FEASIBILITY OF EPS AS A LIGHTWEIGHT SUB-BASE MATERIAL IN RAILWAY TRACK STRUCTURES

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Abstract

The paper presents results of a study on feasibility of Expanded Polystyrene (EPS) material in a railway track design. In this research, performance of a track structure without ballast, a so-called Embedded Rail Structure (ERS), with an EPS layer between a concrete slab and subsoil has been investigated. The static and dynamic behavior of such structure has been analyzed in order to validate the applicability of EPS. Finally, an optimization of material properties of EPS applied to an ERS track has been performed. The optimization criteria were minimization of the 'dead' weight of a track structure as well as the costs related to the sub-grade improvement while imposing constraints on the maximum rail displacements and stresses in the EPS and subsoil layers. A set of Pareto optimal solutions has been obtained using a numerical optimization technique based on MARS (Multipoint Approximations based on Response Surface fitting) method. The results have demonstrated feasibility and advantages of using EPS in an ERS design especially for subsoil with very poor stiffness properties.

Keywords: EPS Geofoam Application, Railway Track Design, Multi-criteria Optimization, Pareto Optimality

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1 Introduction

Large areas of the densely-populated western and northern parts of The Netherlands consist of subsoil with geotechnical characteristics ranging from poor to very poor. Building of railway structures under these conditions would require a substantial improvement of the bearing capacity. The conventional approach consists of replacing a great deal of the poor soil by sand (sub-grade improvement). Even if pre-loading of a sub-grade layer is applied, relatively large settlements due to high weigh of a track structure are likely to occur during the initial phase of the structure's life. With the application of ultra-light materials, such as Expanded Polystyrene (EPS), a so-called "equilibrium" structure can be created, which would practically prevent the increase of grain stresses in the sub-grade. In other words, the weight of the track structure plus lightweight material should approximately compensate the weight of the excavated material. In this paper an unconventional railway track, a so-called Embedded Rail Structure (ERS) is considered. Traditional ballast is replaced by a reinforced concrete slab in such a structure. To reduce the total weight of a structure and consequently stresses in the sub-grade an EPS layer is applied between the slab and sub-grade. The static and dynamic properties of such a track investigated in Chapter 2 to demonstrate the feasibility and advantages of EPS usage in railway track design.

As the behavior of a track structure has been analyzed, the next step is to optimize it. Here a numerical optimization technique (TU Delft) has been used to minimize the 'dead' weight of a track structure as well as the costs related to the sub-grade improvement. The stiffness of EPS and soil has been varied during the optimization while imposing several constraints on maximum stresses in the components of a structure. The results of optimization are discussed in Chapter 3. Finally, some conclusions and recommendations on application of EPS in railway track design are given in Chapter 4.

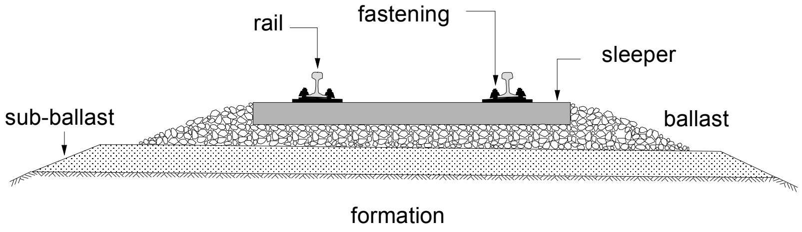


Figure 1 Classical railway track

2 Track Structure with an EPS Sub-base

In the light of the positive experiences with heavy-duty lightweight pavement structures, TU Delft decided to investigate the possibilities and conditions for the application of an EPS sub-base in both ballasted and non-ballasted track structures [8]. The density of EPS is directly related to its Young's modulus and other material characteristics. The EPS types examined in this study were EPS20 and EPS35. The mechanical properties of EPS were taken from [1] according to which the Young's modulus E_{EPS} of EPS could be approximated by the function

$$E_{eps} = A\rho_{eps}^{B} \text{ [MPa]} \tag{1}$$

where

ρ_{EPS} [kg/m^3] is the density of EPS;

$A = 0.1284$ and $B = 1.368$ are the parameters of the approximation.

