Reinforced unpaved roads: parametrical analysis of design procedures

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ABSTRACT: Geosynthetics are commonly used for unpaved roads with a low volume of traffic. Unpaved roads, consisting of unbound granular bases overlying cohesive subgrades, are usually temporary roads, rural roads and haul roads. These roads are subject to problems like excessive rutting and mud-pumping, making the road unusable for the traffic. Conventional design procedures differ for subgrade failure mode, type of load distribution and type of reinforcement support mechanism. This paper deals with the results of a parametric analysis varying soil and geosynthetic mechanical properties, allowable rut depth and traffic conditions. The main objective of the present study is to compare these different design procedures aimed at estimating the base thickness required for unpaved roads reinforced with different geosynthetics.

Keywords: unpaved road, geosynthetic, reinforcement mechanisms type, design methods.

1 INTRODUCTION

The technique of soil-improvement using geosynthetics is extensively used in the construction of unpaved roads. Geosynthetic reinforcement becomes increasingly effective as the displacements become large, so when the substantial surface rutting is acceptable. This assumption is usually correct in the case of unpaved structures. Unpaved roads are usually used for temporary roads. They remain in service for only short periods (often less than 1 year), and are usually subjected to low volume traffic (less than 10000 load applications). This kind of roads include detours, access roads and tracks, low cost roads and stabilized working bases for heavy machinery. When the subgrade is weak, due to its poor consistency and high compressibility, generally, a geosynthetic reinforcement (geogrid and/or geotextile) is placed over the subgrade followed by a compacted granular fill layer. This technique is particularly effective because the performances of reinforced unpaved roads are enhanced by reducing permanent rut deformation for a given number of axle loads. Therefore the goals of geosynthetic reinforcements are an increase of the road service life; a decrease of the construction cost by decreasing the base layer thickness (if the cost of the geosynthetic reinforcement is less than the cost of the saved base material); a decrease of the time required for the construction and of the periodic maintenance interventions. In literature, on this topic, several methods for unpaved road design as well as some numerical and experimental works have been presented. Conventional design procedures differ for subgrade failure mode, type of load distribution and type of reinforcement support mechanism. This paper deals with the results of a parametric analysis varying soil and geosynthetic mechanical properties, allowable rut depth and traffic conditions. The main objective of the present study is to compare Barenberg et al. (1975) and Giroud and Noiray (1981, 1985) design procedure aimed at estimating the base thickness required for unpaved roads reinforced with different geosynthetics.

2 UNPAVED ROAD IMPROVEMENT BY GEOSYNTHETICS: FUNCTIONS AND MECHANISMS

Geotextiles and geogrids are two main types of geosynthetics used in the reinforcement of unpaved roads. However, there is a significant difference between them. The confinement due to the geogrid interlocking with aggregate minimizes lateral movement of aggregate particles and increases the modulus of the base course, which leads to a wider vertical stress distribution over the subgrade and consequently a reduction of vertical subgrade deformation (Giroud et al. 2004). The degree of interlocking depends on the relationship between geogrid aperture size and aggregate particle size (Giroud et al. 1985 and 2004, Cazzuffi et al., 2011 and 2014; Moraci et al., 2014 a and 2014 b, Calvarano et al.2014, Cardile et al. 2014, Cardile et al. 2016) instead the effectiveness of interlocking depends on the in-plane stiffness of the geogrid and the stability of the geogrid ribs and junctions (Webster, 1993). As a result of interlocking, the mechanisms of reinforced unpaved structure are different for geotextiles and geogrids. Under repeated load, the behavior of the base-geogrid-subgrade system is complicated. During surficial loading a geosynthetic layer may contribute to improve the soil layer by several mechanisms. Previous studies (Giroud and Noiray, 1981; Giroud et. al, 1985; Perkins et. al., 1997) focused on reinforced roadways with the use of geosynthetics have identified that two are the main important reinforcement mechanisms: lateral confinement effect and tension membrane effect. These mechanisms were originally based on observation and analysis under static load. They were also observed by some other studies under cyclic loading condition (Haas et. al., 1988; Webster, 1993). These mechanisms require different depth values of rutting in order to mobilize. At small permanent deformation magnitudes, the lateral restraint mechanism is developed by the ability of the base aggregate to interlock with the geogrid. When the aggregate layer is loaded by a vehicle wheel, the aggregate base tends to move (sliding) or to spread laterally and so it is restrained by the geosynthetic reinforcement through friction or interlocking of particles within geogrid apertures. Geotextiles, instead, provide little benefit if any with regard to lateral displacement because of relatively poor frictional characteristics between the aggregate and this kind of reinforcement (Webster, 1992). Perkins and Ismeik (1997) hypothesize that the lateral confinement action may have an effect before substantial rutting occurs. As increasing of permanent deformations, the tension membrane mechanism (Barenberg et al., 1975; Giroud and Noiray, 1981, Giroud et al., 1984) develops as a result of vertical deformation creating a concave shape in the tensioned geosynthetic layer. If the geosynthetic has a sufficiently high tensile modulus, tensile stresses will mobilized in the reinforcement, and a vertical component of this tensile membrane resistance will help to support the applied wheel loads.

