EVALUATION OF SUBGRADE IMPROVEMENT BY GEOGRID REINFORCEMENT

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Abstract: Current methods used in roadway construction projects to address soft subgrade conditions include excavation-substitution, soil improvement with chemical additives, and mechanical reinforcement using geosynthetics. When the later method is applied, a top layer of subgrade is excavated and backfilled with geosynthetic-reinforced aggregates. The objective is to obtain an adequate platform for the planned roadway construction. In this paper a quantitative assessment of subgrade improvement by geogrid reinforcement is presented, on the basis of numerical modelling and parametric studies. In order to make the results applicable in a simple and practical way, the effect of geogrid reinforcement is quantified in term of enhanced CBR (California Bearing Ratio) of the improved subgrade. The numerical model was a simplified simulation of quasi-static loading and unloading cycle of a reinforced two-layer system. Both the soft subgrade and the aggregate were modelled as elastoplastic materials while the geogrid was represented as linear elastic with perfectly interlocking interfaces. Computations were performed using the finite element software, ABAQUS. Parameters that were varied included material and geometric parameters. In the paper, the methodology is described and the results of the parametric studies are presented using permanent deformation as a basis for discussion. The notion of enhanced subgrade CBR is introduced and its potential for practical application is discussed.

Keywords: subgrade, soft soil, geogrid reinforcement, finite element.

INTRODUCTION

In the Midwest region of the United States, the problem of soft subgrade is often mentioned by highway engineers as one of the main causes of construction and maintenance difficulty. Aggregate placed on such poor foundation is prematurely subject to excessive permanent deformation or rutting during construction, and hence design expectation cannot be met for the roadway.

Methods employed in this region for addressing soft subgrade conditions have included excavation-substitution, stabilization with chemical additives and, more recently, mechanical reinforcement using geogrids. A common practice is to combine the excavation-substitution and geosynthetic reinforcement techniques: in this case only a top layer of subgrade is excavated and then substituted with geogrid-reinforced aggregate. The tensile-resistant properties of the geogrid provide mechanical support and stiffness to the aggregate layer. It is expected, as a result, that the modified subgrade response will be improved in terms of bearing capacity and permanent deformation. Designing this type of subgrade improvement for surface applied load at construction stage is a problem similar to that of reinforced unpaved road design but, for practical reason, it is desirable to develop a procedure in which the mechanical improvement would be quantified using a parameter common to reinforced as well as unreinforced subgrades. Such was the purpose of the study reported herein.

Considerable literature has been published on the analysis and design of geosynthetic-reinforced unpaved roads. These models have been based, for instance, on plastic equilibrium (Milligan et. al. 1989), or on subgrade bearing capacity theories (Giroud and Noiray, 1981; Giroud and Han, 2004). In the present study elastoplasticity is assumed for the materials and the boundary value problem is analyzed using the finite element method. Parametric studies are performed using the numerical model and lead to a design approach in which the geogrid reinforcement effect is summarized as an enhancement of the subgrade capacity. The improvement is quantified as an equivalent increase in the subgrade California Bearing Ratio (CBR), compatible with current design methods where no reinforcement is used.

NUMERICAL MODELLING

Geometry

A model was formulated using the finite element software, ABAQUS, to numerically simulate a two-layer system (i.e. subgrade overlaid with substitution aggregate) including optional reinforcement at the interface. Simplified axisymmetric geometric and surface loading patterns were adopted. A general layout is shown in Figure 1.

Material constitutive models

Linear-elasticity was postulated for the geogrid reinforcement as, in the present context, the deformation required for mobilizing its strength is relatively small. Since axisymmetric solid elements were used for simulating the geogrid as well as other materials, equivalent homogenised values had to be determined based on actual biaxial grid characteristics.

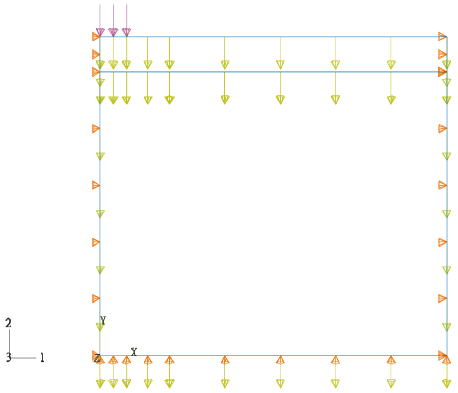


Figure 1. Numerical model layout for two-layer reinforced system (arrows at the surface represent applied loading, arrows at boundaries represent degrees of freedom, left-side boundary is symmetry axis).