In order to use EPS as a sub-base material in conventional track design (Figure 1) the concrete slab should to be placed under the ballastbed, which has no bending stiffness.

As compared to traditional sub-base materials, EPS has a very low value for density, Young's modulus, water absorption capacity and thermal conductivity. Because EPS has a relatively low strength, a concrete slab on top of the EPS layer is inevitable. In fact, this made an integrated slab track solution very attractive. Here a non-conventional track structure without ballast, a so-called Embedded Rail Structure (ERS), has been considered. A typical ERS contains a concrete slab wherein rails are embedded in polyurethane-cork mixture as shown in Figure 2. Because of relatively soft soil (formation layer in Figure 2) a sub-base layer in such structure usually consists of stiffer concrete roadbed and some base materials. The total weigh of the structure, which determines the level of stresses in the foundation, can be reduced by using EPS as sub-base material. An ERS with EPS sub-base layer investigated here is presented in Figure 3.

To validate the use of EPS in railway track design, the static and dynamic behavior of an ERS with a EPS sub-base layer has been analyzed numerically using GEOTRACK and RAIL software. The results are discussed below.

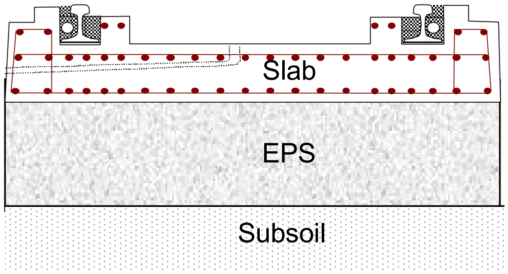
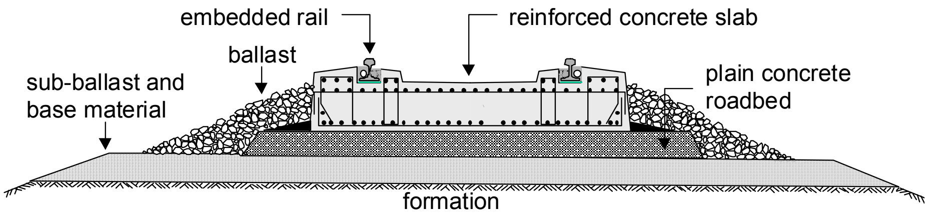


Figure 3: Embedded rail structure with an EPS sub-base

2.1 Static performance

The minimum thickness of the concrete slab on top of the EPS layer was determined by a static analysis carried out with GEOTRACK. Based on the maximum permissible rail deflection and the maximum acceptable stresses and strains in the different layers of the structure the minimum thickness of the concrete slab was found to be 25 cm. The stress in the EPS sub-base remained within the linear-elastic range.



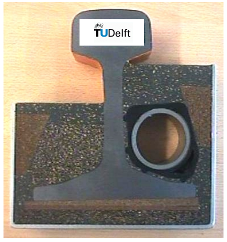


Figure 2 Typical Embedded rail Structure with conventional (UIC54) rails

Figure 4 shows that ERS with an EPS sub-base, the vertical stresses at the top of the sub-grade are maintained at the original value of 15 kPa, while for ERS with a sand sub-base the stresses are twice higher. This clearly reveals the potential of such lightweight sub-base solution. Three years of experience with an EPS sub-base in a tram track in Rotterdam confirms its low-settlement behavior . In [8] it is shown that the difference in stress development for EPS20 and EPS35 is negligibly small under all practical conditions, which means that application of EPS20 is sufficient.

2.2 Dynamic performance

The influence of an EPS sub-base on the track dynamic behavior was investigated with the program RAIL of TU Delft [3, 5]. In this program the modeling of real track geometry was achieved by downloading track recording car data from NS. The model produces response values for car body accelerations, wheel-rail forces, track deflections and stresses in the track structure due to moving train sets. The damping coefficient of EPS was not determined experimentally, but was estimated via literature by the damping ratio [2].

The overall dynamic behavior of the track structure, expressed in the so-called Frequency Response Functions (FRF), was determined by applying an impulse load. As an example, Figure 5 shows the FRF functions for the Embedded Rail Structure, with the concrete slab resting on a sub-base of sand, EPS 35 and EPS 20 respectively.

