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# Ground Improvement under Dynamic Loading

M. Ittershagen

*Baugrundinstitut Franke-Meißner und Partner GmbH, Germany*

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# GROUND IMPROVEMENT UNDER DYNAMIC LOADING

**Dr.-Ing. M. Ittershagen**
Baugrundinstitut Franke-Meißner und Partner GmbH
Max-Planck-Ring 47
65205 Wiesbaden-Delkenheim, Germany

ABSTRACT

To analyze the dynamic soil-structure interaction of railway lines on soft soil experimental and numerical investigations have been carried out. The mean intention was to get information about the influence of different soil improvement layouts and further on to establish a design tool for railway lines on soft soil based on the additional results of a numerically supported parametric study. The principle part of the paper is the presentation of the experimental and numerical investigations.

## INTRODUCTION

Maintenance and renewal of railway limes

Railway lines especially on soft organic soils are connected with extensive operational costs that could be subdivided into one-time investments and maintenance investments. One-time investments are e.g. the renewal of the substructure, the ballast or soil improvement works under the railway line. Maintenance investments are e.g. the recurring lifting of the ballast substructure by means of additional gravel.

If the deformed railway line on soft soil must be restored two extreme cases are possible, pictured in Fig. 1. The first one is to lift up the sleepers and fill in additional gravel until the required position of the track is reached. This first scenario is connected with very low one-time investments for the track construction machine and the gravel ($B_1$) and probably very high maintenance investments ($M_1$) in the next years due to the recurring settlement of the sleepers and the bars. The quality standard in this case is very poor.

The second alternative is to build a foundation on bored piles under the existing substructure. This version is definitely connected with very high one-time investments ($B_2$) for the pile foundation and probably very low maintenance investments ($M_2$) in the following years. The quality standard in this case is very high. Both examples are more or less expensive due to the total investment.

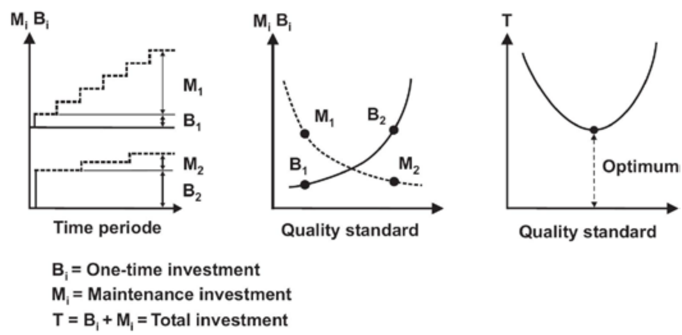


*Fig. 1. Interaction between one-time and maintenance investment.*

To find a technical and economical optimized solution project specific investigations are necessary. For railway lines on soft soil one technical and economical method to reduce the total investment is to improve the dynamic performance of the ground by means of column shaped soil improvement. This is connected with an increase in the dynamic stiffness and further on with a reduction of the traffic introduced vibrations in the ground. To get more information about the vibration reduction field tests with different soil improvement configurations are initiated and performed in conjunction with the German National Railway Administration. The purpose of the investigations is to find a technical and economical optimised ground improvement design for a railway line on a 10 m deep soft soil layer and to derive general statements for soil improvement under dynamic loading.

Traffic introduced vibrations in the ground

During the passage of the train the subsoil below the track system is set into damped oscillation. The introduced energy is transmitted in the subsoil by compression and shear waves and at the surface by rayleigh waves. Fig. 2 shows the distribution of these waves from a circular footing under dynamic loading on a homogeneous, isotropic, elastic half-space after Woods (1968). The propagation velocity of these waves depends mainly on the stiffness, the density, the Poisson's ratio and the saturation of the ground. Similar to a static loading the introduced shear waves are connected with dynamic shear strain in the ground.

