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Railway Track Maintenance: Evaluation of Geogrid Benefits by Finite Element Analysis

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Abstract – At the present time, railway transportation is facing several challenges. The reason is that there has been not much development regarding the railway track design, but significantly higher demands are imposed on its bearing capacity. This means that existing lines that already need urgent maintenance are exposed to solicitations they have not been designed for. With this in mind, it is extremely important to carefully schedule maintenance measures and optimize interventions according to the cost/benefit ratio. This is particularly true in Portugal, where prolonged financial crisis has caused a shortage of resources. This paper analyses numerically possible benefits of geogrids applications for railways rehabilitation.

Keywords- Rehabilitation of railway lines, Geogrid, Numerical Simulation, Finite Elements, Nonlinear Behaviour, ANSYS, LS-DYNA.

1. INTRODUCTION

European railway network is currently facing several challenges. Most of the existing lines are affected by aging factors, and thus requiring urgent interventions, and on the other hand, demands on the network and bearing capacity are increasing. Freight transport evolved to solutions with much higher axle loads, and therefore, railway infrastructures are subjected to loads, which are much higher than the ones that were used for their design. Having in mind European Union regulations dictating shifting as much as possible air and road transport to rail, it can be concluded that efficient rehabilitation interventions must be carefully scheduled. Efficiency can be accomplished with the help of new materials like geosynthetics (e.g., geotextiles and geogrids), because these materials have several beneficial properties and their implementation in lines construction and rehabilitation is rapidly increasing.

Geogrids have been used in pavement reinforcement for several decades. They can give quite a significant contribution to the reduction of pavement deterioration in time, as documented already in Milligan and Love (1985). Experimental tests showed that geogrids can bring up to 40% benefits and enlarge the mean value of the stress distribution angle from 38º to 50º.

The use of geogrids in new rail tracks and track rehabilitation is more recent, as it extends for approximately last 30 years. Despite of previous recommendations that geogrids should be employed in regions subjected to high tensions (Figure 1) in the way to activate the membrane effect, it can be concluded that positioning according to Figure 1 is quite complicated especially for rehabilitation intervention. In order to activate the membrane effect, high displacements are necessary, which is not typical in railway applications, where requirements on rail geometry are quite restrictive.

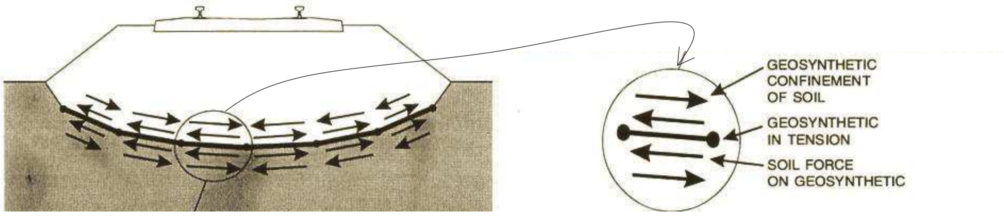

Fig. 1 Recommended geogrid position, adapted from Selig and Waters (1994)

Recent investigations concluded that geogrid can be placed at a level that is easily accessible by standard rehabilitation vehicles, in fact, positioning between ballast and sub-ballast layers have been found particularly efficient, as it provides confinement to the ballast layer, leading to a significant reduction in the vertical and lateral displacements, which in turn assures more resilient long-term performance of the ballast layer (Indraratna et al., 2010). Indeed, a research by Ngo et al. (2018) involving large-scale laboratory tests, field investigation and numerical modelling of laboratory tests by discrete elements, carried out to evaluate the improved performance of railway ballast reinforced by geogrids, showed that the inclusion of geogrids increases the interface shear strength and decreases the ballast deformation. This is attributed to the interlock occurring between the geogrid and surrounding ballast aggregates, providing ballast confinement.