3 UNPAVED DESIGN METHODS PROSED

Over the years, various design methods aimed at estimating the aggregate base thickness required for unpaved roads, have been developed. They typically use the relationship between rut depth, traffic conditions and the effects that the geosynthetic inclusion has on allowable rut. The behavior of geosynthetic-reinforced unpaved structure depends on the properties of geosynthetic, base and subgrade material, and the soil–geosynthetic interaction. Conventional design procedures differ for subgrade failure mode, type of load distribution and type of reinforcement support mechanism. Two are the design techniques for geosynthetic reinforced unpaved road, with a low volume of traffic, that are compared in this analysis. The former was proposed by Barenberg et al. (1975). The authors developed a design procedure to determine the thickness of the base layer, including the membrane effect, based on the limit equilibrium bearing capacity theory. It was assumed that significant rutting occurs, the deflected shape of the reinforcement was a circular arc, the reinforcement provides a separation function and no slip occurs at the interface. The limit equilibrium bearing capacity theory is based on selecting an aggregate base thickness such that the vertical stress applied to the interface geosynthetic-subgrade purified the amount of the wheel load which is supported by the reinforcement, if exists, is below the theoretical limits for subgrade shear failure:

$$\sigma_z - \Delta\sigma_{z,GSY} = \sigma_{all} \qquad (1)$$

where: σ_z is the maximum vertical stress on the reinforcement, calculated in accordance with the elastic Boussinesq theory under a uniform circularly loaded area [kN/m^2]; $\Delta\sigma_{z,GSY}$ is the amount of the wheel load which is carried by the geosynthetic for a given rut geometry and reinforcement tensile strength [kN/m^2]; $\sigma_{all}=N_c \cdot c_u$ is the maximum allowable stress of subgrade expressed as function of the undrained cohesion, c_u [kN/m^2] and of the bearing capacity factor (N_c). Being the failure mode of the unreinforced system characterized by local shear failure, while the failure mode of a geosynthetic-reinforced system by a general shear failure, due to additional distribution of the load, Barenberg et al. proposed N_c values equal to 3.3 and 6.0 for unreinforced and reinforced systems, respectively.

The latter design approach was proposed by Giroud and Noiray (1981, 1985). In this procedure the required thickness of reinforced unpaved road is function of traffic loading, subgrade shear strength and geosynthetics properties. In particular the assumptions were: a undrained soft saturated clay subgrade; a granular base with a CBR ≥80; a pyramidal stress distribution with a fixed stress distribution angle (in order to estimate the vertical stress at the interface base-subgrade); a reinforcement well anchored outside the loaded area and a parabolic deformed shape of the reinforcement. So, chosen an allowable rut depth the strain in the reinforcement, and hence the reinforcement tension (tensioned membrane effect) could be calculated. This procedure was also based on limit equilibrium bearing capacity theory with modifications to include benefit offers by reinforcement, which was taken into account using an enhanced bearing capacity factor. For unreinforced unpaved roads N_c is equal to 3.14, which is the elastic limit for a saturated undrained subgrade. For geotextile-reinforced unpaved road, on the assumption that the geotextile provides mainly a separation function, N_c is equal to 5.14. Finally, if the fabric used as reinforcement is a geogrid, which offers improved interface shear resistance due to interlocking, as compared to a geotextile, a bearing capacity factor even more amplified equal to 5.71 was chosen, in order to take into account the effect of the lateral restraint.

