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Working platforms for cranes – review of design approaches and recommendations for a safe design

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ABSTRACT: This paper provides a technical insight into the essential aspects to be considered in the proper design of a safe working platform for heavy construction machinery. Considering the complexity of the operational boundary conditions, the uncertainties of the ground characteristics and the variability of the loads applied by the construction machinery, a clear understanding of the possible failure modes and the definition of a criterion for the design of countermeasures seems to be essential in this application. This can be better achieved by considering the significant increase in cost and time delays associated with the failure of the working platforms. This paper discusses various possible failure mechanisms in the working platforms and examines the advantages of using geosynthetic reinforcing elements to avoid the risk of failure.

1 INTRODUCTION

In recent years, a number of heavy construction machines such as drilling rigs, trenchers, pile drivers, mobile cranes and crawler cranes have been involved in serious accidents due to incompetent working platforms. Considering the size and weight of such machines, the overturning of such equipment is often associated with fatal injuries, damage to third parties or work teams, high costs due to recovery of the collapsed equipment, replacement of a new machine as well as production loss or installation delay. Figure 1 shows examples of the working platform failure and the resulting installation machine accident. In addition, these major accidents always have a significant psychological impact on the site personnel. The main cause of most of these accidents is the mismatch between the shear strength provided by the platform and the actual operational loads. This mismatch between available and required shear strength can be the result of improper design of the platform, inadequate knowledge of the geotechnical and geological site conditions and/or insufficient information on the load combinations induced by the equipment in different working conditions. In this context, an adequate design of a competent working platform should properly consider the coupled interactions in the ground and consider all possible failure modes in accordance with an appropriate design method.

Figure 1. Examples of construction machinery overturning.

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Considering the significant need to obtain a deep insight into the system behaviour, this paper has investigated and discussed different aspects around the problem, including the coupled interactions such as excess pore pressure evolution and dissipation, relevant failure mechanisms for different loading conditions, and the necessary design criterion. Furthermore, the need to develop advanced and comprehensive numerical tools to predict all these engineering phenomena and not only some of them has been discussed.

2 MEHTODOLOGY AND NUMERICAL MODELLING

In the present study, in order to demonstrate the capability of the finite element modelling approach to evaluate the likely failure mechanism and critical design aspects, a numerical model of a 1 m thick working platform with two layers of geogrid with a short-term nominal tensile strength of 400 kN/m has been developed. In this model, the lower layer of geogrid is placed at the contact between the weak subsoil and the fill material, while the upper layer is placed 0.3 m above the other. The non-cohesive working platform material is assumed to have a friction angle of 38°, dilatation of 8° and modulus of elasticity of 180 MPa, while the undrained soft subgrade with a thickness of 2 m has an undrained shear strength of 20 kPa. This soft subsoil is underlain by a low plasticity silt with an undrained shear strength of 50 kPa. Given the rapid nature of crane loading, an undrained analysis was carried out. The machine track is assumed to be 1.5 m wide with a center-to-center distance of 8 m, carrying a maximum pressure of 200 kPa. The water table is assumed to be 1 m below the ground surface, while the soft subsoil above the water table is assumed to be saturated.

3 TECHINAL ASPECTS IN THE DESIGN OF WORKING PLATFORMS

3.1 *Bearing capacity of the working platform*

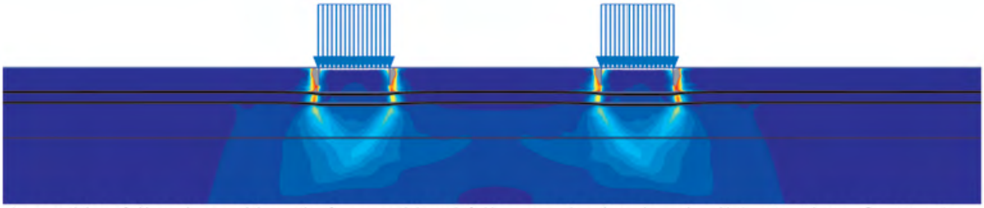
One of the essential aspects to be considered in the proper design of a working platform is the correct determination of the available load-bearing capacity according to a realistic failure mode. In this context, it is important to consider all possible failure modes, such as punch, local and global shear failure, and their potential combination in the fill materials of the platform as well as the subsoil as a system.

