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Research on the mode of operation of geosynthetic reinforced load-bearing systems over soft layers in railway lines

Weisemann, U.
GEPRO Ingenieurgesellschaft für Geotechnik, Verkehrs- und Tiefbau und Umweltschutz mbH, Dresden, Germany

Lieberenz, K.
Hochschule für Technik und Wirtschaft (FH), Dresden, Germany

Vogel, W.
Deutsche Bahn Netz AG, München, Germany

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ABSTRACT: Because of the layout of the line, railway lines were frequently led over embankment locations and/ orthrough level terrain over soft layers. The soils with a low load-bearing capacity prevailing in the subsoil have a low shearing resistance and a high ductility. Under the influence of the own as well as of the travelling loads a consolidationor partial consolidation usually occurs so that a state of equilibrium is reached. An increase in the traffic load (speed, wheel-set load, route utilization) can once again lead to problems in the serviceability and in the stability of the earthstructures and hence to restrictions in the availability of the lines. The earth structures and their foundations then have to be reinforced in order to cope with the increased traffic loads. In order to reduce and to steady possible subsidence ef-fects, geosynthetic reinforced load-bearing systems can be used successfully. This increase in the resistances in the areaclose to the tracks can be combined with a reduction of the influences exerted by means of the use of elastic elements in the superstructure of railway lines. This article aims at reporting on the development of the fundamental principles, the execution of construction stages, the measurement technology investigations and the mathematical simulation regarding the mode of operation of geosynthetic reinforced load-bearing layers.

1 SUBJECT

The biggest part of the approx. 40,000 km of railroad lines in Germany is led over earth structures in embankment, excavation or shelf locations and/or through level terrain. A large part of these was already constructed during the 2nd half of the 19th century under technical conditions which were relatively modest.

On account of the routing of the lines, the railroad lines were frequently led over soft layers in this process. The soils prevailing in the subsoil with a low load-bearing capacity have a low shear strength and a high deformability. The impact of the own and traffic loads usually led to a consolidation or a partial consolidation in the existing lines so that an equilibrium state was arrived at.

An increase of the traffic load (speed, wheel-set load, route utilization) can in turn lead to problems regarding the serviceability and the load-bearing capacity of the earth structures and hence to restrictions in the availability of the routes again. The earth structures and their foundation then have to be improved in order to make sure that these correspond to the requirements of the increased traffic loads.

The constructional measures required to that end pose a large number of geometric and geotechnical problems but also of construction operational and ecological problems. The improvement of the earth constructions of existing railroad lines usually comprising two tracks is made more difficult on account of the fact that the improvement measures on the railroad line have to be carried out under the continuous influence by the railroad traffic on the track in operation. In this context, safety on the track under construction and on the track in operation has to be ensured without any restrictions. The geometrical and geotechnical as well as construction operational interdependencies between the track under construction and the track in operation influence the choice of the improvement procedure and almost make alternative improvement concepts a matter of necessity.

2 FUNDAMENTAL PRINCIPLES

Traffic loads act on the overall system which is responsible for the removal of loads in railroad lines and which consists of a superstructure, substructure

as well as of the subsoil and, moreover, this overall system is exposed to changing climatic, geological and hydrological conditions. To that end the impacts do not only have to be considered statically or quasistatically but also dynamically.

The quasi-static load shares are characterized by the respective wheel-set loads of the trains travelling over the tracks, the travelling speeds as well as by typical carriage distances, axle bases and distances between bogies. Additional dynamic loads emerge on account of mutual interactions between the vehicle and the route on which it travels, such as e.g. on account of cases of unevenness in the route (waves, ripples) or on the vehicle (eccentricity of the wheel). Figure 1 shows the prevailing vibration velocities for travelling of an Intercity train depending on the respective frequency ranges as an example.