4 DESIGN PARAMETERS

Design parameters relating to geosynthetic mechanical properties, allowable depth ruts, subgrade mechanical characteristics, traffic conditions are given below (Table 1). The study presented in this paper is focused to the use of geogrid in unpaved roads. Six bi-oriented geogrids, commercially available, of different tensile stiffness were selected. Geogrids mechanical properties were investigated by means wide-width tensile tests (according EN ISO 10319). Tensile modules at 2% (in transverse direction along which the geogrids carry the higher mechanical characteristics) varying from 315 kN/m to 2100 kN/m and reduced by factor of 1.1 to takes into account the working conditions in site, were chosen in the implementation of the design procedures.

A serviceability criteria offered by AASHTO design guidelines (AASHTO 1993) consider allowable rut depths from 13 to 75 mm. In the case of unpaved access roads, allowable rut

depths greater than 75 mm are sometimes used, such as 100 mm. So three allowable rutting values equal to 0.025m, 0.075m and 0.100 m were chosen.
Also, for unpaved roads, geosynthetics with reinforcement function are required only for weak subgrade (AASHTO 1993) characterized by California Bearing Ratio (CBR) less than 3÷4 or undrained shear strength (c_u) less than 90÷120 kPa. So, in this analysis the undrained shear strength values varying from 5 kN/m^2 to 80 kN/m^2 were used.

Table 1. Design parameters

Allowable rut, r (m)	Geogrid Stiffness, $J_{2\%}$ (kN/m)	undrained shear strength, c_u (kN/m^2)
0.025	315	5
0.075	530	10
0.100	750	15
	1017	25
	1630	50
	2100	60
		80

About traffic assumptions, being vehicular traffic channelized, it is characterized by the number of passes (N_{cycles}) of a given axle during the road design life. The theory used by Barenberg et al. (1975) is based on static loading (i.e., up to 100 vehicle passes) while the Giroud and Noiray (1981) method extends this value of N_{cycles} up to a maximum of 10000 vehicle passes. For this reason, the comparison between two design models was done for a same number of vehicle passes (e.g. $N_{cycles,G\text{-}N}$= 100).
About the axles and loads design parameters, the wheel load (P) is the load applied by one of the wheels, in the case of single-wheel axles, or the load applied by a set of two wheels, in the case of dual-wheel axles and is considered to be half of the axle load (P_{Axle}). In this analysis P_{Axle} =80 kN, so P=40 kN and a tire contact pressure (P_c) of 556 kPa, were assumed.
Geogrid reinforcement improves the load distribution through geogrid-aggregate interlocking mechanism. So, in the design method proposed by Giroud and Noiray, the load distribution improvement ratio ($\tan\alpha/\tan\alpha_o$) was suggested to be variable between 1.1 and 2.5 (Giroud et al., 1985). This ratio is dependent on the expected degree of confinement and separation that the geogrid provides to the system, therefore this ratio could been considered as a linear function of the tensile modulus at 2% as follows:

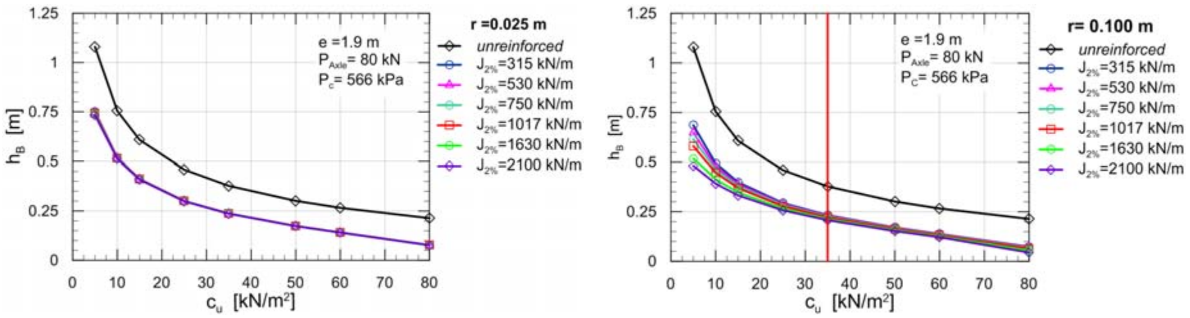
$$\tan\alpha/\tan\alpha_o=1.1+0.0005 * J_{2\%} \qquad (2)$$

where $\tan\alpha_o$ is the stress distribution angle in unreinforced base layer that could be considered constant for all unpaved roads constructed with unbound aggregate and equal to 0.6÷0.7. These results was confirmed by interpretation of cyclic plate loading tests performed by Gabr (2001) and Qian (2013); and $\tan\alpha$ is the stress distribution angle in reinforced base layer.