Both aggregate material and subgrade soil were modelled as elasto-plastic. For the aggregate layer considered as a purely frictional material the Drucker-Prager yield criterion was applied. Poisson's ratio was assumed to be 0.35. The (resilient) elastic modulus M_R is related to the average bulk stress θ (AASHTO, 1993),

$$M_R = k_1 \, \theta^{k2}$$

where according to Perkins and Edens (2002), $k_1 = 9109$, $k_2 = 0.63$, with M_R and θ in kPa.

The subgrade was assumed, in this study, to be made of soft saturated fine-grained soil. Under the type of load of interest for roadway infrastructure modelling it can be assumed to remain undrained. This was modelled in terms of total stress as an elastic-perfectly plastic behaviour where deformation occurs at constant volume (i.e. Poisson's ratio close to 0.5) and yielding is controlled by undrained shear strength, c_u ,with $\varphi_u=0$. In roadway design the CBR is often used for characterizing the subgrade strength through correlation with c_u. Such practice was followed in the present study by using an empirical relationship between undrained shear strength and CBR coefficient (Giroud and Noiray, 1981),

$$c_u = 30 \; CBR$$

where c_u is in kPa. For the subgrade Young's modulus the empirical relationship proposed by Huekelom and Klomp (1962) was used,

$$E = 10350 \; CBR$$

where E is in kPa.

Interface conditions

Interaction between geogrid and soil is a complex mechanism. In a continuum mechanics model, drastic simplification is unavoidable. Accordingly full interlocking of soil particles in grid apertures was assumed herein. In the finite element formulation this translates in full adhesion and shear continuity at interfaces between reinforcement, aggregate and subgrade. It is recognized the assigned interface condition represents the upper bound in the range of physical possibility but it is considered a reasonable approximation.

Loading

Surface loading was applied in the model through a circular area. In all simulations performed the loaded area was 0.15m in radius and the maximal average pressure is 550kPa. These features are intended to represent, in a simplified way, the load induced by the tire of a 40kN single axle. A quasi-static loading and unloading cycle was simulated by applying pressure increments. This allowed observation of maximal stresses and deformation under peak load as well as permanent deformation after unloading.

Numerical model validation

The validity of the numerical model was tested by comparing its response to the results of an earlier study reported by Perkins (1999,) and Perkins and Edens (2002, 2003). Geometric and material data were input to fitting the published conditions: a 300mm thick aggregate layer above 1125mm of subgrade. Aggregate modulus, Poisson's ratio and angle of internal friction were 100.9 MPa, 0.35 and 30 degrees, respectively. Subgrade CBR was estimated to be 1.5. The geogrid homogenised elastic modulus was 400MPa.

Only a sample of the results is presented herein. The variations of radial strain at the base of the aggregate layer and tensile deformation in the reinforcement in function of distance from the symmetry axis are shown in Figure 2 (a) and 2(b), respectively. The developed model response is in good agreement with results obtained by Perkins (1999) and Perkins and Edens (2002), in terms of both radial distributions and values.

