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Road and Rail Infrastructure III

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DESIGN OF RAILWAY TRACKBEDS WITH GEOCELLS

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Abstract

Geosynthetics in the form of geotextiles and geogrids made of polymeric materials are being used to improve the bearing capacity of railway trackbeds. These materials provide a confinement effect through friction. In the same manner, geocells refer to a synthetic, honeycomb-like cellular material, the structure of which is interconnected by joints to form a cellular network used for the confinement of soils. A literature survey reveals that the introduction of a 200-mm-high geocell into the upper subgrade layer increases the resilient modulus of this reinforced layer by an average multiplier factor, termed MIF (Modulus Improvement Factor), of 2.5. The MIF is supported both by in-situ FWD and by pressure-cell testing. Empirical calculations, furthermore, indicate that MIF is a function of the properties of the geocell. Thus, this reinforced layer can be regarded as part of a railway trackbed structure. Given these findings, the paper suggests the use of an equivalency procedure in order to calculate the effective thickness of a 200-mm reinforced subgrade layer in terms of the thickness of type A (CBR=60%) sub-base material in railway trackbed structures. For example, when a given subgrade with a CBR value of 10% is reinforced by the 200-mm height of a high-standard geocell, this reinforced subgrade can substitute for a 150-mm type A sub-base layer. Finally, it should be pointed out that (a) the proposed equivalency procedure is valid for a subgrade CBR of up to 12%, and (b) the use of geocell reinforcement should be accompanied by a strictly detailed QA plan for in-situ density and modulus (plate-load testing) of the reinforced layer.

Keywords: CBR, confinement, equivalency factor, geocell, Modulus Improvement Factor (MIF), Railway-trackbed, resilient modulus

1 Introduction

With increased use and development of transportation facilities in Israel, railway trackbeds need to be stable, with no excessive deformation under load, in addition to satisfying the tolerable criteria in terms of load repetitions for fatigue and rutting mechanisms. Often, when carriage loads are increased, there is the possibility of plastic deformation owing to the absence of confinement in the lateral direction when vertical loads are applied. Thus, the effects of confinement on the performance of the railway trackbeds are significant. In the absence of proper confinement, failures in these beds are likely to occur.

Geosynthetics in the form of geotextiles and geogrids made of polymeric materials are being used to improve the bearing capacity of railway trackbeds. These materials provide a confinement effect through friction. In the same manner, geocells, which are a three-dimensional form of geosynthetic materials with interconnected cells filled with soil, have many important advantages when used in railway trackbeds (see Fig. 1). In more detail, a geocell refers to a synthetic, honeycomb-like cellular material; a structure of these cells interconnected by joints to form a cellular network is used for the confinement of soils.

Figure 1 Typical geocell mattress, after [1]

In Israel, the present design guidelines for railway trackbeds given by Livneh et al. in [2] do not include the use of geocells. Thus, it seems necessary to include this use in the design guidelines. In light of all the above, the objectives of this paper are as follows:
- conducting a literature review of the increase of the resilient modulus as a result of introducing geocell enforcement into a given layer;
- examining the values of the Modulus Improvement Factor (MIF) through empirical equations to display the influence of the geocell properties on these values;
- developing equivalency factors for the geocell-reinforced layer as a function of (a) the MIF value and (b) the CBR value of the given layer prior to reinforcement.

The sections to follow will detail the process of attaining this paper's three objectives and present associated conclusions.

2 Literature review of resilient modulus increase

Al-Qadi and Hughes [3] conducted field studies to evaluate the use of geocells in flexible pavements. The researchers selected the reconstruction of a road that showed excessive rutting. The use of geocells was chosen as the solution on an experimental basis, and the results pointed to the fact that the pavement laid on the confined base showed no signs of rutting. Unfortunately, it was difficult in all these cases to isolate the effect of the geocell-confinement system as has been used in combination with geogrid, geotextile, or both. However, it can be concluded that in sections where 100-mm-thick geocells were used, the resilient modulus of the aggregate layer increased almost twofold owing to the material's confinement—i.e., MIF=2.0. As a result of the aggregate confinement provided by the geocell and the subgrade separation from the sub-base provided by the geotextile, it appears that a geotextile-geocell combination may provide a significant improvement to overall stability when used on top of a weak subgrade of a heavily trafficked pavement.

