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2020 SYMPOSIUM

GEOTECHNICAL ASPECTS OF RENEWABLE ENERGY

National Wine Centre

Corner of Botanic and Hackney Roads, Adelaide

Friday 6 November 2020

8.30am to 6:00pm

Organising Committee

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ADVANCED DESIGN PROCEDURE FOR SOFT SOIL STABILISATION IN WINDFARMS AND SOLAR FARMS

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ABSTRACT

The development of wind farms and solar farms requires transportation of site construction traffic followed by large prefabricated wind tower components as well as heavy cranes to erect the wind turbines under very severe safety working conditions, and then service vehicles throughout the life of the wind farm. By their very nature, onshore windfarms are typically in remote and, frequently, environmentally sensitive locations with poor soils with low bearing strength. These factors coupled with increasingly onerous bearing capacity and deformation demands for access roads and working platforms require innovative designs and solutions to result in an economical yet safe construction. This paper presents the latest development to stabilise the soft subsoil to design and build access roads and working platforms using geosynthetic reinforcement. A full-scale calibrated procedure for designing reinforced access roads and a modified BRE470 procedure for designing working platforms is discussed and presented. To verify the design methodologies, in-situ full scale field experimental tests were performed in a wind farm. Based on field tests, the actual design methods for both reinforced access roads and reinforced working platforms were calibrated and verified. Further, a Finite Element (FE) numerical model was created and validated for designing working platforms based on the in-situ results. The paper presents the results (numerical and analytical) and the resulting conclusions and design procedures. These methods have resulted in more feasible and economical designs for both roads and working platforms and numerous savings to clients compared to unreinforced or even traditional geogrid reinforced solutions.

1 INTRODUCTION

Wind energy is one of the Australia's main sources of renewable energy, generating enough electricity to meet 7.1 per cent of the nation's total electricity demand. According to Australian Renewable Energy Agency, at the end of 2018, there were 94 wind farms in Australia, delivering nearly 16 GW of wind generation capacity, with new wind farms expected to deliver electricity at around $50-65/MWh in 2020 and below $50/MWh in 2030. Solar farm (also known as Large-Scale Solar or LLS) generation is also growing rapidly in Australia. By January 2019, large-scale solar farms operating in Australia had the ability to generate over 3GW, with an additional 2.9GW either under construction or financially committed. This energy type is one of the lowest-cost sources of new electricity supply in Australia. The contribution of solar farm generation to Australia's total energy mix has nearly tripled in a year, from 0.3 per cent in 2017 to 0.8 per cent in 2018.

Unbound granular pavements are usually selected for access tracks and crane pads required for the construction, maintenance and decommissioning of the wind farm and solar farms, with a typical operational design life of 25 years. By their very nature, onshore windfarms and solar farms are typically in remote and, frequently, environmentally sensitive locations with soft soils with low bearing capacity. Design and construction of access roads and working platforms on these soft soils and peats require a high safety factor and can sometimes lead to a thick granular layer. Some treatments such as deep excavation and replacement or lime stabilisation are typical traditional treatments for soft subgrades. These solutions are not always economical and environmentally friendly. Close to 40% of the world's energy consumption and greenhouse gas emissions are related to construction. This provides the construction industry with an enormous opportunity to improve and provide more sustainable solutions to reduce the costs and environmental risks and damage.

Stabilising soft soils using geosynthetic reinforcement is now an accepted sustainable alternative solution for construction of access roads and crane pads with proven success through various projects in Australia and worldwide. According to the Scottish Natural Heritage (SNH) report on floating roads on peats (SNH, 2010), most modern floating wind farm roads are usually designed as stabilised haul roads with one or two layers of geogrid depending on the particular site circumstances and the geogrid selected. A floating road on peat is a road that is constructed directly on top of the peat (instead of stabilising the subgrade first) relying on the strength of the in-situ peat for its support. The road does not actually float on the peat rather an equilibrium builds up between the weight of the road and the in-situ strength of the peat whereby the combined system comes into balance (SNH, 2010). The main benefit of inclusion of geogrids is that the overall thickness of the road structure can be significantly reduced (between 30% to 50% or sometimes higher) whilst retaining the load spreading capabilities of the road. Settlements can also be reduced and become uniform due to geogrid reinforcement. Figure 1 shows a 5.3m wide floating road in a Scottish wind farm constructed on 1.0 to 1.2m of peat.

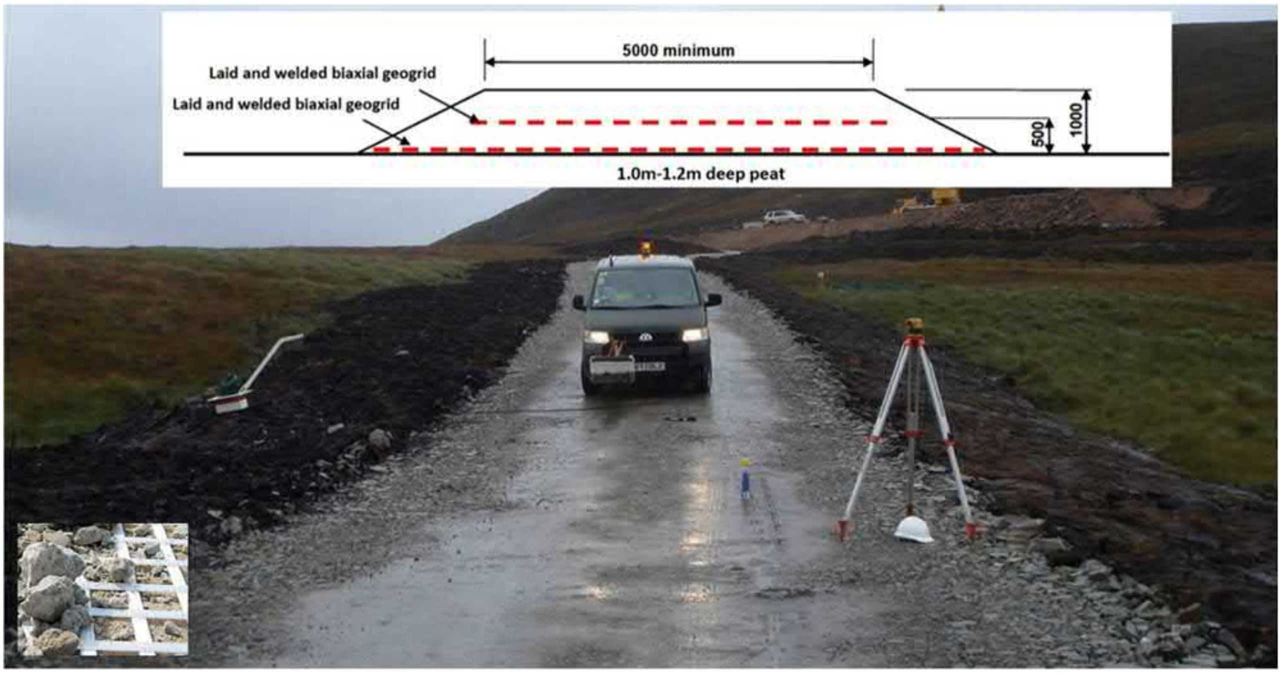


Figure 1: Designed and constructed geogrid reinforced floating road on a peat in a Scottish windfarm (SNH, 2010)

The results showed that the double geogrid arrangement appeared to have produced a good interlock layer that had settled fairly uniformly into the peat by approximately 200mm. Figure 2 shows the GPR survey results and the minor deformation in geogrids during installation and construction trafficking. Results showed no significant degree of rutting on the finished road surface.

