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Soil reinforcement design with geosynthetics for wind farms.

M. Miuzzi, Maccaferri de México S.A. de C.V., Querétaro, México
O. Escamilla Cayetano, Maccaferri de México S.A. de C.V., Querétaro, México
P. Dos Santos, Maccaferri do Brazil, Jundai, Brasil

ABSTRACT

Nowadays the generation of electricity from fossil sources in Mexico goes around the 80% of the total generation. According to the Mexican Wind Energy Association, Mexico has a commitment to reduce this percentage to the 65% for the 2024. To achieve this goal, wind technology plays a fundamental role, since in most countries with similar goals, wind energy has been responsible for around two thirds of the total target. Increasing of the scale of the application the dimensions of the wind turbines increase quickly, reaching dimensions and loads unbelievable only some years ago.
On shore wind farms can easily involve heights of 150 m. and the rotor spins diameters can exceed the 125 m. These dimensions exponentially elevate the load applied to the ground, which certainly plays an important role in defining the perfect place to install a wind farm, moreover of the wind analysis, as velocity and direction. Develop a wind farm means large scale projects in remote areas, Mexico has a great history of inadequate soft soils to support this type of loads, there are expansive soils and also mobs
One of the main problems in the choice where the parks will be located is how to install the towers and the blades without a base collapse. A quick and cost-effective solution is the use of geosynthetic materials, such as geogrids and geotextiles for the reinforcement of the roads of internal roads and for loading platforms. Geosynthetics help to increase the load capacity of the soil and avoid failures in the installation process, as well as reduce costs. The aim of the authors for this article is to give a guide for the reinforcement of the soil in such cases referred to specific areas of the Mexican Republic characterized by soils that can not afford large loads caused by the infrastructure of the wind farm.

KEYWORDS

Wind farms, soil reinforcement, haul roads reinforcement, base reinforcement, geogrids, biaxial extrude geogrids

1. INTRODUCTION

It is quite recent the news that in the UK the renewable energies overcome the fossil energies. In this area obviously the climate changes and the focus on ecofriendly technologies, with the increasing demand of energy drove the market request to the development of green energies.

Due to morphology and geographic conditions, wind energy had a great growth in the last few years in Mexico, although the Mexican Republic was a pioneer in this kind of installations, with the first wind farm built in 1994 in La Ventosa, Oaxaca, one of the most important wind areas worldwide.

From to 1994 to nowadays the wind energy generation grows a lot in Mexico and in the 2018 it was of 5000 MW and the AMDEE (The Mexican Wind Energy Association) who is hoping to have a 27% increment for the 2019.

The two states with the highest wind energy production are Oaxaca, with the Ventosa region, which generates 2,756 megawatts (Forbes 2019, Figure 1) and the state of Tamaulipas with 1,163 megawatts, both characterized by having soft soils.

Figure 1. Geographical distribution of the wind farms in the Mexican Republic (Forbes Mexico, 2019)

Generally, the equipment used for wind power generation are voluminous, with great dimensions and very high that exceed the limits of normal transportation and load capacity of the soil foundation.

In Mexico, it is necessary to carry out sophisticated engineering processes for route planning for optimal transport. Many destinations are not equipped for oversized or overweight loads. The use of this type of equipment in areas with limited soil support capacity presents a challenge in the appropriate design method to ensure the stabilization of the wind turbine and the cranes necessary for construction procedures. Today, this should not represent a problem for the project area. Geosynthetics are already considered as one of the most favorable and efficient solutions to solve problems of stabilization of soft soils and areas with low load capacity.

The objective of the document is to expose the design procedure of the unpaved road and the proposed work platform for a wind farm located in Reynosa, Tamaulipas, the second most productive area of wind energy in Mexico

The 424 MW Reynosa wind farm will produce clean energy capable of supplying almost one million inhabitants. The total financing of the project amounts to an approximate amount of 600 million dollars, about 510 million euros.