Emersleben and Meyer [4] conducted large-scale model tests and field tests, and these showed similar results to [1], which verified the fact that geocells reduce surface deflections and vertical pressure on the subgrade. The tests also studied the effect of aspect ratio, and these results demonstrated that performance improved as the height-to-diameter ratio was increased. At the end of the study period, it was found that the use of geocells not only reduced the material required, but also improved the speed of construction. Along with these field tests, Emersleben and Meyer conducted large scale model tests in test boxes measuring 2m x 2m x 2m. Those tests showed that surface deflection was less in a geocell-confined section. The results were verified by falling weight deflectometer (FWD) measurements carried out in field studies. More specifically, compared to an unreinforced test section, the stresses beneath the geocell layer were reduced by about 30 percent. In addition, the FWD results showed that back-calculated layer modules in the first test section were 290 MPa for 400 mm gravel and

320 MPa for 200 mm gravel plus 200 mm geocell. In the second test section, the back-calculated values were 350 MPa and 450 MPa, respectively. With the aid of these values, it can be shown that the resilient modulus of the gravel layer increased for the first test section by only MIF=1.2, and for the second test section by MIF=1.6, both because of the gravel confinement. Rajagopal and Kief [5] argued that results of studies demonstrated that the unique interaction of soil, cell, and shape in cellular confinement systems acted to stiffen pavement foundations as a result of the soil-confinement mechanism. Their paper describes a case study, together with the in-situ testing details, and the analysis and explanation of the structural contribution of a three-dimensional cellular confinement system on soft soil. The authors came to the conclusion that the resilient modulus of the gravel layer increased by MIF=5.0, from 100 MPa to 500 MPa, because of the gravel-confinement effect as expressed in the readings of the installed pressure cells. This conclusion is derived for a case in which the loading has been induced directly on the surface of the granular reinforced layer, and not for the case of real structures (i.e., on top of additional structural layers covering the reinforcement layer). Again, note should be made that the conclusion was not derived from FWD measurements, but from cell readings. For this type of loading, the installed pressure cells showed, that compared to an unreinforced section, the stresses beneath the geocell layer were reduced by about 51 percent.

Hegde and Sitharam [6] indicated the beneficial effect of geocell reinforcement in soft clay beds through 1-g model plate load tests and numerical simulations using FLAC2D. Results showed that the provision of geocells leads to a fivefold increase in the load- carrying capacity of a very soft clay bed. This impressive finding, however, is limited to cases in which only plasticity failure takes place. Thus, for cases in which the theory of elasticity holds (such as the design of a railway trackbed), this finding is not applicable. The paper also revealed that the overall performance of the very soft clay bed improves further because of the provision of planar geogrid at the base of the geocell. Numerical results were also in line with the experimental findings.

In contrast to the aforementioned plasticity case, Zang et al. [7] showed for the elasticity case that by confining the upper 200 mm of the soil surface with geocell, it can be assumed, based upon laboratory and field-test results, that the reduction in maximum vertical stress is about 35%. This finding led Kief [8] to obtain an increase in the resilient modulus by MIF=4.7, together with an unexplained transition zone beneath the reinforced layer that possessed a 1.5-time increase in resilient modulus. Here, it must be noted that Reference [8] also objects to the running of FWD measurements for exploring the rate of increase in the resilient modulus resulting from the geocell confinement effect. This objection, however, is not compatible with the use of FWD measurements in [3] and [4].

Kief [8] showed that the resilient modulus of the gravel layer increased by MIF=2.4, from 420 MPa to 1,010 MPa, because of the gravel-confinement effect. As in [5], this conclusion is derived from pressure-cell readings (and not from FWD measurements) for the in which the loading has been induced directly on the surface of the granular reinforced layer, and not for the case of real structures; i.e., on top of additional structural layers covering the reinforcement layer.