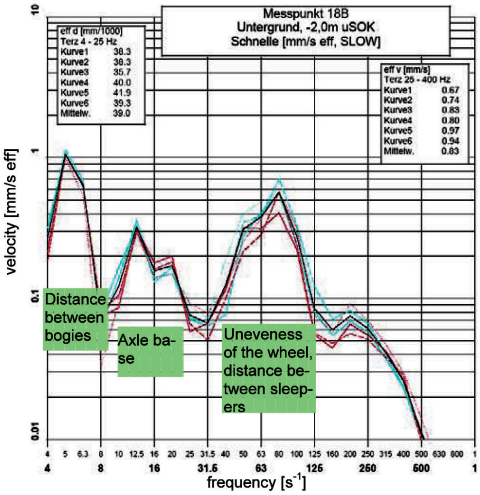

Figure 1. Third octave-vibration velocity-spectrums by passenger carriages with a speed of approx. 160 km/h at a depth of approx. 2 m below the upper edge of the sleeper in the frequency range from 4 to 1000 Hz.

An increase of the influences usually leads to subsidence effects in case the resistances in the subsoil are too low for taking up and removing the loads without damage. In particular in case of soft layers subsidence effects will be relatively large on account of the deformation potential of such layers and such effects can occur over a longer period of time.

Hence, inadmissibly large changes in the position of track can be caused. As a result of this a problem with regard to the serviceability of the line will have to be expected which in turn usually leads to restrictions in the availability of the railroad line.

3 IMPROVEMENT CONCEPT IN PARTICULAR BY MEANS OF GEOSYNTHETIC REINFORCED LOAD-BEARING SYSTEMS CLOSE TO THE TRACK

From this complex consideration of the elements of superstructure, substructure and subsoil within the system of the vehicle/carriageway an expanded approach can be derived with regard to improvement measures (Figure 2).

The deep-foundation constructional measures in the substructure and in the subsoil, which have been used primarily so far, should, in the future, be supplemented and, hence, optimised even more consistently with measures on the track and/or close to the track and with measurement technology measures. In particular in the course of the improvement of railroad lines with soft layers a new level of quality also with regard to the operation of the construction and ecological aspects can be achieved with the help of a combination of the following concepts:

(a) *Geosynthetic reinforced load-bearing systems close to the track* distribute and steady possible cases of subsidence to lengths which are not critical with regard to the position of the track and the travelling comfort. Hence, they ensure a sufficient serviceability and a use requiring little maintenance.
The effect of the improvement and/ or preservation of the load-bearing capacity which is inherent in geosynthetic materials in systems of load-bearing layers can be explained with the help of the effective basic functions
– separation and reinforcement as primary functions,
– but also of filtering and draining as secondary functions
which result in a complex working principle. One further effect is the damping effect of geosynthetic materials which is caused by the distinct elastic behaviour of the reinforcement layers. By means of this vibration velocities are reduced.

→ Increase of the resistances in the substructure and reduction of the influences arising from traffic.

(b) *Elastic elements* in the superstructure reduce the dynamic impacts as spring and damping elements. Moreover, tensions arising on account of the formation of a bigger elastic line of the track are distributed close to the track more effectively.

→ Reduction of the effects of the traffic.

(c) *Measurement technology measures* do not only offer an additional safeguard against inadmissible deformations and states of failure, they also permit the establishment of realistic and improved soil

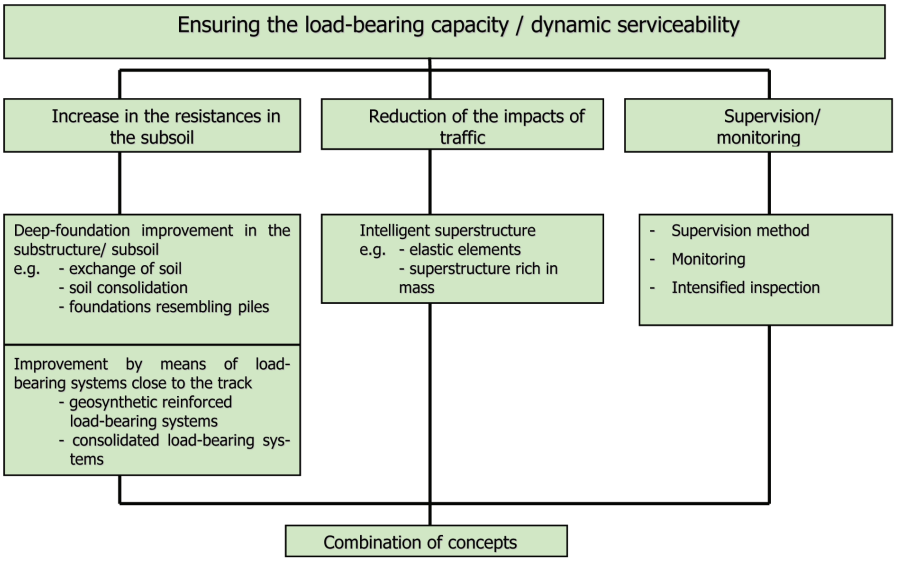

Figure 2. Measures for the improvement of railroad lines.

parameters on the basis of the measurement values by means of model calibration.