2. CHALLENGE

When wind turbines reach a higher altitude, they are said to obtain a higher generation as they intercept faster gusts of wind. Wind turbines are manufactured in a wide range of vertical and horizontal axes. As explained in Figure 2, in 20 years the size of these systems has grown by 50%. The design of its foundations and all the access infrastructure, such as roads and work platform, is the main challenge that the geotechnical and structural engineer must face once the construction zone has been chosen after the wind analysis. The transport of these turbines gives the geotechnical engineer a great challenge because their safety and balance must be guaranteed during the installation phase.

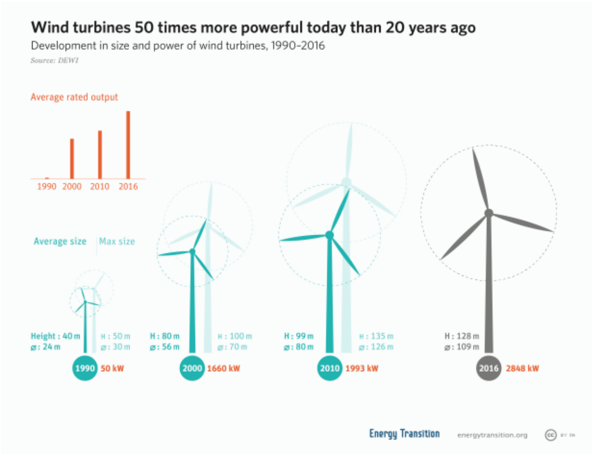


Figure 2. Wind turbines dimensions increase in the last 20 years (Energytransformation.org)

Focusing on the geotechnical problem, the base of a road is essentially a system to distribute the wheel load on the subgrade. In fact, if the load is not distributed correctly and extends in a soft subgrade, the road may fail for one or more of the following causes:

- Application of a single concentrated load that exceeds the load capacity (failure to drain);
- Accumulation of small permanent deformations (due to plastic deformations), which result in excessive settlement, incompatible with the functionality of the road (Figure. 3);
- Large deformations due to structure failure.

Figure 3. Effect of traffic and loads on an unpaved road on weak soil.

It is easy to understand that in wind farms it is essential to have a good infrastructure to support the load of the turbine and its installation process, since they are equipment with high costs and high technology.

In the calculations below, the owner of the wind farm wants to analyze three different traffic loads for unpaved roads to safely transport wind turbines to their installation sites.

3. GEOSYNTHETICS SOLUTIONS FOR WIND FARMS

Geosynthetics are a fast and less expensive alternative than traditional stabilization and reinforcement methods, such as lime and cement utilization stabilization. The inclusion of a correctly selected geosynthetic reinforcement in the untied layers of the road allows:

- Reduce the thickness h to equal values of cohesion c, friction angle φ, number of load cycles N (Figure 4);
- Increase the life of the pavement structure (which is the number N of load cycles) to equal values of h, c, φ (Figure 5);
- Reduce the compaction quality to the same number N of load cycles and thickness h.

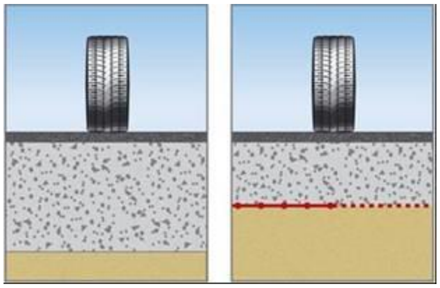


Figure 4. Reduction of base thickness using GSY (Maccaferri Design Manual for Unpaved and Paved Roads)

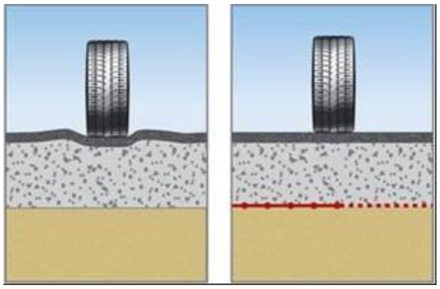


Figure 5. Increase of life cycles using GSY (Maccaferri Design Manual for Unpaved and Paved Roads)

A geosynthetic reinforcement improves the performance of a base layer through the following mechanisms:

- Reduces horizontal deformations;
- Prevents contamination between the base aggregate and the fine soil in the subsoil;
- The reduction of deformations prevents the loss of added resistance.