5 RESULTS OF ANALYSIS

Based on unpaved roads design procedure of Barenberg et al. (1975), Figure 1a and Figure 1b show design curves relating to unreinforced and reinforced base aggregate thickness ($h_{B,unrenif}$ and $h_{B,reinf}$), respectively, for the maximum and minimum value of the allowable rut (r = 0.025 m and r = 0.100 m), varying the subgrade mechanical properties (c_u = 5 ÷ 80 kN/m^2) and for each geogrids tensile stiffness ($J_{2\%}$ = 315 ÷ 2100 kN/m) chosen. As expected it is clear a decrease in $h_{B,unrenif}$ and $h_{B,reinf}$ with increasing subgrade undrained shear strength.

In reinforced case the geosynthetic stiffness has no effect on the design base thickness if r=0.025 m and if c_u > 35 kN/m^2 (Figure 1a and Figure 1b). The former behaviour is due because the ruts depth, and consequently the plastic deformations in the subgrade surface, have to be great enough to develop membrane type support. The latter behaviour is due because the influence of each reinforcement mechanism will go down with stronger subgrade conditions. On the other hand, for weak subgrade and by increasing rut magnitude (r>0.025 m and if c_u < 35 kN/m^2, Figure 1a and Figure 1b), the geogrid reinforcement achieving higher values of deformation, so higher tensile stresses are mobilized proportionately to geogrds' stiffness, reducing the vertical stresses transferred to the subgrade with consequent improvement in term of lower reinforced base thickness.



a) b)

Figure 1. Barenberg et al. (1975) unpaved roads design procedure - Unreinforced and reinforced base aggregate thickness varying undrained shear strength of substrate (c_u = 5 kN/m^2 ÷ 80 kN/m^2) and for each geogrids tensile stiffness ($J_{2\%}$ = 315 kN/m ÷ 2100 kN/m): a) r =0.075 m; and b) r= 0.100 m.