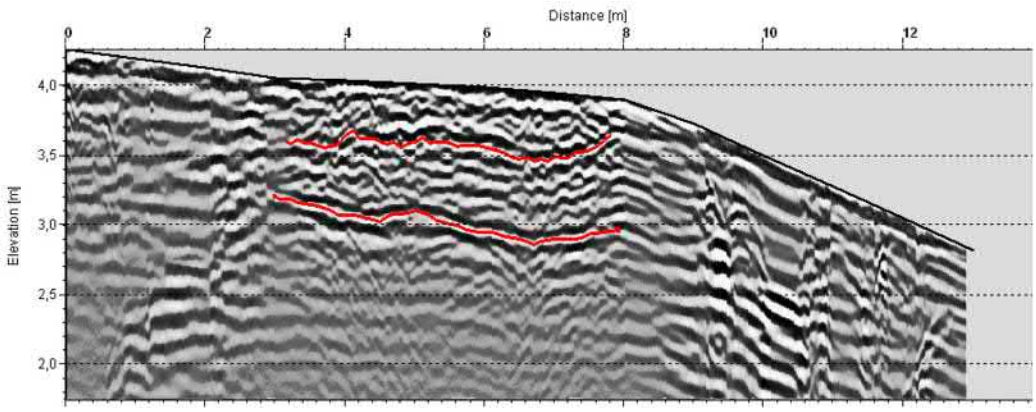


Figure 2: GPR Survey Results, Geogrid reinforced floating road cross section (SNH, 2010)

Through shear interaction of the base aggregate with the geogrid, the aggregate is laterally restrained or confined, and tensile forces are transmitted from the aggregate to the geogrid. This interaction between geogrid and base course material increases the shear strength and thus the load distribution capacity of the base course material. The increased load distribution capacity reduces vertical stresses on the subgrade, which enables the reduction of reinforced base course thicknesses in comparison to unreinforced layers (Figure 3).

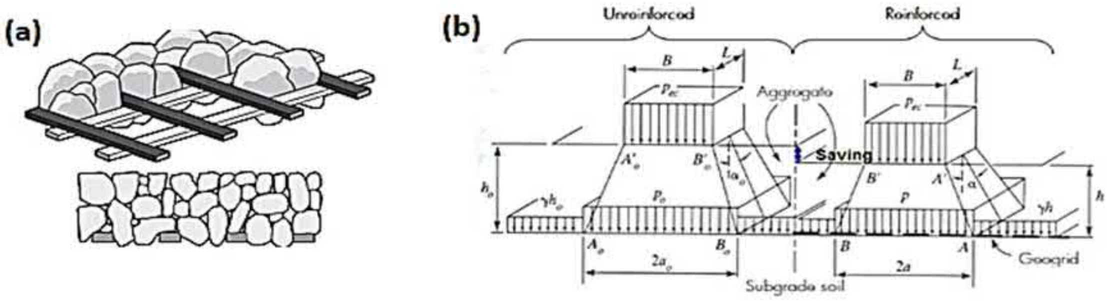


Figure 3: Aggregate-geogrid interlocking and confinement (a) and thickness reduction as a result of geogrid reinforcement and stabilisation (b)

This not only reduces the construction costs and environmental impacts, but also reduces fuel use, noise, dust and other pollutants associated with heavy plant operations. Geogrid reinforcement can also control differential settlements and lead to less total settlement and increase the global stability. In addition, geogrid reinforcement will result in a lower carbon footprint compared to traditional solutions. As an example, Figure 4 shows environmental savings based on accumulated energy and CO_2 consumption when comparing lime stabilisation with geogrid solution for a road project in Germany.

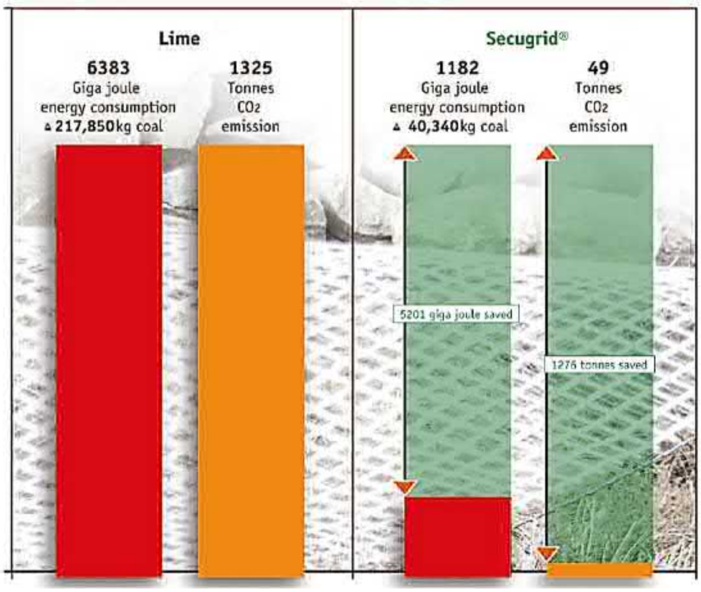


Figure 4: Environmental savings based on accumulated energy and CO_2 consumption: Lime vs geogrid stabilisation

This paper presents the latest design considerations and procedure for geogrid reinforced/stabilised access roads and working platforms and crane pads for windfarms and solar farms. Design considerations over soft subgrades or peats should consider global failure in bearing and serviceability issues including rut development and settlement. Results from full scale trials and FE modelling are also be presented.

2 DESIGNING ACCESS ROADS

Access roads should be able to withstand the transportation of heavy loads, be accessible and keep their bearing capacity all the time even in case of heavy rainfall. There are normally two design criteria and checks for access roads in renewable energy application: allowable rut depth as the typical requirement for access roads, and minimum bearing capacity. The final cross section of the road is the maximum thickness of these two design checks.

2.1 DESIGING ACCESS ROADS FOR ALLOWABLE RUT DEPTH

The design philosophy requires the rut development to be minimised during the construction period by the use of geogrid reinforcement in the pavement construction. The rutting on the access road is normally limited to a maximum rut depth of 50mm to 100mm, depending on the application and importance (ARRB, 2009).