In order to evaluate geogrids benefits numerically, there are still many questions that must be addressed. Several investigations use discrete elements, which are convenient for simulating the interlocking mechanism, but then the simulation is restricted to reproducing of the laboratory tests, i.e. simulating only the granular layers and not the whole track subjected to a moving vehicle. For complete railway track models, traditionally finite elements (FE) are used. Questions that arise in such models are the following: (i) how to model the interface between the granular material and the geogrid; (ii) how to model the geogrid itself; and (iii) how to introduce the interlocking and confining effect?

In FE model the granular layers are modelled as continua, therefore the geogrid is also introduced as a thin continues layer. Several researchers then use cohesive layers to model the interfaces, as for instance in Chawla and Shahu (2016) where very detailed analyses concluded that only the coupled analysis can have acceptable agreement with the experimental data.

Nevertheless, if FE model is composed of horizontal continues layers, then its resistance to a vertical force in linear range can be approximated by an equivalent spring, which effective stiffness is obtained as inverse value of inverse layers stiffnesses (springs in series) and thus the final value would be practically unaffected by the geogrid presence, due to its low thickness. Even if compression resulting from lateral compaction would be imposed as some additional in-plane effect, i.e. as a localized effect within a thin layer under small out-of-plane displacement, due to the Saint-Venant principle it would not propagate to the surrounding material to a sufficient extent. Therefore, there must be some additional feature which is not modelled by layered continua. Interesting solution is presented in Jirousek et al. (2010), but this technique would be quite difficult to introduce in a real 3D model.

Lança et al. (2018) modelled the track and the passing vehicle using a commercial explicit dynamic software LS-DYNA. Firstly, the authors validated the model by comparison with experimental data. Then, a fictitious scenario of the same track with a deteriorated region which was further rehabilitated by a geogrid was analysed. Different situations were compared in terms of lateral and vertical displacements at several levels. Insignificant differences were found between vertical responses of the track related to different solutions, which was attributed to the linearity of the constituents involved.

In this work, influence of geogrids on overall stabilization and reinforcement of railway tracks is studied numerically. A section of the Portuguese railway line is selected for the case study. Firstly, numerical studies are conducted in two-dimension (2D) using software ANSYS, then three-dimensional (3D) model is created and analysed under cyclic force, still within ANSYS by transient analysis with implicit time integration, and finally, full model subjected to passing vehicle is run in explicit dynamic code LS-DYNA. In 3D implicit model the effect of interfaces was also analysed. In the same way as in Chawla and Shahu (2016), interfaces in form of cohesive layers were introduced between all layers, but no significant differences were found between the results obtained on models with and without interfaces. As it is generally accepted that the most important mechanism ensuring the proper ballast stabilization and reinforcement by a geogrid is the interlock of the ballast aggregates with the geogrid, this allows to conclude that, in reality, there is no weaker thin interface, because modern geogrids have especially designed rib cross-sections, that fix properly ballast grains to prevent sliding. On the contrary, stiffening should be introduced in the geogrid proximity.

In this paper, only some of the results obtained are presented. As the main contribution it is concluded that the geogrid benefit can be evaluated numerically in simple 2D models subjected to oscillating force, but only under appropriate non-linear mechanical behaviour of the granular layers specifying accumulation of permanent deformations, i.e. under an adequate settlement law.

2. MODEL SPECIFICATION

Case study is related to an existing railway line, same as already investigated in Lança et al. (2018). Three layers in the superstructure are modelled, namely ballast, sub-ballast and capping layer. Basic input data are obtained from Paixão (2014). In Figure 2 a detail of the FE model with degradation, used in LS-DYNA, is shown.

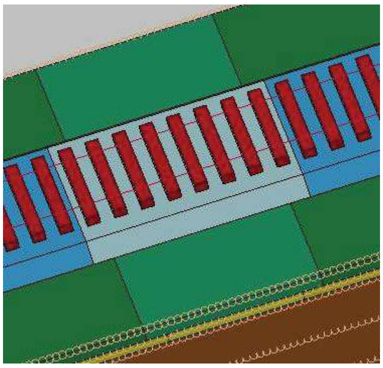

Fig. 2 Detail of the model in LS-DYNA, Lança et al. (2018)

Analyses were conducted on 2D model under generalized plane strain condition and on 3D model, both subjected to a harmonic force; and 3D model subjected to the passing vehicle. Here, only some results from the 2D model will be shown. Due to the symmetry, only half of the model could be created, but for better comparison, both halves were modelled: one with geogrid and the other one unreinforced, with no connection on the symmetry axis. In this way, it was possible to analyse reinforced and unreinforced model at the same time.

