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Finite element modelling of unpaved road reinforced with geosynthetics

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Abstract

The technique of soil mechanical stabilization, using geosynthetics, is extensively used in the construction of unpaved roads with a low volume of traffic. Unpaved roads consist of unbound granular bases overlying cohesive subgrades. When built on weak subgrades, these roads are subject to problems like excessive rutting and mud-pumping, increasing maintenance costs and usually leading to periodic interruptions to traffic. Particularly, the field applications of geosynthetic reinforcement placed above a weak subgrade can markedly improve the performance of these roads decreasing permanent vertical deformations, increasing lateral restraint ability, which results in increased pavement service life or reduced base thickness to carry the same number of load repetitions. This paper focuses on providing a numerical investigation using a bi-dimensional Finite Element Method (FEM), using ABAQUS software, to analyze the improvement of reinforced unpaved road under repeated wheel traffic load conditions in terms of aggregate base course thickness saving.

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Keywords: Geosynthetics, unpaved road, design methods, FEM analysis.

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1. Introduction

The technique of soil-improvement using geosynthetics is extensively used in the construction of unpaved roads. Unpaved roads are usually used for temporary roads. They remain in service for only short periods (often less than 1 year) and are subjected to low volume traffic (less than 10000 load applications). Unpaved roads typically consist of an aggregate layer resting on the subgrade. The aggregate base distributes the load. The subgrade carries the vehicular load. When the subgrade is weak, due to its poor consistency and high compressibility, a geosynthetic reinforcement is generally placed at the base-subgrade interface to improve the road performance. This technique is particularly effective because the performances of reinforced unpaved roads are enhanced: either by reducing permanent rut deformation for a given number of axle loads and a given base layer thickness, or by increasing the road service life for a given allowable rut depth and a given base layer thickness. Alternatively, for the same traffic and allowable rut depth, the use of geogrid reinforcement allows a reduction in the construction cost by decreasing the base layer thickness in comparison with the thickness required when the base layer is unreinforced (if the cost of the geosynthetic reinforcement is less than the cost of the saved base material). Anyway, the use of reinforcement leads to a decrease of the time required for the construction road and for the periodic maintenance interventions [1, 2].

Geosynthetics used in unpaved roads are essentially geotextiles and geogrids. In this paper, the attention is focused on the use of geogrids as reinforcement, which offer improved interface resistance due to interlocking as compared to geotextile. 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 and lateral pavement deformations (Fig. 1 a) [3]. The degree of interlocking depends on the relationship between the geogrid aperture size and the aggregate particle size (Fig. 1 b) [3, 4, 5, 6, 7, 8, 9, 10, 11 and 12]. On contrary, the effectiveness of interlocking depends on the in-plane stiffness of the geogrid and on the geogrid ribs and junctions stability [13]. Because of interlocking, the mechanisms of reinforced unpaved structure are different for geotextiles and geogrids. Two are the main reinforcement mechanisms: lateral confinement effect and tension membrane effect, which require different depth values of rutting in order to be mobilized. At small permanent deformation magnitudes, the lateral restraint mechanism is developed by the ability of the base aggregate of interlocking with the geogrid. As the permanent deformations (which are often acceptable in unpaved roads) increase the tension membrane mechanism [14, 15] develops. If the geosynthetic has a sufficiently high tensile modulus, tensile stresses will be mobilized in the reinforcement, and a vertical component of this tensile membrane resistance will help to support the applied wheel loads.

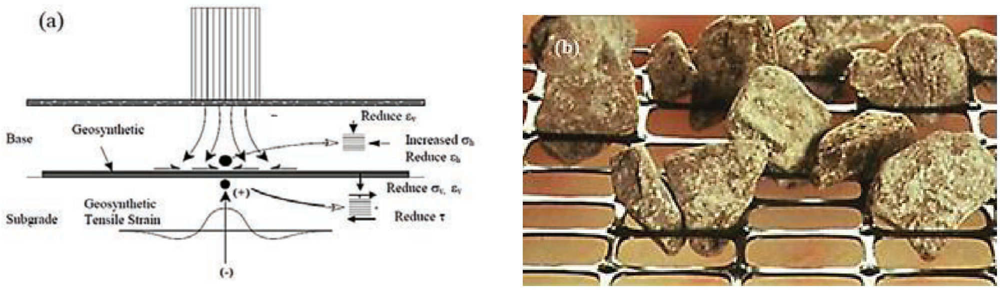

Fig. 1. (a) Mechanisms of reinforcement; (b) Example of good interlocking between aggregates and geogrid.