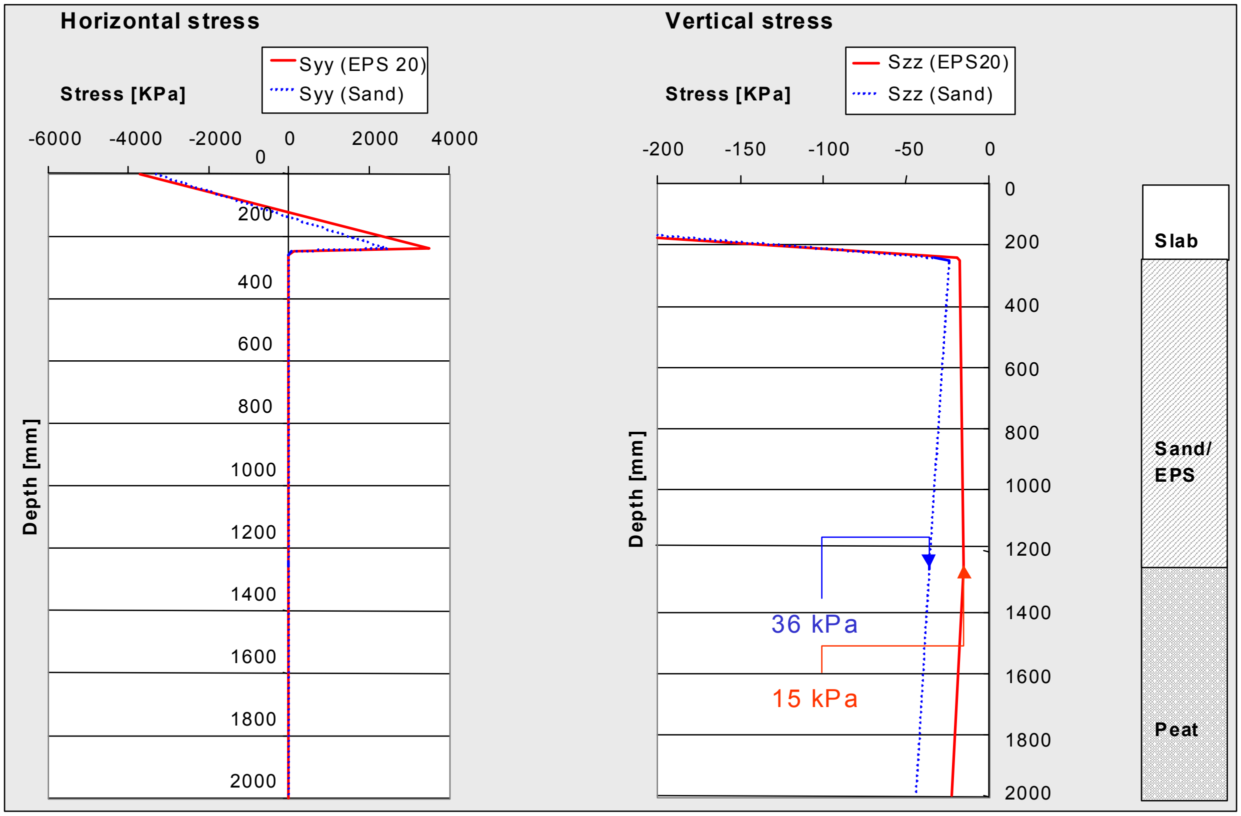


Figure 4: Stress distribution in an embedded rail structure under a static load of 112.5 kN