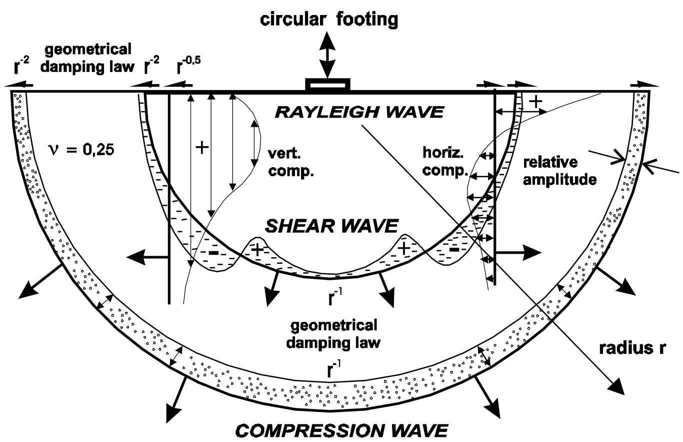


*Fig. 2. Distribution of displacement waves from a circular footing on a homogeneous, isotropic, elastic half-space.*

The amplitude of dynamic shear strain is significantly influenced by the ratio β (Eq. 1) of the activated circular frequency $\omega_A$ (rad/s) due to the speed of the train and the natural circular frequency $\omega_N$ (rad/s) of the total system. If the activated circular frequency $\omega_A$ is equal to the natural circular frequency $\omega_N$ ($\beta = 1$) the motions for the undamped system becomes infinite. This type of deformation behavior is commonly called resonance. It must be annotated that the natural soil body consists geometrical and material (frictional) damping. In a damped system the motions increase strongly at $\beta = 1$.

$$\beta = \frac{\omega_A}{\omega_N} \quad [-] \tag{1}$$

The resonance problem is relevant for railway lines on soft soil with a maximum layer thickness of 10 m because the natural frequency $f_N = \omega_N / 2\pi$ (Hz) of the soft soil layer below the track and the exciter frequency $f_A$ (Hz) due to the train crossing with a train speed of $V \leq$ 150 km/h are is the same frequency domain of $f_i \leq 10$ Hz.

To investigate the soil-structure interaction of railway lines founded on soft soil experimental field tests accompanied by dynamic measurements are a proper and valuable method.

Measurements in Ledsgard (Sweden)

To observe and analyse the mitigation of the ground vibrations the Swedish National Rail Administration initiated a research project, described in Holm et al. (2002). The purpose of the investigations is the dynamic response of the ground before and after the soil improvement work. The subsoil profile below the railway line consists of a layer of very soft organic soil called gyttja overlaying a soft clay stratum. The gyttja has a maximum organic content of 20 % and a shear resistance of $c_u$ = 20 kN/m². The soil improvement was done by Lime-Cement Columns placed in grids. To observe the vibration reduction the dynamic response of the ground measurements was measured before (May 2000) and after (December 2000) the column installation. In Figure 3 the amplitude of the measured vertical particle velocities for two different test sections are presented, the first section with a 2 m and the second one with a 3 m thick layer of gyttja. The measurements were performed by geophones in a distance of 3 m from the track. The values in Fig. 3 are measured in the middle of the test train.

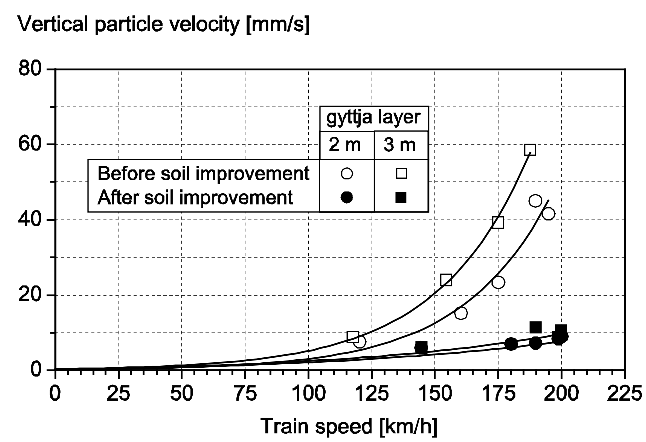


*Fig. 3. Amplitude of vertical particle velocity before and after the installation of soil improvement*

Without the Lime-Cement Columns the amplitudes of the vertical particle velocities increases nearly exponential with increasing train speed. This trend is an indication for the "high speed phenomenon". The measured particle velocities before and after the soil improvement in Figure 3 clearly demonstrate the strengthening effect and the vibration reduction of the Lime-Cement Columns placed in a grid.

