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Optimising Design of Temporary Working Platforms Made From Hydraulically Bound Materials

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Abstract **–** Working platforms are temporary geotechnical structures that provide stability to heavy plant on construction sites. Traditionally made from granular unbound material of sufficient thickness, platforms are implemented where the natural ground is not strong enough to support imposed loads. To reduce the depth of minimum required fill, hydraulically bound materials (HBM) can be used. However, there is no design guidance on HBM working platforms as any available methods were developed for purely granular material. This paper considers the case of HBM platforms of varied thicknesses made from lime treated Mercia Mudstone (MMG). The platforms were designed under the industry approved methods and the outputs were analysed using Discontinuity Layout Optimization software. The analysis included comparison between the bearing capacity of granular platforms and HBM of different strength parameters. Results showed that the industry design methods are heavily reliant on the frictional angle of platform material, and they could not properly account for strength of HBM which mobilise substantial strength through cohesion. Although the granular platform design obtained through these methods aligned well with the DLO analysis, they were found to underestimate bearing capacity of HBM platforms when compared to the software. Further DLO analysis showed that the granular platforms had much lower bearing capacity than that of HBM. In the scenarios considered, even adding 0.75% of lime had the potential to decrease the required platform depth to 0.1m (although such a large reduction is not recommended with the design guidance limit advised as 0.3m), compared to 0.7m which would be required if a granular platform was used. It is concluded that future work into the subject with the use of additional analytical software method, while considering the strength of the subgrade as another variable, would give stronger understanding of how HBM platforms could be designed to the greatest benefit.

Keywords**:** working platform, hydraulically bound material, discontinuity layout optimization, lime stabilisation

1. Introduction

Working platforms are temporary geotechnical structures that support high, short-term loads from heavy plant on construction sites. They are required where natural ground in place is not strong enough which could lead to dangerous cases of mobile cranes toppling over resulting in injury or death. Traditionally, the platforms are constructed from granular unbound material with thicker platforms being able to provide greater bearing capacity. The formulas used in the design processes originate from shallow foundation design methods, where the system is taken as two soil layers. The stronger platform material can reduce the imposed pressure which is then transferred to the weaker underlying formation [1].

While there is no British or European Standard method detailing the design of working platforms, in the UK, there are three industry approved methods for this. They vary in complexity and how design robustness is achieved e.g., through partial factors, but each approach determines the minimum platform thickness [2].

From the author's experience, the most widely used method for the design of working platforms in the UK appears to be the BR 470 [3]. Its semi-empirical approach was developed from experimental model by Meyerhof for a footing punching through a strong platform material placed over a weak subgrade [3]. Through assuming that the platform develops punching shear resistance thus supporting some of the load applied, the bearing pressure on the formation is reduced. The model does not account for the weight of the platform material or any benefit from surcharge and assumes no lateral shear strength occurs at the formation level [1].

The second and lesser used method, CIRIA Special Publication 123 (SP123), instead considers lateral stresses within the platform material assuming that the pressure from the tracked plant applied is spread through the platform at a load spread angle and applied to the formation level over a wider area [4]. The vertically applied load leads to an increase within horizontal stresses in platform fill, developing a horizontal thrust in platform material which is partially supported by passive resistance. As this resistance is limited due to low self-weight of fill, the reduced horizontal stress is transferred onto the clay subgrade as an outward shear stress [4].

The third design method is the Temporary Works forum (TWf) model which is similar in concept to SP123 as it also accounts for horizontal shear on the formation, except it expands on this model through using other industry accepted geotechnical methods. For example, it adapts Boussinesq theory to derive nominal effective area so that the pressure on the subgrade is not underestimated. The method is heavily based on the use of charts, making it a much more involved and time-consuming process [1].

All the above methods have been designed for platforms made from unbound granular materials. Provided suitable physical and chemical properties of the ground, Hydraulically Bound Materials (HBM) can be taken as an alternative to granular platforms [5]. HBM are mixtures which set and harden under hydraulic reactions upon using a hydraulic binder. Different binders may be used, with lime and cement being the most common for cohesive fills, with the main purpose being modifying to an optimum moisture content for compaction and strengthening weaker soils through changes to the clay particle structure and development of cementitious bonds [6]. As the binders can improve the natural ground in place, import requirements can be minimised, making it a sustainable alternative to unbound granular material [6]. As HBM generate strength in a fundamentally different way to unbound granular material, the use of industry design methods has proven difficult in practice. As the most common strength test methods for HBMs comprise Unconfined Compressive Strength (UCS) or California Bearing Ratio (CBR), there is difficulty in determining appropriate input design parameters to use in above noted design methods. This difficulty in knowing how to link the determined strength to the design method has constrained these sustainable working platforms from being widely adopted.