Lateral confinement action consists of limiting the horizontal movements of the road base aggregate. Both geotextiles (by friction) and geogrids (by interlocking) can provide lateral confinement, but the interlocking action of geogrids results to be more efficient than the friction action of geotextiles. (Figure 6)
Lateral confinement produces an increase in base layer stiffness, that is of the elastic modulus E_{base}, since at equal deformations it is possible to apply a higher load.

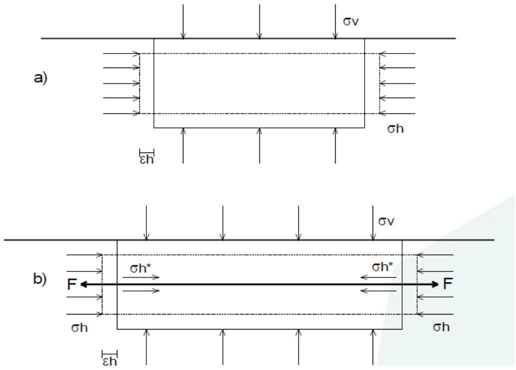


Figure 6. Lateral confinement and pressure given by the use of GSY in paved and unpaved roads (Maccaferri Design Manual for Unpaved and Paved Roads)

4. DESIGN METHODS FOR UNPAVED ROADS

The design of the unpaved roads reinforced with geosynthetics in this case was carried out using the Giroud - Han method, valid for both geogrids and geotextiles. The most common solution employed in Mexico are woven geotextiles, but the aim of this paper is to propose a valid alternative.

Giroud-Han method assumes that the load is applied with a single wheel or with double wheels, as a uniform load in a circular area of radius r and that the tensions are distributed according to a dispersion angle of the load α. The reinforcement of geosynthetic inclusions is characterized by torsional stiffness J. once obtained the thickness of reinforced and unreinforced structure, with geotextile and geogrid, the Geogrid Design Method was used to define geogrid's resistance and distribution.

The geosynthetic reinforcement is designed on the base of the following reinforcing mechanisms:
- Base course lateral restrain mechanism for horizontal stresses generated by base course soil self-weight;
- Base course lateral restrain mechanism for horizontal stresses generated by wheels loading;
- Membrane mechanism at the base course – subgrade interface."

4.1 Calculations and results

The objective of this calculation is to find the stability of the ground where the vehicles that will transport the wind turbine parts will pass, as well as the area where the cranes will work, despite the maintenance during normal working time. Due to the characteristics of the soil and the excessive loads in the wind farms, the use of geosynthetics for the unpaved road is necessary to have a notable reduction in the thickness of the filling material, as well as the reduction or elimination of the upper layer of the soil.

For this project as filling material, we will use a poorly graded clay gravel as indicated in Table 1.

Table 1. Characteristics of soil used for road infrastructure.

Description	Gravel with clay
UCS classification	GP-GC
Unit weight Kg/m^3	1663
Unit weight with cement (Kg/m^3)	2036
Humidity content (%)	5.9
LL (%)	29
LP (%)	13.5
IP (%)	15.5
Equivalent in sand (%)	15.2
CBR (%)	72.6

For the calculation of the unpaved structures it was necessary to assume three different equivalent axle loads:

- 343,000 equivalent axles
- 10,000 equivalent axles
- 8,500 equivalent axles

The thickness of the unreinforced structures assumed by the client was 0.47 m for the higher equivalent axles and 0.41 for both 10,000 and 8,500 equivalent axles and the subbase CBR of the ground soil 4.2 %.