The measurements in Ledsgard, Sweden clearly reveal that soil improvement is an adequate method to reduce the particle velocity in the ground.

Task

During the train passage the ground is set into oscillations that will cause long time deformations of the track. The amount of these deformations is significantly influenced by the amount of the oscillations. The amplitude of these oscillations depends mainly on the soil stiffness and the train speed. With decreasing soil stiffness the amplitude increases (Kramer, 1996). To reduce the oscillations in the ground it is state of the art to increase the dynamic stiffness by soil replacement or soil improvement (Hildebrand, 2001).

To get more information about the influence of the soil improvement layout experimental field test are initiated and performed. The results of the experiments will be used to develop a numerical based design tool for different ground conditions like deeper soft soil layers and varying stiffness properties.

## EXPERIMENTAL INVESTIGATIONS

To investigate the influence of the soil improvement layout under a railway line on soft soil experimental investigations were done in a 300 m long testing area in northern Germany.

Column arrangement in test track TS0 – TS4

In Fig. 4 the column arrangement installed in the five different test tracks TS0-TS4 is given. The ground improvement was constructed by Lime-Cement Columns with a column diameter of 0.6 m. Based on the Design Guide for Soft Soil Stabilisation (BRE, 2002) a dry mixture of 90 % cement and 10 % lime was used, the amount of binder mixed in was about 110 kg/m³.

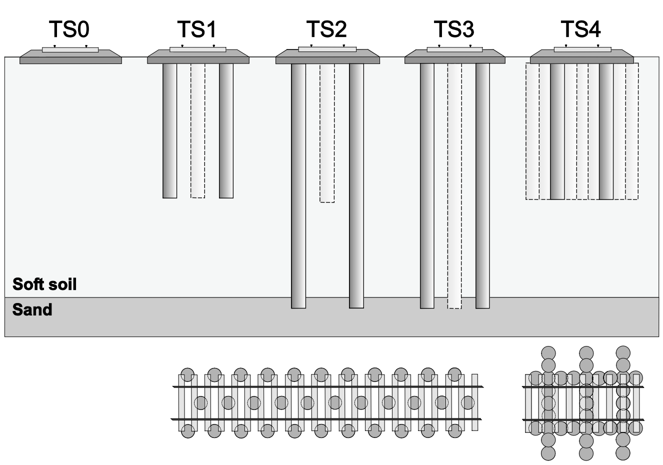


*Fig. 4. Cross section and column arrangement installed in the test tracks TS0 - TS4*

Subsoil conditions in the testing area.

The subsoil in the testing area consists of a soft soil layer with a depth of about 10 m overlaying a good bearing middle dense to dense sand stratum. The average consistency index of the soft soil is $I_C$ = 0.4, the water content varies with depth between w = 0.6–1 and the average organic content is about 10–15%. The groundwater table was 1 m below the surface. The mean mechanical parameters of the soft soil and the sand are given in Table 1.

Table 1. Parameters of the subsoil

| Parameter | Symbol | Unit | Soft soil | Sand |
|---|---|---|---|---|
| Elastic module | E | MN/m 2 | ≤ 3 | 65 |
| Friction angle | $\varphi'$ / $\varphi_u$ | ° | 25 / 0 | 30 / 0 |
| Cohesion | c' / $c_u$ | kN/m$^2$ | 5 / 40 | 0 / 0 |
| Density | $\gamma$ | kN/m$^3$ | 14–17 | 18–19 |

Layout of the measurement program

Each test track was equipped with multiple measurement devices pictured in Fig. 5 and Fig. 6 to observe the dynamic response of the subsoil and the railway structure during operation. During the tests the area was passed for three month with different train speeds of $V_1$ = 30 km/h, $V_2$ = 50 km/h, $V_3$ = 70 km/h and $V_4$ = 90 km/h ($V_4$ only for the passenger trains). Altogether 1.200 train crossings were observed and recorded.