For the 2D case, three variants were considered: (i) first with thin layer representing the geogrid (LM), (ii) second, modelling the geogrid as elastic springs, strengthen when placed into the model (SM), and (iii) third, where additional tension was applied in the position where the geogrid should be placed (TM). Compacting effects were also simulated by increasing Young's modulus according to the actual values of the hydrostatic pressure. In the first model variant, LM, a perfect contact between the granular layers and the geogrid was assumed, for the reasons specified in the previous section.

LM was firstly tested for geogrid position, namely location at the three different interfaces, between the ballast, sub-ballast, capping layer and subsoil were considered, termed as position 1 to 3. Nonlinear behaviour of granular layers was simplified as rate independent Mises plasticity, because small differences were found between these results and results obtained with more appropriate Mohr-Coulomb criterion. Selection of Mises plasticity was dictated by stable numerical performance of the models.

Four cycles of harmonic load oscillating between zero and 60kN were used to evaluate the geogrid effectiveness, based on three measures: first two were specified as L2-norm of the difference between the vertical displacements (L2U) and vertical stresses (L2S) in position slightly above the geogrid and analogous position in the unreinforced model. The third criterion used was the percentage improvement in rail displacement (R%I).

3. RESULTS

The results showed clearly that the most favourable position of the geogrid is the one at the interface between the ballast and the sub-ballast layer. This is demonstrated in Figures 3-4, where the distribution of vertical displacements and stresses is shown for grid position 1 and 2, corresponding to the ballast/sub-ballast and sub-ballast/capping layer interfaces, respectively.