With these input data, as first step we need to define the thickness of the unpaved road, to support these loads using the Giroud-Han method. The method assumes that the load is applied by a single wheel or by double wheels, as a uniform surcharge on a circular area of radius r and that stresses distribute according to a load spreading angle α. Giroud and Han considered the geosynthetic reinforcement characterized by the torsional stiffness J. Modulus J [Nm/deg], obtained from the torsional stability test developed by Kinney et al (1995), corresponds to the torque (in N·m) that shall be applied to the geogrid plane for getting the rotation of 1 deg. The torsional stability test has been developed based on the experimental observation that the wheels of moving heavy vehicles produce a circular distribution of stresses, rather than a linear one, in the base aggregate. Hence the base aggregate is subject to torsional stresses.

The Method proposed by J.P. Giroud and J. Han ("Design Method for Geogrid-Reinforced Unpaved Roads I & II", ASCE Journal of Geotechnical and Geoenvironmental Engineering, 2004) and included in the "Geosynthetic Design and Construction Guidelines" manual by the Federal Highway Administration (FHWA, 2008), provides a method to design the base course thickness of both reinforced and geosynthetic-reinforced unpaved roads over a soft subgrade.
Giroud and Han calibrated the bearing capacity mobilization coefficient and combined the equations to arrive at the following simple design equation for the minimum thickness of the base course h, Equation 1.
It incorporates important properties such as the strength and modulus of the aggregate, variations of the stress distribution angles through the aggregate and stiffness (aperture stability modulus) of the selected geosynthetic reinforcement.

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

h= Base thickness;
J= Torsional rigidity;
R= Equivalent contact areas radius
N= Traffic (standard Axles)
P= Tire pressure

R_E= limited modulus ratio of base course to subgrade soil
The bearing capacity mobilization factor is described in Equation 2

$$m=\left(\frac{s}{f_s}\right)\left(1-0.9exp\left(-\left(\frac{r}{h}\right)^2\right)\right)= \qquad [2]$$

m= Bearing capacity mobilization factor
s= Ruth depth
fs= 75mm
N_c= Bearing capacity factor
CBRsg= CBR subgrade

The bearing capacity factor N_c can vary depending on the type of reinforcement:

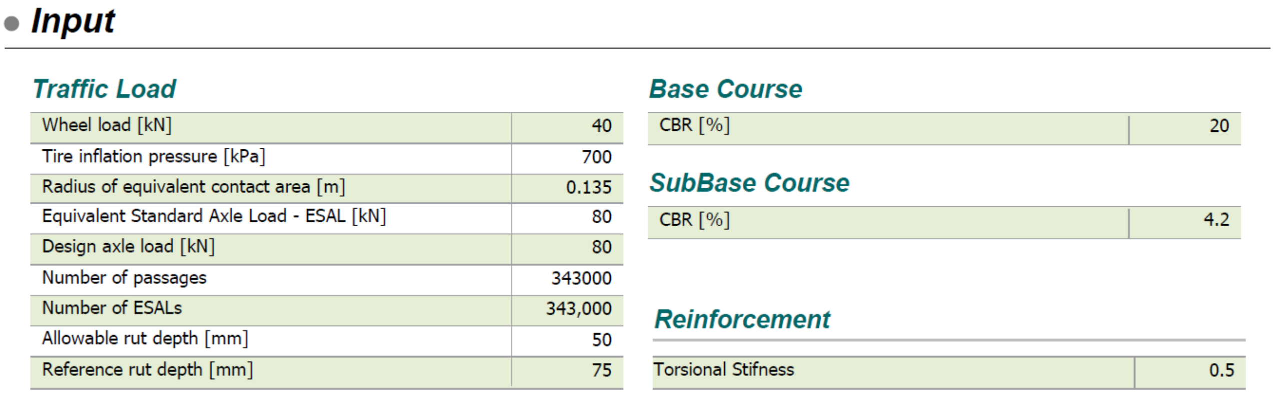
- No reinforcement: Nc = 3,14; J = 0
- With geotextiles: Nc = 5,14; J = 0
- With geogrids: Nc = 5,71; J = $J_{geogrids}$ [N-m/deg]

as the J, torsional rigidity:

- For EXTRUDED geogrids 0.3 < J < to 0.9
- For WOVEN geotextiles J = 0

Typically, h decreases with the increment of J and N_c.