For example, in the case of a thin platform, there is a high probability that a punch failure will occur within the platform body, which may be associated with a local or global failure of the subsoil. In this context, it should be noted that, depending on the nature of the subsoil material and the water table, the bearing capacity must be determined on the basis of the total or effective shear parameters in the case of a frictional soil or the undrained shear strength parameters for a cohesive soil.

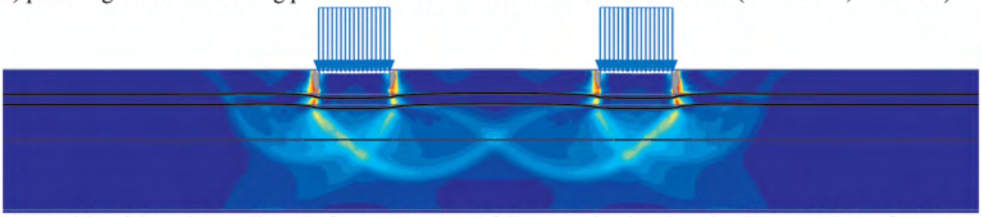
It should be noted that the difference between local and global shear failure in the soil is mainly due to the settlement of the foundation. In other words, local shear failure often corresponds to lower levels of settlement where less shear strength of the soil is mobilised, while the global shear failure mechanism often corresponds to extremely large settlements. In this context, special attention must be paid to the sensitivity of the machine to settlement before considering global shear failure to determine the bearing capacity.

As can be seen in Figure 2, since the mobilisation of the soil shear strength requires the development of strain in the soil, the bearing capacity of the system must essentially be defined in terms of the acceptable settlement in the system.

One of the most commonly observed phenomena with relatively thin (but competent) working platforms is the so-called "trampoline effect". In this situation, the soft, fully saturated subsoil reacts almost undrained to the application of dynamic loads. However, during the operation of the construction machine, the excess pore pressure generated in the



a) punching failure in working platform and local failure mechanism in subsoil (σ=150 kPa, δ=4.9cm)



b) punching failure in working platform and general failure mechanism in subsoil (σ=200 kPa, δ=8.3cm)

Figure 2. Evolution of the failure mechanism and bearing capacity through progressive loading (deviatoric shear strain obtained from FE modelling).

subsoil begins to dissipate (see Figure 3). As a result of this consolidation process, further settlement would develop, particularly below the machine. Accordingly, settlement or, more generally, displacement in the working platform and in the ground occurs as an inevitable part of the system and it is often not appropriate to assume that the only role of the working platform is to distribute the load as a purely elastic rigid body over a wider area in depth. Such an idealised conceptualisation of the design method, without consideration of platform failure, requires a justification for no displacement in the ground. Otherwise, the membrane effect and, consequently, the evolution of the tensile force in the geosynthetic layers is an essential event in the kinematics of the system that must be considered in the design phase.

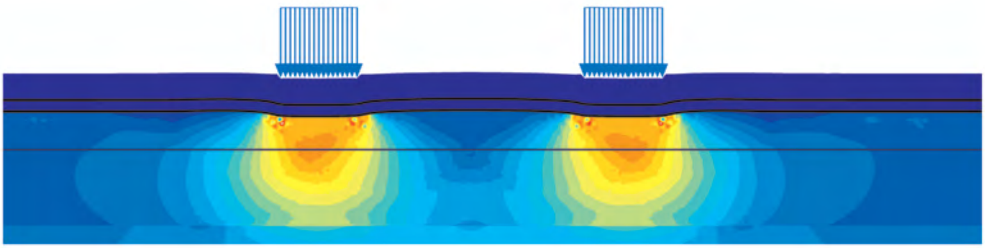


Figure 3. Excess pore pressure in subsoil obtained from FEM ($\Delta u_{max.=}$120 kPa, σ=200 kPa).

