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# Evaluation of the available design models for the analysis of geosynthetic-reinforced working platforms

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**Abstract.** The working platforms for heavy construction machines demand a reliable, safe and economical ultimate limit state design procedure which enables a complete verification of safety against different failure modes. Despite considerable advances in the analysis of geogrid-reinforced working platforms through the contribution of several research studies, their proof of the stability against some crucial failure modes is still neglected in the current engineering practice. In fact, there is no universal method for the design procedure and the application of current methods and models leads to dissimilar outcomes. In this study, a comprehensive review and analysis of the current knowledge and models is performed for design of working platforms subject to the high localized forces. Accordingly, a comparative analysis is conducted to evaluate the current design models and identify the weaknesses and strengths of each prediction model.

## 1 Introduction

Dimensions of piling rigs and cranes as well as their operating loads have grown considerably over the last years as the demand to install larger structural components is increasing (e.g. piled foundations, on-shore wind turbines, etc.). This has resulted in an increasing number of applications using geogrid-reinforced base courses and increased knowledge of understanding the interaction of reinforcement to stabilize granular soils [1]. Transferring the beneficial behaviour to working platforms results in a competitive solution to thicker unreinforced aggregate layers, especially in terms of both costs and response to heavy loads induced by tracked plant. Working platforms for this increasingly heavy construction machines require a safe but optimized design process incorporating a holistic safety verification against the failure modes caused by the large concentrated loads. So far, several failures have been reported due to unfavourable design of working platforms.

For the stability against the rotational and overall slip surfaces, several commercial design software including the analytical slope stability models and the numerical models (e.g. Finite Element models) are available. This crucial design step is however often neglected in the design practice.

## 2 Failure mechanism of working platforms

To comprehend the concept of ultimate soil bearing capacity under tracked plant and accordingly track the mode of shear failure, the case of a rectangular footing of width $w_d$ located at the surface of the working platform is shown in Figure 1. The working platform is subject to the concentrated loads of tracked plants (or crane pads) with a load of Q1 and Q2 under the left and right tracks, respectively. When estimating the foundation stability, the allowable subsoil and working platform bearing capacity, the required tensile strength of the geosynthetic reinforcement, the loads arising from the equipment tracks and the position of the construction equipment play an important role. The strength and deformation capacity of the soil and geogrid reinforcement determine the load capacity and deformation of the track foundation.

In general, three types of failures may happen on site for a working platform under localized forces by construction machines:

a) *Punching shear failure:* This is the most used type of failure in the calculation phase in practice. It occurs due to the typical bearing pressure imposed on a reinforced working platform overlying several soft subsoil strata. When the foundation settles under the application of the load, a triangular wedge-shaped zone is pushed down immediately under the loaded area. In turn, the wedged zone presses the zones underneath the edge of the loaded area sideways and then upward. At the ultimate pressure (Q) the soil passes into a state of plastic equilibrium and shear failure occurs by sliding. Due to this failure type, a part of the working platform will settle and sink into the subgrade soil. Commonly the failure does not extend up to the surface.

