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Reinforced Soil Shear Key to Mitigate Extrusion Failure in Soft Soils under Working Platforms

Clé de cisaillement du sol renforcée pour atténuer les défaillances d'extrusion dans les sols meubles sous des plates-formes de travail

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ABSTRACT: Geogrids and geotextiles are widely used in working platforms to increase the allowable surface bearing pressures and reduce the platform thickness required. While analytically based approaches exist for the design of these platforms, these vary in their complexity and the range of critical properties they consider, leading to uncertainty in which ones to suggest. They can be over conservative compared to empirical methods based on historical performance.
For projects with combinations of high rig loading and very soft underlying ground (c_u < 20 kN/m^2), there is greater potential for extrusion and edge circular failures. The edge stability of platforms can be improved with a number of measures such as increased stand-off zones, loading mats, balancing mounds and shear trenches. This paper considers the extrusion mechanism and how a wrapped shear trench can be used to counteract edge instability and extend the suitability of platforms over very soft soils. The effectiveness of this method is demonstrated with a UK case study.
This paper covers a brief introduction to working platform design, before comparing a range of approaches. The paper discusses the extrusion failure mechanism and a solution using a wrapped shear key trench.

RÉSUMÉ: Les géogrilles et les géotextiles sont largement utilisés dans les plates-formes de travail pour augmenter les pressions admissibles sur les surfaces et réduire l'épaisseur de la plate-forme requise. Bien qu'il existe des approches analytiques pour la conception de ces plates-formes, leur complexité et la gamme de propriétés critiques qu'elles considèrent varient, ce qui conduit à une incertitude quant aux propriétés à suggérer. Elles peuvent être trop conservatrices par rapport aux méthodes empiriques basées sur les performances historiques. Pour les projets combinant une charge élevée de la plate-forme et un sol sous-jacent très mou (<20 kN / m2), le risque d'extrusion et de ruptures circulaires des arêtes est plus important. Un certain nombre de mesures peuvent améliorer la stabilité des bords des plates-formes, telles que l'augmentation des zones d'espacement, le chargement de tapis, les buttes d'équilibrage et les tranchées de cisaillement. Ce document examine le mécanisme d'extrusion et comment utiliser une tranchée de cisaillement enveloppée pour contrer l'instabilité des bords et étendre l'adéquation des plates-formes aux sols très mous. L'efficacité de cette méthode est démontrée par une étude de cas au Royaume-Uni.

Ce document couvre une brève introduction à la conception de la plate-forme de travail, avant de comparer différentes approches. L'article décrit le mécanisme d'échec d'extrusion et une solution utilisant une tranchée à clés de cisaillement enveloppée.

Keywords: Working Platforms; Extrusion, Shear Trench; Reinforcement; Geosynthetics.

1 INTRODUCTION

Working platforms are required to support construction plant and traffic loads over ground with insufficient bearing capacity. These platforms are typically formed of a layer of granular fill, this can be as thin as 300 mm or in some cases over 2000 mm. This stronger soil medium, typically featuring large-sized aggregates, disperses the imposed loading over a greater area, to reduce its intensity over the weak subgrade. The required thickness of the platform depends on many factors including the loading intensity, the strength and stiffness of the platform material and the underlying soil strength and features of the sub-formation. Generally, the platform's thickness is determined by ensuring sufficient bearing capacity or by limiting deformation at the surface.

Geosynthetics, in the form of geogrids, geotextiles and geocomposites can be used to increase the efficiency of this system through, reinforcement and separation / filtration (Figure 1). Separation and filtration prevents the intermixing of larger platform soil particles with the finer subgrade, whilst allowing ground water to permeate. Geogrids and geotextiles reinforce the soil, to increase the platform's ability to support higher imposed loads or to reduce platform thickness (Corke and Gannon 2010).

Figure 1. Reinforcement/Stabilisation (Left) and Separation/Filtration (Right).