As shown in Figure 3, excess pore pressure is generated in the subsoil with high water table. Depending on the type of soil, either undrained shear strength (s_u) or effective shear parameters (i.e., φ' and c') must be used to determine bearing capacity.

In the working platforms reinforced with the geosynthetic layers, the proper interlocking between the geosynthetic layer and the fill materials allows the development of a load transfer arch within the working platform. Figure 4 shows the load transfer mechanism in the working platform with two layers of geogrid. As can be seen, the kinematics of the membrane developed by settlement in the geosynthetic leads to the formation of an arch to transfer the machine load to a wider area. This arching effect is a natural consequence of the deformation in the system and has nothing to do with the oversimplification of assuming a linear load transfer in the working platform.

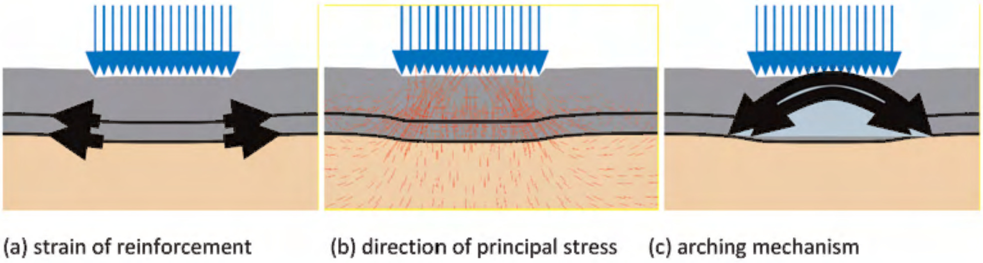


Figure 4. Load transfer mechanism in the working platform.

Instead of using fill material with adequate shear strength to construct the working platform, the use of material with low shear strength combined with increased thickness of the working platform is often considered as an alternative solution. In such conditions, a special attention should be paid to properly assess the possibility of shear failure within the platform body (see Figure 5). In this context, the bearing capacity of the working platform alone must be determined and compared with the load applied by the machine operation. If it is necessary to use fill material with a lower bearing capacity, more layers of geogrid must be installed at the design vertical spacing to ensure no shear failure in the working platform.

Figure 5. Failure within a thicker working platform with insufficient shear strength (h_{platform}=2 m, φ_{p}=27°).

3.2 *Slope stability analysis*

Given the limitations in the availability of high-quality fill material and the relatively high cost of properly constructing a competent working platform, there is often debate about minimising not only the thickness but also the area of the working platform and reducing the distance between the machine stand and the side slopes of the working platform. However, this is an essential technical issue that must be addressed in a proper design. To do this, the dimensions of the working platform must be such that (1) it provides sufficient stability against slope failure and (2) it provides sufficient resistance to pullout failure of the geosynthetic reinforcement by allowing sufficient length for the reinforcement to extend beyond the zone of the load application. To assess slope stability, classical approaches such as Bishop's method can be used to determine the safety of the slope against failure, considering the distance between the slope and the machine loads (see Figure 6).