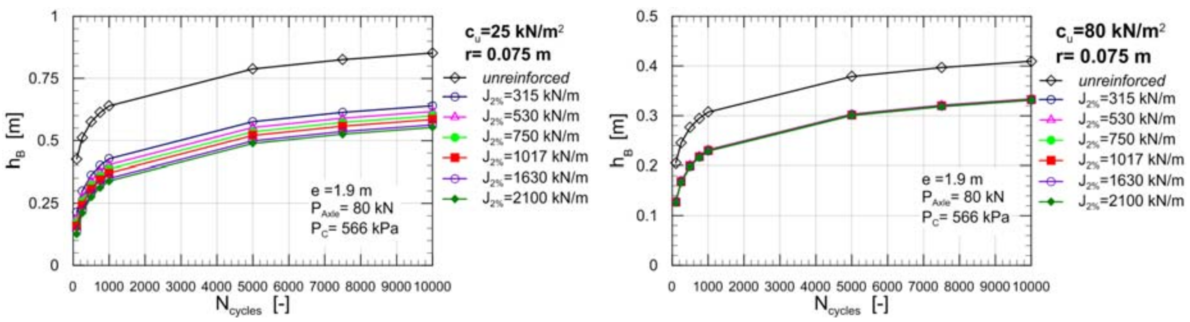


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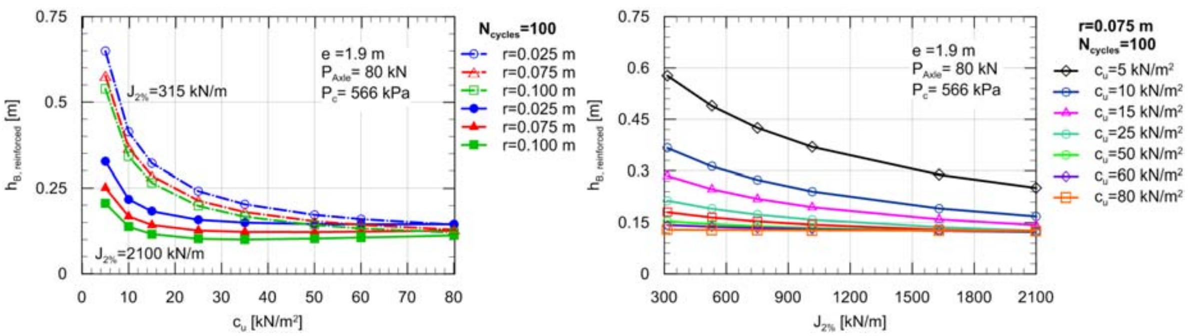
Figure 2. Giroud and Noiray (1981) unpaved roads design procedure - Unreinforced and reinforced base layer thickness vs number of cycles wheel load (N_{cycles} = 100 ÷ 10000), at the same allowable rut (r=0.075 m) and for each geogrids tensile stiffness ($J_{2\%}$ = 315 kN/m ÷ 2100 kN/m): a) c_u = 25 kN/m^2; b) c_u = 80 kN/m^2.

Giroud and Noiray (1981) unpaved roads design procedure moves away from static condition assumed by Barenberg et al. (1975) taking into account the effect of wheel load repetitions on the thickness of both unreinforced and reinforced base layer. Indeed, at the same design conditions (i.e., undrained strength shear of the subgrade and allowable rutting) it is noted, as expected, that the required base thickness increases as the number of wheel load cycles (N_{cycles} = 100 ÷ 10000) and with decreasing tensile stiffness modulus of geogrid reinforcement (Figure 2a and Figure 2b).
It is evident that the rate of base thickness growing is more pronounced in the first load cycles ($N_{cycles} \leq 1000$), to settle back down after a number of repetitions beyond a certain threshold (e.g. $N_{cycles} \geq 5000$). It could be due because for too great base thickness (obtained

for a more high number of wheel repetitions) the repeated loads on the road surface do not lead to the subgrade limit pressure, so that further load cycles has little or no influence on the response of the road unpaved structure. Moreover, with increasing subgrade undrained strength shear (comparing Figure 2a and Figure 2b) the required base thickness, for both reinforced and unreinforced case, decreases, as well as the reinforcement modulus has practically no effect since the subgrade can resist by itself the applied loads (Figure 2b).
In Giroud and Noiray (1981) procedure all depth values of rutting chosen (r = 0.025m ÷ 0.100m) are large enough to make work the geosynthetic layer which provide a reinforcement support proportionally to own tensile stiffness (Figure 3a). This suggests that the better performance is not only due to a membrane effect, but it is also due to lateral restraint of the base soil which develops for more reduced rut depth and it is, therefore, always the first mechanism to be active. Then, by increasing rut depth, the membrane mechanism, that requires higher values of geosynthetic deformation to be achieved, takes over. Also, assuming equal the other design variables (i.e. N_{cycles}, r, c_u, Figure 3a), with the increase in geogrids mechanical properties lower reinforced base layer thickness are obtained with a consequent saving of aggregate material needed for its construction. Figure 3b confirms that, at equal N_{cycles}, geogrid benefits increase with decreasing subgrade strength and with the use of more stiff geogrids. Particularly for $c_u \leq 60$ kN/m^2 reinforcement with higher stiffness provide more benefits.



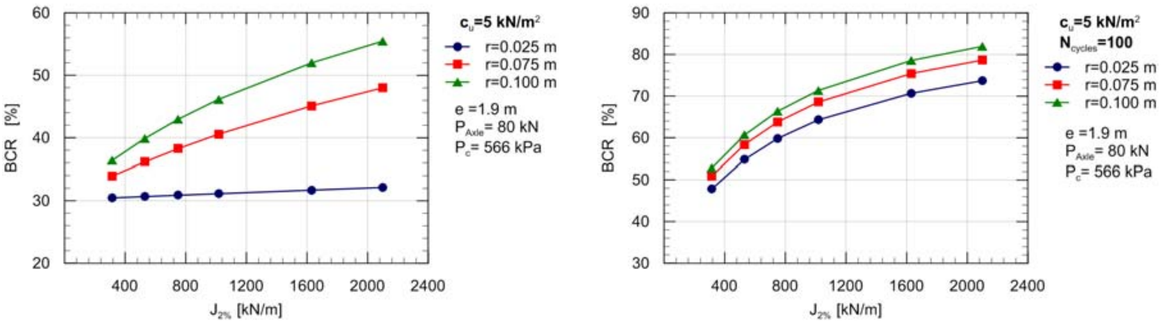
a) b)