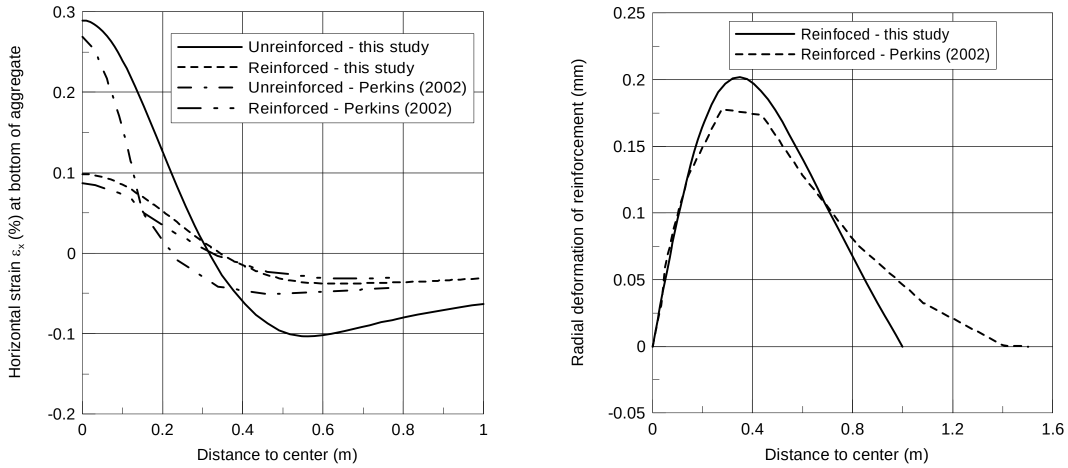


Figure 2. Numerical model validation: (a) Horizontal strain at base of aggregate layer. (b) Radial deformation of reinforcement

PARAMETRIC STUDY

The numerical model was employed to perform a series of simulations in order to investigate its sensitivity to parameter variations. For this parametric study, the model size was larger than in the validation study: the maximal depth from the surface was 1.575m and the radius was increased to 1.5m.

Parameters

Subgrade CBR: This is likely the most critical parameter since it controls both the subgrade modulus and undrained shear strength. Characterization of CBR stiffness based on CBR range is shown in Table 1. Based on such description and the range of interest in the present study, the CBR was varied in the computations between 0.75 and 3.

Table 1. Characterization of subgrade stiffness based on CBR range (McCarthy, 1982)

Description	Very soft	Soft	Medium	Stiff	Very stiff	Hard
Subgrade CBR	<0.4	0.4-0.8	0.8-1.6	1.6-3.2	3.2-6.4	>6.4

Aggregate thickness: Computations were performed with aggregate thickness, 100mm, 150mm, 300mm and 450mm.

Reinforcement tensile modulus: Two different moduli were used for the reinforcement, 205 MPa and 300 MPa. In both cases the reinforcement was modelled as isotropic (in order to simulate biaxial geogrids) and placed at the interface of the two layers.

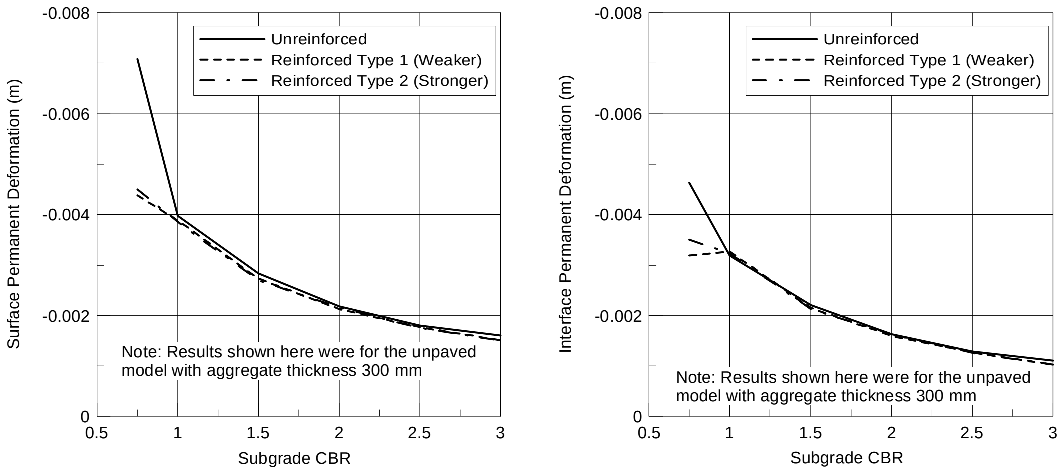
Constant parameters were:

- Aggregate material friction angle, 35 degrees, cohesion, 0 kPa, elastic modulus, 100930 kPa, Poisson's ratio, 0.35, unit weight, 19kN/m^3.
- Subgrade apparent angle of internal friction angle, 0 degree, unit weight, 19kN/m^3.