The input data are reported in the Figure 7, the torsional stiffness J, for a biaxial geogrid of 20 kN/m, is J=0.5 Nm/deg



Input

Traffic Load

Wheel load [kN]	40
Tire inflation pressure [kPa]	700
Radius of equivalent contact area [m]	0.135
Equivalent Standard Axle Load - ESAL [kN]	80
Design axle load [kN]	80
Number of passages	343000
Number of ESALs	343,000
Allowable rut depth [mm]	50
Reference rut depth [mm]	75

Base Course

CBR [%]	20

SubBase Course

CBR [%]	4.2

Reinforcement

Torsional Stifness	0.5

Figure 7. Input data for the design of the unreinforced/reinforced structures (MacRead Studio 2.0).

Calculation had been made thought the software MacRead Studio 2.0 and for the heaviest traffic of 343,000 equivalent axles, starting from an unreinforced structure of 0.47 m, using a geotextile the reinforced structure thickness was 0.33 m with a saving of 30% and using a biaxial geogrid: 0.20 m with a saving of 57% as explained in Figure 8.

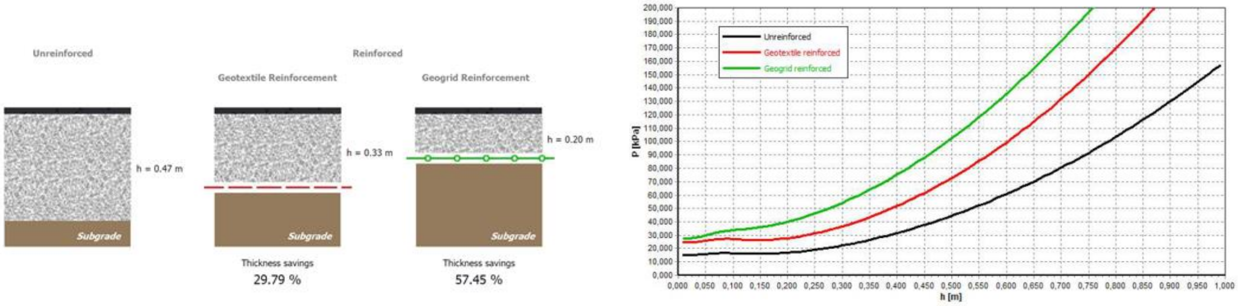


Figure 8. Results for 343,000 axles loads, Giroud-Han Design Method (MacRead Studio 2.0).

The difference between the geotextile structure and the geogrid ones must be referred to the torsional rigidity mostly and to the installation damages factors, lower in extruded geogrids. Hence bidirectional geogrids are different from other full surface geosynthetics, like geotextiles, since they allow soil interlocking between the upper and bottom faces, thus avoiding the formation of any preferential shearing surface.

With a lower traffic load, 10,000 and 8,500 equivalent axles, the thickness of the unreinforced section is 0.41 m, the reinforced ones are 0.27 m with geotextile and 0.13 m with biaxial extruded geogrid. in Figure 9.

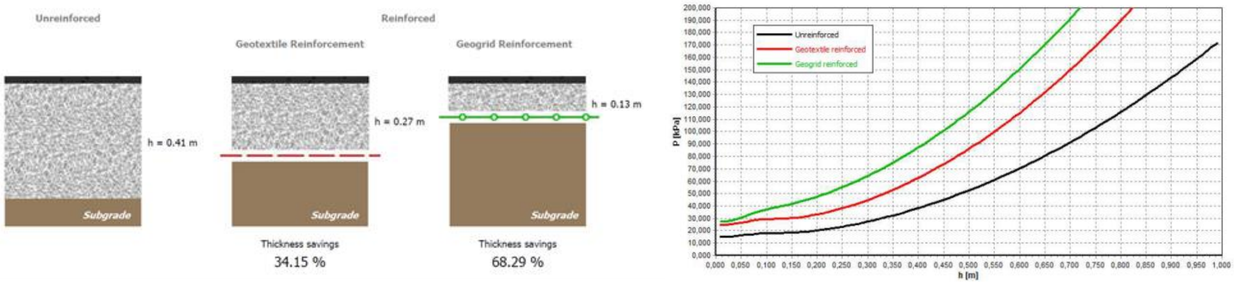


Figure 9. Results for 10,000 and 8,500 axles loads, Giroud-Han Design Method (MacRead Studio 2.0).