(d) *The permanent monitoring* over certain periods of time also permits a considerably increased certainty regarding the measured values and hence the soil parameters established on the ba-sis of these; hence, this permits more precise knowledge regarding the behaviour of the structure and of the subsoil.

4 DOUBLY GEOSYNTHETIC REINFORCED LOAD-BEARING CAPACITY CLOSE TO THE TRACK IN CASE OF ORGANIC SUBSOIL DURING THE CONSTRUCTION PROJECT REGARDING THE HAMBURG – BERLIN RAILROAD LINE

In the framework of this construction project the travelling speed along the Hamburg - Berlin railroad line was increased from 160 km/h to 230 km/h. In the section concerned an embankment with a height of between 4 and 5 m had to be improved on an organic soft layer with a thickness of approx. 1.2 m.

A deep-foundation constructional measure was dispensed with. Instead of such a measure a doubly geosynthetic reinforced load-bearing layer system was installed with the following structure of the layers:

- 30 cm of a well graded grain mixture with a low permeability ($k \leq 10^{-6}$ m/s) and a high compactness,
- a woven geogrid Fortrac 40/40-35T on an intermediate subgrade within the load-bearing layer,
- 30 cm of a well graded grain mixture with a higher permeability ($k \geq 5 \times 10^{-5}$ m/s) and a high compactness,
- a geocomposite Comtrac 50/50 B25 on the soil subgrade.

The elasticity of the superstructure was increased by means of an increase in the thickness of the gravel layer to 35 cm and of the installation of an elastic intermediate layer Zw 700 with a stiffness of 60/90 kN/mm.

5 MEASUREMENT TECHNOLOGY EXAMINATIONS

5.1 *Extent of the measurements*

With the help of the measurement technology examination we can establish what the effects of a superstructure with a higher elasticity and of a geosynthetic reinforced load-bearing layer system are on the substructure and the subsoil.

The measurement cross sections 4 and 5 established to that end can be characterized as follows:

- a doubly geosynthetic reinforced load-bearing layer system with an elastic superstructure over an organic subsoil (measurement cross section 4) and
- a reference cross section with an elastic superstructure without a soft layer in the subsoil (measurement cross section 5).

So far, the following measurement campaigns have been carried out in the period of time from 2002 until 2004:

- Measurement of the vibration acceleration:
  - Berlin-Hamburg track: 3 measurement campaigns (in July 2002, February/March 2003 and May 2004),
  - Hamburg-Berlin track: 2 measurement campaigns (in February/March 2003 and May 2004).
- geodetic and inclinometer measurements:
  - 4 measurement campaigns on both tracks (July 2002, March 2003, August 2003 and June 2004).

5.2 *Deformation measurements*

In the course of the geodetic measurements the deformations of the dam embankment were monitored over the entire period of time from July 2002 until June 2004. At the same time, the subsidence effects on the embankment at a depth of between approx. 2.0 m and 3.5 m below the upper edge of the tracks were recorded with the help of the inclinometer measurements.

In the course of the control measurements with the inclinometer cases of subsidence and/ or heave amounting to 2 to 3 mm were found compared to the original measurement (see Figure 4). Since these deformations ascertained only fall within the range of the measurement precision, we can assume that the embankment does not display any outstanding characteristics with regard to the deformations from the subsoil.

The geodetic measurements of the geometry of the embankment confirm the results obtained in the inclinometer measurements and do not show any conspicuous movements of the dam embankment.

5.3 *Vibration measurements*

The vibration measurements were realized with the help of vertical vibration acceleration sensors. On the basis of this vertical vibration paths (elastic sags) and vibration velocities can be derived.

In Figure 5 herein below the saggings established for the measurement cross section 4 for the reinforced load-bearing layer system with an organic subsoil and for the measurement cross-section 5 (reference case) are displayed along the depth. In this process it becomes obvious that though the deformation potential in measurement cross section 4 is higher, the deformations which occurred were approximately of the same dimension.