Summary of results

Influence of subgrade CBR on permanent deformation

The criterion used herein for discussing the model response is the maximal permanent (i.e. plastic) vertical deflection after the surface applied pressure. It has been incrementally increased up to 550kPa and then decreased until complete unloading is achieved. Results obtained with an aggregate layer of 300mm (effect of aggregate thickness is discussed in the next section) are shown in Figures 3(a), 3(b), for surface and interface deformations, respectively. Permanent deflections at the surface of the aggregate as well as permanent deflections at the interface between layers are quite sensitive to the subgrade soil CBR, especially in the range of medium to soft soils. The general trend is an increase of plastic deformation as the subgrade becomes softer (i.e. decreasing CBR) especially in absence of reinforcement. Since Figure 3(a) shows permanent deflections due to plastic deformation of both layers and Figure 3(b) shows deflections due to plastic deformation of the lower subgrade layer only, comparison between these two sets indicates deformation is mainly due to yielding of the subgrade. Another observation is the role of the reinforcement in reducing permanent deformation. With the aggregate thickness used in this case, this is evidenced only when the subgrade CBR is lesser than approximately 1. It is also only in this lower range that a higher-modulus reinforcement seems to have an effect by reducing further the deformation.

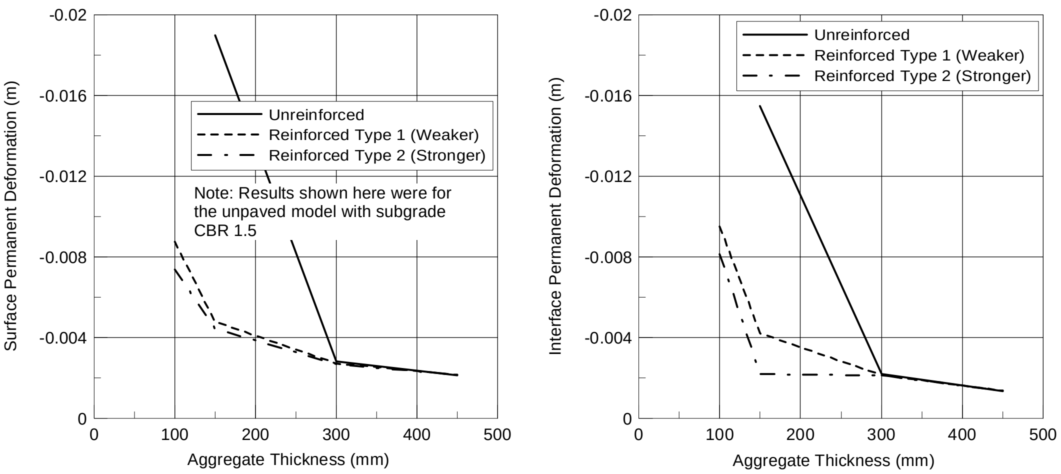


(a) (b)

Figure 3. Permanent deformation at surface (a) and at interface (b) in function of subgrade CBR

Influence of aggregate thickness on permanent deformation

The thickness of aggregate substituted to the soft subgrade is the other controlling factor in the model response. Permanent vertical deformations of the aggregate surface and at the interface of the two layers, with subgrade CBR of 1.5, are plotted in function of aggregate thickness in Figures 4(a) and 4(b), respectively. As expected, when the thickness of the aggregate layer is increased, the amount of permanent deformation decreases dramatically. This trend confirms previous knowledge on the effect of aggregate substitution in subgrade improvement. The mechanism is well known as a load diffusion through the aggregate layer and a resulting attenuation of interface stresses. For the subgrade CBR of 1.5 used in the case shown here, the benefit from increasing the aggregate thickness is less sensitive for large thicknesses (e.g. 300mm and thicker) than for thinner layers. It is also in combination with relatively thin aggregate layers that the reinforcement has a significant effect. As shown in Figures 4(a), 4(b), permanent deformations are not affected by the presence of reinforcement when the aggregate layer is thicker than about 300mm while significant reduction is observed in presence of thinner layers. It can also be seen that the reinforcement tensile modulus, within the range of values used in the present analysis, has only a minor effect on the permanent deformation patterns.