To sum up, the range of the multiplier increase in the resilient modulus of a given layer because of geocell reinforcement varies between MIF=1.2 and MIF=5.0 according to the aforementioned findings. Kief [14] makes almost the same statement that MIF varies between 1.5 and 5.0. The upper values of this range, however, are rather questionable, as no FWD measurements have been conducted to prove the existence of these upper values. Here it is important to note that according to Han [15], FWD measurements utilize too small deformations to mobilize geosynthetic to be effective. Thus, this method is incapable of detecting the benefit of geosynthetic reinforcement. If this last statement is true, one may question Han's [15] contention that this method is capable of detecting the above-mentioned benefit for trafficked pavements if a control section is available. FWD measurements, then, cannot be ruled out for pavements containing geosynthetic reinforced layers.

3 Geocell reinforcement equations

Rajagopal et al. [9] proposed the following equation for the layer modulus of geocell-confined granular material in terms of the secant modulus of the geocell material (M) and the modulus number of the unreinforced sand (Ku):

$$E_G = 4 \times (\sigma_3)^{0.7} \times \left(Ku + 200 \times M^{0.16}\right) \tag{1}$$

where:

E_G layer modulus of geocell-confined granular material, in kPa;
Ku modulus number for unreinforced granular material as defined by Duncan and Chang in [10];
M secant modulus of geocell material, in kN/m;
σ_3 confining pressure, in kPa.

This equation is based on the older model of the dependency of granular modulus on confining pressure. However, newer equations for the granular modulus exist in the technical literature [16]. Also, the additional confining pressure owing to the membrane stresses can be calculated using the following equation given by Henkel and Gilbert in [11]:

$$\Delta\sigma_3 = 2 \times M / D_o \times \left[1 - (1 - \varepsilon_a)^{0.5}\right] / (1 - \varepsilon_a) \tag{2}$$

where:

$\Delta\sigma_3$ increase in the lateral pressure base on the membrane correction theory, in kPa;
D_o initial diameter of the geocell, in meter;
ε_a axial strain of the geocell.

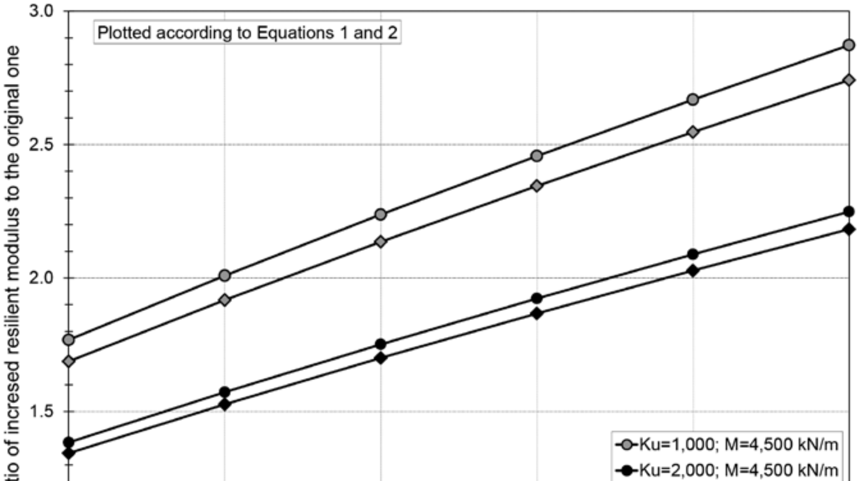

Figure 2 Geocell confinement effect on the resilient modulus as calculated from Eq. (1) and Eq. (2)