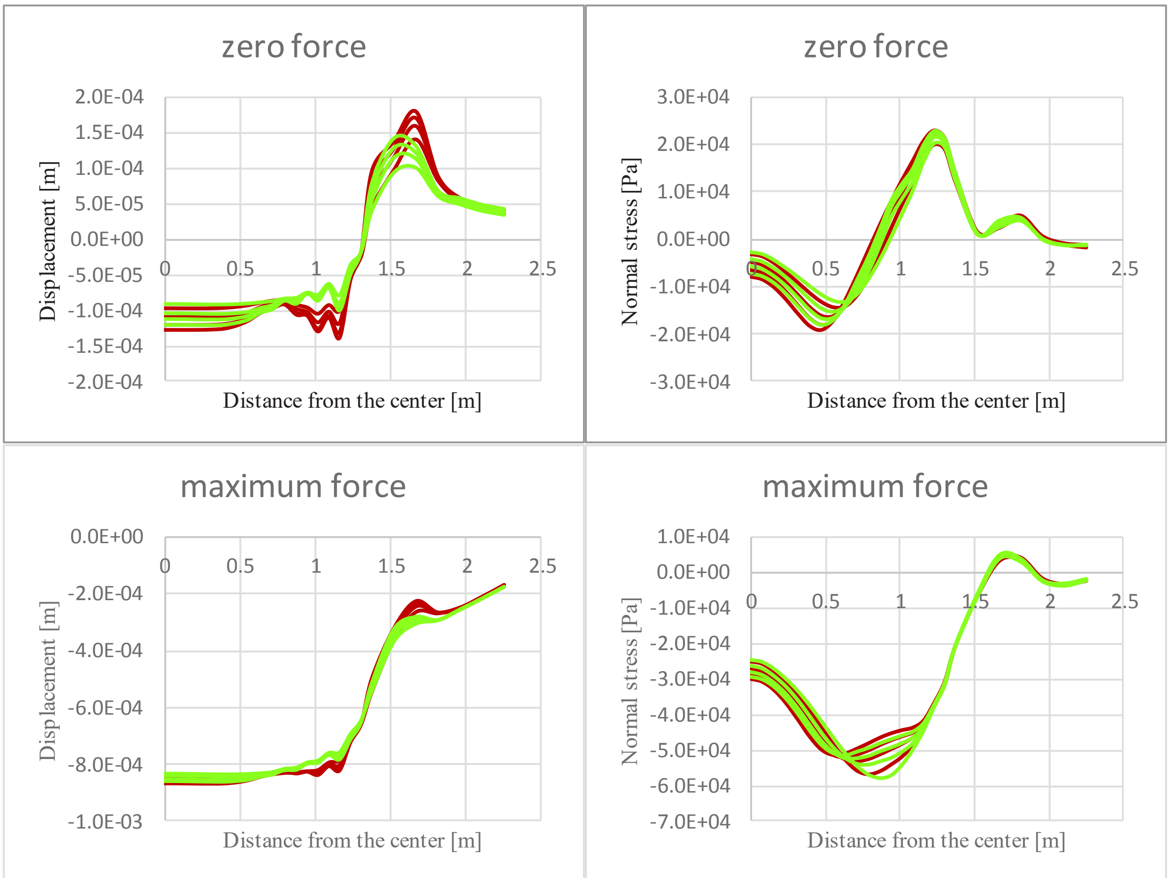

Fig. 3 Distribution of vertical displacements and stresses for grid position 1

Extreme values of the applied force were selected for the graphs. Without the lack of clarity, all four cycles are shown in one figure: green colour stands for the reinforced track and red colour for the unreinforced one. In Figure 4 only displacements are shown, because differences are very small and stresses comparison would not bring anything new. Results for grid position 3 are also omitted, as there are no significant differences between the curves, as in Figure 4. When analysing R%I (Figure 5), it is seen that values are always positive, indicating better performance of the reinforced structure at each time step, but the overall tendency is decreasing. Therefore, the model was additionally tested on material properties to see what values affect the results obtained the most.