(a) (b)

Figure 4. Permanent deformation at surface (a) and at interface (b) in function of aggregate thickness

ENHANCED SUBGRADE CBR

Notion of equivalent subgrade

In Figures 5(a), 5(b) and 5(c), three subgrade configurations, all with the same total thickness, are shown. In case (a) the upper layer of subgrade was excavated and substituted with aggregate. In case (b) the same aggregate substitution was made but in addition a geosynthetic reinforcement was placed at the interface. Case (c) is only made of subgrade soil with no aggregate or reinforcement. Let us assume all three profiles, when subjected to the same loading sequence, produce the same permanent deformation at the surface. If the subgrade CBR is the controlling parameter, this can occur only if the CBR in case (c) is higher than in cases (a) and (b). This also means, assuming the reinforcement is effective, the CBR in case (b) is higher than in (a). In other terms, aggregate substitution and geosynthetic reinforcement in cases (a) and (b) have an effect on permanent surface deflection, equivalent to enhancing the subgrade CBR. The practical advantage of such an interpretation is that, when the CBR enhancement equivalent to the effects of aggregate and reinforcement has been quantified, then it can be introduced in existing design methods that were originally formulated for homogeneous subgrade conditions with no reinforcement.

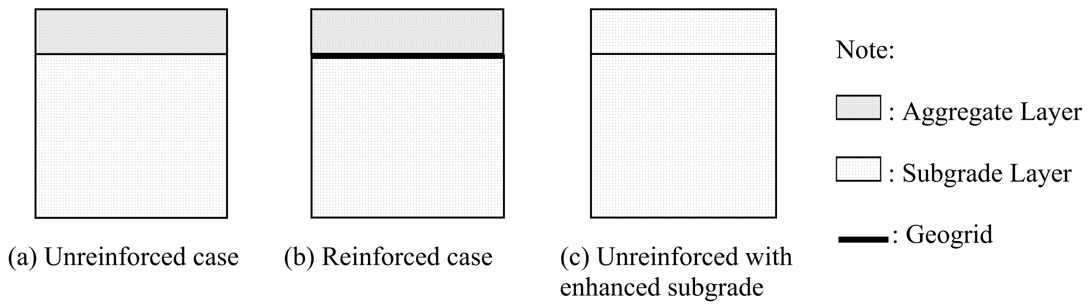


Figure 5. Model layout for analysis of equivalent subgrade CBR

Synthesis of results in terms of enhanced subgrade CBR

The database constituted by the parametric study results was utilised for quantifying the improvement using the notion of enhanced subgrade CBR. The analysis is shown in Figure 6 for a 100mm aggregated thickness. When, for instance, the actual subgrade CBR is 1.5, the permanent deflection is 0.7mm with aggregate substitution and geogrid reinforcement. If no reinforcement was placed and only aggregate substitution was used, the subgrade CBR would have to be 2.4 in order for the permanent surface deflection to be the same, and if no aggregate or reinforcement was used the CBR would have to be as high as 3.2. For this particular set of data, one concludes the subgrade CBR is enhanced from its original value of 1.5 to 3.2 by the combined effects of aggregate and geosynthetic reinforcement, whereas the geogrid contributes 0.9 to the total CBR improvement. The relative contributions of the aggregate and the reinforcement to the total CBR enhancement can be obtained by subtraction.

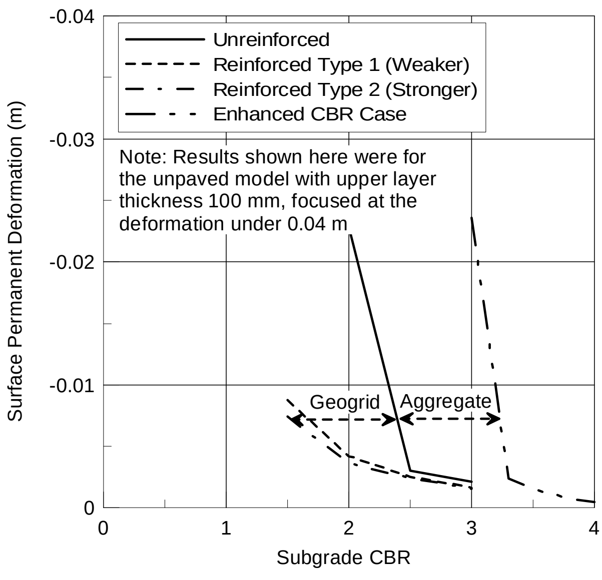


Figure 6. Enhanced subgrade CBR analysis for upper layer thickness 100mm

Similar presentation of the results is shown in Figures 7(a) through 7(d) for the different thicknesses of aggregate considered in the parametric study. Data are also summarized in Table 2 for subgrade CBR values of 1.5 with aggregate thicknesses, 100mm and 150mm, and for subgrade CBR of 0.75 with aggregate thicknesses, 300mm and 450mm. In the lower sections of the table the relative contributions of the geogrid and the aggregate (in % of the total CBR enhancement) are provided. When thin layers of aggregate are used the geogrid contribution to the overall improvement is significant but, as the thickness of aggregate is increased it becomes the sole source of improvement. These results can also be seen as indication of the amount of aggregate that the addition of a geogrid reinforcement would allow to spare for an equivalent CBR enhancement.

