 changes progressively with platform thickness. For (h/B) not larger than 1 the punching failure in platform material is followed by the generalized failure in the soft subsoil. As the relative thickness of the platform increases the failure pattern doesn't penetrate the soft layer further but is constrained within the interface between two layers.

The generalized failure mechanisms for the relative thickness of the platform (h/B) equalling 2 is given in Fig. 5. In this case the failure takes place in the platform material only.

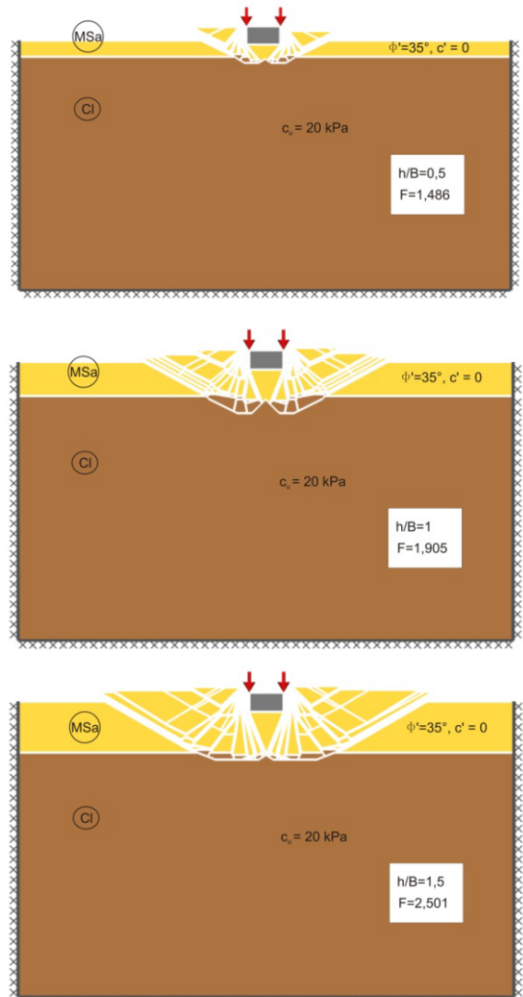


Figure 4. Punching failure for (h/B) from 0.5 to 1.5.

The calculated factor on load is given in Fig. 6 as a function of relative thickness of the platform (h/B) . For small (h/B) values up to 0.75 almost the same factor on load is obtained regardless of the effective friction angle of the platform

material. It means that the punching failure occurs in the platform with generalized failure in the soft subgrade and the bearing capacity of the working platform is mostly governed by the undrained shear strength of the weak subgrade. For relative thickness of the platform (h/B) larger than 0.75 the calculated factor on load increases with the effective angle of internal friction of the platform material. The factor on load reaches its maximum value, being a function of the internal friction angle ϕ' , for the relative thickness of the platform (h/B) larger than 2. It should be pointed out that for higher values of internal friction angle some side effects were observed for higher platform thickness with sliding lines approaching the lateral boundaries of the domain, which led to overpredicted values of the calculated factor on load. In such cases the calculations were repeated using enlarged domain.

If typical safety coefficient for shallow foundation equalling 2 is applied, one can determine the necessary relative thickness of the platform to satisfy bearing capacity condition. This relative thickness (h/B) should exceed 1.1 for $\phi'=32^\circ$, 0.9 for $\phi'=35^\circ$ and 0.85 for $\phi'=38^\circ$.

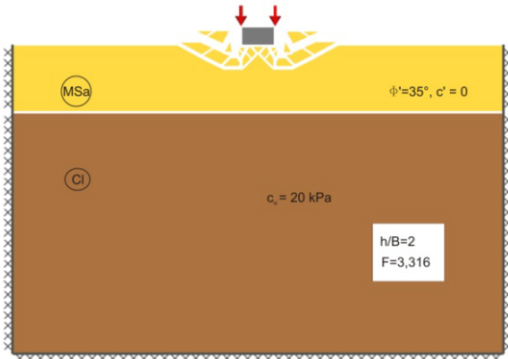


Figure 5. Kinematic mechanism of failure for $(h/B)=2$.