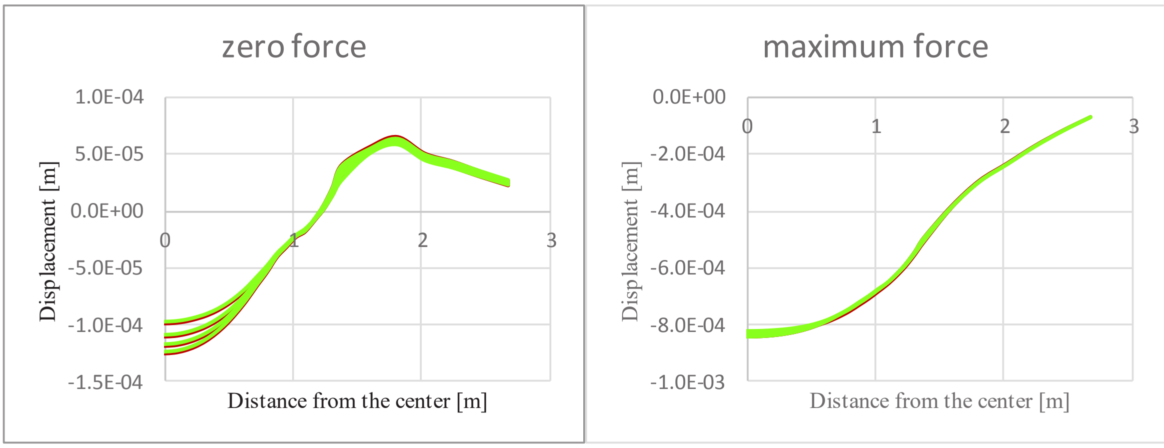

Fig. 4 Distribution of vertical displacements for grid position 2

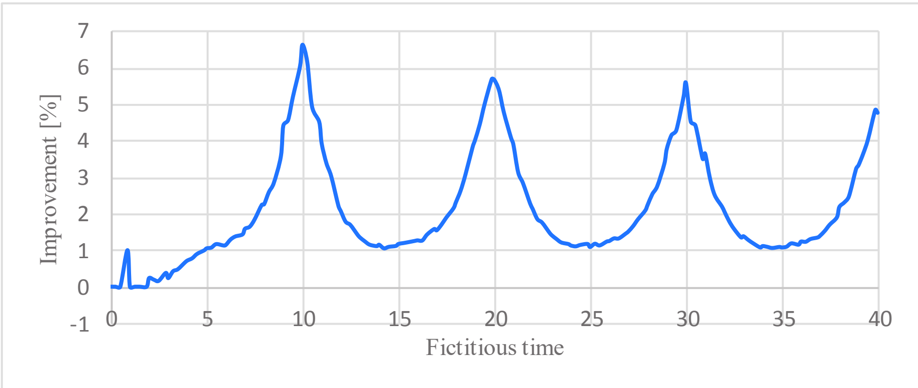

Fig. 5 R%I as a function of fictitious time for grid position 2

Design of experiments (DOF) was performed by full factorial analysis on six parameters listed in Table 1, to identify the key parameters that govern the benefits.

Table 1 Designation of parameters for DOF

Data	E geogrid	E ballast	E sub-ballast	Y ballast	Y sub-ballast	E subsoil
Designation	A	B	C	D	E	F

In Table 1, E stands for Young's modulus and Y for "yield" stress, which in this context means stress level at the onset of permanent deformations. A convenient hardening modulus was also used, in order to obtain typical non-linear load-displacement curves. In the factorial analysis, 10% decrease or increase was considered on parameters specified in Table 1. This implied 64 analyses, from which the one having the best performance was characterized.

Results obtained are shown in Figures 6-7. It can be seen that percentual benefit is clearly increasing. Statistical treatment of the data obtained showed clear dominance of single effects, but some of the combined effects are also important. In Figure 8 dominance of single factors and their multiplicity is shown for normalized L2U and last value of R%I. It can be concluded that the major influence on the results obtained can be attributed to the onset of permanent deformations and their combination. It is also interesting to see that the single effects in this case have opposite signs, and that both results have similar tendency. In addition, normal probability plots are also shown in Figure 9. Thus, if the variations in input data had no actual influence on the results obtained, the points in the probability plot would form a straight line, corresponding to the normal distribution. It is thus confirmed once more, that the single effects D and E and their combination have the main influence on the response. But also single effects A, F and combined effects AE, EF are significant, depending on the specification of the confidence interval. This also indicates that the onset of permanent deformations in the layer below the geogrid is more important than in the layer above.