Discontinuity Layout Optimization (DLO) is a limit analysis method which has the potential for being successfully implemented in working platform design, as it has been previously applied to reinforced and unreinforced embankments [7], as well as unbound working platform problems reinforced with geogrids [8]. The method uses the perfect plasticity model with an upper bound yield to determine kinematically admissible mechanisms of plastic collapse. Optimization techniques then identify the critical layout of discontinuities at collapse [7]. DLO is able to incorporate the Mohr-Coulomb strength model to determine the resistance generated along the failure planes at collapse and is therefore able to include both the angle of shearing resistance (φ'), and cohesion, (c') for effective stress analysis, or cohesion undrained (C_u) in a total stress analysis.

This paper presents the results of HBM working platforms designed through industry methods and compares them to the outputs of DLO analysis. The comparisons between the strength of granular platforms and their HBM equivalents are also discussed, highlighting the benefits of lime treatment in context of temporary platforms.

2. Methodology

The general approach taken was (1) Carry out working platform designs using data for stabilised and well graded granular material following the three industry approved methods, (2) conduct a DLO analysis of the designed platforms, and (3) compare and contrast the industry methods vs DLO outputs.

2.1. Material Properties

The method assumed the case of a single, deep layer of cohesive subgrade underlying a working platform. Four different platform materials were considered, one granular type and HBMs of different lime contents and cure periods. Material parameters for the granular fill considered were taken from the BR470 industry guidance document [3]. For the HBM, the authors had access to secondary data (from a larger research project delivered in collaboration with Balfour Beatty Vinci) which included extensive commercial lab results on 100mm diameter triaxial test specimens for a lime treated fill of Mercia Mudstone Group (MMG) weathering grade 4a. The soil samples were treated with 0%, 0.75%, 1.5% and 3.0% of lime and were tested in a multistage consolidated undrained triaxial test, using cell pressures of 50, 250 and 500kPa and after lab temperature curing for 28, 90 and 180 days. Compaction of all fill specimens used standard (2.5kg) proctor compactive effort at a moisture content between 1.05 to 1.1 times the Optimum Moisture Content (a moisture condition deemed generally suitable for placement of such fill by the separate ongoing study). The parameters for the subgrade material were also taken from site data with a cohesion undrained taken as the characteristic value for insitu MMG grade 4a. Table 1 summarises all the material properties and it can be seen from the data that the effect of lime treatment is to cause a significant increase in φ’ and substantial increases to c’. Both φ’ and c’ show a general increase with prolonged cure and higher binder addition, which is most pronounced in the latter with the 180-day 3% specimens having a c’ of 165kPa; 11 times greater than untreated.

Table 1: Material parameters used in the study

Material	Unit Weight (kN/m^3)	φ’(°)	c’ (kN/m^2)	C_u (kN/m^2)
Untreated MMG (to indicate the change caused by lime treatment)	20.9	35	15	-
HBM 0.75% lime @28 days	20.3*[1]	43.8	39.4	-
HBM 0.75% lime @90 days		43.5	47.2	-
HBM 0.75% lime @180 days		45.7	58.7	-
HBM 1.5% lime @28 days	20.1*[1]	42.6	38.2	-
HBM 1.5% lime @90 days		40.3	56.9	-
HBM 1.5% lime @180 days		45	95.9	-
HBM 3.0% lime @28 days	18.9*[1]	47.5	75.7	-
HBM 3.0% lime @90 days		44	150	-
HBM 3.0% lime @180 days		48	165	-
Granular platform	20	40	-	-
MMG subgrade*[1]	20.89	-	-	75

Note:
*1 Derived from bulk density at 28 days cure.