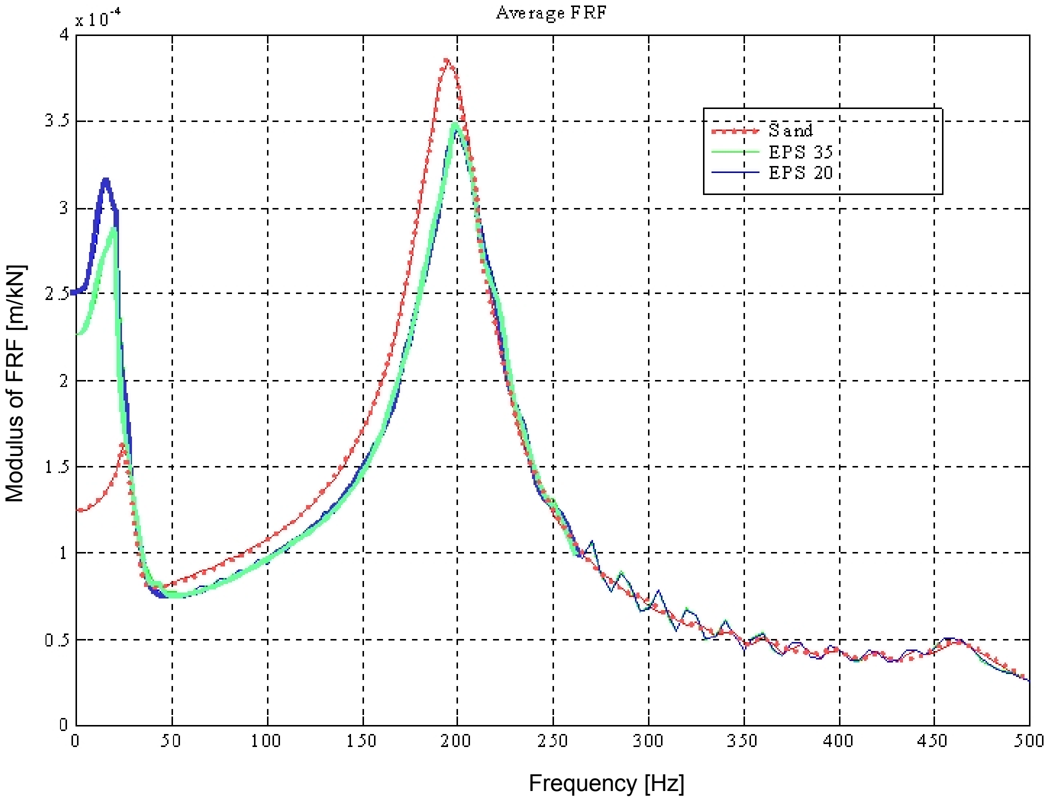


Figure 5: FRF of an embedded rail track with three different sub-bases, $\xi = 0.25$

Obviously, the static deflection of the EPS sub-base is greater than that of the sand sub-base, as EPS is a much weaker than sand. The first natural frequency of a structure with an EPS sub-base is lower than of the one with a sand sub-base. The second natural frequency at 200 Hz is the same for all three sub-bases, and it is mainly associated with the polyurethane-corc material of the embedded rail. The two natural frequencies for the three different sub-bases (EPS20, EPS35 and sand) are shown in Table 1.

Sub-base	1st natural frequency [Hz]	2nd natural frequency [Hz]
EPS20	16	200
EPS35	18	200
Sand	27	200

Table 1: Natural frequencies of the three sub-bases

The results mean that frequencies above 20 Hz may be filtered out better with an EPS sub-base than with a sand sub-base. However, the first resonance peak is somewhat higher for an EPS sub-base, due to the higher static response. It should be noted that the damping coefficient of the EPS material was determined theoretically, and may differ from an experimentally determined damping coefficient. This might have a major influence on the height of the first peak of the FRF, which seems to correspond with the vibration damping characteristics of EPS referred to in [4]. In the scarce literature on the dynamics of EPS it is pointed out that an EPS sub-base might show some vibration damping in the frequency range between 20 Hz and 40 Hz.

Other series of analyses presented in [8] consider track responses due to passing vehicles. The rail geometry was set at the maintenance intervention levels of Railways (NS), which allow a maximum vertical deviation of 3 mm at construction and 12 mm for maintenance. The results of the analyses have shown that, under these loads, stresses and strains in the EPS sub-base, as well as deflections of rails remain within the admissible limits. In the dynamic analysis, the difference in results for the two different EPS densities was also small. Based on the frequency response function EPS20 is indeed slightly better, which again indicates that this material is an acceptable sub-base material for railway track structures.