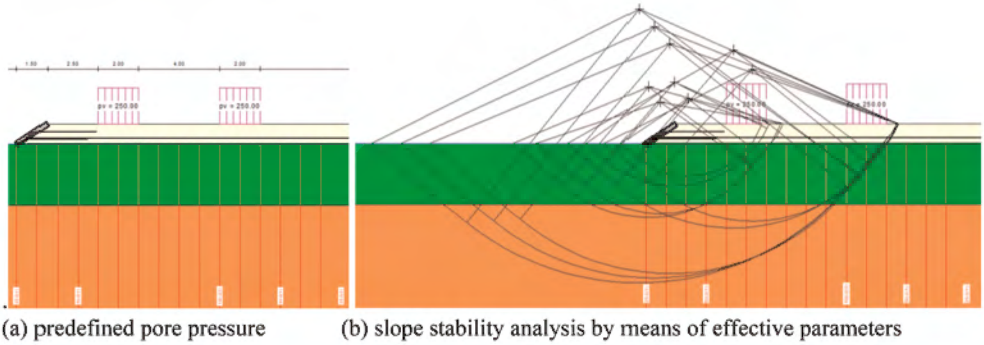


Figure 6. Slope stability analysis to determine allowable working area.

If the stability analysis is carried out in conjunction with the effective shear strength parameters (e.g., $\varphi'$and c'), the possibility of the development of excess pore pressure in the subsoil and its effect on the stability analysis in conjunction with the analytical solutions should be investigated and properly introduced into the model. The results of the slope stability analysis would be used to determine the permissible working area for the construction machine. In the case of stability analysis based on undrained shear strength, it is recommended to consider the increase in undrained shear strength with effective vertical stress as mentioned in the literature (Mesri 1975). Figure 6 shows a standard stability analysis combined with an analytical approach to design the minimum distance between the permissible working area and the edge of the working platform.

3.3 *Lateral extrusion failure in soft subsoil*

Another mode of the failure that should be investigated in a proper design of working platforms is the extrusion of the weak subsoil at the under heavily loaded working platforms. For this purpose, it is essential to verify whether the weak subsoil has sufficient strength to resist the unbalanced horizontal load that induced by the active earth pressure. In this frame, Scotland *et al.* (2019) discussed different possibilities to increase the shear strength against lateral extrusion or squeezing of the subsoil. The use of a geosynthetics with adequate interlocking properties would help to reduce the horizontal load transfer to the weak soil. Figure 7 shows how the contribution of the geosynthetic layers can reduce the deficit between the resistance to extrusion and the active earth pressure due to high vertical loads.

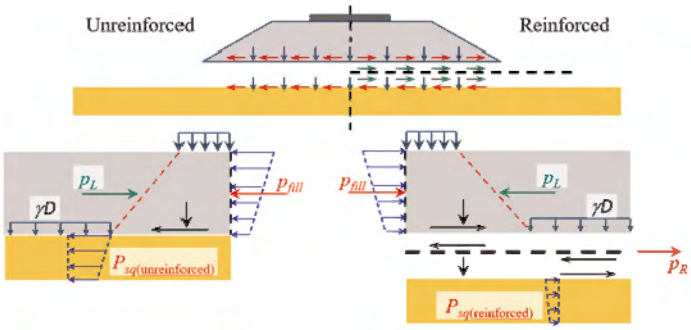


Figure 7. Reducing the susceptibility of the platform to lateral extrusion through geosynthetic reinforcement.

Giffen 2015 proposed the construction of a shear key trench to disrupt the potential for lateral extrusion where the use of geosynthetic reinforcement at the base of the working platform does not fully mitigate the risk of weak lateral soil spreading. This shear key can be constructed as (a) full depth unreinforced, (b) full depth reinforced or (c) partial depth reinforced. In the case of a full depth shear key, the trench involves replacing the full height of the weak soil to achieve the required lateral resistance and improve the drainage capacity of the weak soil. Considering the challenges of excavating in saturated soft ground, the construction of a reinforced partial depth trench is of great preference. The load transfer of extrusion mechanisms with reinforced shear trenches according to BS 8006 (2016) is shown in Figure 8.

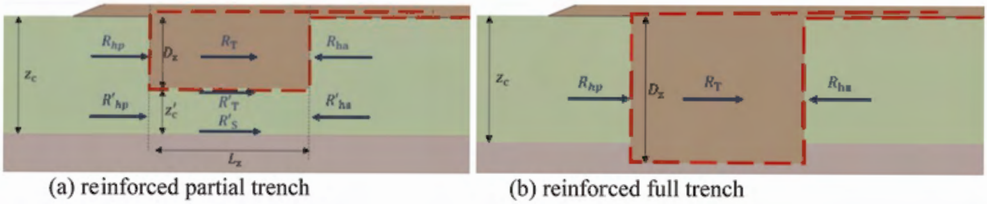


Figure 8. Load transfer of a working platform with reinforced shear trenches (BS 8006, 2016).