2.2. General Design Approach

The general approach using the three industry methods was to:

1. Assume the working platform would be loaded by the plant track with breadth 0.7m and length 3.1m.
2. Use the industry method and the material parameters in table 1, to calculate the design resistance of a working platform for thicknesses between 0.1 and 0.6m using 0.1m intervals. These calculations included the partial factors relevant to the method as summarised in table 2.
3. LimitState:GEO software was used to set up a model simulating the same 0.7m wide track (see figure 2 and further details on the model set up are given below in section 2.4). The resistance calculated by the industry method was input as the characteristic loading onto the simulated track, which required that the design resistance was divided by the partial factor for the variable action (as relevant to the method followed; table 2) to produce this characteristic load.
4. The software would undertake a DLO equivalent analysis of each industry method to determine the failure mechanism and the associated collapse load. The software included options to include the same partial factors for the materials and actions as used for each method (table 2).
5. An adequacy factor of the DLO equivalent model is determined i.e., DLO equivalent resistance / industry method resistance. An adequacy factor of 1 would mean the methods output the same resistance, whereas a factor >1 would mean the DLO method has calculated proportionally higher resistance and vice versa.

Table 2: Design partial factors

Design parameter \ Design Method	BR470*[1]	TWf*[1]	CIRIA SP123
Variable action	1.2	1	1.14
Angle of internal friction	1	1.25	1.25
Cohesion undrained	1	1.4	1.25
Effective cohesion *[2]	1	1.25	1.25

Note:
*1 Assuming load case 2
*2 Value not explicitly specified in design guidance and so consistency with the source document was used i.e., unity for BR470, EC7DA1 Comb 2 for TWf and 1.25 for SP123

2.3. Industry Design Approach

Calculation spreadsheets were implemented for all methods, each in accordance with their published methodology. Separate resistances were output for granular and then the HBM material properties as specified in table 1. As each of these industry methods were developed for platforms made from granular materials, this meant they were characterised only by φ' and weight density. Thus, φ' had a significant effect on the design resistance determined. This was evident in the design equations, which for brevity are not fully reproduced from the published methods (that are accessible to any interested party), but as an example from the BR 470 method [3] the expression for bearing resistance for cohesive subgrade and as modified by the working platform is:

$$R = c_u N_c s_c + \left(\frac{\gamma_p D^2}{W}\right) K_p tan\delta . s_p \quad (1)$$

where:

R is bearing resistance of a platform in kN/m^2
c_u is undrained cohesion of the subgrade in kN/m^2
N_c is the bearing capacity factor for cohesive subgrade
s_c and s_p are shape factors
D is the thickness of platform material in m
γ_p is bulk weight density of platform in kN/m^3
W is the track width in m
$K_p$tanδ is the punching shear resistance coefficient

The punching shear resistance coefficient ($K_p$tanδ) was a function of the angle of shearing resistance of granular platform material (φ'), where $\delta = \frac{2}{3}\varphi'$, as presented in figure 1.

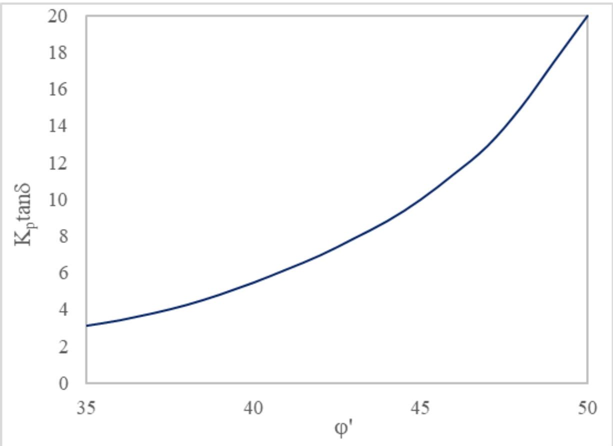

Figure 1: Design values of $K_p$tanδ (reproduced from [3])

Figure 1 demonstrates the relationship used in BR 470 is very sensitive to changes in φ' of the platform fill [2] and the TWf and SP123 methods have similar reliance on φ', without scope to account for strength increase relating to the drained cohesion intercept, c'. This highlights the difficulty of using such methods to account for how HBM platforms develop strength and these analyses for the HBM could only include the φ' values in table 1.

2.4. DLO Analysis and Comparison with Industry Methods

The DLO analysis was undertaken using software LimitState:GEO 3.6 with the baseline model as per figure 2. The model boundaries were initially set up as per published guidance for Finite Element Analysis [10] and then initial analyses checked to ensure the failure mechanism was not in contact with the model boundaries [8] and this did require some alterations to those indicated in figure 2. The analysis was conducted under fine nodal resolution to obtain more accurate results [8]. The 0.7m wide track was modelled as a rigid footing through which the design load was applied. As the model accounts for friction between the underside of the track and the platform, a conservative assumption made was that half of platform frictional strength would be utilised at this interface. Due to lack of available guidance, no shape factors were included in the model [8], and the track was assumed as a continuous footing; a conservative assumption.