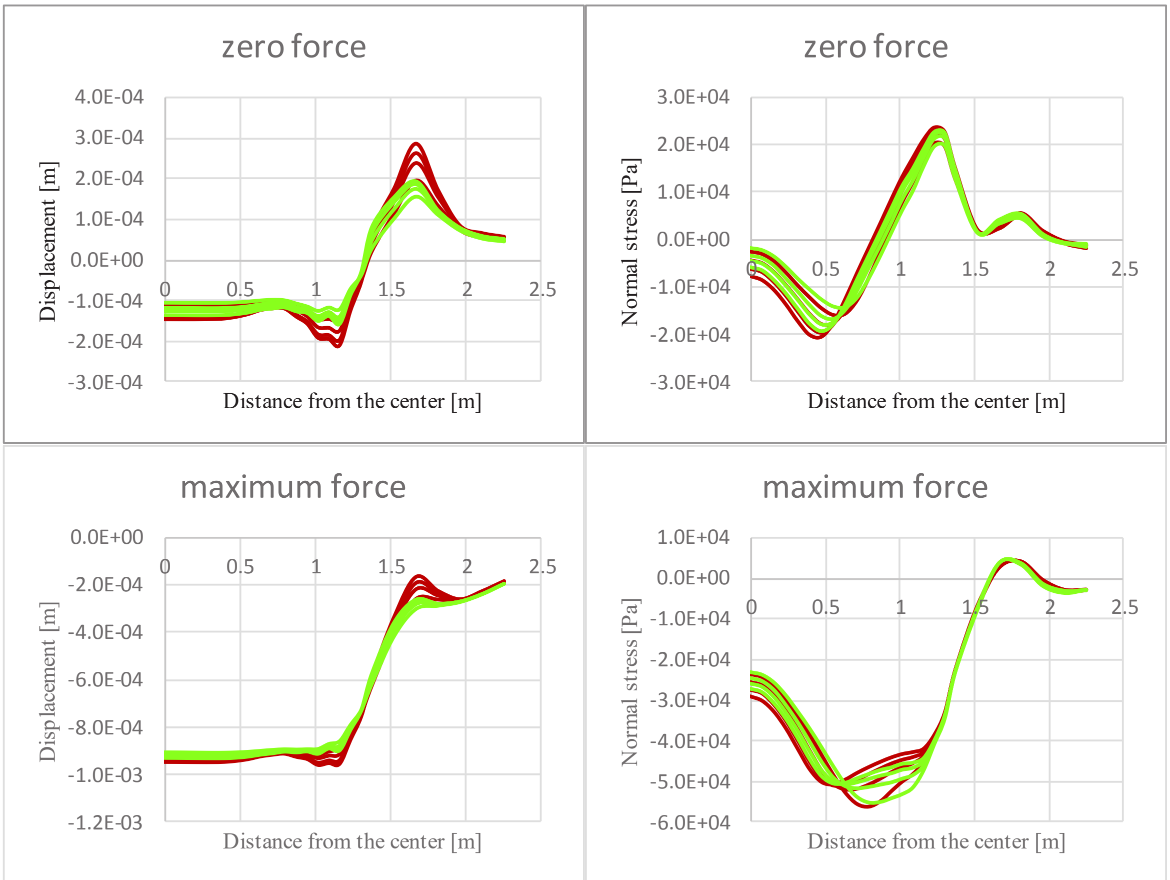

Fig. 6 Distribution of vertical displacements and stresses for the best combination from DOF

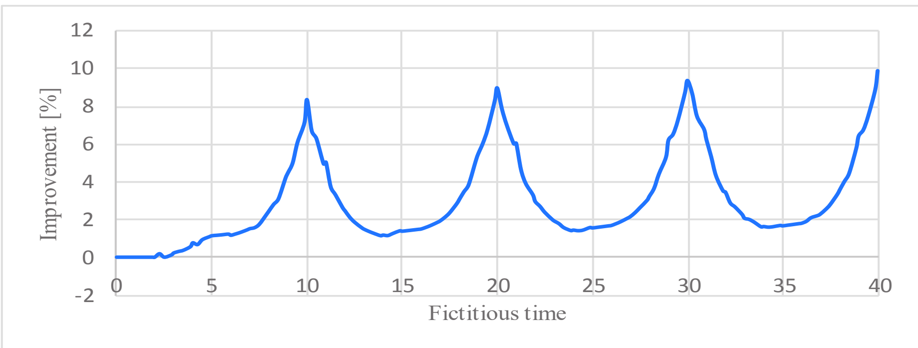

Fig. 7 R%I as a function of fictitious time for the best combination from DOF, 4 cycles

4. LONG-TERM BEHAVIOUR

Finally, the long-term behaviour is analysed on the best combination of parameters obtained from DOE. Definition of the cyclic force is maintained, but 8000 cycles were imposed. It is necessary to highlight that in this preliminary analysis, no dynamic effects were considered, therefore densities and damping properties were omitted and thus the results are analysed against fictitious time. In further investigations, dynamic effects will be included, and force cycles will be defined according to the frequency of passing train axles.