Once we obtain the thickness of the reinforced structure using an extruded geogrid, 0.20 m and 0.15 m respectively for the different loads, it is possible to define the necessary resistance of the geogrid. For the static analysis of multilayer was proposed in 2012 by Rimoldi and Scotto. Once the reinforced platform thickness has been designed, the geosynthetic reinforcement shall be designed on the base of the following reinforcing mechanisms:

- Base course lateral restrain mechanism for horizontal stresses generated by base course soil self-weight;
- Base course lateral restrain mechanism for horizontal stresses generated by wheels loading;
- Membrane mechanism at the base course– subgrade interface.

Each of these mechanisms describe above produce tensile forces in geogrid reinforcement layers.
The general scheme of a platform may include the following layers:

- Asphalt course AC;
- Base course BC;
- Subbase course SB;
- Subgrade SG.

Therefore, a four layers model has been developed for geogrid design: the general scheme of the model and all symbols, that will be used for subsequent calculations, are shown in the following Figure 10.

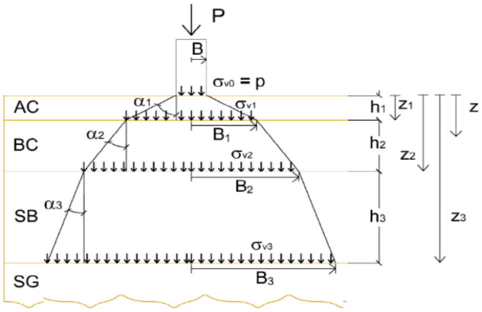


Figure 10 - General scheme of the 4 layers of different soil characteristics

The model assumes that the load is applied as a uniform vertical pressure $\sigma_{v0} = p$ on a rectangular area with half-length L and half width B; this load spreads in the 3 layers of the platform structure (AC, BC and SB) according to their load spreading angles α_1, α_2, α_3.
In our method, at least the base layer shall be present and shall be reinforced with geogrids; the asphalt layer may not be present and, if present, it is not reinforced; the subbase course may be present or not; when it is present, it may be either reinforced with geogrids or unreinforced.

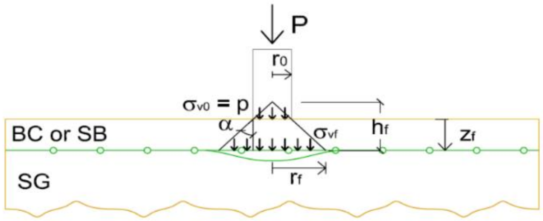


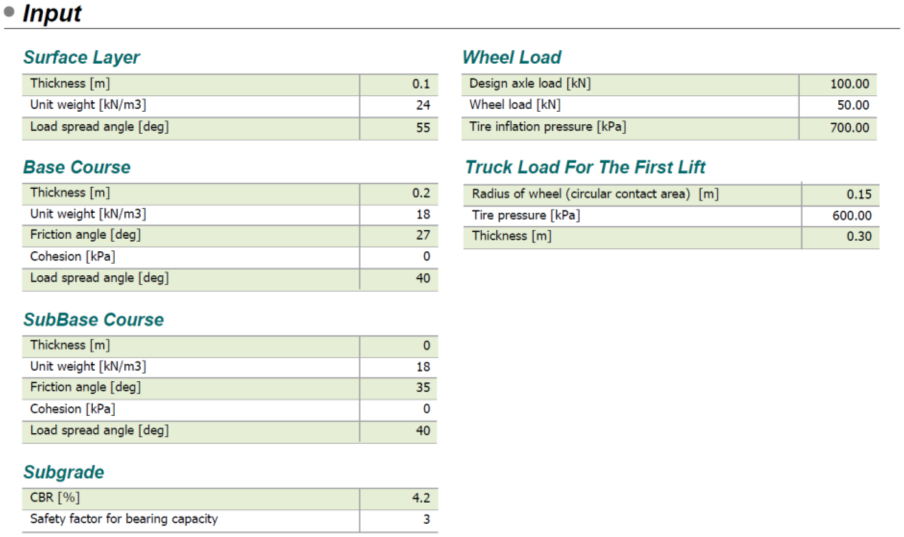
Figure. 11 - Scheme of the first geogrid layer