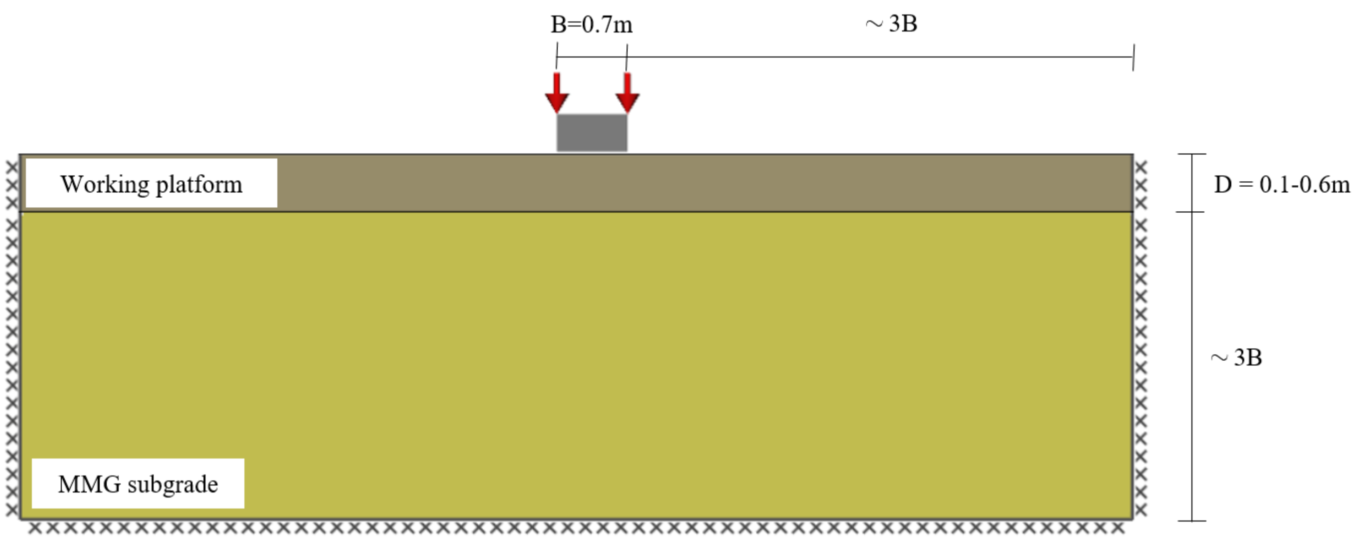

Figure 2: Geometry of the DLO model

3. Key Findings and Discussion

3.1 Comparison of industry methods with DLO analysis for granular platforms

Figure 3 shows the DLO adequacy factor as undertaken on platform thicknesses ranging from 0.1m to 0.6m and using parameters for a granular platform. This provides a direct assessment of how the DLO method compares with the three industry approaches. Different observations are noted across the three industry methods, and these are discussed in turn.

Figure 3 identifies that adequacy factors for the BR470 method ranges between 0.93-0.99 across the 0.1-0.6m platform depths, indicating that DLO outputs are closely aligned (<7% difference). This is supported generally well by figure 4.a, which shows that calculated resistances are broadly similar and there are similar increases in resistance computed by both methods between 0.3m and 0.6m platform. These findings are consistent with a previous study [8] on working platform design which reported that that the BR470 bearing capacity value were within 4% of the collapse values produced with the LimitState:GEO software.