There are obvious economic advantages to using less of the tight-specification platform fill. In the UK this is typically a Class 6F2, 6F5 or Type 1 fill (Highways England 2018). This can cost as much as £30 to £40/m^3. Hence saving more than 100mm of platform thickness, covers the additional cost of geosynthetic reinforcement. In addition, there are reductions in embodied energy and carbon emissions associated with the transportation and construction of these bulk materials (WRAP 2010). Whilst there is a strong economic and environmental reasoning for utilising reinforced working platforms, the biggest challenge has been the agreement of design methods to analyse and compare reinforced and non-reinforced platforms. The following chapter details working platform design methodology, in particular using geosynthetic reinforcement.

2 WORKING PLATFORM DESIGN

Although there is a requirement for all geotechnical design to be undertaken according to *BS EN 1997-1:2004+A1:2013* (BSI 2013), more commonly known as Eurocode 7, the design of working platforms for construction is not specifically included by current guidance. Instead designers are initially referred to additional publications: *BR 470: Working platforms for tracked plant* (BRE 2004) and *SP 123: Soil Reinforcement with geotextiles* (CIRIA 1996). These documents explain prescriptive procedures of working platform design, and highlight the suitability of existing design guidance.

2.1 *BRE BR470 Working platforms for tracked plant*

This is the *de facto* standard for undertaking working platform design. This document was developed to improve safety for tracked plant on construction sites, following a number of high profile failures. The guide introduced a straightforward semi-empirical design method. Its methodology is based on a punching shear failure of a loaded track through a platform on to the subgrade. It is based largely on empirical bearing capacity factors that can be used with cohesive or granular subgrades. The approach is limited to subgrades of strengths between 20 kN/m^2 < c_u < 80 kN/m^2. Outside this range, designers are suggested to seek alternative guidance such as SP123 (CIRIA 1996).

The method is extremely sensitively to the shear strength (ϕ') of the platform fill. Corke and Gannon (2010) showed only a small increase in platform strength from 40° to 45° (17%), led to a 27% reduction in platform thickness.

Geosynthetic reinforcements can be included to reduce the thickness of the platform by providing additional punching resistance. However, the reduction is limited by an 'unreinforced' safety check, to prevent disproportionately strong reinforcements.

2.2 *CIRIA SP123 Soil Reinforcement with geotextiles*

The special report by CIRIA features a predominantly analytical approach considering the bearing capacity of a subgrade limited by outward shear stress. The complex equations require iterative computations, hence calculation sheets are preferred to deploy systematically.

The method determines the bearing pressure at the formation of the working platform, where the surface loading (tracked plant or wheel) is dispersed through the fill to the base of platform. A load distribution angle (β) is assumed to determine the vertical and outward stress applied. It is typical in geotechnical engineering to use a load spreading angle of 26.6° (2:1, Vertical to Horizontal). However, many studies show load dispersal in reinforced platforms can be significantly higher. For geotextiles this has been observed around 40°, while for geogrid reinforcement this has been recorded to be as greater than 45° (Palmeira and Antunes 2010).

The underlying subgrade's bearing capacity factor N_c varies non-linearly with mobilised shear stress τ, up to a maximum of π+2, where no outward support is required. The average horizontal earth pressure, resulting from this distribution is used to determine the horizontal force to be resisted by the geosynthetic.

For reinforced platforms, the document suggests the full bearing capacity of the soil can be mobilised when the reinforcement can resist all the lateral shear stresses. This can require high strength reinforcements, unless the platform thickness is increased, to reduce the net outward stress.

2.3 *EN 1997-1 Foundation Bearing Analysis*

Historically, bearing capacity analyses has been assessed using a similar approach to that for spread foundations in line with BS EN 1997-1:2004+A1:2013 (British Standards Institute 2013). Adapting these for working platforms usually requires assuming a load spread angle (β) to reduce the imposed rig load pressure throughout the platform. With little guidance on suitable partial factors, these are often designed in line with permanent foundations and as a consequence can be excessively conservative.