The total horizontal force that the i-th geogrid layer, Equation 3, must withstand is then:

$$T_{tot-i} = T_{zi} + T_{pi} + T_m \qquad [3]$$

Where:
T_{zi} = Force due to horizontal soil thrust in the i-th geogrid layer
T_{Pi} = Force due to horizontal stresses generated by wheels loading in the i-th geogrid layer
T_m = Force due to membrane mechanism at the interface with subgrade
The i-th geogrid layer shall be able to provide a tensile force equal to or larger than T_{tot-i} at a maximum strain of 5%.

Input data for the Geogrid design calculations are reported in Figure 12, considering 343,000 equivalent axles:



Input

Surface Layer

Thickness [m]	0.1
Unit weight [kN/m3]	24
Load spread angle [deg]	55

Base Course

Thickness [m]	0.2
Unit weight [kN/m3]	18
Friction angle [deg]	27
Cohesion [kPa]	0
Load spread angle [deg]	40

SubBase Course

Thickness [m]	0
Unit weight [kN/m3]	18
Friction angle [deg]	35
Cohesion [kPa]	0
Load spread angle [deg]	40

Subgrade

CBR [%]	4.2
Safety factor for bearing capacity	3

Wheel Load

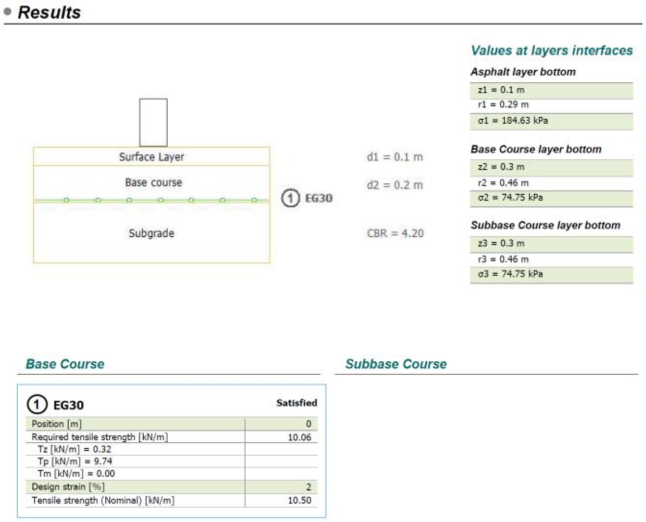
Design axle load [kN]	100.00
Wheel load [kN]	50.00
Tire inflation pressure [kPa]	700.00

Truck Load For The First Lift

Radius of wheel (circular contact area) [m]	0.15
Tire pressure [kPa]	600.00
Thickness [m]	0.30

Figure 12. Input data for 343,000 axles loads, Geogrid Design Method (MacRead Studio 2.0).