For SP123 the adequacy factors are also relatively closely aligned with a range of 0.95-1.08 (figure 3), suggesting a similar good relationship between this method and the DLO analyses (<8% difference). With regard to resistance calculated, figure 4.b identifies that the SP123 approach shows no increase in resistance with increasing platform depth and the DLO analysis is very similar with only small differences between platform depths and actually the highest resistance is found in the thinnest (0.1m) platform depth. This may seem surprising given the BR470 results, but this type of trend in some working platforms is directly discussed in the CIRIA SP123 publication which on page 243 states “the bearing capacity of the fill may act as a cut off to the envelope of available resistance” [4]. This may well be the case in this work as the characteristic φ' value of 40° used for the platform strength is relatively conservative and then the SP123 method requires it is factored by a factor of 1.25 to a design value of 33.9°. This could also explain why the 0.1m platform recorded the highest resistance, as a greater proportion of the failure planes would pass through the subgrade material, where it appears that the design undrained shear strength contributes more resistance than the equivalent granular platform. It is further noteworthy that for the HBM designs where working platform design strengths were notably higher, this strength cut off did not occur and the expected trend of increasing resistance with platform depth was present and this is discussed further below (section 3.2). Notwithstanding, a good correlation between the SP123 method and the DLO software was established and deemed satisfactory for comparison with HBM going forward.

For the TWf method substantially different trends were noted, with an adequacy factor of 0.88 for a 0.1m platform which progressively reduced to 0.55 for a 0.6m platform, thus indicating a relatively poor correlation between the TWf and DLO approaches. Furthermore, figure 4.c clarifies that the reason for the poor correlation is that the TWf method outputs progressively higher resistance with increasing platform thickness. However, as was the case in the SP123 comparison, the DLO equivalent analyses showed little difference in resistance regardless of depth and it appears that a similar situation where the platform shear strength were acting a resistance cut off in these analyses. As there were two discrepancies for this method in the granular material, further use of the TWf method was not considered in this study. Although, with reflection it may have proven that using a higher design friction angle may have shown stronger correlations between the methods; but this was not explored.

In summary, the initial comparison of the DLO outputs with the industry methods identified that the DLO method provided similar outputs to the industry methods indicating the DLO method had potential to quantify the resistance from the cohesive and frictional strength of HBM. Of the two industry methods, SP123 provided more conservative values of maximum bearing pressures, which was due to the partial factors applied to the internal shear angle significantly reducing the bearing capacity factor of that method and also the equivalent DLO resistance [11].