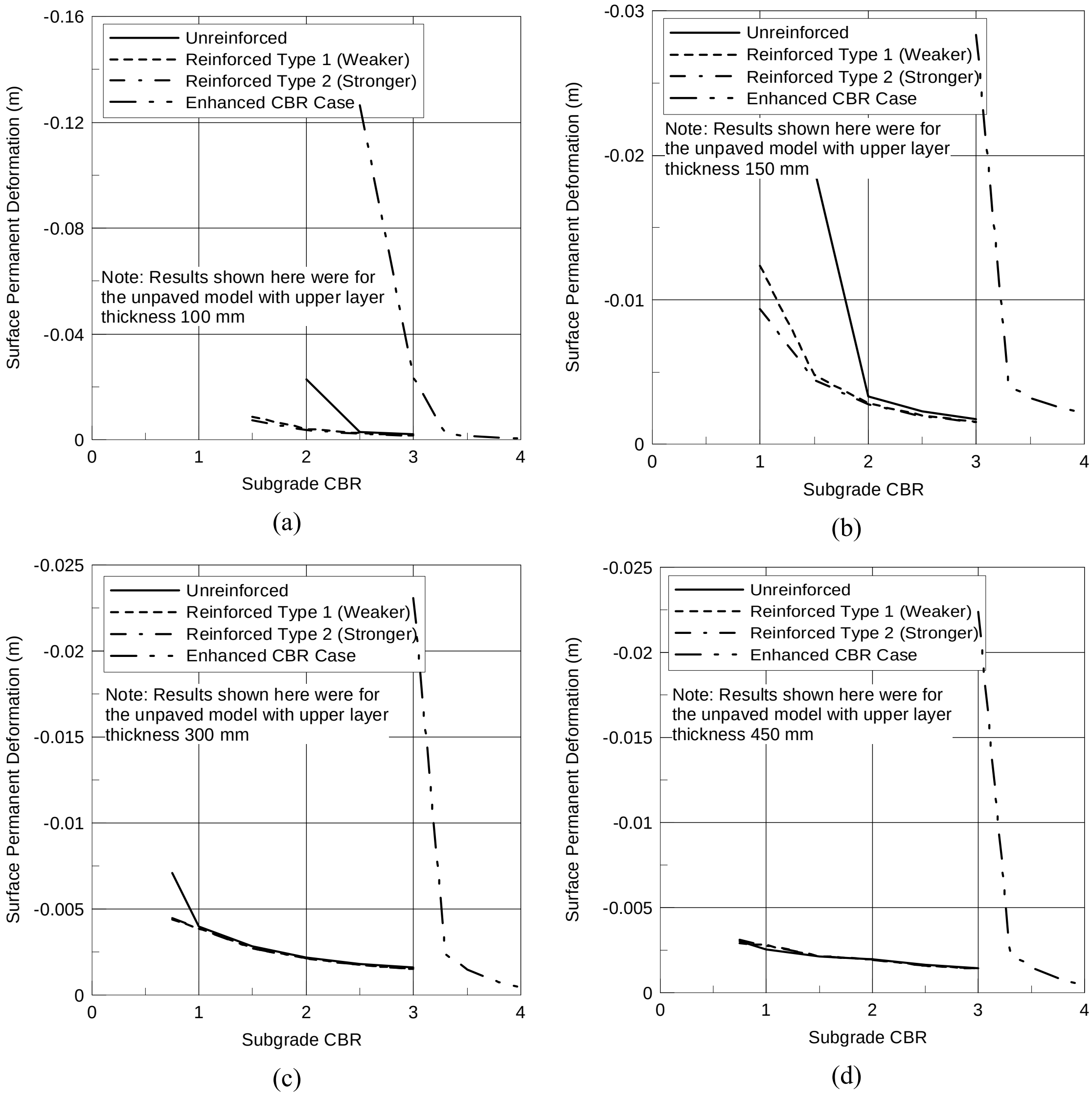


Figure 7. Enhanced subgrade CBR analysis for different upper layer thicknesses

Table 2. Equivalent subgrade CBR for different reinforcing scenarios

Enhanced subgrade CBR analysis		Aggregate thickness (mm)			
		100	150	300	450
Actual subgrade CBR		1.5	1.5	0.75	0.75
Equivalent CBR	With aggregate and no reinforcement	2.4	1.9	0.9	0.75
	With aggregate and reinforcement	3.3	3.25	3.3	3.3
Improvement from geogrid + aggregate material		1.8	1.75	2.55	2.55
Improvement from geogrid		0.9	0.4	0.15	0.00
CBR improvement contribution (%)	Geogrid	50	23	6	0
	Aggregate	50	77	94	100

Figure 8 is an example of design chart in which the original (actual) CBR of the subgrade is scaled in abscissa while the enhanced value, in presence of aggregate and reinforcement, is in ordinate. The diagonal line is provided as reference. The curves in the left side sector allow determining the enhanced CBR in function of the original value for the two cases of aggregate thicknesses, 100mm and 150mm where there is significant contribution from the geogrid.

CONCLUSIONS

Finite element analyses of two-layer systems reinforced at the interface and subjected to surface applied loading were performed, in order to simulate the behaviour of a soft subgrade when its upper layer has been excavated and substituted with geogrid-reinforced aggregate. The numerical procedure was validated by comparison to an established earlier model.

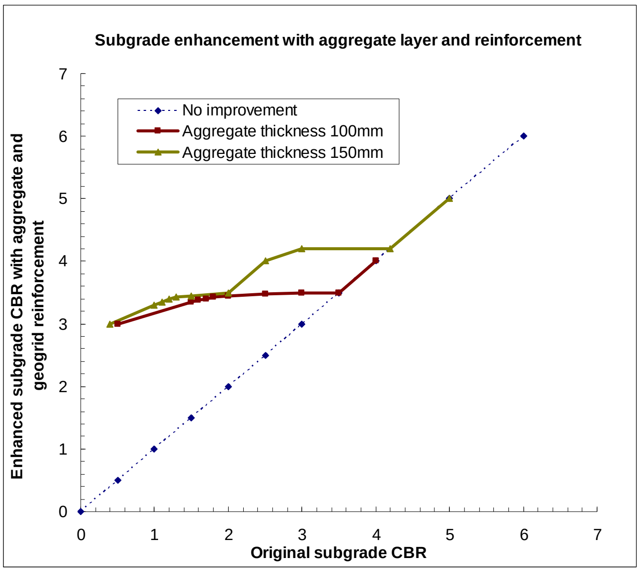


Figure 8. Equivalent subgrade CBR with aggregate and geogrid reinforcement