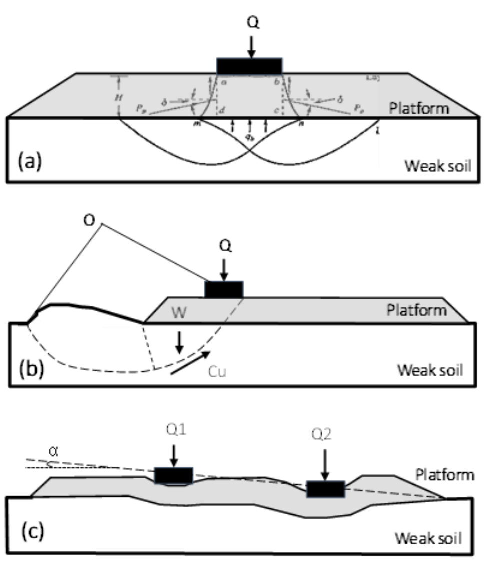



**Fig. 1.** Probable failure modes for a working platform under concentrated loads from tracked plants.

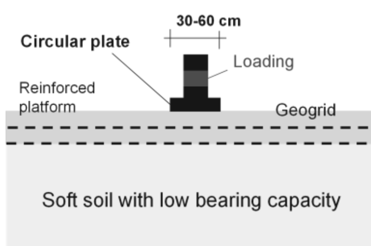
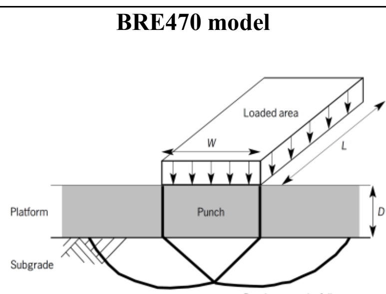
b) *Rotational shear failure:* Experience from several accidents in the past has proven that under certain circumstances, this failure mode might be dominant especially for a piling rig which stands close to the platform edge. This failure is characterised as sudden and catastrophic failure with a fully developed failure plane and bulging of locus the ground surface. The procedure involves a slip surface analysis search along the base of the working platform to determine the profile (locus) of the tensile load in the reinforcement that is necessary to provide an adequate margin of stability.

c) *Large deformation and settlements:* In case of large deformation in soil, the differential settlement under the tracked plant (or crane pad) may exceed the allowable level and correspondingly, following a progressive load increase, the construction equipment may overturn. The significance of any settlement is a matter for the designer and the design specification.

## 3 Available design models for analysis of reinforced working platforms

Over a long period, there has been no universal design procedure (including classical models such as [3-8]) for the estimation of the load-bearing capacity and the settlement of reinforced working platforms under localized loads. This has led to the development of a wide range of empirical, analytical, and numerical models along with numerous experimental tests to investigate the behaviour of geosynthetic reinforced working platforms. The following table provides an overview of the methods currently used in practice or academia.

**Table 1.** Selected available design models used for the design of reinforced working platforms

<table>
<tr><th>Design models</th><th>Strengths & Weaknesses</th></tr>
<tr><td>Target CBR model<br>

<br>
Failure mode = Punching (Partially)<br>Complexity = Very Easy</td>
<td>The target bearing capacity method is the simplest method used for the design of geogrid reinforced platforms. The biggest disadvantage of this method is that, it does not account for the influencing parameters affecting the resistance of a working platform and solely focuses on a specific bearing capacity to be achieved over the platform area. The effect of loading, soil shear strength etc. cannot be addressed while using this method.<br>In addition, this model is only valid under the application of certain geogrid levels. The effect of geogrid tensile strength is neglected by the model.<br>Overall, it is not recommended to use this method for the final design of working platforms. The model is generally known to be misleading as effects of load width results in the underestimation of stress and subsoil reaction.</td></tr>
<tr><td>BRE470 model<br>

<br>
Failure mode = Punching<br>Complexity = Easy</td>
<td>The main advantage is the wide range of applications for both cohesive and non-cohesive soils [2].<br>BRE470 may lead to unoptimized results due to the fact that, the model does not consider the curved shear planes develop between the edge of the track and the formation and assumes a vertical shear plane which underestimates the working platform shear strength.<br>The effect of the geogrid tensile strength in the basic resistance equation proposed by BRE470 has not been considered around the perimeter of the track [9].<br>The effect of relative subgrade-working platform stiffness in the reduction of working platform shear strength as suggested by [10] is neglected in BRE470 model.</td></tr>
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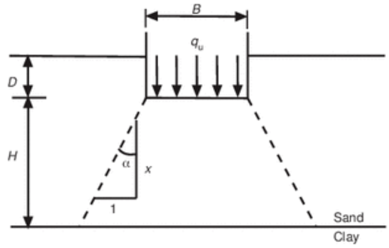
**Load distribution model**




Failure mode = Partially Punching<br>
Complexity = Easy

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The loads are taken to be dispersed based on a defined load spread angle (a). The determination of the angle in relation with the fill type and geogrid characteristics is though very challenging. The load spread angle has been recommended to be equivalent to 1H:1V under the application of geogrid by several design guidelines.