In the calculated example of [1], Ku is equal to 1,000 and M=4,500 kN/m. For these values, Fig. 2 shows that the ratio of the increased resilient modulus of the reinforced layer to its original resilient modulus prior to reinforcement varies as a function of the ratio of the increased lateral pressure to its original pressure from MIF=1.8 up to MIF=2.9 (MIF - Modulus Improvement Factor). For the reinforcement of a stiffer granular layer possessing Ku=2,000 with the same geocell possessing M=4,500 kN/m, the above range is lower, starting at MIF=1.4 and then increasing up to MIF=2.2. For the example in [1], the calculated value of the increased resilient modulus of the reinforced layer was 760 MPa. This value seems to be rather high.
As a result of this high value, Fig. 2 includes the two MIF curves calculated for a lower value of M—i.e., 2,250 kN/m. These two curves indicate that their associated MIF are lower than those associated with M=4,500 kN/m.
In addition, Fig. 2 indicates that the resilient modulus of the reinforced granular layer increases with the increase in the value of M—i.e., the secant modulus of the geocell material. Values of M, which are given in [12], vary from 100 kN/m up to 1,000 kN/m. Thus, the use of geocells possessing these low values of M leads to lesser MIF values shown in the figure. To sum up, it seems that for design purposes, the suggested MIF value can be taken as 2.5. This value is supported by both the literature review presented earlier and the geocell reinforcement equations given in the present section.

4 Geocell reinforcement equivalency

The Israeli guidlines for the structural design of railway sub-ballast trackbeds [2] utilizes the equivalency method. In this method, 100 mm of sub-base type A (CBR =60%) are equall to 125 mm of sub-base type B (CBR=40%) or 175 mm of subase type C (CBR=20%). In other words, it can be shown that for 100 mm of sub-base type A (CBR=60%), their eqivelancy in terms other sub-base types possessing any design CBR can be formulated as follows:

$$H_{EQ} = 0.03125 \times CBR^2 - 4.375 \times CBR + 250 \tag{3}$$

where:

H_{EQ} equivalent thickness of 100 mm of sub-base A in terms of a sub-base with an inferior strength value type, in mm;
CBR design CBR of the inferior sub-base, lower than 60%.

Obviously for CBR=60%, H_{EQ}=100 mm. Now, the suggested method outlined in the present section is based on the fact that the introduction of the geocell reinforcement increases, as mentioned in the two previous sections, the existing resilient modulus of the infill material by a ratio of M. This increase also increases the CBR rate of the reinforced material in the following way:

$$CBR_{IN} = CBR_{EX} \times \left(E_{IN} / E_{EX}\right)^{1.41} = CBR_{EX} \times (MIF)^{1.41} \tag{4}$$

where:

E_{EX} existing resilient modulus;
E_{IN} reinforcement resilient modulus;
CBR_{EX} existing CBR value;
CBR_{IN} increased CBR value.

At this junction, it is worth noting that Eq. (4) is based on the following equation, taken from [13]:

$$\mathrm{CBR} = \left(\mathrm{E}/\alpha\right)^{1.41} \quad (5)$$

where:

E	existing resilient modulus of the given mateial;
α	regression coefficient;
CBR	existing CBR value of the given material.

From the material equivalence thickness reported in Eq. (3), and the proper substitutions, it can be shown that $\mathrm{CBR_{IN}}$ leads to the following equivalence thickness ($\mathrm{H_{EQIN}}$):

$$\mathrm{H_{EQIN}} = 0.03125\times\left[\mathrm{CBR_{EX}}\times\left(\mathrm{MIF}\right)^{1.41}\right]^2 - 4.375\times\left[\mathrm{CBR_{EX}}\times\left(\mathrm{MIF}\right)^{1.41}\right] + 250 \quad (6)$$

Here, $\mathrm{H_{EQIN}}$ denotes the equivalent thickness of 100 mm of sub-base A in terms of a reinforced subgrade layer with a strength value (prior to the reinforcement) of $\mathrm{CBR_{EX}}$. In other words, a 200-mm reinforced subgrade layer can reduce the subgrade type-A layers in the railway trackbed by $\Delta\mathrm{H_A}$, a value expressed in the following expresson:

$$\Delta\mathrm{H_A} = 200\times\left(100/\mathrm{H_{EQIN}}\right) \quad (7)$$

Finally, Fig. 3 depicts the variation in $\Delta\mathrm{H_A}$ with the increase in $\mathrm{CBR_{EX}}$ for the various rates of MIF. As shown at the end of Section 3, the suggested design rate of $\mathrm{E_{IN}/E_{EX}}$ is MIF=2.5. For this rate of MIF and $\mathrm{CBR_{EX}}$=10%, the figure shows that ΔHA is equal to 150 mm. Furthermore, it is suggested that the final structure will contain at least a sub-base type-A layer of 200 mm thickness. Obviously the figure allows $\Delta\mathrm{H_A}$ determinations for other values of $\mathrm{CBR_{EX}}$ and MIF.