The worldwide accepted design method to determine the thickness of the geogrid reinforced access roads is the design approach from Giroud & Han (2004a), which is as follows:

$$h \geq \frac{r}{tan\alpha}\left(\sqrt{\frac{P}{\pi r^2 m N_c c_u}} - 1\right) \qquad (1)$$

where h is the road thickness (m), P is the wheel load (kN), r is radius of the equivalent tire contact area (m), α is the stress distribution angle, N_c is the bearing capacity factor, m is the bearing capacity mobilisation coefficient, and C_u is undrained shear strength of the subgrade (kPa). It is through the factors $tan\alpha$, m and N_c that Giroud & Han (2004b) consider the effect of geogrid reinforcement on the base course thickness. After many empirical correlations, the authors propose the final equation as follows:

$$h = \frac{0.868+(0.661-1.006J^2\left(\frac{r}{h}\right)^{1.5} log\, N}{[1+0.204(R_E-1)]}\left(\sqrt{\frac{\frac{P}{\pi r^2}}{\frac{s}{f_S}\left[1-0.9e^{-\left(\frac{r}{h}\right)^2}\right]N_c f_C CBR_{sg}}} - 1\right) r \qquad (2)$$

where J is the aperture stability (Torsional rigidity) of the geogrid (mN/°), N is number of axle passages, R_E is limited modulus ratio of base course to subgrade soil, s is allowable rut depth (mm), f_S is factor equal to 75mm, f_C is factor equal to 30 kPa, and CBR_{sg} is CBR of the subgrade soil. The fundamental basis of the above relationship is a cyclic plate load test program by Gabr (2001) at North Carolina State University. However, since cyclic plate load tests are not directly applicable to pavements, the Gabr (2001) results were further modified based on other studies by other researchers (e.g. Hammitt, 1970) to arrive at the final form of the equation.

This design approach can be used for any type of geogrid. However, the final equation (equation 2) needs to be calibrated for every geogrid individually through full scale field trials. Large-scale trafficking trials (Cuelho et al., 2014; Vollmert, 2016) have confirmed the good performance and led to calibration factors for considering product specific performance in the above design approach. Cuelho et al. (2014) full-scale field trial will be discussed here as an independent reference.

2.1.1 Full-scale field trial and calibration-Cuelho et al. (2014)

During summer 2012 the Western Transportation Institute (WTI) at Montana State University (MSU) carried out a research project for Federal Highway Administration (FHWA)-US Department of Transportation (USDOT) where 17 unsealed test sections were constructed at the TRANSCEND test facility in Lewistown, Montana, to evaluate the performance of 12 different geosynthetic products commonly used for subgrade stabilisation for unsealed roads. The design of the test section was based on previous work completed by Cuelho and Perkins (2009) and focused on creating a uniform roadway to study the effects of geosynthetic stabilisation, subgrade strength and base course gravel depth. Three control sections (i.e., no geosynthetic) were constructed, each having different thickness of base course aggregate, and geogrid reinforced sections were constructed with about 300mm of granular layer constructed on a weak subgrade with a CBR of 1.7% and trafficked by a fully loaded three-axle dump truck. Figure 5 shows the site preparation and test sections before and after trafficking and rutting. More details about construction and monitoring and analysis of the results can be found in Cuelho et al. (2014).

Figure 5: Geogrid reinforced unsealed road full-scale field trial: from construction stage to end of trial (Cuelho et al., 2014)

The performance and serviceability criterion was maximum allowable rutting of 75mm (3inches). Rut depth along with discrete measurements of displacement was monitored throughout the trafficking period. Figure 6 shows the rut depth results for sections stabilised with different reinforcement/stabilisation geosynthetics with no extra separation/filtration function (i.e. geogrids). The results verified that geogrids could reduce the amount of rutting compared to the control (unreinforced) section.

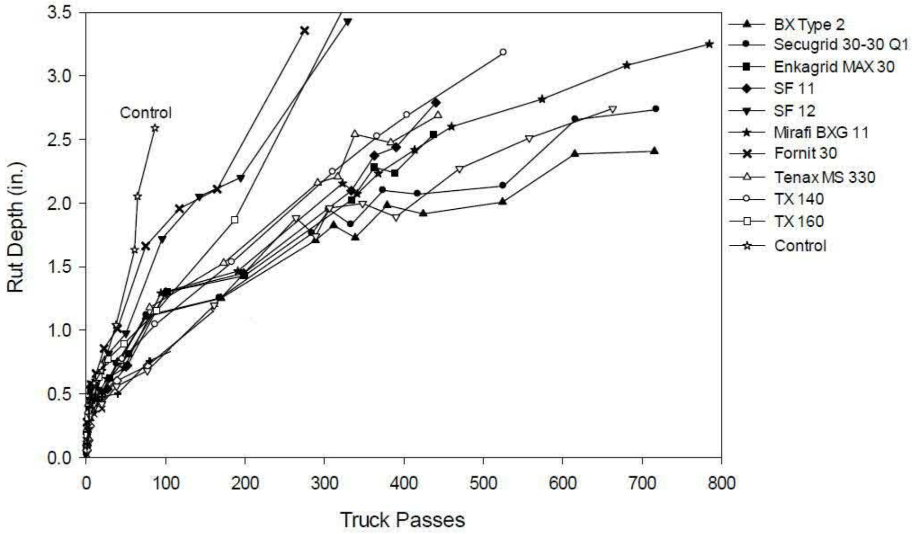


Figure 6: rut depth results for sections stabilised with different geogrids (after Cuelho et al., 2014)

This large-scale field trial also verified that geogrid reinforcement and stabilisation can increase the performance of the unsealed roads and provide benefits in terms of reduction in the gravel thickness (Base Course Reduction-BCR) and/or increase in the number of traffic passes (Traffic Benefit Ratio-TBR). The amount of BCR and TBR for this test series and conditions for different geogrid reinforced sections are published in the field trial full report by Cuelho el al. (2014) and shown in Table 1 which verifies all geogrid could provide reduction in the base course thickness.

Table 1: BCR and TBR results for different sections (after Cuelho et al., 2014)

	BX Type 2	Secugrid 30-30 Q1	Enkagrid MAX 30	Synteen SF 11	Synteen SF 12	Mirafi BXG11	Fornit 30	MS 330	TX140	TX160
BCR (%)	**23.8**	**21.9**	**19.6**	**19.0**	**11.7**	**19.3**	**10.2**	**17.7**	**17.4**	**13.1**
TBR	**7.9**	**6.6**	**5.2**	**4.9**	**2.6**	**5.1**	**2.3**	**4.4**	**4.3**	**2.9**

It also showed that the performance of geosynthetics used for subgrade stabilisation is related to different properties which are effective at different stages of rut deformation in unpaved road applications. At the early stage of rut development, stabilisation (a.k.a. lateral restraint) of the aggregate through interaction between geogrid and base course aggregate is important. The results of this field experiment have shown that a transition between lateral confinement/stabilisation of the base course towards a tensioned-membrane effect is apparent, which mobilises tensile forces in the geosynthetic at increasing rut depth.