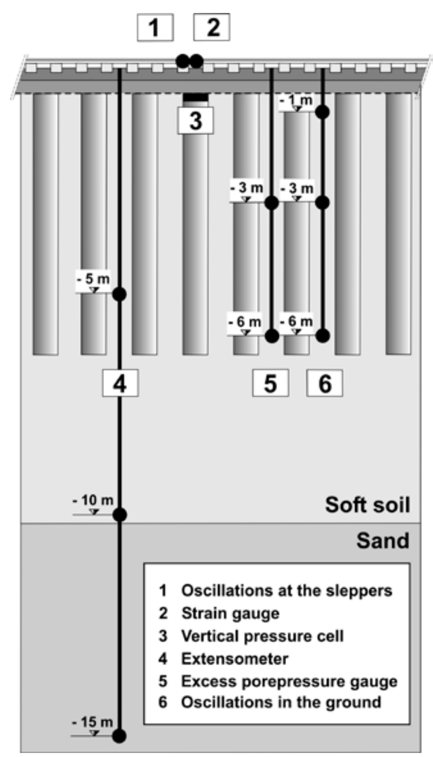


*Fig. 5. Layout of the measurement devices (Example: TS1).*

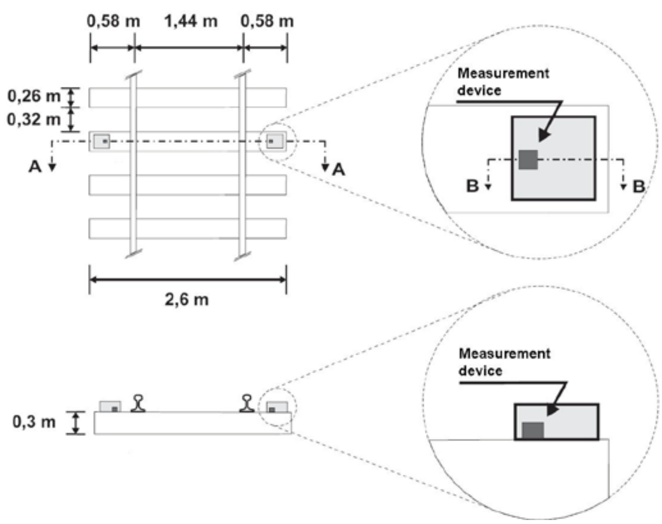


*Fig. 6. Arrangement of the measurement devices to observe the oscillations of the sleepers.*

Results of the experimental investigations

In Fig. 7 the measured vertical stress for a passenger train with V = 30 km/h and a freight train with V = 50 km/h are shown. The stress measurements were done in a depth of 0.4 m below the sleepers.

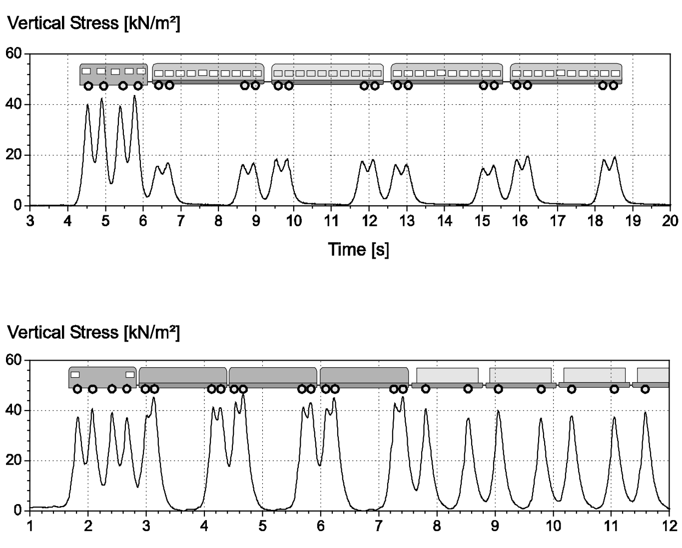


*Fig. 7. Vertical stress for passenger and freight train.*

The crossing of a train axis leads to a single stress amplitude. The frequency of the dynamic loading is strongly influenced by the distance of the wheel sets. Due to the lower weight the stress amplitudes of the passenger wagons are obviously smaller compared to the freight wagons. The axial loading for the passenger train was about 100 kN and for the freight train 225 kN witch is coincident with the maximum axial loading allowed in Germany.