Figure 6 compares the relative vibration velocities for the two measurement cross sections. In this illustration the positive effect of the geosynthetic reinforced load-bearing layer system with regard to dynamic stress is shown clearly. On the track formation the vibration velocities of the two measurement cross sections are roughly of the same dimension. However, below the reinforced load-bearing layer system the vibration velocities are up to approx. 20 per cent lower than in the reference case.

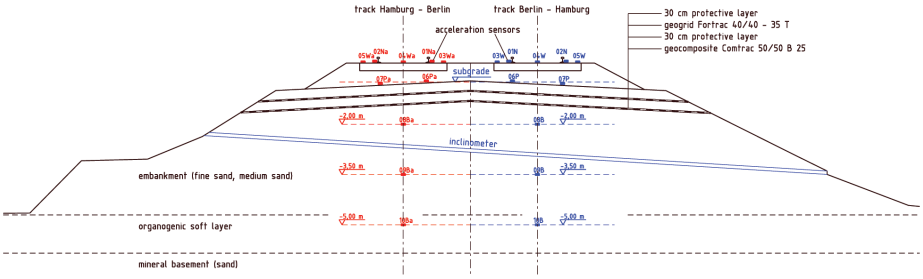

Figure 3. Measurement cross section 4 with a representation of the load-bearing system installed, of the inclinometer and the aeration sensors.

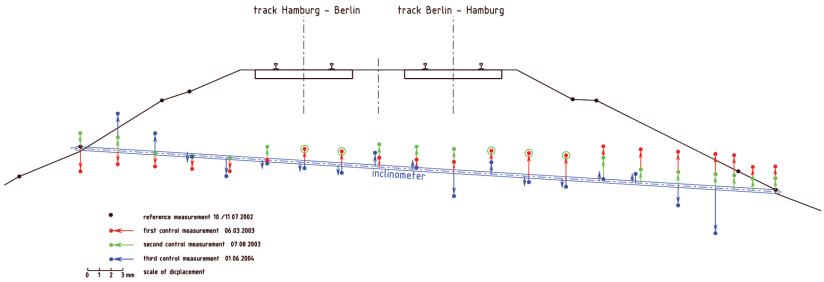

Figure 4. Inclinometer measurements on measurement cross section 4 with an organic subsoil.

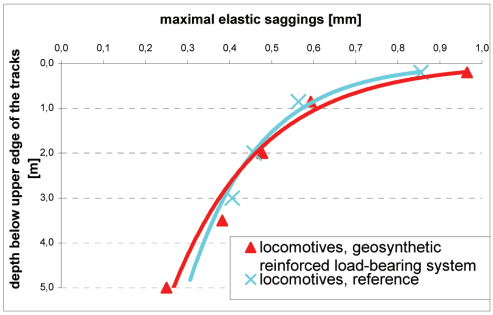

Figure 5. Elastic saggings on account of the passage of locomotives at a speed of 160 km/h.

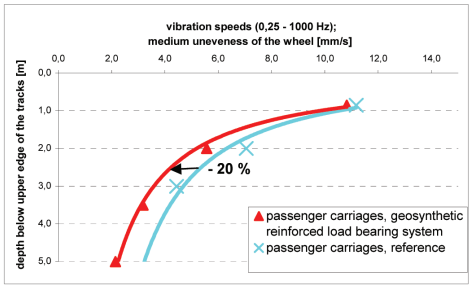

Figure 6. Vibration velocities in the reference case and in the geosynthetic reinforced load-bearing layer system on account of the passage of passenger carriages at a speed of 160 km/h.

6 CALCULATORY SIMULATIONS REGARDING THE MODE OF OPERATION OF GEOSYNTHETIC REINFORCED LOAD BEARING LAYERS

The dynamic behaviour of the overall system consisting of the superstructure, substructure and subsoil was established on the basis of the results obtained in the vibration acceleration measurements with the help of calculations in accordance with the finite element method (FE calculations). These dynamic FE calculations resulted in sags, vibration velocities and shear extensions for different speeds and load cases.