Comparing the findings from this full scale trial and the previous work by Cuelho et al. (2009), the relevant geosynthetic performance parameters which influence the rut development can be summarised as follows: in the first phase of the rut development, loads are transmitted into the geosynthetic, especially in the transverse direction as the geosynthetic confines/stabilises the base aggregate when it spreads laterally under the applied load. This mechanism was found to be primarily influenced by the tensile stiffness in transverse direction (tensile strength at 0.5%, 2% and 5% strain) as well as by the junction strength and junction stiffness. In the second phase, when the rut depth increases the role of the junction strength and junction stiffness diminishes whereas the tensile stiffness in cross machine direction (at 0.5%, 2% and 5% strain) as well as the ultimate tensile strength in the machine direction are decisive.

This full-scale trial and analysis of the results also showed that a geotextile separation and filtration layer is required along with geogrid reinforcement to prevent fines migration from subgrade into the granular layer. Presence of this filtration and separation function/layer could increase the performance of the road and reduce the rut depth due to maintaining the properties and performance of the granular material.

These results were again later verified through more full-scale field trials by Vollmart (2016). Details about these field trials can be found in Vollmart (2016) and Shahkolahi et al. (2019). Results were also used to calibrate the Giroud and Han (2004) equation for designing unpaved roads using laid and welded biaxial geogrids. Figure 7 shows an example of an access road design using calibrated Giroud and Han (2004) equation for a laid and welded biaxial geogrid.

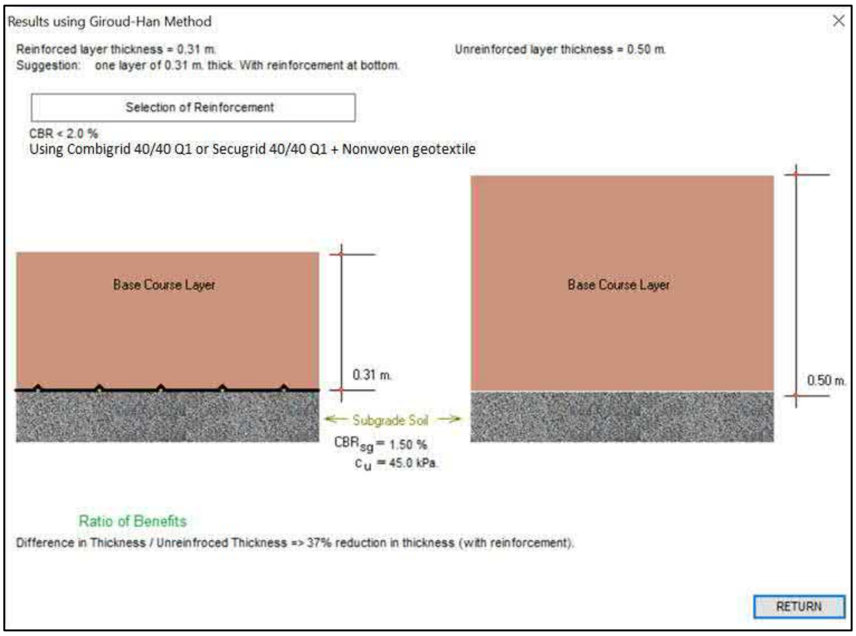


Figure 7: Unpaved road design example using calibrated Giroud and Han (2004) equation for laid and welded biaxial geogrids

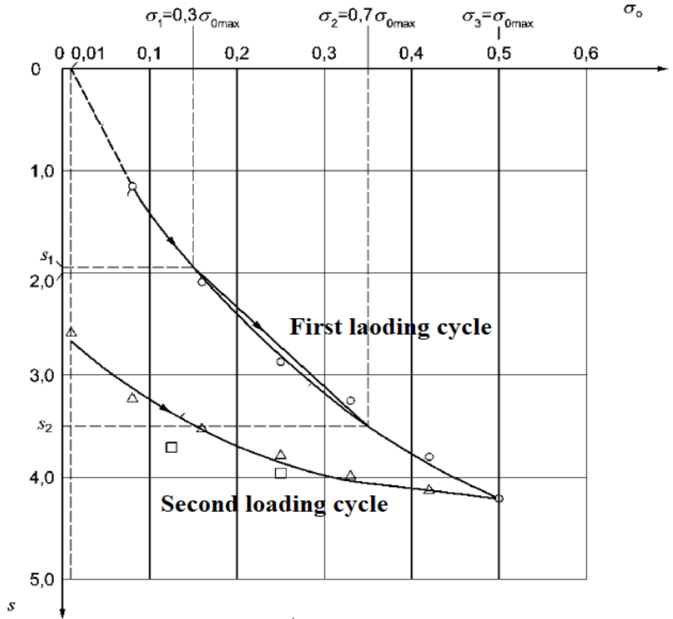
2.2 DESIGNING ACCESS ROADS FOR BEARING CAPACITY CRITERIA

Access roads in wind farms and solar farms should meet minimum requirements for bearing capacity and compaction. This criterion can be defined by the required bearing capacity in kPa, or the required strain modulus E_{v2} in MPa. The second approach is more common. It can also be easily tested and verified on site by using a Plate Load Test (PLT) under the standard test method of DIN 18134 (2012). Furthermore, the strain modulus ratio of E_{v1}/E_{v2} can be used to check and verify the compaction of the granular layer. A typical bearing capacity criterion for access roads for wind farms is shown in Table 2.

Table 2: Typical bearing capacity requirement for access roads in windfarms (Enercon E-70 E4)

Natural Ground	**$E_{v2} \geq 45$ MPa**
Substructure	**$E_{v2} \geq 80$ MPa**
Base/wearing course	**$E_{v2} \geq 100$ MPa**
Ratio E_{v2}/E_{v1}	**≤ 2.2**
Maximum axle load of transport vehicles	**12t**
Maximum axle load of crane	**12t**
Maximum vehicle weight	**130t**

According to DIN 18134 (2012), E_v expresses the deformation characteristics of a soil, calculated from the secants of the load settlement curves obtained from the first or repeat loading cycle between points 0.3(σ_{0max}), and 0.7(σ_{0max}), where σ_{0max} is the maximum average normal stress below the loading plate in the first loading cycle (Figure 8). The first loading cycle curve is used to calculate E_{v1} and the second loading cycle curve is used to calculate E_{v2}.



$$E_{V1} = 1{,}5 \cdot r \cdot \frac{\Delta\sigma}{\Delta s} = 1{,}5 \cdot r \cdot \frac{\sigma_2 - \sigma_1}{s_2 - s_1}$$

Figure 8: Load-settlement curve and fitting curves for the first and second loading cycles, and example calculations for E_{v1} (DIN 18134, 2012)

Geogrids will improve the E_{v2} value and so improve the performance of the granular material. In another word, by using geogrid reinforcement, a thinner granular layer is required to achieve the same E_{v2} as a thicker unreinforced layer. The required thickness with geogrid of course depends on the granular material, subgrade CBR, and geogrid type. Individual design charts or equations need to be used for every geogrid.