In Fig. 8 the excess porewater pressure in a depth of 3 m for a freight train with a speed of about 30 km/h is represented for test track TS0, TS1 and TS4. The measurements reveal that only a small amount of the dynamic loading is transferred in the porewater. For the test track configuration TS0 without any soil improvement the additional porewater pressure is p ≤ 3 kN/m².

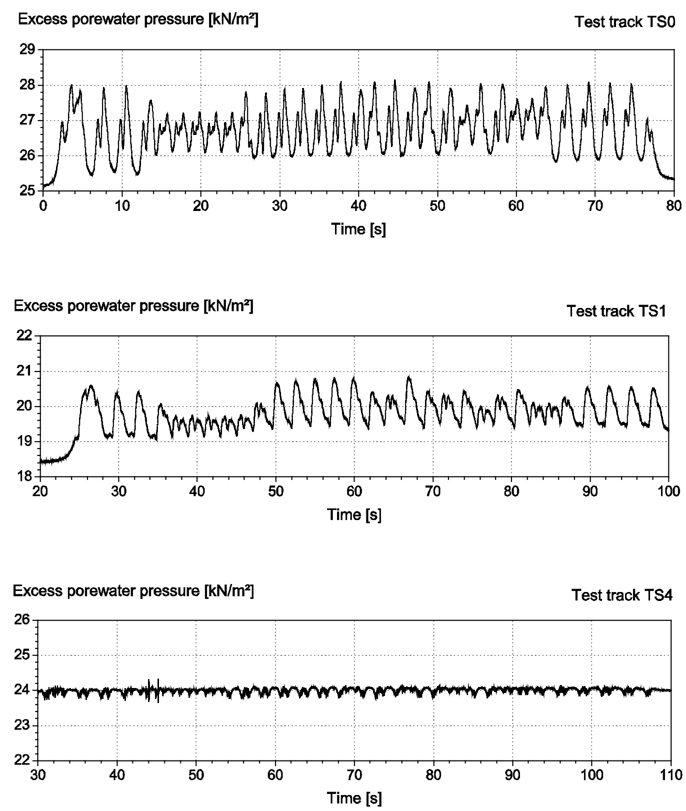


*Fig. 8. Comparison of the measured excess porewater pressure in test track TS0, TS1 and TS4.*

Compared with test track TS0 in a depth of 3 m the measured porewater pressure in test track TS1 and TS4 are lower due to the higher hydraulic permeability of the young lime-cement matrix (Broms et al., 1977). Experiences made by Brandl in 1999 confirm that the hydraulic permeability of the young column matrix until the age of approximately 1 year is 400-1000 times higher than that of unstabilised soil. The highest hydraulic permeability thus is observed in test track TS4 were the columns are placed in grids.

To get information about the oscillations in the ground during the train passage triaxial acceleration measurements were performed in a depth of 1 m, 3 m and 6 m below the surface. The vertical accelerations are integrated into velocities and converted into the Root Mean square Values according to DIN

1311-1:2000-02 (Eq.1) calculated from the vertical oscillations, abbreviated RMS.

$$RMS = \sqrt{\frac{1}{T}\int_0^T x^2(t)\,dt} \qquad (1)$$

In Fig. 9-11 the results for the freight trains for different train speeds in test track TS0, TS1 and TS4 are presented. To compare the results best fitting curves with an exponential function are added.