Over the years, various design methods aimed at estimating the aggregate base course (ABC) thickness required for reinforced unpaved roads have been evolved. The earliest design techniques for geosynthetic reinforced unpaved road, with a low volume of traffic, were proposed by Barenberg et al. [14] and by Giroud and Noiray [15] and both include the membrane effect assuming that significant rutting occurs. A comparison between the above mentioned procedures was carried out by Calvarano et al. [16]. Further headways were made by Giroud and Han [3, 17] and Leng and Gabr [18]. The last above cited design procedures take into account the effects of degradation of base course mechanical characteristics; the number and size of vehicular axle passes (number of load cycles, N_{cycles}); mechanical geogrid properties; how the load distribution angle, within the base course, decreases with time. In addition, Leng and Gabr [18] associate the degradation of unpaved road with how both the base course-subgrade elastic modulus ratio (E1/E2) and the load distribution angle degrade with the increasing of number of wheel load repetitions. Calvarano et al. [19], also, carried out a parametric analysis between the last procedures. In particular, the authors [16, 19] introduced a Base Course Reduction factor (BCR) to analyze the benefits offered by the geosynthetic reinforcement in reducing the amount of aggregate needed to build the lower thickness of reinforced ABC layer.

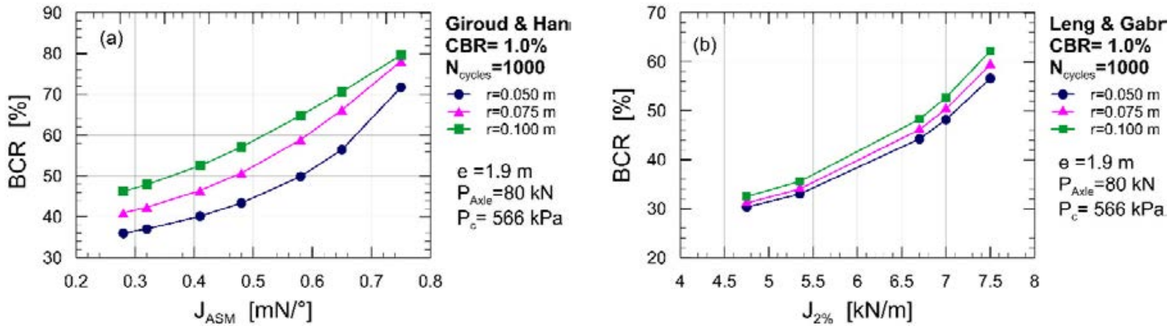

Fig. 2. Unpaved roads design procedures - Iso-rutting curves relating to Base Course Reduction factor (BCR) at N_{cycles} = 1000 and varying reinforcement stiffness (for mechanical parameters relating to geosynthetic mechanical properties see Calvarano et al. [19] : a) Giroud et Han [3, 17]; b) Leng and Gabr [18].

The BCR was defined, at equivalent traffic capacity, as a percent reduction in the reinforced base layer thickness compared to the unreinforced one, with the same material constituents, to reach the same defined failure state (in terms of rutting). The expression is the following (1):

$$BCR[\%] = \left[\frac{\left(h_{B,unreinf} - h_{B,reinf} \right)}{h_{B,reinf}} \right] \cdot 100 \qquad (1)$$

Fig. 2 a and Fig. 2 b show BCR obtained by Giroud et Han [3, 17] and Leng and Gabr [18] design procedures, respectively, varying the geogrid mechanical proprieties (in terms of aperture stability modulus [3,17, 19] and tensile stiffness [18, 19], respectively), at the same subgrade mechanical proprieties and traffic conditions, for three allowable rut depths. Therefore, the use of reinforcement geogrid, at the base-subgrade interface, leads to a reinforced base layer thickness reduction, proportionally to geogrids' mechanical properties, with a consequent saving of aggregate material needed for its construction and consequently a reduction in the road construction cost.

2. Finite Element Method: results analysis and discussion

The goals of herein analysis are to evaluate the performance of a reinforced aggregate base course (ABC) placed over a soft subgrade. The improvement is evaluated in terms of base aggregate thickness saving under repeated wheel loading. A Finite Element Method (FEM) analysis using the ABAQUS software is conducted taking into account reinforcement stiffness, interface properties, geometrical and mechanical properties of base and subgrade layers, and number of vehicle axle passes.

Two unpaved road sections were simulated. The former was unreinforced with an ABC thickness equal to 300 mm, the latter, which ABC thickness was equal to 150 mm, was reinforced with a geogrid placed at the base-subgrade interface.