Benefits of geogrid reinforcement in improving E_{v2} values have been proven through various tests. In 2014, Minazek and Mulabdic (2014) used a large box having dimensions of 1900x900x1200 mm to facilitate the static plate load test. Because of the large layout area of the box there was a possibility of conducting two static plate tests on one soil layer. Standard static plate load test in accordance with DIN 18134 (2012) from German Institute for Standardisation (Deutsches Institut für Normung) was used to determine the reinforced soil modulus. The diameter of the steel plate was 300 mm. A biaxial polypropylene laid and welded geogrid with pre-stressed flat and wide bars was used as geogrid reinforcement and well graded gravel was used as soil fill (Figure 9). Test results were recorded and used for developing load-deformation curves to calculate deformation modulus E_{v1} and E_{v2} according to DIN 18134 (2012).

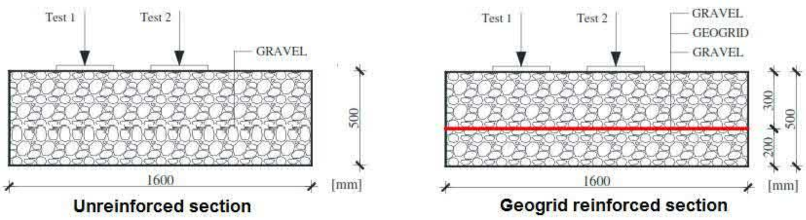


Figure 9: Large-scale laboratory plate load testing (Minazek and Mulabdic, 2014)

Deformation modulus E_{v1} (for first load) and E_{v2} (for second load) were obtained using expressions from DIN 18134 (2012) test method. Figure 10 shows the results of the plate load test in terms of deformation modulus E_{v1} and E_{v2} for unreinforced soil with thickness of 500 mm and reinforced soil with the biaxial laid and welded geogrid with 300 mm cover soil.

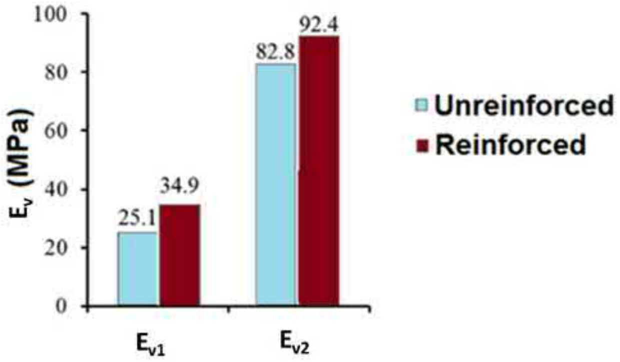


Figure 10: Plate load test results for unreinforced and geogrid reinforced sections (Minazek and Mulabdic, 2014)

Test results show up to 39% increase in the deformation modulus E_{v1} and up to 12% increase in the deformation modulus E_{v2} with geogrid reinforcement using a biaxial laid and welded geogrid under that test conditions.

Further investigation and full-scale trials and testing by Shahkolahi et al. (2019) showed more than 20% improvement in E_{v2} value because of using a laid and welded biaxial geogrid between the soft subgrade (CBR of about 2.5%) and granular layer (Figure 11). More details can be found in Shahkolahi et al. (2019).

Figure 11: Effect of geogrid reinforcement on E_{V2} improvement (after Shahkolahi et al., 2019)

The improvement factor and required thickness of the granular layer for a geogrid reinforced pavement depends on subgrade conditions, gravel types, and geogrid type. Some design charts were presented in the report by Saathoff et al. (1999) for E_{v2} modulus for unreinforced unbound granular layers and geogrid reinforced layers using a biaxial punched & drawn (extruded) geogrid. In 2000, Reuter et al. (2000) developed similar design charts for a laid and welded geogrid based on multiple verification field trials using plate loading tests following the methodology of DIN 18134. In 2003, a design manual for the laid and welded geogrid was published which included different design charts for different granular materials. A design software was also developed to determine the thickness to achieve a required E_{v2} value with and without a laid and welded biaxial geogrid based on the above design manual and design charts. More information can be found in Shahkolahi and Klompmaker (2018).

3 DESIGNING WORKING PLATFORMS AND CRANE HARDSTANDS

The importance of providing a stable working platform increased due to incidents involving overturning of piling rigs and cranes in past years. Designing working platforms and hard stands for wind farms and solar farms consists of an ultimate limit state (ULS) design, and a serviceability limit state (SLS) design or check for settlements. ULS design itself consists of designing for bearing failure and designing/checking of required strain modulus E_{v2}. The final thickness for ULS design is the maximum of these two design criteria/checks. This paper only presents the ULS design.

3.1 ULTIMATE LIMIT STATE DESIGN FOR BEARING FAULIRE

In regards of the design for working platform, two common types of failure may occur for a working platform exposed to high concentrated loads: (i) punching shear failure of the reinforced platform subjected to the high localised forces; (ii) rotational failure of the working platform founded on the soft cohesive soil. For the punching shear failure, a model derived from the Meyerhof's method (1963) can be applied to account for the footing punching through a strong platform material overlying a soft cohesive subgrade. For the rotational and overall failure, a Kinematic Element Method (KEM) can be implemented to examine the stability of the working platform over the subsoil, which is out of the scope of this paper.

The ultimate bearing capacity R of the in-situ subgrade underneath a square/rectangular plate (crane mat) can be estimated as follows according to Meyerhof's equation (1963):

$$R = c_u N_c S_c + g D N_q S_q + 0.5 g B N_g S_g \quad (3)$$

According to conventional methods, a thick granular layer is needed to provide the required bearing capacity. A better improving method which results in a more uniform stress distribution on top of the weak soil involves the introduction of geosynthetic reinforcements between natural soil and granular fill and within the granular material (where required). The benefits of this solution are the reduction of granular material required for working platforms resulting in cost savings both in procurement and transport, increasing bearing capacity of the reinforced soil system, a better response of the working platform under heavy loads and improved working conditions for heavy plant. The quality of granular material required for the working platform can also be reduced due to the incorporation of a suitable geosynthetic reinforcement. The savings highlighted above are matched also by environmental benefits.