Figure 3. Reinforced base layer thickness by Giroud and Noiray (1981) procedure at N_{cycles}=100: a) iso-rutting curves varying subgrade undrained shear strength relating the minimum and the maximum values of the geogrid tensile stiffness ($J_{2\%}$ = 315 kN/m and 2100 kN/m); b) iso-c_u curves in function of geogrid tensile stiffness.

To analyze the sensitivity that the geosynthetic stiffness and the rut depth have on both Barenberg et al. (1975) and Giroud and Noiray (1981) design procedures Figure 4a and Figure 4b are discussed. In particular, the analysis is conducted in term of Base Course Reduction factor (BCR). The BCR can be define, at equivalent traffic capacity, as the percent reduction in the reinforced base layer thickness from the unreinforced layer thickness, with the same materials, to reach the same defined failure state (in term of rutting) that can be define from as follows:

$$BCR= [(h_{B,unrenif} - h_{B,reinf})/ h_{B,unrenif}]*100 \qquad (3)$$

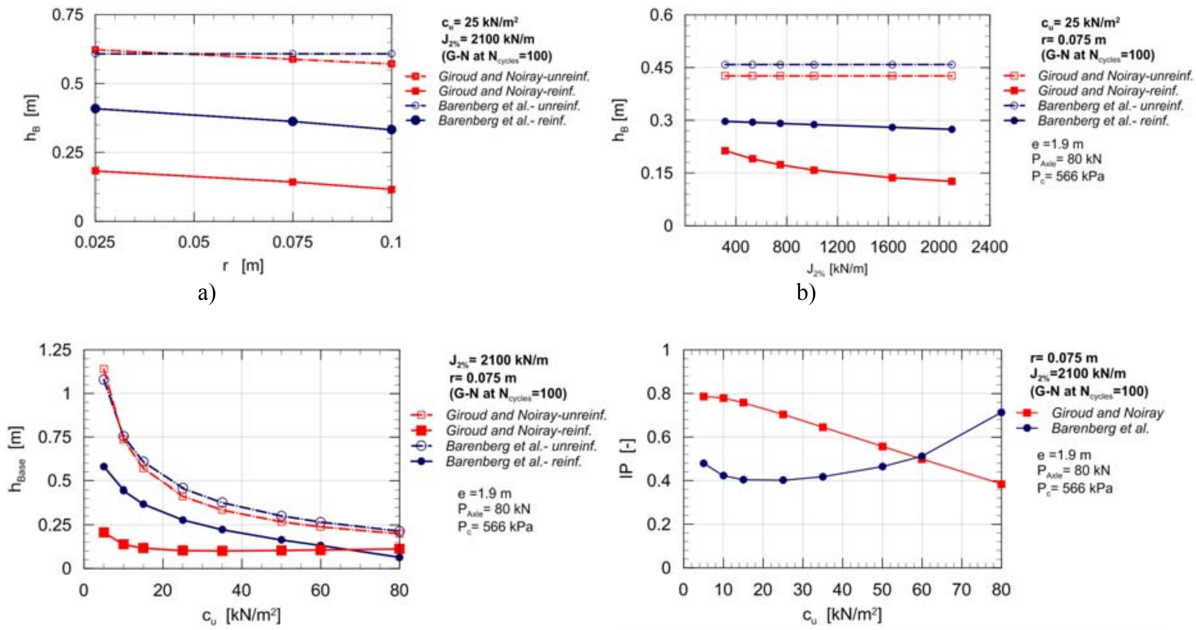
In other words, these Figures show the improvement offered by the reinforcement in unpaved roads, varying tensile stiffness of reinforcement, at the same mechanical characteristics of subgrade (i.e., cu =5 kN/m^2, for which the differences are more evident). Therefore, in order to take into account the influence of $J_{2\%}$ an iso-rutting curve relative to the maximum rut depth (r= 0.100 m, curve in green for which the greatest differences are shown) is analyzed. The use of a more rigid reinforcement (from 315 kN/m to 2100 kN/m) leads to a reduction of the reinforced base layer thickness corresponding to an improvement of 19% and of 29% respectively for Barenberg and Giroud and Noiray procedures.



a) Barenberg et al. b) Giroud and Noiray

Figure 4. Unpaved roads design procedure - Iso-rutting curves relating to Base Course Reduction factor (BCR) at c_u = 5 kN/m^2 and varying reinforcement stiffness: a) Barenberg et al.; b) Giroud and Noiray.