And the results of the analysis are reported in Figure 13:



Results

d1 = 0.1 m
d2 = 0.2 m
CBR = 4.20

Values at layers interfaces

Asphalt layer bottom
z1 = 0.1 m
r1 = 0.29 m
σ1 = 184.63 kPa

Base Course layer bottom
z2 = 0.3 m
r2 = 0.46 m
σ2 = 74.75 kPa

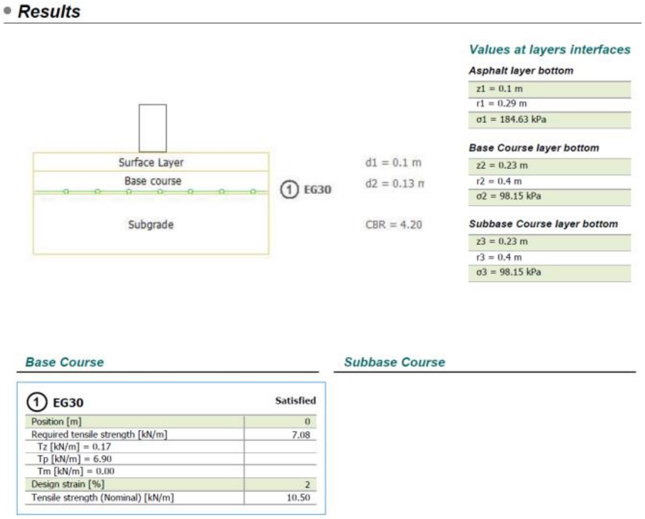
Subbase Course layer bottom
z3 = 0.3 m
r3 = 0.46 m
σ3 = 74.75 kPa

Base Course

Subbase Course

① EG30	Satisfied
Position [m]	0
Required tensile strength [kN/m]	10.06
Tz [kN/m] = 0.32	
Tp [kN/m] = 9.74	
Tm [kN/m] = 0.00	
Design strain [%]	2
Tensile strength (Nominal) [kN/m]	10.50

Figure 13. Results for 343,000 axles loads, Geogrid Design Method (MacRead Studio 2.0).



Results

d1 = 0.1 m
d2 = 0.13 m
CBR = 4.20

Values at layers interfaces

Asphalt layer bottom
z1 = 0.1 m
r1 = 0.29 m
σ1 = 184.63 kPa

Base Course layer bottom
z2 = 0.23 m
r2 = 0.4 m
σ2 = 98.15 kPa

Subbase Course layer bottom
z3 = 0.23 m
r3 = 0.4 m
σ3 = 98.15 kPa

Base Course

Subbase Course

① EG30	Satisfied
Position [m]	0
Required tensile strength [kN/m]	7.08
Tz [kN/m] = 0.17	
Tp [kN/m] = 6.90	
Tm [kN/m] = 0.00	
Design strain [%]	2
Tensile strength (Nominal) [kN/m]	10.50

Figure 14. Results for 10,000 and 8,500 axles loads, Geogrid Design Method (MacRead Studio 2.0).

5. CONCLUSIONS

Wind farm haul roads are subjected to high loads and high traffic due to great dimensions of wind turbines. Geosynthetics became in the last years on of the most suitable solutions for unpaved roads base reinforcement.

For the case exposed in the paper the use of an extruded biaxial geogrid of 30 kN/m, helps to reduce the haul road un reinforced structure of 0.47 m to 0.20 m with a 57% saving in the hardest configuration. Considering a woven geotextile with J=0 the saving it's only of the 30%. This can be easily reflected in money saving, it will be necessary to replace only 20 cm of existing soil, that is a direct benefit for the wind farm owner and constructor. The inclusion of a geogrid produces the interlock of the base aggregate within the geogrid apertures. The geogrid opposes the aggregate movements; henceforth it absorbs the stresses applied to the aggregate. Finally, the geogrid itself is subject to torsional stresses, thanks to the higher the torsional stiffness of the geogrid and the higher the stabilizing capacity of base aggregate. Bidimensional products, with a uniform distribution of rectangular apertures, having high tensile strength and modulus, both in longitudinal and transversal direction allow to get a confining action on soil granules and are an excellent solution for reinforcing wind farm unpaved roads, with high saving of aggregate thickness. As geogrids show limited separation capacity: very often the best results are got by coupling the reinforcing capacity of geogrids with the separation capacity of geotextiles. The recommendation was to couple the 30 kN/m biaxial extruded geogrids to a 200 gr/m^2 no woven geotextiles to have both separation and resistances functions.

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