The effect of geogrid tensile strength as well as soil-geogrid interaction is neglected by the model.

Different geogrid manufacturers provide guideline for the determination of correct load distribution angle as a function of geogrid type and fill characteristics.

For the proof of subsoil bearing capacity against the projected loads, commonly the model from [4] or [5] is being used.

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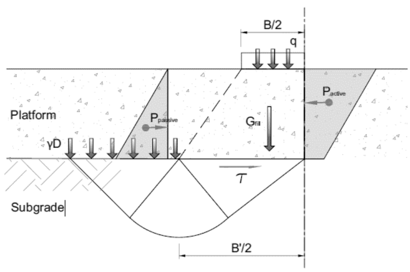
**CIRIA model**




Failure mode = Partially Punching<br>
Complexity = High

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This analytical method is based on classical bearing capacity methods but allows for consideration of lateral stresses in the platform material. In the unreinforced case, the lateral loads are considered to be carried as a horizontal shear stress by the formation. In the reinforced case, the lateral shear at the formation is carried by the reinforcement, thus allowing the full bearing capacity to be used [11].

The method is applicable only for the cohesive subgrade.

Although advice is offered, the selection of angle of load spread is somewhat subjective and has to be assumed prior to commencing the calculation.

The design method is only valid for single strata with no alternative offered for multi-layered subgrades [11].

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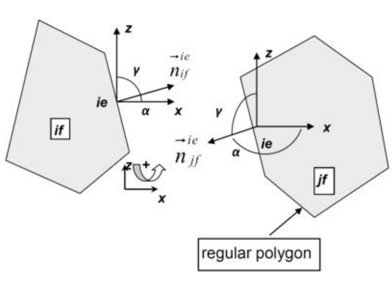
**Kinematic Element Model (KEM)**




Failure mode = Rotational<br>
Complexity = Mediocre

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The KEM model implements the rigid body approach to examine the equilibrium state, thus enabling a full interaction of soil wedges with the intersecting geosynthetic reinforcement. There is no need to estimate elastoplastic soil behaviour and complex deformation-dependent interaction between structures, reinforcement and soil [12] while using KEM. The main advantage of the KEM is that one can calculate forces and degrees of utilization resulting from failure mechanisms only based on inner friction and cohesion of the soil mass. The Kinematic Element Model (KEM) allows to investigate any- shape failure mechanisms and support the correct inclination of the inner gaps.

The main limitation is however, using a KEM model, only the rotational stability of the working platform can be investigated. The punching failure model shall be investigated using another tool or