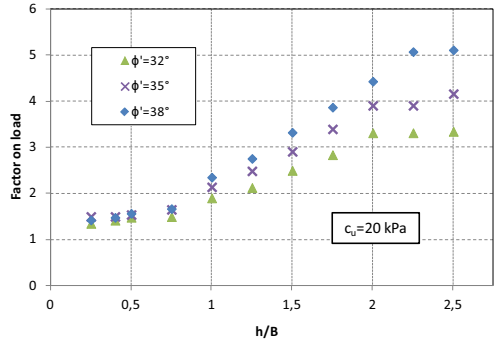


Figure 6. Factor on load vs. relative thickness of the platform for different values of internal friction angle.

In the next part of this study the different schemes for undrained shear strength distribution were taken into consideration (see Fig. 3). Two constant profiles of c_u were analyzed with undrained shear strength equalling 10 kPa and 20 kPa. Additionally, the profile with c_u starting at 10 kPa and increasing at 2kPa/m and the c_u profile starting at 20 kPa and decreasing at 2kPa/m with depth were taken into account. Two different angles of internal friction of the platform material were considered, i.e. ϕ' equalling 35° and 38° . The calculation results of factor on load for $\phi'=35^\circ$ are given in Fig. 7. One can notice a considerable difference between the factors on load obtained for c_u equalling 10 kPa and 20 kPa. Only a small effect of the undrained shear strength increase or decrease with depth on the factor on load is observed. The necessary relative thickness of the platform to satisfy bearing capacity condition should exceed 1.5 for $c_u = 10$ kPa and 0.9 for $c_u=20$ kPa.

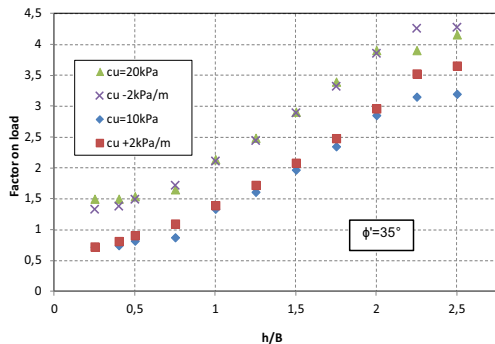


Figure 7. Factor on load vs. relative thickness of the platform for different c_u schemes.

The results obtained for factor on strength calculated with different angles of internal friction and the undrained shear strength of the weak subgrade of the platform and the undrained shear strength of the weak subgrade $c_u=20$ kPa constant in the soil profile are given in Fig. 8. This factor increases with the relative thickness of the platform and with the effective angle of internal friction of the platform material, however some fluctuations of the results can be observed. The margin of safety obtained with factor on strength cannot be however interpreted in such straightforward manner as using the factor on load approach. In the next chapter the results will be compared to analysis obtained with Plaxis.

4.2. Results according to Plaxis

The analyses were performed for the internal friction angle $\phi'=38^\circ$ and the undrained shear strength of the weak subgrade $c_u=20$ kPa for varying relative thickness of the platform. The ϕ, c reduction procedure was applied at the end of calculation of bearing capacity of strip foundation and the factor on strength was determined.

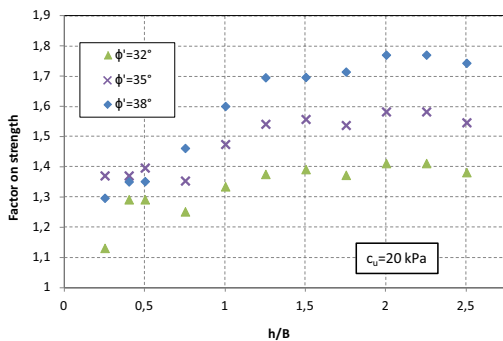


Figure 8. Factor on strength vs. relative thickness of the platform for different angles of internal friction.