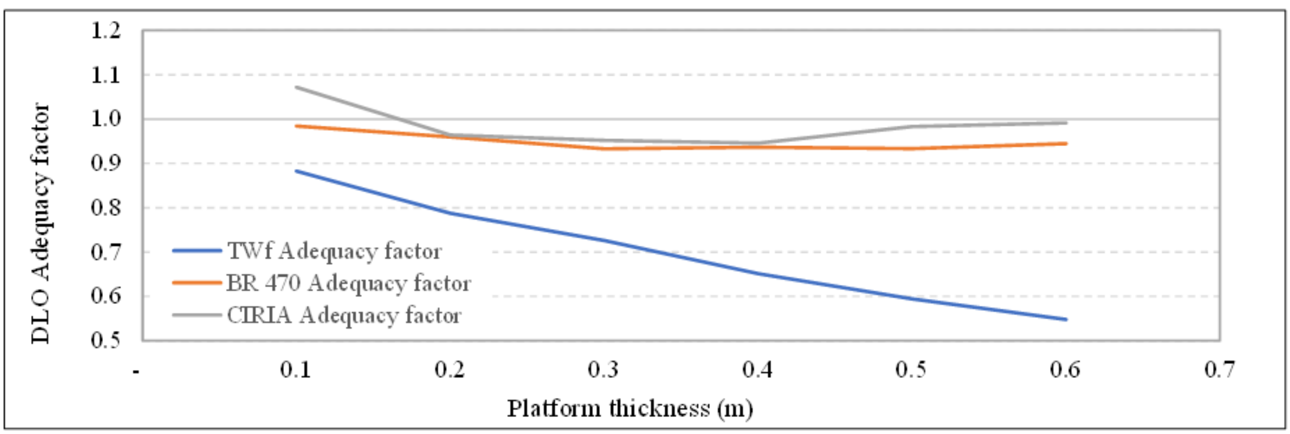

Figure 3: DLO adequacy factor plot for granular working platform design

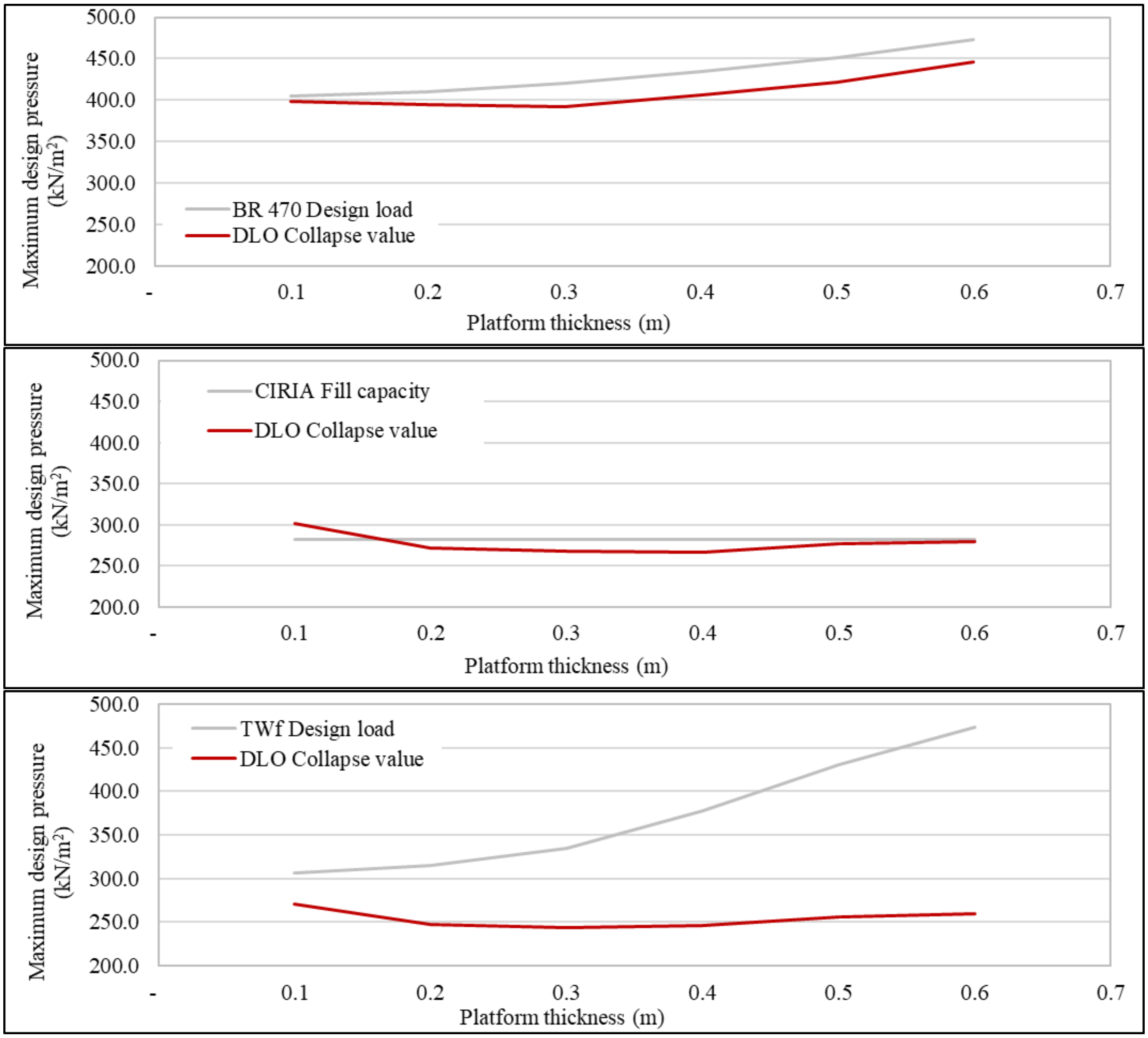

Figure 4a to 4c: Industry resistance versus DLO collapse load for granular platform as determined for each method 4.a (top) = BR470; 4.b (Middle) = CIRIA SP123; 4.c (bottom) = TWf.

3.2 Comparison of industry methods with DLO analysis for HBM platforms

Through undertaking the initial designs following the BR470 and SP123 methods, it was noticed that there was generally a consistent increase in the resistance of the HBM platforms in comparison to the granular equivalents. This was in line with the HBM having a higher ϕ' than the value selected for granular fill (table 1). However, as the published methods had no way to include the c' of the material, the increases were relatively small and there was not a significant difference in resistance between the higher lime content or longer curing times. This is not considered true for the real performance of HBMs where both longer curing and higher binder dosage impart substantial benefit. [6].