On the other hand, to investigate the effect of the rut depth the comparison is conducted for the same value of $J_{2\%}$. In the present analysis the highest value of geogrid stiffness (i.e. $J_{2\%}$ = 2100 kN/m) is selected because in this case the biggest differences are measured. It can be seen that the increase of the rut depths (from 0.025m to 0.100 m) leads to a reduction of BCR of 23% and 8% respectively for Barenberg and Giroud and Noiray methods.
It follows that, with equal subgrade mechanical properties, the sensitivity (or weight) of two variables $J_{2\%}$ [kN/m] and r [m] in Barenberg et al. (1975) unpaved reinforced design procedure is the same. On the other hand in Giroud and Noiray case, the geosynthetics tensile stiffness has a greater weight than allowable rutting.



c) d)

Figure 5. Comparison between design procedures proposed by Barenberg et al. and by Giroud and Noiray: a) influence of rut depth; b) influence of the reinforcement tensile stiffness; c) influence of the undrained subgrade shear strength; d) Performance Index (PI).

The amount of improvement due to reinforcement effect can be related to a Performance Index (PI) which is definite as follows:

$$PI= 1- [(h_{B,unrenif} -h_{B,reinf})/ h_{B,unrenif}] \quad (4)$$

Figure 5d reports PI versus c_u, at the same design conditions in term of equivalent traffic capacity, allowable rutting and geosynthetic reinforcement used. In the range of undrained subgrade shear strength chosen, generally Giroud and Noiray design procedure shows higher PI than Barenberg et al. method, where the higher differences are at lower c_u values. It happens because being the reinforced base layer obtained by Barenberg too high the reinforcement works less. Probably the reasons would be due to how each methods estimate the pressure on the substrate surface: Barenberg et al. (1975) consideres a load distribution according to the Boussinesq theory and no takes into account the base mechanical characteristics, while Giroud and Noiray (1981) adoptes a trapezoidal distribution of pressures taking into account the base aggregate mechanical proprieties. This aspect highlights the more conservative nature of Barenberg et al. (1975) design procedure.

6 CONCLUSIONS

On the basis of the parametrical analysis carried out on the implementation of Barenberg et al. (1975) and Giroud and Noiray (1981) unpaved roads design procedures, the following conclusions could be drawn.
Because both design methods, aimed to obtain the reinforced base thickness layer of an unpaved road system, consider the membrane action of reinforcement, the dependency of the required aggregate layer on rut depth and reinforcement tensile modulus are reflected on the results. Particularly, reinforcement benefits generally increased with increasing allowable rut depth and with the use of stiffer geogrids.
The analysis conducted in term of Base Course Reduction factor (BCR) shows that above variables (r and $J_{2\%}$) have the same sensitivity on Barenberg et al. (1975) design procedure, instead in Giroud and Noiray (1981) one, a greater sensitivity of the geosynthetic tensile module, than allowable rut depth, is shown.
Anyway, as undrained subgrade shear strength increases, so decreases the design base thickness and the benefits offered by reinforcements.
The amount of improvement introduced by the reinforcement can be related to a Performance Index defined as one minus the reduction in the reinforced base layer thickness from the unreinforced layer thickness. In the range of undrained subgrade shear strength chosen, generally Giroud and Noiray design procedure shows higher PI than Barenberg et al. method, where the higher differences are at lower c_u values. Probably, the reasons would be due to how each methods estimate the pressure on the substrate surface: Barenberg et al. (1975) considers a load distribution according to the Boussinesq theory and no takes into account the base mechanical characteristics, while Giroud and Noiray (1981) adopt a trapezoidal distribution of pressures taking into account the base aggregate mechanical proprieties. This aspect highlights the more conservative nature of Barenberg et al. (1975) design procedure.

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