3 Optimal Track Design with an EPS Sub-base

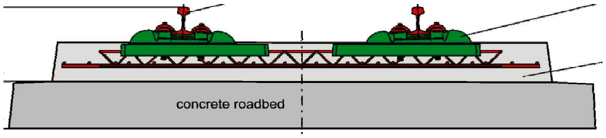


Figure 6 Cross-section of Rheda-2000 track design

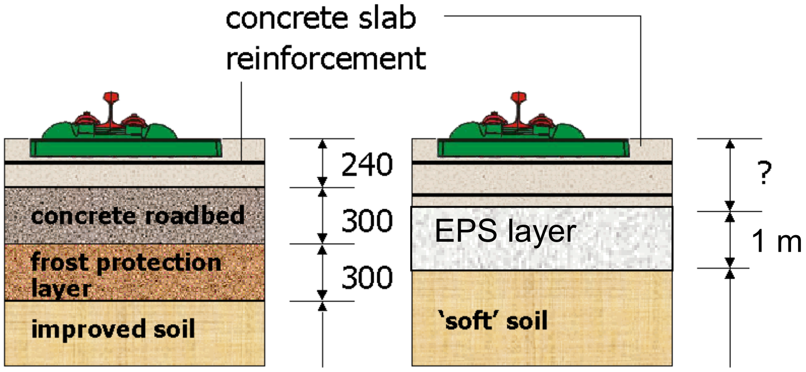
Probably, one of the most promising slab track designs called Rheda-2000 has been recently introduced in Germany. A structure consists of twin-block sleepers with lattice reinforcement, which are directly fastened to a concrete slab (Figure 6). An alternative design of a Rheda 2000 design has been suggested in [9] by applying the reinforcement closer to the top and bottom of a slab (in traditional Rheda-2000 the reinforcement is placed at the position of the neutral line). The bending stiffness of such slab is considerably higher as compared to the one in traditional Rheda-2000 design. Therefore, the supporting layer can be softer meaning that soil should be less improved or not improved at all.

Here, the modified Rheda-2000 with EPS sub-base (Figure 7) is used in the optimization. The optimization searches for a design that minimizes the total cost of the structure while satisfying some safety requirements. The objectives, constraints and design variables of the optimization problem are discussed below.

The total costs of the track can be reduced by eliminating or reducing the efforts related to soil improvement, which means that the stiffness of the foundation E_{gr} should be minimize. By increasing the bending stiffness of a concrete slab, the stiffness of soil layer required for a safe operation can be reduced as well. The stiffness of a slab can be increased by for example increasing the high of a slab h_{sl}. To prevent deterioration damage the stresses in foundation should be below the prescribed limits. The maximum allowable stress in foundation can be calculated using the following empirical formula [2]:

$$\sigma^*_{gr} = \frac{0.006 \cdot C_{gr}}{1 + 0.7 \cdot \log(n_i)} \qquad (2)$$

where



a. b.

Figure 7 Traditional (a.) and modified (b.) Rheda 2000 track structure (one sleeper) with EPS sub-base

C_{gr} is the dynamic elasticity modulus of foundation;

n_i is the number of cyclic loadings. In the calculations here $n_i = 2 \cdot 10^6$ loadings has been used.

To reduce the stresses in the foundation the density of EPS ρ_{eps} should be minimized.

Too soft foundation results in relatively large vertical displacements in a structure resulting in high bending moments in a concrete slab M_{sl}, which should be restricted. The procedure for calculation of the maximum allowable stress in a concrete slab M_{sl}^* used here is described in [9]. It takes in to account:

- fatigue of concrete;
- fatigue of reinforcement steel.

To prevent the damage of EPS layer the deformations ε_{eps} in it have been prescribe to $\varepsilon_{eps}^* = 0.5\%$ [1] whereas the height of the EPS layer was $1\,m$ during the optimization. The maximum displacements of rails u_{rail} should not exceed the $u_{rail}^* = 3\ mm$.

Finally, to find an optimal slab track design the following optimization problem has been formulated:

Find

$$x^* = [C_{gr}^* \ \rho_{eps}^*]^T \tag{3}$$

such that

$$C_{gr} \to \min, \quad \rho_{eps} \to \min \tag{4}$$

subject to constraints

$$\varepsilon_{eps} \le \varepsilon_{eps}^*, \quad \sigma_{gr} \le \sigma_{gr}^*, \ u_{rail} \le u_{rail}^*, \quad M_{sl} \le M_{sl}^*. \tag{5}$$

The lower and upper bounds of the design variables (3) are given in Table 2.