DLO analysis of the HBM working platforms using the BR470 partial factors are shown in figure 5 and this shows substantial increases in resistance that results from including both the c' and φ' of these materials compared with the granular equivalent. As an example, for a 0.3m deep platform, the granular DLO analysis calculates a resistance of 392kN/m^2, whereas for 1.5% lime cured for 28 days this is 1.6 times greater at 639kN/m^2. The effect of higher lime and longer curing is reflected in the results with 0.3m deep platform of 3% lime cured for 90 days with 937kN/m^2 resistance i.e., 2.4 times greater than the granular platform.

Figure 5 indicates that even the mixtures with the smallest portion of lime at the shortest cure times (0.75% and 28 days) had the potential to reduce the platform thickness from 0.7m to 0.1m for the same amount of resistance, i.e., 500kN/m^2. Thus, replacing the granular fill with HBM would have a great economic and environmental gain should an appropriate design method were implemented. However, it should be noted that the BR470 recommends the minimum temporary platform depth should be 300mm as shallower depths are unlikely to have a significant impact on bearing resistance [8]. Nevertheless, even with this imposed minimum of 300mm the use of any HBM would have the potential to increase the bearing capacity of a 0.3m thick platform by at least 1.6 times comparing to unbound material of same thickness and the benefits increase further with greater platform depth, higher binder addition and longer curing. While not directly considered in this study, similar benefits should be apparent with other HBMs such as cement stabilised soils, which would have further benefits of achieving the higher shear strengths much sooner e.g., within 7 days.

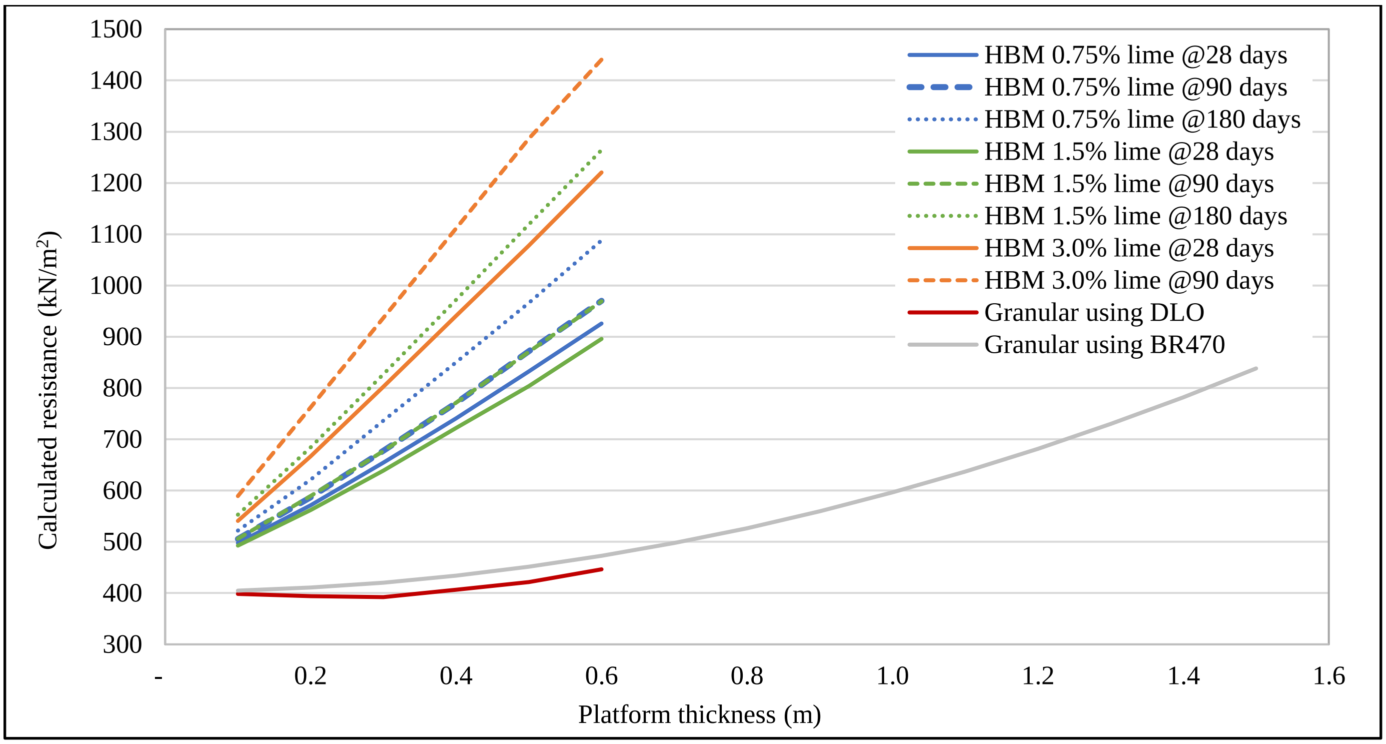

Figure 5: Resistance of granular and HBM platforms as analysed by the DLO method using the BR470 partial factors. A comparison with the BR470 industry method is included for granular material only.