Okamura *et al.* (1998) enhanced this model by analysis and formulating the bearing capacity of a granular fill overlying an undrained soil. This provided more realistic bearing capacity, but included no option to consider reinforcement.

2.4 *Numerical Analysis*

In addition to analytical and empirical models, it is possible to use numerical tools to analyse the complex failure planes, and bearing capacity. The can be undertaken by typically bearing capacity or limit equilibrium software. Increasingly Discontinuity Layout Optimisation (DLO) modelling is being used to check bearing capacity. The indiscriminate nature of the check allows realistic bearing shear failure planes to be found for complex problems (Figure 2). More information on the study of working platforms using this tool can be found in Smith and Tatari (2016).

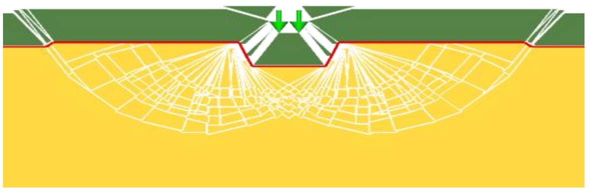

Figure 2. Typical DLO analysis of reinforced bearing capacity.

2.5 Empirical methods

Empirically-based methods can be used for the design of reinforced platforms. These use performance databases to determine the platform thickness and geosynthetic. These often show large reductions in platform thicknesses compared to the analytical approaches, but are limited to the range of the dataset (loading, shear strength, reinforcement products etc.). Similar empirical methods have historically been used to determine the thickness of unreinforced access roads (TRRL 1984), but the industry is moving away from this approach, in favour of more analytically based methods (BRE 2004).

2.6 Design Approach Comparison

The variety of approaches result in ranging suggested platform thicknesses. To illustrate this, the minimum unreinforced and reinforced platform depths have been considered for the following methods BR470, SP123 and Okamura et al. (1998). A range of subsoil strengths were compared for a typical working platform case, detailed in Table 1.

Table 1. Input Parameters for Design Comparison

Loading Conditions		
Rig Loading Pressure	w_s	200 kN/m^2
Track Width	W	0.5 m
Track Length	L	2.4 m
Platform Fill Properties		
Frictional Shear Strength	ϕ'	40°
Unit Weight	γ	20 kN/m^3
Subgrade Properties		
Undrained Shear Strength	c_u	20 kN/m^2
Unit Weight	γ	19 kN/m^3

Figure 3 highlights the large range of minimum platform thicknesses required by each approach. Reinforced platforms are thinner than unreinforced platforms, but the saving in BR470 is less than in CIRIA due to its 'unreinforced' check.

There is closer agreement between the unreinforced platform thicknesses than the reinforced platforms. Direct comparisons between BR470 and CIRIA SP123 are not straightforward, as stronger reinforcements can be used to reduce the platform thickness in BR470. Over soft soils, this can lead to high shear forces which are borne by the reinforcement. The most conservative thickness is often found in CIRIA SP123, followed by Okamura et al. (1998). The traditional approaches tend to underestimate the other methods, as they do not account for the shear strength and load spreading of the overlying granular layer.

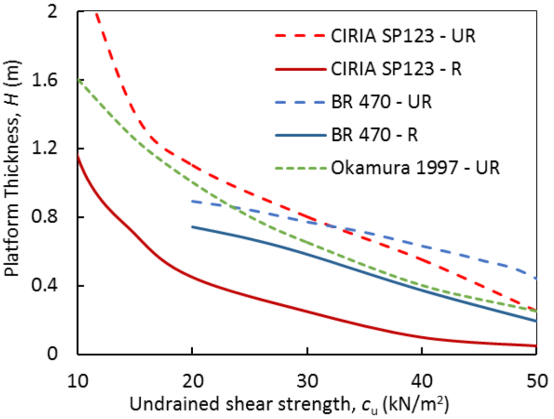

Figure 3. Minimum Working Platform Thickness Comparison; UR – Unreinforced, R- Reinforced.