Design variable	**Lower bound**	**Upper bound**	**Initial value**	**Units**
C_{gr}	20	90	80	kN/m^3
ρ_{eps}	15	45	30	kg/m^3

Table 2 Design variables and their limits

A set of Pareto optimal solutions has been found by solving the optimization problem (3)-(5) several times for a constant slab height varying from 0.05m to 1m with a step of 0.05m. The optimization problems have been solved using a technique based on the MARS (Multipoint Approximations based on Response Surface fitting) method [6]. The method has been especially developed for optimization problems involving time-consuming response analysis calculations.

The optimal solutions are shown in Figure 9. The corresponding values of the constraints (5) are shown in Figure 8. From Figure 9, it can be seen that an ERS with an EPS sub-base can be applied on a soil with a very poor stiffness properties ($C_{gr} \le 40 KN/m^3$). From Figure 8 it can be seen that the stress in soil is a decisive response quantity since the corresponding constraint is always active. It can also be concluded that the foundation is working optimally (fully stressed design) whereas the slab performance can be improved for example by using less reinforcement in concrete (the current is 2%).

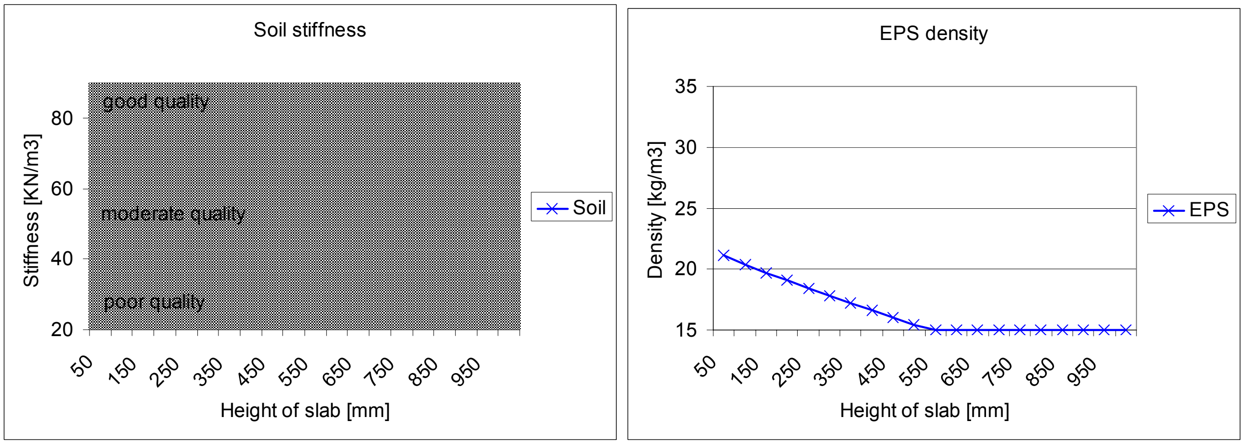


Figure 9 Pareto optimal solutions of track optimization

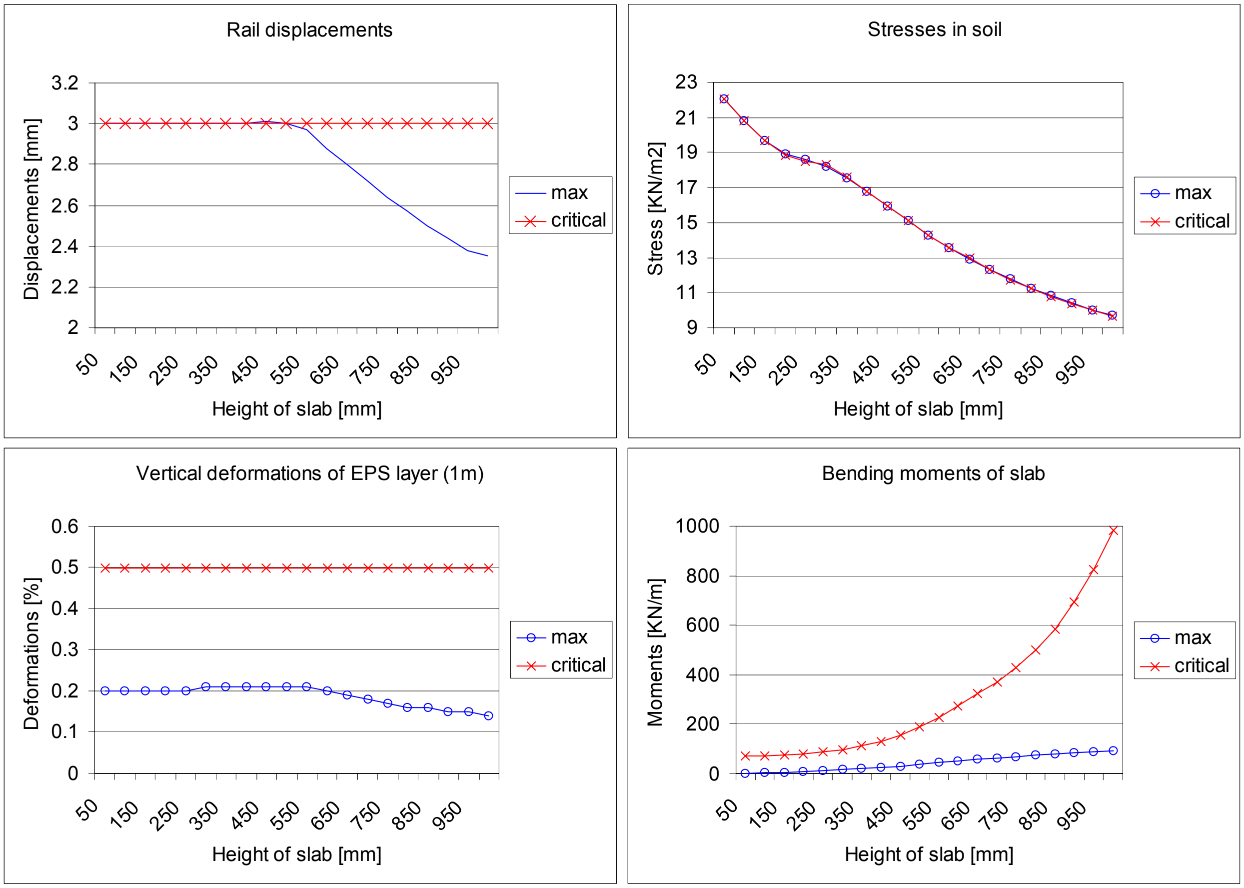


Figure 8 Constraints of optimisation problem

In [6] a similar optimization has been performed on a modified Rheda-2000 track structure without an EPS sub-base. Figure 10 shows the results of optimization of the modified Rheda-2000 embedded rail structure with EPS layer and without EPS (from [7]). From this figure, it can be observed that the introduction of EPS layer makes it possible to apply the ERS track on a softer foundation as compared to ERS design without EPS sub-base, which again demonstrates the advantage of EPS application in railway track design.

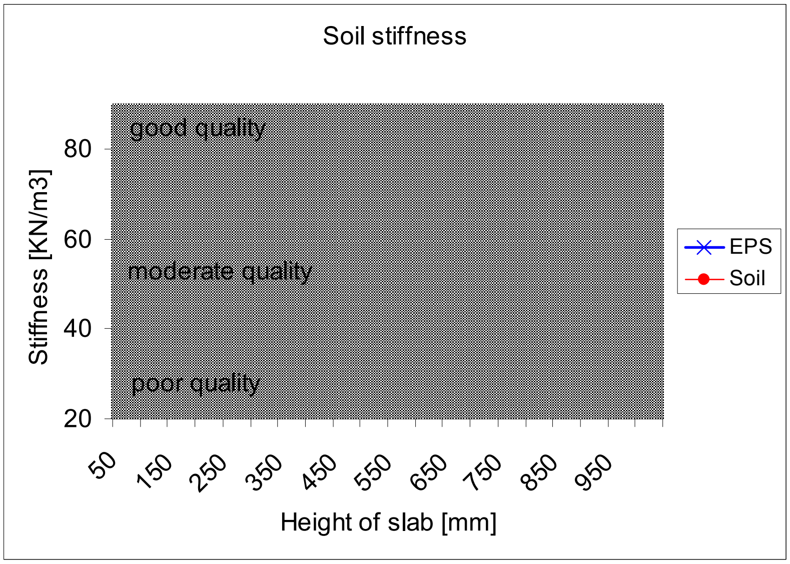


Figure 10 Results of optimisation of Embedded Rail Structure with EPS layer and without EPS layer (from [7])