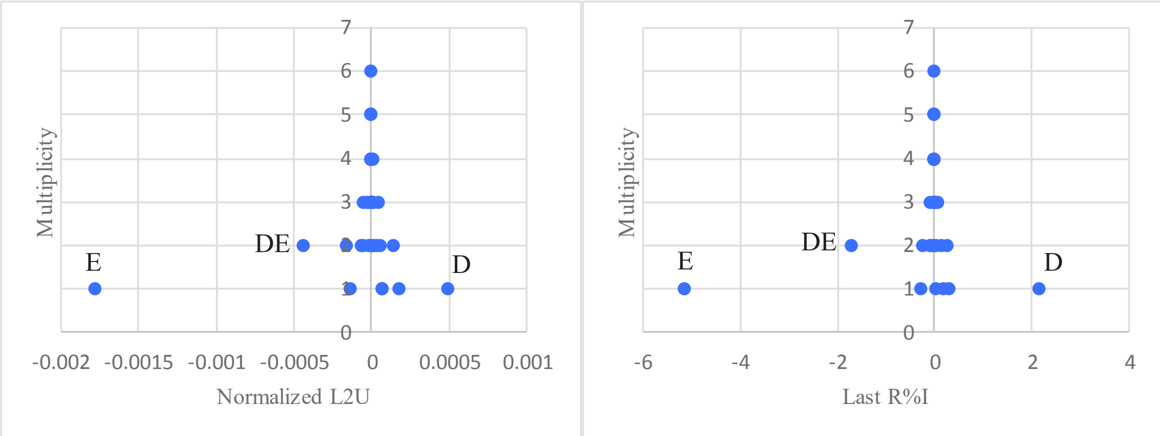

Fig. 8 Dominancy of single and combined effects

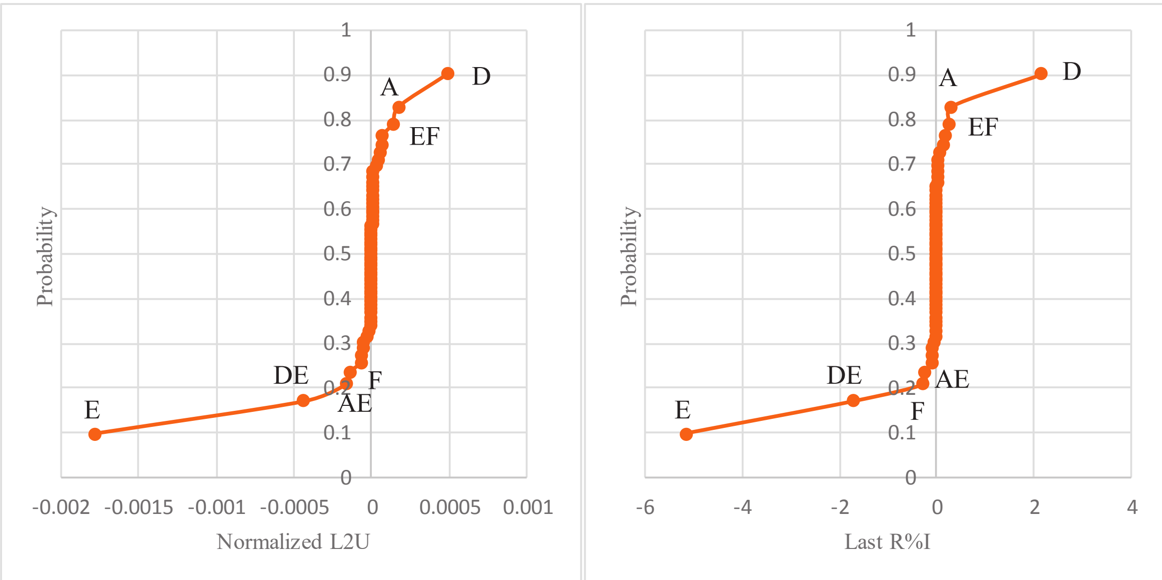

Fig. 9 Normal probability plots of the effects

Figure 10 shows the same result as Figure 7, but now for all 8000 cycles. As the higher number of cycles is very high, it is not possible to distinguish them, but the filled region in Figure 10 indicate the margin of percentual benefit along the cycles. It can be concluded that the benefit is quite significant, which is in agreement with other published works, based mainly on experimental investigations.

It is necessary to highlight, that in order to obtain these results, quite high value of Young's modulus of the geogrid was implemented. This indicates that biaxial geogrids could have better performance than triaxial ones, because railway vehicle passage imposes very small in-plane shear solicitation and therefore low shear in-plane stiffness does not seem to be disadvantage and in-plane isotropy does not provide an added value. Biaxial geogrids with ribs aligned longitudinally and transversally can just make advantage of the highest stiffness they can provide.