3 EXTRUSION AND EDGE STABILITY

The aforementioned design approaches cover the design of infinitely wide platforms. They do not provide design approaches to assess edge stability. As with other embankments, there is a requirement to check external and global failure mechanisms such as extrusion and edge rotational failures (Figure 4). These are well covered by chapter 8 of BS 8006-1 (British Standards Institution 2016), which includes design approaches for both mechanisms in reinforced platforms, albeit considering them as permanent embankments.

Figure 4: Embankment External Failures: Top: Rotational Failure; Bottom: Extrusion failure

Extrusion is particularly problematic for heavily loaded embankments over thin layers of weak soils. Here the imposed loading can cause extrusion of the weak underlying soils, which have insufficient strength to resist the out of balance active earth pressures. Like a toothpaste tube under pressure, this soft soil undergoes plastic deformation out from underneath the embankment, causing the platform to settle by displacement.

Smith and Tatari (2016) investigated the susceptibility of reinforced embankments over weak soils to cause extrusion. Their analysis using the DLO software programme, LimitState:GEO and looked at the failure mechanisms of the platform over varying soil strengths. The stability of highly reinforced platforms was dominated by a susceptibility to this "squeezing" deformation in the lower stratum. Depending on the geometry and reinforcement strength, the embankment itself either undergoes very localised shearing and vertical "sinking" translation or rotational "snapping". In both these cases further increasing the strength of the reinforcement does little to improve stability of the platform.

Where extrusion is a problem, standard solutions have included increasing the side slopes of the embankment, incorporating a set-back from the edge of the platform. Mounded fill around the platform can provide counter pressure to extrusion. While sheet piling can be used to cut off and retain these soft soils. However, the latter solution is often prohibitively expensive for large temporary sites. Where the soft soil depth is limited in depth (e.g. 2 to 3 m), it may be more economical to simply excavate it and replace with competent granular fill.

3.1 Shear Key Trenches

Rather than excavating and replacing all the underlying weak soils, this activity can be limited to the perimeter of the site in a trench, creating a shear key. These is a well-established earthworks technique used to disrupt potential weak slip-planes (Giffen 2015). There are three possible categories of shear key:

Unreinforced Full Depth: Typically extending through the weak soil layer(s) and embedded in to stronger soils below, the key completely isolates the weaker layer, preventing extrusion. The granular fill to these trenches improves the drainage of the soft underlying soils

Reinforced Full Depth: To limit the width of the key, and excavation, geotextiles can be used to encase the trench and maintain the integrity of a smaller shear key trench.

Reinforced Partial Depth: Where the depth of the soft layers makes a full depth trench uneconomical, a trench can be considered that extends only a limited distance into to the soft soil. This extends deep enough to limit the effective thickness of the soft layer, until the destabilising extrusion pressure can be resisted.

3.2 Analytical Equilibrium

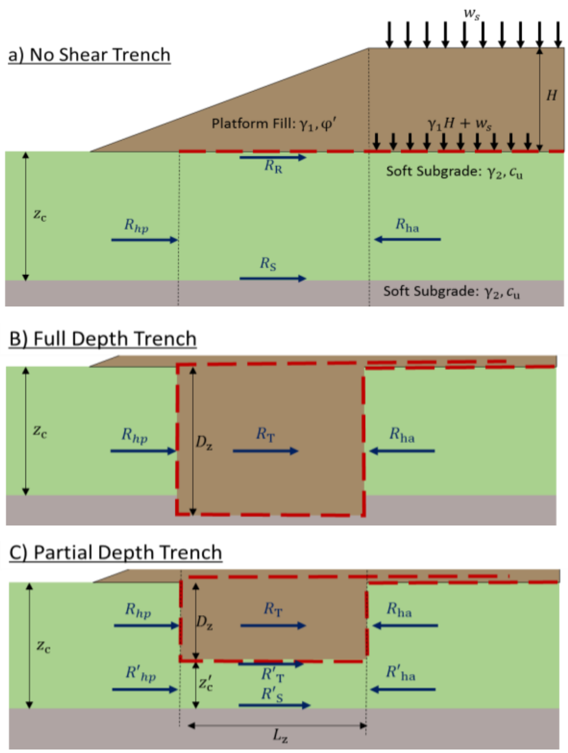

Figure 5: Simplified Extrusion Mechanisms with and without shear trenches, adapted from BS 8006 (2016)