Recommendations for the design of working platforms is given in BR470 (2004), which was prepared by the British Research Establishment (BRE). The design calculation given in BR470 is based on simplified analysis for a footing punching through a strong platform material overlying a weak subgrade. The bearing resistance of a platform on soft soil is considered to be the sum of the shear required to punch through a vertical plane in the granular platform material and the bearing capacity of the subgrade (Figure 12).

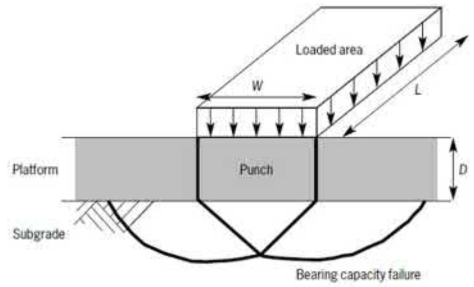


Figure 12: Bearing resistance of a platform on soft soil (BRE470, 2004)

BRE470 equations for bearing capacity (R) and platform thickness (D) for an unreinforced working platform are as follows:

$$R = c_u N_c S_c + (D^2/W_d)\, \gamma_p K_p \tan\delta\, s_p \quad (4)$$

$$D = \sqrt{[Wd\,(qd - cu\, Nc\, Sc)/\gamma p\, Kp \tan\delta\, sp]} \quad (5)$$

where D is the thickness of the platform material, W_d is the track width of the plant, N_c is the bearing capacity factor for a cohesive subgrade, $K_p \tan\delta$ is the punching shearing resistance coefficient, γ_p is the bulk unit weight of the platform material, and S_c and S_p are shape factors, which are functions of W and L (the effective track with and length of the plant).

The punching shearing resistance coefficient for a granular platform material, $K_p \tan\delta$ is a function of the value of the angle of friction of the platform material (ϕ), and can be calculated using Meyerhof (1974) taking $\delta = (2/3)\phi$. It also depends on the ratio of strength of the platform and subgrade. Note that BR470 states it is not suitable for material with c_u <20 kPa.

The current BRE470 approach considers the effect of geogrid as a reinforcement layer designed to take tensile loads which creates additional bearing resistance to the working platform. BRE470 differentiates this from situations where geosynthetics are incorporated into a working platform for other purposes. By using geosynthetic reinforcement at the base of the working platform to take tensile loads, the required thickness of platform can then be reduced. The design tensile strength of the reinforcement (T_d) is evaluated by applying a minimum factor of 2 to the ultimate tensile strength (T_{ult}) of the reinforcement so that:

$$T_d = T_{ult}/2 \quad (6)$$

For flexible reinforcements including flexible geogrids (woven/knitted geogrids) and woven geotextiles, a higher reduction factor should be used or their tensile strength at 5% elongation should be considered as the design tensile strength (T_d) in the design (BRE BR470, 2004). This is mainly due to the difference in the tensile behaviour, reinforcement mechanism and load distribution improvement between stiff and flexible reinforcements. Where the geosynthetic reinforcement does not have the same tensile strength in both longitudinal and transverse directions, the lesser of the two value should be used in the design.

The additional bearing resistance is calculated as $2T_d/W$. For example, for a platform on a cohesive subgrade:

$$R = c_u\, N_c\, S_c + (D^2/W_d)\, \gamma_p\, K_p\, \tan\delta\, s_p + 2T_d/W_d \qquad (7)$$

$$D = \sqrt{[W_d\, (q_d - c_u\, N_c\, S_c - (2T_d/W_d))/\gamma_p\, K_p\, \tan\delta\, s_p]} \qquad (8)$$

The current approach is very simplified and relies only on the tensile capacity of the geogrid. This approach does not consider the complete involvement and extra benefit of geogrid reinforcement due to the interaction of geogrid and granular material. A revised procedure has been developed to be used along with BRE BR470 (2004) approach to be able to account for this extra benefit of geogrids which can lead to more reduction in the platform thickness compared to the current BRE BR470 (2004) geogrid reinforced platform approach.

3.1.1. BRE470 Revised procedure for designing geogrid reinforced platforms

Various investigations and research works including the research carried out by Ziegler & Ruiken (2010) have verified that the interaction of the aggregate material with geogrids results in a measurably higher internal friction angle at low lateral compression (Figure 13).

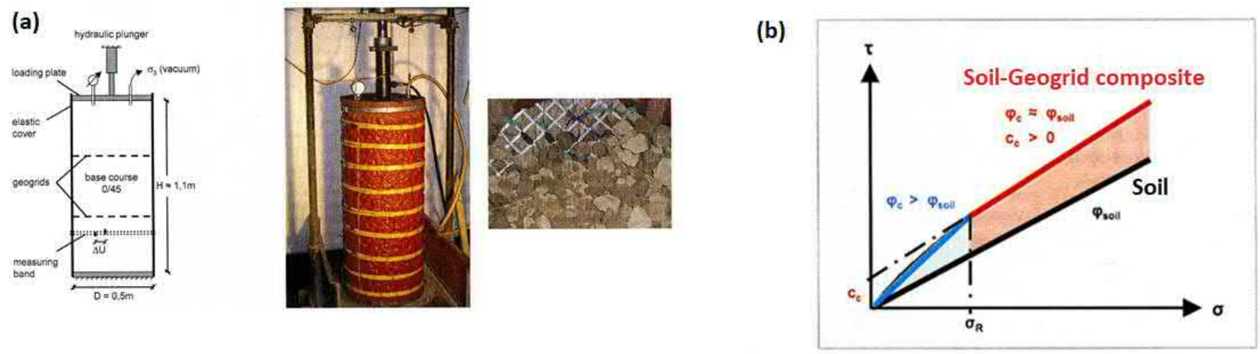


Figure 13: (a) Large scale triaxial test with biaxial laid and welded geogrid and (b) bilinear boundary condition for the soil and soil-geogrid composite material (Ziegler & Ruiken, 2010)

As the punching shearing resistance coefficient for a granular platform material ($K_p \tan\delta$) is a function of the value of the angle of friction of the platform material (ϕ), the increase in the ϕ value due to presence of the geosynthetic reinforcement will increase the punching resistance and so the bearing resistance of the platform, which leads to reduction in the required thickness based on equation (8). The current approach in BRE470 for geogrid reinforced platforms ignores this benefit and considers same friction angle for unreinforced and reinforced platforms in the thickness calculations. Figure 14 demonstrates the sensitivity of the calculated platform thickness as a result of varying the internal friction angle for a 50t piling rig at a constant undrained shear strength value (C_u = 30kPa) of the in-situ subgrade.