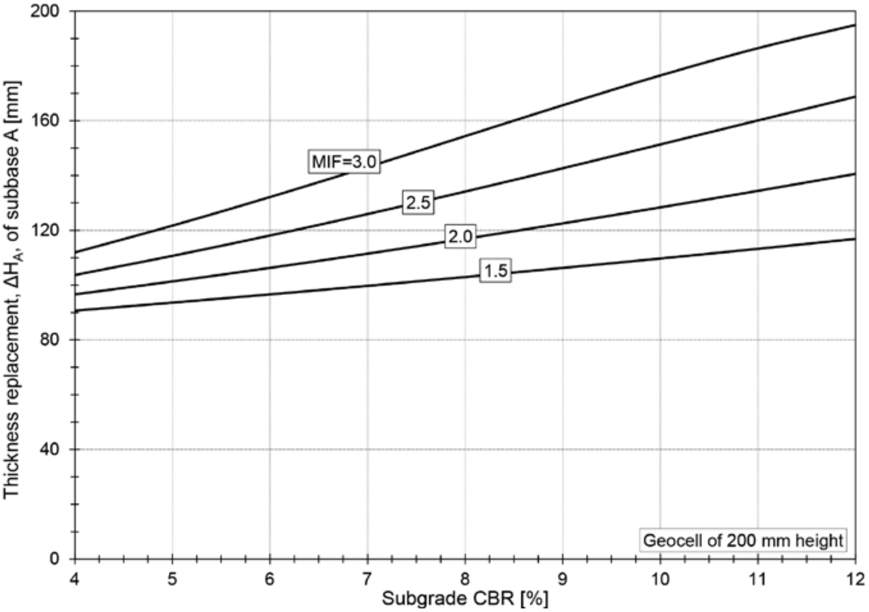

Figure 3 Thickness replacement of sub-base type A as a function of installing Geocell into the subgrade material possessing a given CBR value

To conclude, it should be stated that the present proposed equivalency procedure is valid for a subgrade CBR of up to 12%. Also, beacuse of locally mixed experience, both reasonable and bad, the use of the geocell reinforcement should be accompanied by a strict and approved QC and QA plan for the in-situ density and in-situ modulus of the reinforced layer.

5 Conclusions

This paper dealt with the issue of reinforcing the upper subgrade layer beneath the railway trackbed structure with a net of geocells. The literature review conducted in this paper reveals the increase in the resilient modulus of the reinforced layer as a result of the geocell reinforcement. The increase in the resilient modulus described is expressed by a multiplier factor, termed MIF (Modulus Improvement Factor). According to the literature, MIF varies between 1.2 and 5.0. The upper values of this range, however, are rather questionable, as no FWD measurements have been executed to prove the existence of these upper values.
Following the literature survey and the geocell reinforcement equations presented in the present paper, it seems that for design purposes, the suggested MIF value can be taken as 2.5. To conclude, this paper has developed the necessary equations for calculating the equivalent thickness of a 200-mm-thick, geocell-reinforced, upper subgrade layer in terms of the thickness of sub-base type A (CBR=60%). It has been shown that this equivalent thickness is a function of the existing subgrade CBR (with a maximum value of 12%) and the MIF rate. For a subgrade CBR of 10% and MIF=2.5, this 200 mm can replace 150 mm of subgrade type A in the railway trackbed structure. Finally, it should be emphasized that as the railway-design method does not allow any thickness reduction for upgrading the sub-base layers from CBR=60% to higher CBR values, no thickness reduction is allowed for reinforcing a sub-base layer with geocells.

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