A typical FEM mesh used in this analysis is shown in Fig.3 a. Shell elements were selected for the base course and the subgrade layers. The reinforcement element at base-subgrade interface was simulated by a truss element with a thickness equal to 0.003 m.

With respect to the bound conditions (Fig.3 b), the model was constrained at the bottom (U1 = U2 = U3 = UR1 = UR2 = UR3 = 0), while displacements in x direction and the rotations in y and z directions were prevented on two vertical faces (U1 = UR2 = UR3 = 0). To simulate a heavy vehicular traffic, a cyclic load of triangular type, with amplitude equal to 40 kN (resulted in a pavement pressure of 550 kPa), frequency equal to 0.5 Hertz and number of cyclic repetitions (N_{cycles}) equal to1000, was applied over a circular area with a radius equal to 0.152 m. This load amplitude represented one-half of an axle load from an equivalent single axle load (ESAL).

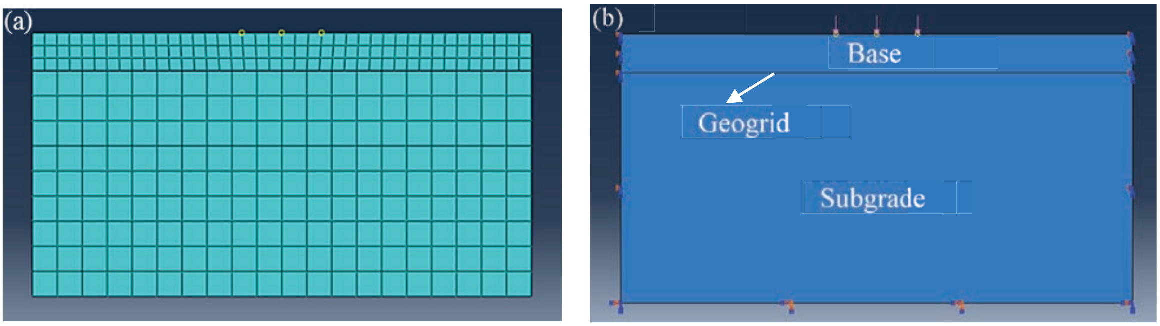

Fig. 3. a) Mesh view; b) Load and bound conditions.

In unpaved structures usually occur relatively large deformations under traffic load due to an elastoplastic behavior of base and subgrade layers. Therefore, an extended Drucker-Prager model was used in this research. The model is based on a hyperbolic yield criterion, available in the ABAQUS software, in which: β is the slope of the yield surface in the p–q stress plane; pt|0 is the initial hydrostatic tensile strength of the material and ψ is the soil dilatancy angle (Table 1). For the geogrid, instead, a linear elastic constitutive model was used. The materials parameters required for the simulations in the FEM analysis, listed in Table 1, are assumed to be realistic, as much as possible, as published in previous studies [20]. Two interfaces were simulated in the geogrid-reinforced section: one was between ABC and geogrid, and the second was between geogrid and subgrade. Only one interface, between ABC and subgrade, was used in the unreinforced section. In all the studied cases, the contact surfaces were connected by a "tie constraint" connection type, which is able to ensure a perfect adherence to each interface.

Table 1 - Materials data and model parameters used in the FEM analysis.

Materials	Model and Parameters	Yield stress [kPa]	Thickness [m]	E [MPa]	υ [-]
ABC	Drucker-Prager	150	0.150	50	0.35
	β=40°, pt|0= 20 kPa, ψ=10°		0.300		
Geogrid	Linear-elastic	3000	0.003	400	0.30
Subgrade	Drucker-Prager	43.6	0.900	10	0.42
	β=10°, pt|0= 10 kPa, ψ=0°				

Fig. 4 and Fig. 5 show the deformed configuration and the vertical displacements relating, respectively, the unreinforced unpaved road section with a base layer thickness equal to 300 mm and the reinforced one with a base layer thickness equal to 150 mm.

The results of FEM analysis confirm, in agreement with the theoretical design procedures (Fig. 2 a and Fig. 2 b), that the reinforced road section with a stiff geosynthetic (i.e., geogrid) placed at the base-subgrade interface works better respect the unreinforced case under the same traffic conditions (i.e. N_{cycles}=1000) and mechanical proprieties of the base and subgrade soil layers. In fact, despite the thickness of the unreinforced road section (0.300 m) is double respect the reinforced one (0.150 m), the former shows a rutting (6.152 mm), under the center line of the wheel load, comparable with the one obtained for the geogrid reinforced unpaved section (5.772 mm). This result is particularly interesting because lower reinforced ABC layer thickness are obtained (e.g., one-half in this case) with a consequent saving of aggregate material required (e.g., of 50% in this case) and, therefore, less in-place construction cost. In addition, further advantages are a decrease of time required for the road construction, less CO^2 atmosphere emissions and then less environmental impact, relative to conventional practice. All these aspects should be monetized too.