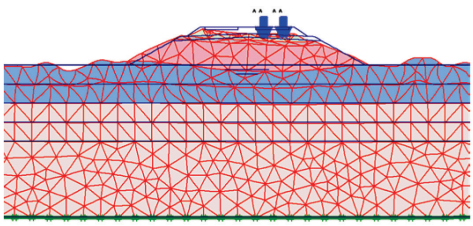

Figure 7. Example of the course of sagging over time during the simulation of the passage of a train on the deformed network (deformations are shown excessively).

Table 1 shows the parameters of the FE calculations, which were recalculated with the help of the measurements.

Table 1. Parameters of the dynamic FE calculations.

layer	dry density ρ_d [g/cm^3]	medial effective stress σ'_0 [MN/m^2]	shear modulus G_{d0} [MN/m^2]	Poisson's ratio ν [–]
protective layer	2.00	40.8	108.9	0.25
embankment (fine sand.	1.70	22.9	57.4	0.30
medium sand)		37.1	731.1	0.30
organic soft layer	1.20	58.8	42.2	0.485
mineral basement (sand)	1.80	60.0	106.1	0.485

Figure 8 shows the calculated and measured maximum elastic saggings, whereas Figure 9 shows the calculated and the measured maximum vibration velocities for the doubly geosynthetic reinforced load-bearing layer system under consideration of different types of vehicles.

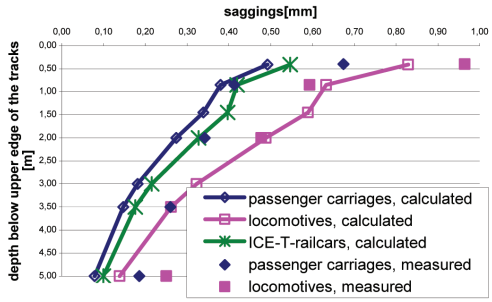

Figure 8. Comparison of measured and of calculated maximum elastic saggings on measurement cross-section 4 (geosynthetic reinforced load-bearing layer system).

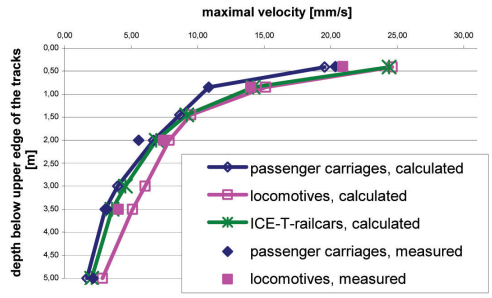

Figure 9. Comparison of measured and calculated maximum vibration velocities on measurement cross-section 4 (geosynthetic reinforced load-bearing system).

On account of the good correspondence between the measured and the calculated values this approach is suitable for the review of the dynamic behaviour of the substructure and of the subsoil by means of the dynamic calculation of such. Hence, a statement can now also be made with regard to configurations of superstructure, substructure and subsoil which have not been recorded by means of measurement technology and, in addition to this, with regard to traffic loads.

For example, it is possible to draw conclusions with regard to the behaviour of the geosynthetic reinforced load-bearing layer system at higher speeds or higher axle loads with the help of the calculation outlined herein above.

7 CONCLUSIONS AND OUTLOOK

An essentially differentiated and more profound consideration of the influences from traffic and resistances within the structure and the subsoil leads to problem-oriented proposals for solutions with regard to the improvement including measures in the superstructure.

Geosynthetic reinforced track systems close to the track turn out to be extremely effective on account of the effect of improving and/ or preserving the load bearing capacity, in particular in areas of soft layers.

The results obtained in measurements and calculations for the construction project regarding the Hamburg – Berlin railroad line described in this article have shown that by means of the installation of geosynthetic reinforced load-bearing layer systems the stresses exerted on the soft layers present can be reduced and the resistances in the substructure close to the track can be increased.

In addition to the explanatory calculation regarding the behaviour of the substructure and of the subsoil the objective of dynamic model calculations can also be that of an evaluation of the dynamic serviceability of geosynthetic load-bearing layer systems. Such evidence can be established for example with the help of the shear extensions established. This value is an expression of the degree of the dynamic stress on soils. High shear extensions show that there is a high degree of dynamic stress. Moreover, they are also a result of dynamic FE calculations. However, there is need for further research with regard to the threshold values of shear extensions in particular in the case of soft layers and geosynthetic reinforced load-bearing layer systems.

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