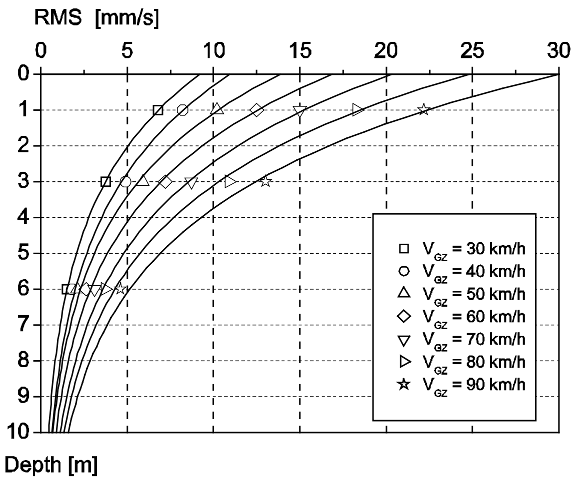


*Fig. 9. RMS vs. depth for test track TS0.*

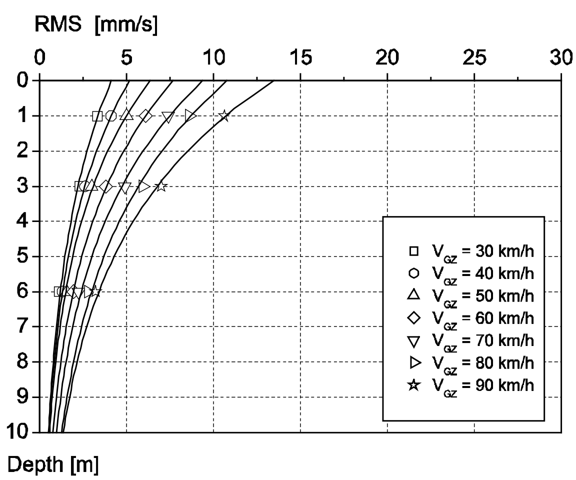


*Fig. 10. RMS vs. depth for test track TS1.*

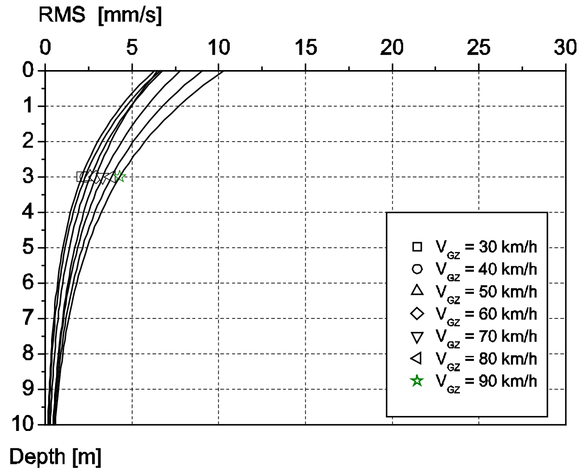


*Fig. 11. RMS vs. depth for test track TS4.*

In Fig. 9 the RMS decreases rapidly with increasing depth, the greatest values are measured in the near of the surface. Beyond this it can be recognized especially for the measurement point in a depth of 1 m that the RMS in test track TS0 increases more than linear with every train speed increment. Compared to test track TS1 and TS4 the RMS-Values close to the surface are obviously smaller due to the higher dynamic stiffness of the soil improvement under the railway track and thus connected with a smaller rate of long term deformation.

## NUMERICAL INVESTIGATIONS

The first aim of the experimental field tests was to analyse the dynamic soil-structure interaction of a railway line on soft soil. The mean intention was to get information about the influence of different soil improvement layouts on the dynamic response of the soil for a specific project in northern Germany.

Beyond this the experience will be used to develop a numerical bases design tool for different ground conditions like deeper soil layers and varying stiffness parameters. The back analysis was done by 3D-calculations after the Finite Element Method (FEM).

### Finite Element Model

The 3D-FE model used is pictured in Fig. 12. The soil improvement was modelled using a area with mixed stiffness parameters below the railway track. In Fig. 13 the cross section of the FE-model with and without soil improvement is shown. In the first step only test track TS0, TS1 and TS4 are computed.