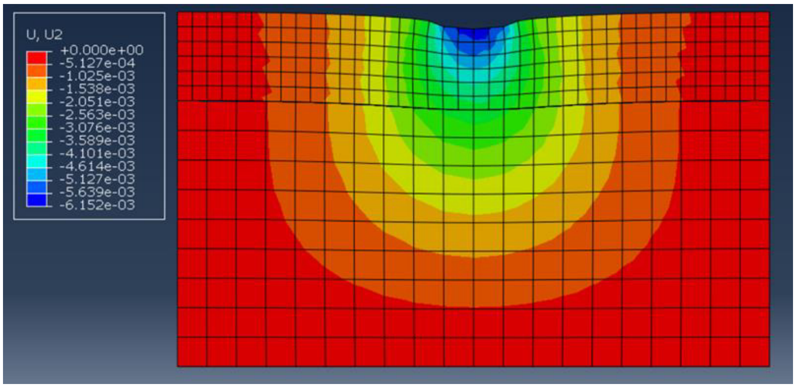

Fig. 4. Deformed configuration and vertical displacements relating the unreinforced unpaved road section with a base layer thickness equal to 300 mm.

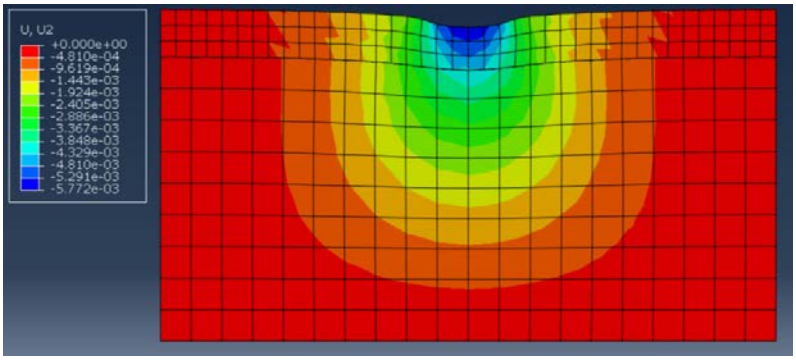

Fig. 5. Deformed configuration and vertical displacements relating a reinforced unpaved road section with a base layer thickness equal to 150 mm.

From a more careful analysis, the comparison between the two simulations shows that the improvement offered by the reinforcement decreases the extension of the radius (from da 0.75 m to 0.65 m), measured from the midline of the loading area, over which the vertical displacements reach values equal to zero. This result is due because when the base layer is loaded by a vehicle traffic, the base aggregate tends to move (sliding) or to spread laterally. However, if the geogrid reinforcement is placed at base-subgrade interface, it restrains the aggregate by means of the friction on the solid fraction of geogrid surface area, and particularly by means the interlocking of particles within its apertures. As a result, this mechanism, minimizing the lateral movement of aggregate, improves the elastic modulus of the reinforced base layer and consequently increases the stress distribution angle of the reinforced base. The results are a less magnitude and a less extension of the superficial vertical deformations.

3. Summary

Based on the FEM analysis carried out by the ABAQUS software, on a reinforced and an unreinforced unpaved road sections respectively, the following conclusions could be drawn.

The unpaved road reinforced with geosynthetic (e.g., geogrid) placed at the base-subgrade interface, at the same traffic conditions and mechanical proprieties of the base and subgrade soil layers, works better when compared to the unreinforced one. In particular, to obtain the same performance, in terms of comparable rut depth, the reinforced ABC required half of thickness. This result is particularly interesting because a saving of ABC thickness leads to a saving of aggregate material required and, therefore, less in-place construction costs. In addition, further advantages are a decrease of the time required for the road construction, less CO^2 atmosphere emissions and then less environmental impact, relative to conventional practice. All these aspects should be monetized too.

In addition, a further improvement offered by the reinforcement is a decrease of the extension or width of rutting. This result is due to geogrids' lateral confinement, offered mainly by geogrid interlocking, that increases the elastic modulus of the reinforced ABC layer and consequently reduces the magnitude and the extension of the superficial vertical deformations.

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