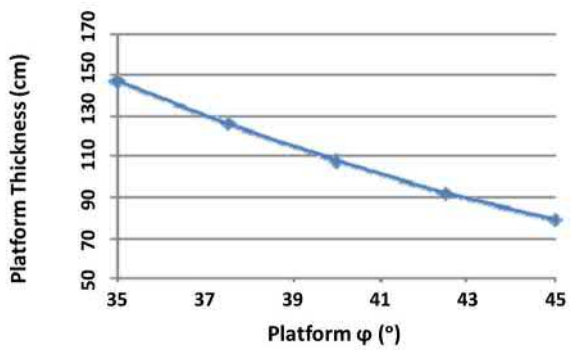


Figure 14: Working platform thickness vs platform material internal friction angle (Batali et al., 2014a)

As a result, a higher ϕ value can be used for a geogrid reinforced working platform material. This additional geogrid-soil interaction benefit benefit, along with the current additional bearing resistance due to geogrid tensile strength can lead to a considerable reduction in the thickness of the working platform compared to unreinforced and current BRE470 geogrid reinforced platforms.

3.1.2. Field verification and FE modelling

To validate the above modification in the design approach for geosynthetics reinforced working platforms for tracked plant described in BRE BR470 (2004), a field monitoring programme was planned at the Sălbatica Windfarm in Romania's Dobrogea region, near Tulcea. The Sălbatica Wind Farm included the construction of 35 turbines in the first stage, followed by another 35 in the second stage, each producing 2MW of power. The subgrade on site was mainly composed of soft silty clays. The soil in its natural state had an undrained cohesion of about 25kPa. The platform was designed following BRE470 using the above revised procedure for geogrid reinforced platform based on available and conducted test results. It was built on the compacted natural ground using 400mm of geosynthetic reinforced compacted well graded crushed stone (0-63 mm). The geosynthetic material used in the field tests was a 30kN/m Combigrid geocomposite reinforcement made of a laid and welded polypropylene (PP) biaxial geogrid with an integrated needle punched nonwoven geotextile, firmly bonded between the cross laid reinforcement bars. The maximum load from the 750t mobile crane was expected when the full counterweight of 225t was directly positioned over the crane pad without having a weight on the boom (Figure 15).

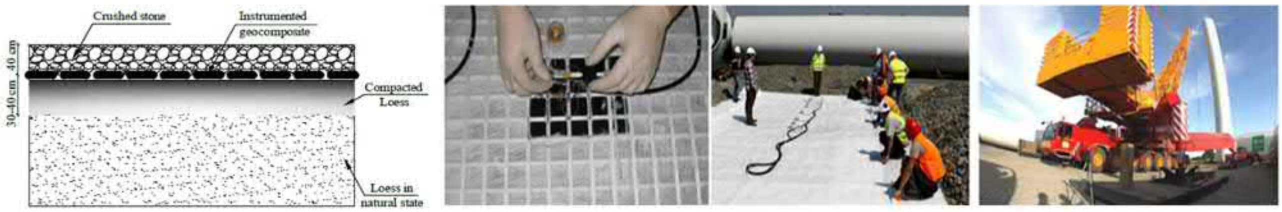


Figure 15: Combigrid reinforced working platform field trial and measurement (Batali et al., 2014a)

The maximum recorded pressure was154kPa and the maximum strain in the geogrid was recorded as low as 0.48%. The maximum measured settlement was about 9.5mm. More detail and information on this field experience can be found in Batali et al. (2014a). The results showed successful use of the revised procedure in designing working platforms. The important performance parameters for this revised approach are the geogrid-aggregate interaction, geogrid stiffness at very low elongation (e.g. 0.5% and 2% strain), and geogrid tensile capacity.

Test results from this field trial were used to calibrate a numerical model to further improve the design method. The numerical model was developed using the FEM software Plaxis 3D (2012), which takes into account the presence of the geogrid reinforcement and its interaction with the granular material. The non-linear behavior of the working platform structure was modeled using Mohr-Coulomb criterion. There was a very good agreement between the results from the model and the results from experimental test (Figure 16).

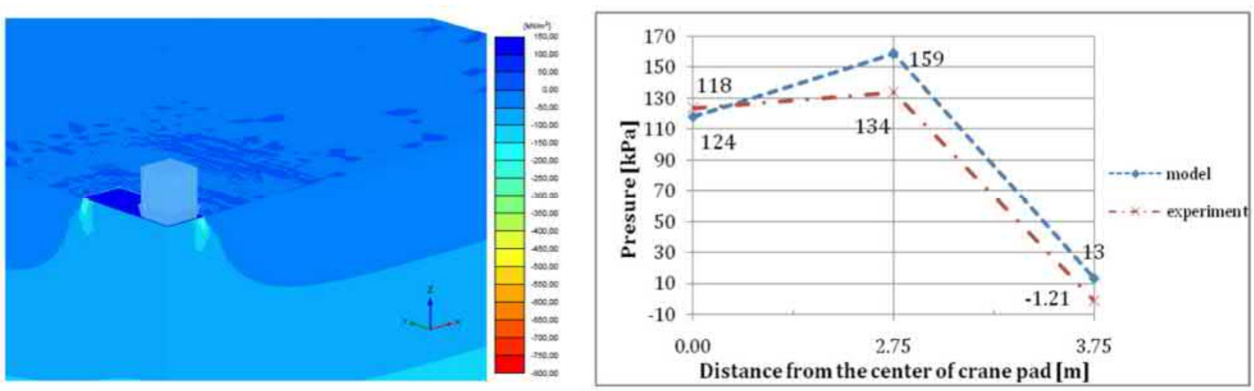


Figure 16: Numerical model results vs experimental measurements (Batali et al., 2014b)

3.2 ULTIMATE LIMIT STATE DESIGN FOR STRAIN MODULUS

Apart from bearing failure design, some guidelines require for a minimum strain modulus E_{v2} for the hardstands. A typical E_{v2} requirement is shown in table 2. This can of course vary for differet projects and cranes. Some guidelines suggest E_{v2} of minimum 120MPa for base/wearing course.

As illustrated in Section 2, using geogrid will assist to reduce the required granular layer thickness to provide the high required E_{v2} value. The final thickness of the ULS design will be the maximum value of the bearing failure and strain modulus design.

4 CASE STUDIES

4.1 SCOUT MOOR WINDFARM, UK

Scout Moor is a 26-turbine onshore windfarm on 900ha moorland in the South Pennines in Greater Manchester being operational since 2008. The construction of the windfarm included design and construction of 26 of 2.5MW turbines, 12km access track, and 26 crane pads on top of moorland environment with up to 4.7m thick peat with very low subgrade bearing capacity (CBR of about 0.5%). The roads had to provide high bearing capacity and resistance to edge failure, be resistant to excessive rutting, withstand more than 8000 HGV axles passing during construction with 25 years design life required for decommissioning purposes. Differential settlement particularly in transitions between bog and stiffer subgrade had also to be minimised. Geogrid solution was used to provide a cost-effective design and construction solution for access roads and hardstands using a laid and welded biaxial welded geogrid combined with a nonwoven geotextile for separation between the soft subgrade and granular layer (Figure 17).