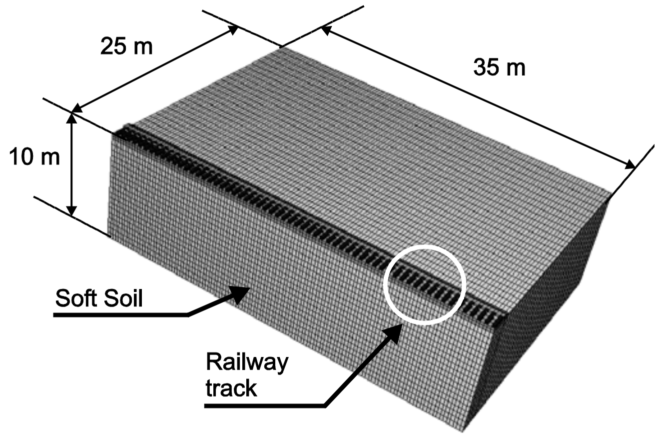


*Fig. 12. 3D-Finite Element Model.*

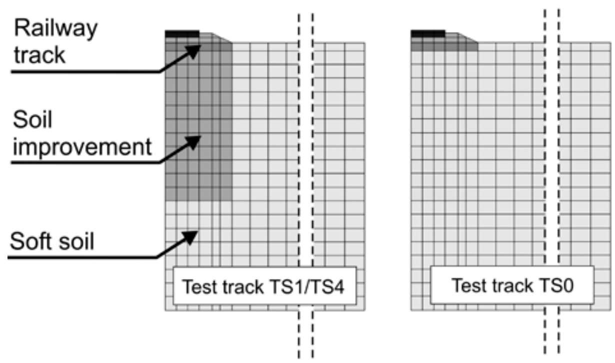


*Fig. 13. 3D-Finite Element Model (cross section).*

To investigate the speed dependent dynamic response of the track system and the influence of the soil improvement layout a short freight train with three wagons pictured in Fig. 14 was used with different train speeds of V = 30 km/h, 60 km/h and 90 km/h parallel to the field tests. The axial load of each wheel set was 225 kN according to the maximum allowed axial loading in Germany. The thickness of the soft soil layer was 10 m. The deeper sand layer was not modelled. Due to the high stiffness of this layer fixed vertical boundary are implemented at the bottom of the FE model.

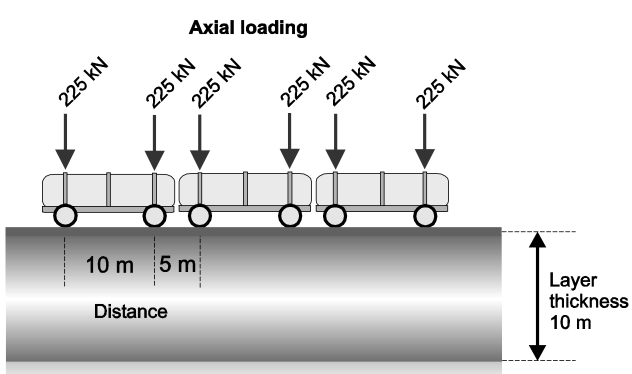


*Fig. 14. Numerical calculated freight wagons.*

Results of the numerical investigations

In Fig. 15 to 17 the measured values in the field and the numerical results for test track TS0, TS1 and TS4 for train speeds of 30 km/h, 60 km/h and 90 km/h are represented.