4 Remarks and conclusions

EPS can be applied in any track structure, but significant advantages will be derived when used on subsoil with a poor bearing capacity. In two special cases [8] – transition between engineering structure and plain track, and when constructing a track doubling – the advantages of EPS to avoid differential settlements may be even more evident.

In [8], also the different track structures were compared with respect to life-cycle costs. In the case of very compressible subsoil, an EPS sub-base was found to be among the cheapest solutions, as maintenance costs would be reduced significantly. This sub-base type would certainly be better for the environment, both during construction and in service.

Based on the research described in this article, the following recommendations could be made:

1. Tests would be needed to obtain a better insight into the dynamic performance of a track with an EPS sub-base, especially with respect to the damping characteristics.
2. A test track with an EPS sub-base would be preferable for studying the performance under operating conditions.
3. It is advised to formulate uniform design criteria for the use of EPS in railway structures.

5 Summary

The paper presents results of a study on feasibility of Expanded Polystyrene (EPS) material in a railway track design. In this research, performance of a track structure without ballast, a so-called Embedded Rail Structure (ERS), with an EPS layer between a concrete slab and subsoil has been investigated.

The static and dynamic behavior of such structure has been analyzed in order to validate the applicability of EPS. Finally, an optimization of material properties of EPS applied to an ERS track has been performed. The optimization criteria were minimization of the 'dead' weight of a track structure as well as the costs related to the sub-grade improvement while imposing constraints on the maximum rail displacements and stresses in the EPS and subsoil layers.

A set of Pareto optimal solutions has been obtained using a numerical optimization technique based on MARS (Multipoint Approximations based on Response Surface fitting) method. The results have demonstrated feasibility and advantages of using EPS in an ERS design especially for subsoil with very poor stiffness properties.

6 References

1 Duškov, M. (1997) *EPS as a Light-weight Sub-base Material in Pavement Structures.* Ph.D. thesis, Delft University of Technology, Delft, June 1997, ISBN 90-9010660-X

2 Esveld, C. (1989) *Modern railway track. MRT productions*. Zaltbommel 1989, ISBN 90-9010660-X

3 Esveld, C., Kok, A.W.M. (1998) Interaction between Moving Vehicles and Railway Track at High Speed. Rail Engineering International, 27, 3, 14-16.

4 Horvath, J. S. (1995) *Geofoam geosynthetic.* Horvath Engineering, P.C., New York, July 1995

5 Kok, A.W.M. (1998) Moving loads and vehicles on a rail track structure: RAIL User's Manual, Report 0321-12202, TU Delft.

6 Markine, V.L. (1999) *Optimization of the Dynamic Behaviour of Mechanical Systems.* PhD Thesis, TU Delft. Shaker Publishing B.V. ISBN 90-423-0069-8.

7 Markine, V.L., Zwarthoed, J.M., C. Esveld, C. (2001) Use Of Numerical Optimisation In Railway Slab Track Design. In. O.M. Querin (Ed.): Engineering Design Optimization Product and Process Improvement. Proceedings of the 3rd ASMO UK / ISSMO conference, Harrogate, North Yorkshire, UK, 9th –10th July 2001. ISBN: 0-85316-219-0 (for text version), ISBN: 0-85316-222-0 (for CD-ROM version)

8 Siderius, R. M. (1998) Feasibility of EPS as a lightweight sub-base material in rail structures. Delft University of Technology, Delft, August 1998, *Report 7-98-211-8*, ISSN 0169-9288

9 Zwarthoed, J.M. (2001) Slab Track design: Flexural Stiffness Versus Soil Improvement. *Proceedings of Rail-Tech Europe 2001 Conference*.