Figure 17: Scout Moor windfarm, UK- construction of geogrid reinforced access roads and hardstands (top) and installation of the wind turbines (bottom, http://www.peelenergy.co.uk)

4.2 BLACK LAW WINDFARM EXTENSION, SCOTLAND

When opened in 2005, the Black Law Windfarm in Lanarkshire/West Lothian, Scotland, was the largest operating wind farm in the UK with 54 turbines and a total capacity of 124.2MW. As the first phase of a two-part extension programme, Scottish Power Renewables decided to add a further 23 turbines to the north of the windfarm in 2014-2015 which could increase the sites output capacity by up to 39MW.

Built on a redundant opencast coal mine which had been restored to shallow wetlands and forestry, the vast majority of the Black Law site was underlain with mine works and had large coverings of blanket peat bog up to 4.5m deep. Furthermore, there was a very soft clay layer beneath most of the peat layer. These low bearing soil conditions with CBR values as low as 0.5% were a major concern when designing unbound access roads at the site. The main challenge was to design and construct unbound access roads to cope with 4000 repeated passes of articulated dump trucks with 15t axle loads and withstand the massive weight of turbine components delivery vehicles. The consultant engineering company, Fehily Timoney & Co, developed a floating road reinforcement strategy designed based on the use of laid and welded biaxial geogrids. A Combigrid geogrid-geotextile composite made of a laid and welded biaxial geogrid with integrated nonwoven geotextile was used on the subgrade level to provide both reinforcement/stabilisation of the granular layer and subgrade as well as separation between the soft soil and granular material, and a laid and welded biaxial geogrid was used within the granular layer to provide intermediate reinforcement/stabilisation (Figure 18).

Figure 18: Black Law windfarm geogrid reinforced access roads and hardstands construction-Combigrid laid and welded biaxial geogrid-geotextile composite on the subgrade (top left) and laid and welded biaxial geogrid intermediate reinforcement (top right and bottom)

The solution to use a geogrid reinforced floating road for the 13km of access roads enabled the designer to provide a feasible cost saving solution to fulfill all site constraints as well as the requirement to achieve an allowable maximum rut depth of 75mm and the required minimum bearing capacity and strain modulus for the life of the access roads (Figure 19).

Figure 19: Black Law windfarm geogrid reinforced access roads, Scotland

4.3 REDLANDS SOLAR FARM, UK

At Pedwell, near Bridgwater, Somerset, juwi Renewable Energies Ltd has completed the construction of a 5.35MW solar farm on a 16.5ha site within an area classified as a level 3 flood zone. The Redlands Farm solar farm delivers 5.3GW/h of electricity per year, meeting the demand of 1,126 local homes. The project design incorporated solar panels sited on tall posts to ensure the site maintains normal levels of operation even in times of flooding. Essential to the project was the construction of more than 1km of unbound access roads. However, juwi's construction team were faced with the challenge of building the roads over a 5m deep blanket of soft, wet peat soil, with virtually no bearing capacity. Work to construct the 6m wide access roads depended on finding a cost-effective way of improving the bearing capacity of the peat soils, without the need to excavate and replace the weak sub-soils. As a result, geogrid solution was chosen by contractor using a Combigrid geogrid-geotextile composite made of a laid and welded biaxial geogrid with integrated nonwoven geotextile was used on the subgrade level to provide both reinforcement/stabilisation of the granular layer and subgrade as well as separation between the soft soil and granular material. The Combigrid geocomposite was installed directly on top of the peat subgrade, followed by a granular fill layer of crushed stone and gravel which created a stabilised roadway to provide access for initial installation of the solar panels, and provided effective access for the long-term maintenance of the solar energy farm (Figure 20).

Figure 20: Redlands solar farm Combigrid geogrid-geotextile composite reinforced access roads

Combigrid interacts with the aggregate course and increases the shear strength and load capacity of the completed access road. The load resisting properties of the geocomposite allowed juwi to install an aggregate base layer of around 400mm thickness for access roads at Redland which provided them with an average of 30% saving when compared to the solution with no geogrid reinforcement. The resultant savings in transport and material costs, along with reduced labour and time on-site achieved were a key factor in this project (Figure 21).

Figure 21: Redlands solar farm, UK

4.3 AUSTRALIAN WINDFARMS AND SOLAR FARMS

With increase in the demand of renewable energy in Australia which has led to increase in the number of windfarms and solar farms, geogrid reinforcement has been used as an accepted cost effective solution to design and construct access roads and hardstands on soft subgrades in various windfarms and solar farms in Australia. This include using laid and welded biaxial Combigrid geogrid-geotextile composites and geogrids in Granville windfarm in Tasmania, Moorabool South windfarm in VIC, Middlemount solar farm in Middlemount Qld, Warwick solar farm in QLD, Darlington Point solar farm in NSW, and many more. Geogrid solution has provided a sustainable solution to replace lime stabilisation or to reduce the thickness of the access roads and hardstands and yet maintain the required bearing capacity, strain modulus requirement, and allowable rutting criteria.

Figure 22 as an example shows Darlington Point solar farm during construction of access roads (Figure 22a) where a laid and welded biaxial geogrid was used and after completion (Figure 22b). The Darlington Point solar farm is a 333MW DC single-axis tracking project located approximately 10km south of Darlington Point in the Murrumbidgee shire of western-NSW, on 1993 acres of former grazing land.

Figure 22: Darlington Point solar farm, Australia-geogrid reinforced access roads during construction (a-left) and after completion (b-right, https://edifyenergy.com/project/darlington-point)

5 SUMMARY AND CONCLUSION

The use of geogrids at wind farm and solar farm project enables access for heavy construction traffic on soft subgrades and moorlands, which consist of extensive poor subgrade or peat bog. With the improved load distribution behaviour of the geogrid reinforced aggregate layers, stress concentrations over the soft subgrade can be reduced, which reduces the required thickness of the granular layer for both access roads and crane hardstands, and minimises differential settlements at the road surface. Apart from the commercial benefits, this generates a reduction in the environmental impact of construction traffic due to the reduced quantities of aggregate required.

Furthermore, a design procedure for geogrid reinforced access roads using welded biaxial geogrids was presented and calibrated through full scale field trials. In addition, a revised procedure for BRE470 design approach for working platform was introduced which considers the extra benefit from the interaction of geogrid and granular layer and reduces the thickness of the platform more than current the BRE BR470 (2004) approach for geogrid reinforcement. A 3D numerical model calibrated with field measurements was introduced which can be used to improve the design procedure.

It should be noted that in addition to the design of the improvement of the subgrade strength, the external stability of the access road and platform embankments has been investigated separately where required.

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David Zhang is a chartered geotechnical engineer with extensive experience in ground investigation, geotechnical design, proof engineering, and construction support. He has been involved in renewable energy projects through feasibility study, consent application, design and analysis, and construction phase services. He has worked on a wide range of solar energy projects from NSW to QLD.

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