In Figure 11 von Mises plastic strain and vertical displacements in [m] are shown in for the maximum force in the last cycle. It is clearly seen that the unreinforced part of the model (left) perform worse than the reinforced one (right).

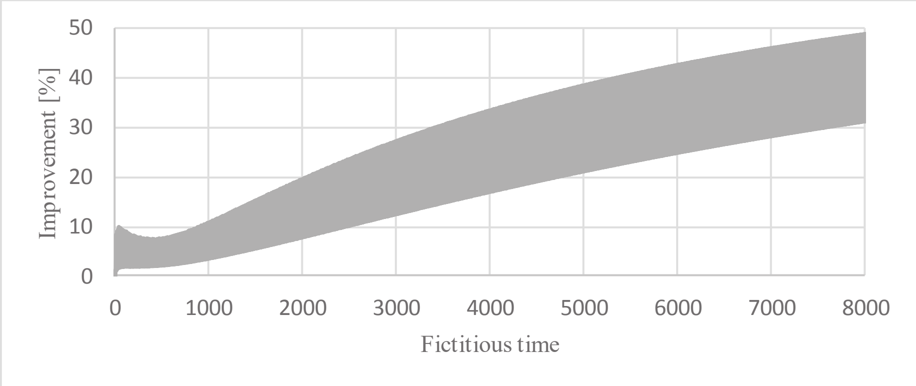

Fig. 10 R%I as a function of fictitious time for best combination from DOF, 8000 cycles

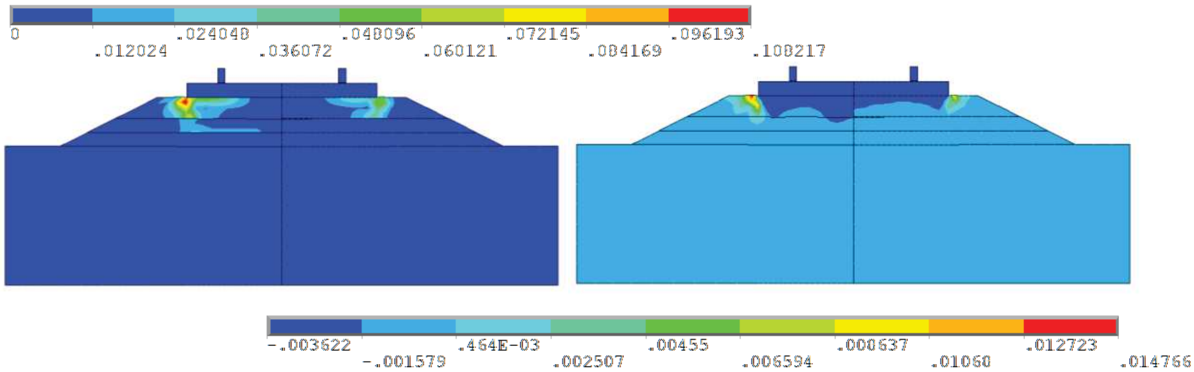

Fig. 11 von Mises plastic strain (left) and vertical displacements (right)

Numerical analyses that provided base for the results presented in this paper required frequent model modifications, therefore the model was fully parametrized and written in ANSYS Parametric Design Language (APDL).

5. CONCLUDING REMARKS

In this paper, benefits that can be added to railway track performance by geogrids implementation were analysed numerically. For the case study selected, it was concluded that the most beneficial geogrid position is the one separating the ballast from the sub-ballast layer. It was also concluded, that potential improvement can be evaluated in simple 2D models subjected to cyclic loads, under assumption of nonlinear behaviour of the granular layers, where the most important indicator is the settlement law. It was also shown that statistical analyses can be useful to identify key factors that are influencing the decisive results. Such treatment allows generation of response surfaces that can identify the optimized solution.

6. ACKNOWLEDGEMENTS

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