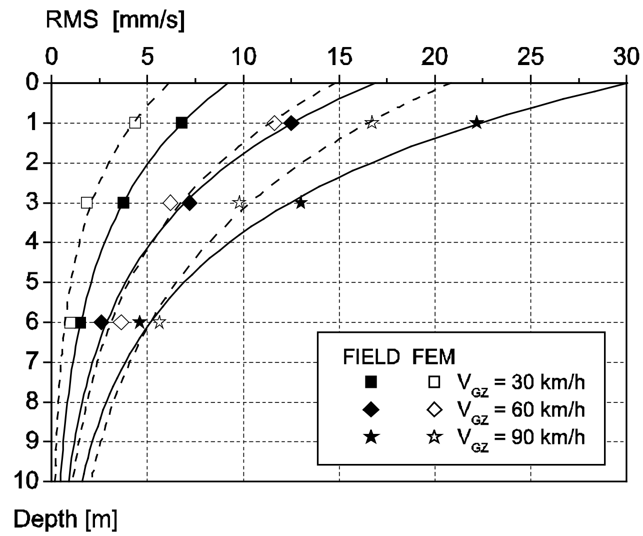


*Fig. 15. RMS, measurement vs. FEM, TS0.*

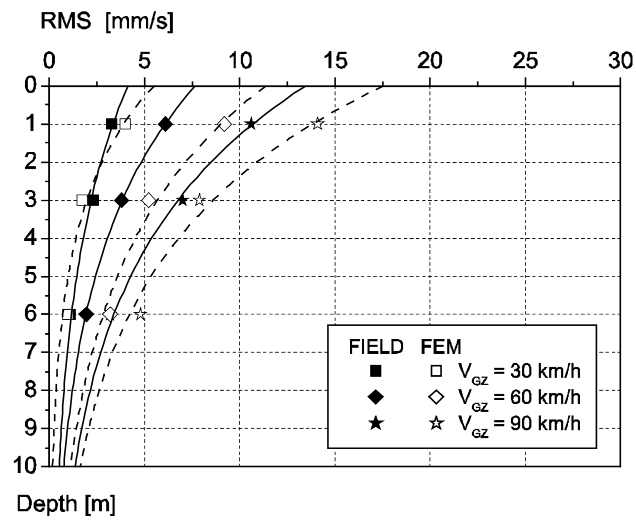


*Fig. 16. RMS, measurement vs. FEM, TS1.*

The comparison gives a good agreement for the fundamental dynamic behaviour of the used FE model. With soil improvement a lower RMS for constant train speed is obtained.

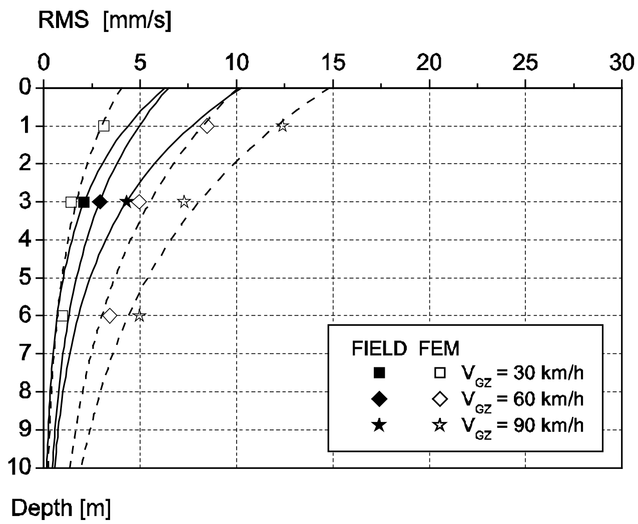


*Fig. 17. RMS, measurement vs. FEM, TS4.*

The numerical computed amount of the vertical oscillations is the same range as the measurements but in the field the reduction due to the different soil improvement layouts in test track TS1 and TS4 is a little higher. The reason for this could be found for instance in the assumption of a constant shear modulus with depth in the numerical model. This first FE model will be corrected with regard to the dynamic behaviour of the soft soil and a progressive model will be used for future calculations.

## CONCLUSIONS

To investigate the speed dependent dynamic response of the track system and the influence of the soil improvement layout experimental field tests combined and completed with additional numerical calculations are a proper and valuable method. The measurements and the results of the FE model demonstrate that the oscillations in the soft soil and thus the rate of long time deformation of the railway track can be reduced clear when soil improvement is done.

These experiences will be used to develop a design tool for soil improvement under railway lines on soft soil because a technical and economical solution depends on the local project conditions.

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