Sensitivity of the model response to the most critical parameters was investigated through a series of computations. It was found that permanent deflections are significantly greater when both the subgrade CBR and the aggregate thickness are decreased. The effect of geosynthetic reinforcement in reducing the permanent deformation is also depending on the subgrade CBR and the aggregate thickness. There seem to be an optimal range for these parameters for the reinforcement to be effective. When the subgrade CBR is relatively high or the aggregate layer thick, further improvement from geosynthetic reinforcement is marginal or non-existent.

A synthesis of the results was presented in which the benefit obtained by placing the geogrid and aggregates in order to improve a soft subgrade is quantified as an equivalent enhancement of the subgrade CBR. This has the practical advantage of providing a design parameter independent of reinforced soil design methods. The proposed approach allows also assessing the relative contributions of the aggregate substitution and the geogrid reinforcement to the overall improvement of the subgrade. It can be observed that when soft subgrade is present, the inclusion of geosynthetic reinforcement would allow reducing the aggregate thickness for an equivalent result.

Limitations of the study are related, in particular, to the constitutive models used in the model. These are simple elastoplastic formulations that could be improved, however at the cost of requiring a larger set of parameters. The criterion chosen to evaluate the system response in presence or absence of reinforcement is based on permanent vertical deformation after unloading. Rutting is certainly a critical aspect of roadway subgrade performance but other criteria could be chosen as well and this could affect the conclusions. Another limitation is that only one cycle of loading and unloading was simulated for each case. More general conclusions would be drawn if multiple cycles could be simulated.

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