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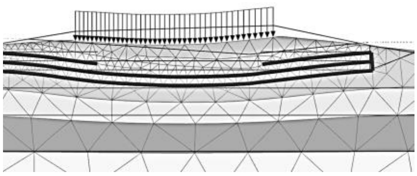
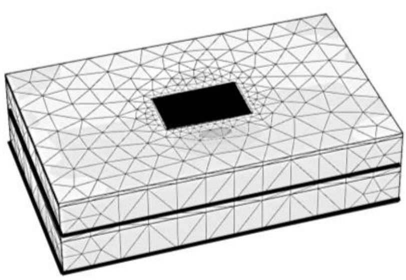
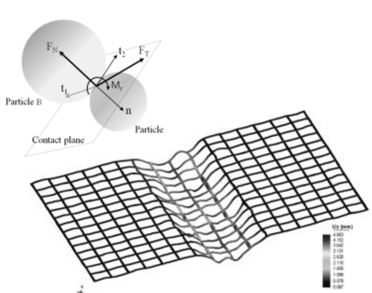
| | calculation method [13]. In addition, KEM is not able to compute the deformations. |
| **FE model (2D)**<br><br>Failure mode = All modes<br>Complexity = Mediocre | Finite element models (FEM) are being used by researchers and designers in order to investigate the bearing capacity and the deformation of geogrid reinforced or non-reinforced working platforms between soil and geosynthetic material. FEM can be used to study soil compaction, settlements and deformations, stress distribution in soil and soil failure patterns.<br>The biggest limitation of the 2D FE models is that, the three-dimensional effect of track length cannot be investigated in the model. Therefore, often the 3D models are recommended to be used for such an application. The other challenge is the modelling of aggregate interlocking with geosynthetic material. It is common sense that, the effect of geogrid is significantly underestimated by the FEM as long as no calibration technique is not implemented. |
| **FE model (3D)**<br><br>Failure mode = All modes<br>Complexity = High | In fact, a 3D FEM discretizes the geometry of the structure as well as the 3D elasticity equations.<br>The main advantage of a 3D model versus a 2D model for the design of working platforms is that, in a 3D model the geometrical boundary condition and the loading situation can be modelled more properly. For a precise design of working platforms, it is crucial to consider the full loaded area along the width and length of the track. The problem to fully capture the behaviour of geosynthetic material e.g. stabilization function still remains unsolved for a 3D FE model as well as a 2D model. Therefore, along with the complexity of the application of Finite Element models in practice they commonly cannot fully capture the membrane and stabilisation functions of geogrid reinforcement and neglect the complex interaction of the reinforcement with the cohesive subgrade and aggregate. |
| **Discrete Element Model (DEM)**<br><br>Failure mode = Punching<br>Complexity = Very High | The discrete element model (DEM) is based on a promising approach for constructing a high-fidelity model to describe the soil-tillage tool interaction. However, the determination of model parameters to control the soil void ratio and the shape of particles, as well as the modelling of breakage and the formation of aggregates of varying sizes and shapes, remain significant challenges and limit the application of DEM for practical engineering problems. |

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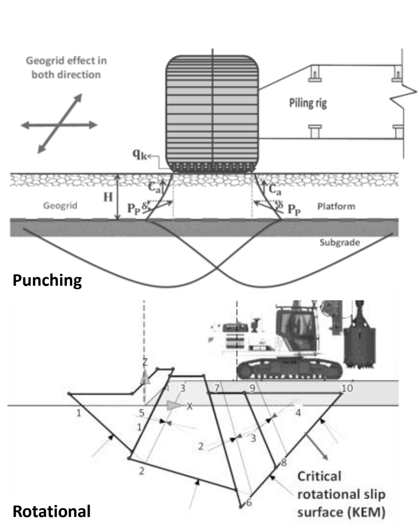
**Hybrid model**




Failure mode = All modes<br>Complexity = Easy

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The Hybrid model has been developed by combination of stability analyses for different failure modes including punching shear failure, rotational failure and the estimation of platform deformation under the localized loads. This has enabled the model to account for all probable failure modes which may happen due to the application of concentrated loads from tracked plant [14].

For the punching shear failure, Meyerhof's method is modified to account for the footing punching through a geosynthetic reinforced granular platform material overlying a soft cohesive subgrade. This has been done by means of the analysis of large-scale laboratory tests [15, 16]. For the rotational and overall failure, the Kinematic Element Method (KEM) has been applied.

The model is able to consider the effect of multiple strata sub-formation.

Both reinforced and non-reinforced designs are covered by Hybrid model.

Using the Hybrid model, it is possible to differentiate between permanent and temporary status as the model implement different safety equations for different situations. [17].

The model is currently applicable for cohesive soil. The application of Hybrid model for non-cohesive subgrade is currently under development.

The Hybrid model has been implemented in a commercial software so-called "Naue Platform" which facilitates the application of the model for the design of reinforced and non-reinforced working platforms.