In addition to analytical solutions, such a lateral spreading failure mechanism can also be evaluated using numerical FE modelling, as shown in Figure 9.

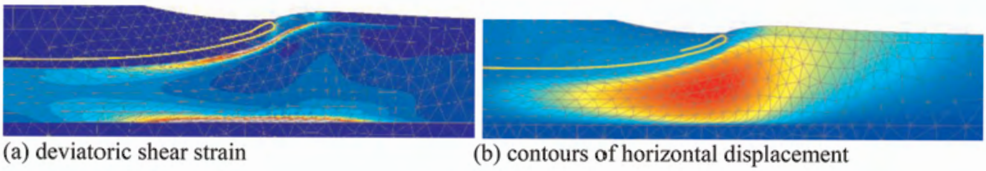


Figure 9. Application of FE modelling to assess the lateral spreading failure mechanism in the weak soil underneath working platforms.

3.4 *Working platform with multiple geosynthetic layers*

The monitoring of the tensile forces in the geosynthetic reinforcements as basal reinforcements has shown a non-identical evolution of the tensile force in the reinforcement layers. In this frame, the lower reinforcement layer is overloaded, while the upper reinforcement would be underloaded compared to the lower one. As the mobilisation of the tensile force in the geosynthetics is a direct function of the tensile strength, the different mobilisation of the tensile force between the layers is mainly due to the unequal loading of the layers at different depths. In this context, the required total tensile strength of multiple geosynthetics should not be defined on the assumption of simultaneous mobilisation of tensile force in different layers.

Figure 10 shows an example of non-identical distribution of tensile force between different reinforcement layers in the case of a working platform with two layers of geosynthetics obtained from FE analysis.

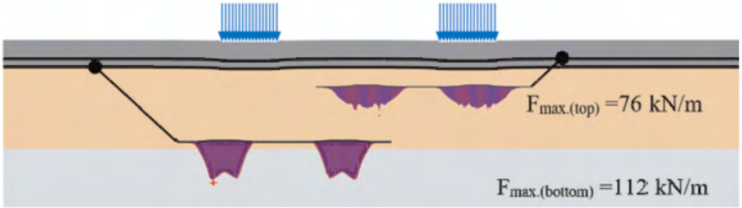


Figure 10. Variation in tensile force in working platform with double layer of geosynthetic reinforcement.

4 CASE STUDY

A project for the construction of a working platform for the storage and transport of offshore wind turbines and their components in northern Germany, Nordenham. The site was located in an area with poor soil conditions and a high water table typical of the region. Both ultimate and serviceability criteria were applied to the storage facility, as the MEWP had to accommodate not only the transient loads from the cranes transporting the heavy equipment, but also the relatively long term loads from the stored wind turbine towers. To overcome the lack of bearing capacity of the existing soil, the use of geosynthetic reinforcement was considered. Woven geotextiles, which provide reinforcement as well as separation and filtration functions, and geogrids were used as reinforcing elements to strengthen the working platform material. Figure 11 shows some construction details and operation of the geosynthetic reinforced working platfrom.

(a) construction of working platform (b) operation of working platform

Figure 11. Geosynthetic reinforced worling platfrom (Nordenham, Germany).

5 CONCLUSION

This study discusses possible modes of failure mechanisms that should be considered in the proper design of a working platform. In addition, the essential technical aspects that should be considered regarding the relevant soil parameters, the type of analysis and the excess pore pressures are reviewed. In addition, it has been shown that finite element modelling can be successfully applied to consider most of these phenomena in the design of working platforms.

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