Extending from the extrusion check in BS 8006-1 (2016), the following approaches has been developed to consider reinforced shear keys to counteract the extrusion mechanism beneath reinforced soil platforms. The equilibrium equations are based to enable the following conditions: The trench extends sufficiently deep to cut-off or ensure the remaining soft layer depth is stable and the trench is wide enough to prevent the soft soil breaking through the key. Alternatively, geotextiles or geocomposites can be placed around the trench to resist the trench itself shearing. This reinforcement should be strong enough to prevent rupture failure, under the extrusion pressure.

The following equations are in line the simplified geometry in Figure 5 and nomenclature BS 8006. For a platform of height, H (m), carrying an imposed load of w_s (kN/m^2) all over a soft soil with limited depth, z_c (m) and undrained shear strength of c_u (kN/m^2), the extrusion stability of the platform edge can be assessed by an equilibrium analysis considering the stabilising shear strength (R_R), boundary interaction (R_s) and passive resistance (R_{hp}) against the destabilising active pressure (R_{ha}). No trench is required if:

$$R_{hp} + R_R + R_s > R_{ha} \tag{1}$$

Shear trenches with depth (D_z) extending beyond the soft layer depth ($D_z \geq z_c$) are required to resist any net destabilising force (R_T):

$$R_T = R_{hp} - R_{ha} \tag{2}$$

The trench should be checked for shear planes through it, where the active earth pressure is resisted by the trench, taking into consideration the frictional shear strength (ϕ') of the trench fill. Should be unstable, the trench width (L_z) can be extended or it can be reinforced by a geotextile wrap. The shearing stress can be fully or partly resisted by a reinforcement, as long as this is less than its design strength (T_D) and pull-out capacity from BS 8006-1 (BSI 2016).

Shear trenches extending only partly through the soft soil layer (i.e. $D_z < z_c$), are designed to reduce the remaining effective depth (z_c'), until self-stabilising. The equilibrium over this effective depth can be check with an adapted version of equation 1:

$$R'_{hp} + R'_R + R'_s > R'_{ha} \tag{3}$$

Once extrusion below the trench is satisfied, the equilibrium of the trench can be found by Equation 2 where net destabilising forces can be resisted by a combination of the trench fill and wrapped reinforcement.

3.3 Additional Edge Stability

Whilst this approach provides a method for analytically checking shear trenches, it does not intend to replace existing methods for checking edge stability, such as the use of Limit equilibrium software. Instead it should be considered in addition to embankment checks set out in BS 8006-1 (BSI 2016).

4 UK CASE STUDY

A new 17 MW, seven turbine wind farm was proposed in Essex. This farm would generate enough renewable electricity to provide electricity for 14,000 homes. In order to erect the planned 100 m tall turbine towers and 50 m long blades, required two sets of specialist cranes. The cranes required to build these turbines was so big that a temporary crane was required to build the main crane. Consequently, this required suitable platforms capable of carrying these large imposed loads in an efficient manner.

4.1 Challenging Ground Conditions

The vegetation and top soil covering the site was removed, revealing varying depths of Tidal Flat Deposits (TFDs) overlying stiffer London Clay. The upper deposits consisted of a thin stronger crust, 1 to 2m deep, overlying softer deposits with undrained shear strength (c_u) as low as 12 kN/m^2 for a depth down to 5 m.