4.3. BRE method

According to BRE recommendation it is possible to estimate the necessary thickness of the platform for a given load and soil conditions. For the purpose of this study the inverse approach was used and the failure load was determined for the assumed platform thickness. All the coefficients concerning the applied load and the

shape of the foundation were assumed equal to 1 in order to compare the results with previous methods. The analysis were performed for the effective angle of internal friction $\phi'=38^\circ$ and the undrained shear strength of the weak subgrade $c_u=20$ kPa. According to restrictions imposed by BRE guide the calculation was made for the relative thickness of the platform (h/B) not larger than 1.5. The failure mechanism for higher values of relative thickness (h/B) differs from the punching failure scheme involved in BRE recommendations, so other calculation methods should be used in such case.

5. Discussion of results

The factors on strength determined with LimitState GEO and Plaxis are compared (Fig. 9) for the effective angle of internal friction $\phi'=38^\circ$ and the undrained shear strength of the weak subgrade $c_u=20$ kPa. Very similar results for both methods were obtained with slightly higher GEO factor on strength for the relative thickness of the platform (h/B) larger than 1.

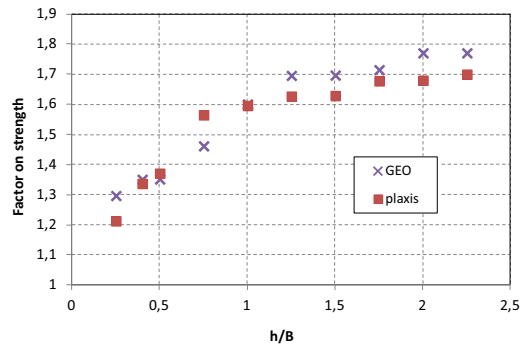


Figure 9. Factor on strength according to GEO and Plaxis calculation.

Finally, the bearing capacity of strip foundation on a working platform was compared for LimitState GEO and BRE methods (Fig. 10). The results are given for undrained shear strength of the soft subgrade equalling 20 kPa. Due to limitation of the BRE method the results for relative thickness (h/B) not higher than 1.5 are plotted. For (h/B) ratios smaller than 0.75 the results are almost the same regardless of the calculation method and the angle of internal friction of the platform material. For higher (h/B)

ratios the influence of shear strength of the platform material is getting more important as the failure mechanism is changing progressively. One can notice that the bearing capacity obtained with LimitState GEO is systematically higher than that calculated according to BRE. It is related to the fact that LimitState provides a kinematically admissible solution which forms the upper bound for the bearing capacity problems.

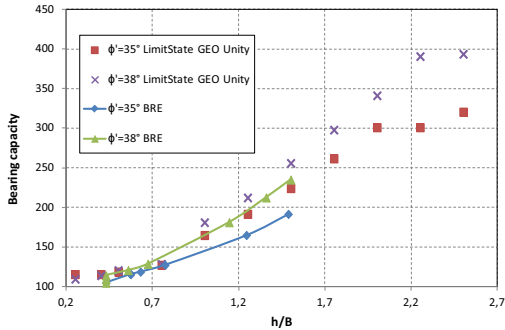


Figure 10. Bearing capacity of the working platform loaded by strip foundation according to BRE and GEO analysis.

6. Conclusions

Three different methods were used to determine the bearing capacity of the strip foundation on two-layered soil. The analysis was focused on the behaviour of the platform on very soft to soft clays. The applied calculation methods should be used with respect to different failure mechanisms observed.

These mechanisms depend first of all on the relative thickness of the platform but also on the effective angle of internal friction of the platform and the undrained shear strength of the soft subgrade as well. Analysis of the failure mechanisms for different relative thickness of the working platform on soft subgrade confirms that the punching failure in the platform material can be observed for (h/B) not larger than 1.5. For

higher (h/B) values the generalized failure mechanism within platform material takes place. It was confirmed that the margin of safety for the bearing capacity problem is sensitive to undrained shear strength, however the influence of c_u distribution with depth according to the admitted schemes was negligible.

It was found that the LimitState GEO method is quite sensitive to the mesh coarseness and to the size of the domain. The influence of boundary effects on the obtained solution should be thus carefully examined in order to get reliable results.

The first attempt to use DMT for the estimation of the soil parameters for the platform and the subgrade in one penetration test seems to be promising. This approach should be verified on other trial fields using other in-situ and laboratory tests.

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