4. Conclusions and recommendations for further work

This study investigated suitability of using industry-accepted working platform design procedures to calculate the resistance of HBM platforms for the case of lime treated Grade IV MMG. Key findings are:

- The SP123 method producing the most conservative bearing capacity values across all granular material and HBM.
- Both BR470 and SP123 industry methods use only the φ' of the platform material to characterise its shear strength and were unable to represent the strength of the HBM which had substantial strength relating to c'.
- DLO equivalent analyses of the BR470 and SP123 methods were able to include both the c' and φ' of the HBM. Results of the BR470 DLO equivalent indicated all lime treatments achieved design resistance of at least 500kN/m^2 from a 0.1m deep platform. To achieve the same resistance, a granular platform of at least 0.7m was required.

- BR470 guidance recommends that the minimum temporary platform depth should be 300mm as shallower depths are unlikely to have a significant impact on bearing resistance. Notwithstanding, even with the 300mm minimal platform depth, a HBM platform would be still less than a half as thick as the unbound material design and would have extra over design redundancy.

Alternative design methods for temporary working platforms, such as DLO analysis can open up the potential for more economic and sustainable HBM designs, departures from tried and tested, but notably limited, methods must be taken with caution. To add robustness to these study findings it is recommended further work to:

- Extend the study scope to include subgrade soils with lower undrained shear strength.
- Consider the reliability / relevance of Consolidated Undrained triaxial tests to represent the design shear strength of the HBM.
- Compare DLO analysis against outputs from other analytical methods, e.g., Finite Element Analysis software or similar. Including, as relevant different constitutive models to represent the platform shear strength.

References

[1] Temporary Works forum, *Working Platforms – Design of granular working platforms for construction plant – A guide to goof practice.* London, TWf, 2019.

[2] D. Egan, J.P. Feest, and G.J. Horgan, "Comparison of Design Approaches for Working Platforms Used for Piling Plant," in *Proceedings of the Piling 2020 Conference,* London, 2021, pp. 343-348.

[3] Building Research Establishment, *Report No 470 Working platforms for tracked plant.* Watford, BRE Bookshop, 2004.

[4] R.A. Jewell, "Working platforms and unpaved roads," in *Soil reinforcement with geotextiles,* R.A. Jewell, Ed. London: CIRIA, 1996, pp. 235-252.

[5] C. Tate, "Site Roads and Working Platforms," in *Temporary Works: Principles of Design and Construction,* G. Murray and P.F. Pallet, Ed. London: ICE Publishing, 2012, pp. 61-77.

[6] H. Skinner, A. Dunster, R. Harrex and F. Moulinier, *Guidance on the use of HBM in Working Platforms.* Oxon, The Waste & Resources Action Programme, 2006.

[7] C.C. Smith and A. Tatari, "Limit analysis of reinforced embankments on soft soil," Geotextiles and Geomembranes, vol. 44, no. 4, pp. 504-514, 2016.

[8] C.C. Smith. (2014, June 5). Working Platform Analysis Using LimitState:GEO (webinar) [Online]. Available: https://www.youtube.com/watch?v=l5D-J658wzg.

[9] S. Hawksbee, C. Smith and M. Gilbert, "Application of discontinuity layout optimization to three-dimensional plasticity problems," in *Proceedings of the Royal Society: Mathematical Physical and Engineering Sciences,* London, 2013, vol. 469.

[10] A. Lees, "How is a geotechnical finite element analysis set up," in *Geotechnical Finite Element Analysis: A practical guide,* A. Less, Ed. London: ICE Publishing, 2016, pp. 1-28.

[11] B. Attewell, G. Johnstone, M. Larish and R. Damen, "Temporary working platfroms – technical guidance on New Zeland Good Practice", in *NZGS Symposium,* Aukland, 2020, vol. 21.