These founding layers were inadequate to bear design loads of 240 kN/m^2 over the 0.6 m x 2.4 m tracks of the main crane. Temporary working platforms were required at each turbine lifting position to facilitate the lifting cranes as well as the construction plant (pile driver, deliveries etc.). These platforms were required to be at least 30 m by 40 m. To complicate options, the site's permit dictated platforms could sit no higher than 0.15m above ground level. The platforms over stronger soils (>20 kN/m^2) were initially designed according to BRE 470, while the platforms over weaker soils were initially designed following CIRIA SP 123. A high-quality imported platform fill ($\phi' >$ 40°) was specified meeting the Class 6F5 classification (Highways England 2016), and a load distribution angle of 45°. These design approaches determined nominal platform thicknesses and reinforcement at each platform.

Platform 6 was the most challenging structure, requiring a platform depth of 1.75m of Class 6F5, in addition to two orthogonally laid high strength woven geotextile (*Stabilenka 1000*). This was required to ensure stability over soft soils (average c_u < 20 kPa) up to 4m deep. The stability of the edges of the platform were considered by using slip circle and non-circular failure analysis in accordance to chapter 8 of BS 8006-1 (BSI 2016) and its partial factors. The extrusion checks of a thin layer (z_c < 2 m) of very weak soil (c_u < 15 kN/m^2) dominated the design of several platforms. The underlying soil had insufficient strength to resist the outward movement.

4.2 Extrusion Option Appraisal

Various solutions were considered. A planning restriction on overall level, prevented mounding to provide counter pressure. Sheet piling was seriously considered but deemed too expensive given the extensive perimeter. Extending the footprint of the platform in plan was ruled out due to the significant increase in excavation and import of expensive class 6F5 required. Excavating deeper was not suitable for platform 6 as the platform was already seated 1.75m below ground level, and further excavation and replacement would have been expensive and caused safety concerns.

Finally, a 2.0 m wide perimeter shear key was adopted (Figure 6), whereby high-strength woven geotextile extended beneath the platform and wrapped around partial depth trenches on the perimeter. The limited excavation required for this solution proved the most cost-effective solution to contain the soft soil underneath the platform and prevent it from extruding under load.

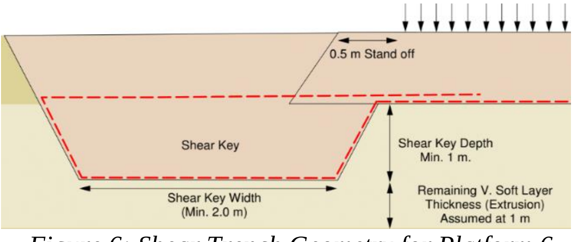

Figure 6: Shear Trench Geometry for Platform 6

4.3 Platform Construction

Construction work began on the site began in late November 2015, initially with the installation of the access tracks and site compounds. Due to the limitations on platform level, excavation was required before constructing each platform using the class 6F5. The two layers of geotextile were installed orthogonally on the excavated formation and perimeter shear trenches (Figure 7), separated by a 150 mm layer to remove potential slip surfaces.

The compaction of the platform was undertaken in line with MCHW (Highways England 2016) for the Class 6F5. Plate load testing was undertaken to confirm the required subgrade modulus of the reinforced platform (E_{v2}>120 MN/m) of the platforms. In addition, a trial was undertaken to demonstrate the requirement for high-strength reinforcements. A representative kentledge load, equivalent to 240 kN/m^2 was left overnight on a trial platform. By the next morning the mass had punched through the unreinforced platform, highlighting the need for the reinforced solution.

The towers and blades were successfully installed in the summer of 2016, justifying the working platform design. The wind farm became fully operational in January 2017.

Figure 7: Geotextile wrapped shear trench under construction, before being wrapped back under platform.

5 CONCLUSIONS

The design of working platforms is maturing as rigorous approaches are developed. The analytical methods lag behind their empirical counterparts, but they are at least on the safe side.

In cases where a combination of high loading and shallow underlying weak soils, the edge stability often dominates design. This paper presented an analytical approach for assessing the stability of a wrapped shear key trench solution to mitigate extrusion type failures. The study demonstrates suitability in deep soft soils (>2m), where excavation would be uneconomical.

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