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## 4 Comparison of selected design models

The selected design models as introduced in Table 1 have been applied to perform a comparative analysis for the determination of required thickness of the reinforced working platform for a specific case. The boundary conditions in terms of loading, subsoil and platform characteristics and the geometry of the assumed working platform have been summarized in Table 2. As in Figure 2 (right), the "Target CBR method" is not able to capture the effect of loading and the other geometrical parameters. In fact, the determined thickness by this method is solely based on the initial bearing capacity corresponding to the subsoil condition and a target CBR value. The "Load distribution method" has a large dependency to the distribution angle thus the analysis here has been performed based on two angles of 45° and 55° which are commonly used for the design process by this model. Overall, there is a considerable uncertainty for the selection of the correct angle as a function of material quality and the reinforcement type. The results show that the BRE470 leads to uneconomic results due to conservative assumptions in the development of the model. The assumption of a vertical shear plane punching through the platform material instead of a curved shear plane has underestimated the resistance of the working platform material against the imposed loads of the equipment. In addition, the resistance of the geogrid is only activated along the width of the track neglecting the mobilized geogrid tensile strength over the track length.

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**Table 2.** Assumed parameters for performance of the comparative study.

| Parameter | Symbol | *Dominant Load* | *Variation Range* |
|---|---|---|---|
| Soil undrained shear strength | $C_u$ | 20 kPa | 10kPa – 60kPa |
| Platform unit weight | $\gamma_p$ | 19 kN/m$^3$ | - |
| Platform friction angle | $\varphi_p$ | 45° | - |
| Track width | $W_d$ | 0.9m | - |
| Track length | $L_d$ | 3.65m | - |
| Track spacing | S | 3.65m | - |
| Characteristic Load | $q_k$ | 194kPa | 100kPa – 600kPa |
| Track distance from the edge of platform | r | 2m | - |

The comparison of the results derived from the application of different models shows that, even though the Hybrid model is a holistic model which examines different modes of failure, it may produce more optimized results in terms of the platform thickness. The main reason is due to the enhancement of the BRE470 model for evaluation of punching shear strength taking into account the weaknesses as described above. In fact, most of the available models in practice fail to examine the rotational stability of the working platform and provide results solely based on the punching shear strength. This effect can be seen in Figure 2 (right) where for a load of less than 250 kPa, Hybrid model tends to propose more economic results. However, by increasing the load (higher than 250 kPa) the rotational failure has governed in the Hybrid design method. Since several accidents due to rotational failure resulting in sudden failures have been observed in practice, certain attention has to be paid with the application of models which fail to consider this crucial mode of failure.

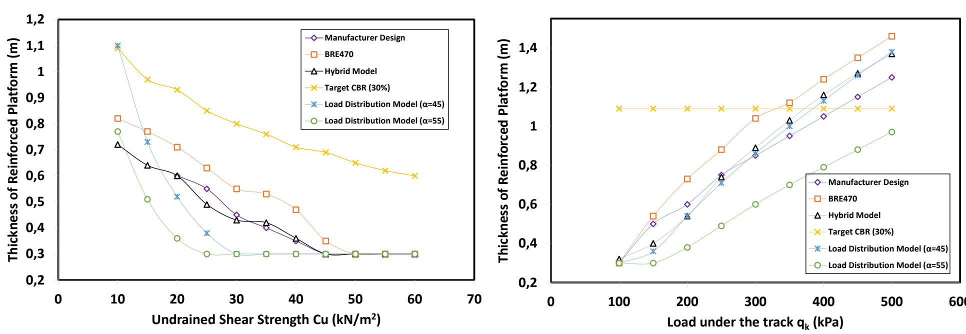


**Fig. 2.** Required thickness of reinforced working platform versus undrained shear strength (left) and load under the tracks (right).

## 5 Conclusion

In this study, a comparative analysis between commonly used models was performed to substantially investigate their weaknesses and strengths.

Despite considerable advances in design and analysis of reinforced working platforms through the contribution of several research studies and design standards including the popular methods of an improved load spread, BR470, etc., most of the currently proposed methods can only consider the bearing capacity of the working platform against punching shear strength (failure mechanism "a") and fail to consider the requirements in terms of bearing capacity to maintain the stability of the working platform over weak subgrades against rotational failure modes. The only available model in practice, which provides a holistic design package, is the Hybrid model as developed by Khansari et al. [14 & 17] which has been developed by combination of stability analyses for different failure modes including punching shear failure, rotational failure, and settlement estimation. This has enabled the model to account for all probable failure modes of working platforms, which may happen due to the application of concentrated loads from tracked plant.

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