NEW DEVELOPEMENTS IN SOIL IMPROVEMENT UNDER RAILWAY LINES ON VERY SOFT SOIL

Rolf Katzenbach & Marc Ittershagen, Institute and Laboratory of Geotechnics, Technische Universität Darmstadt, Darmstadt, Germany

ABSTRACT
To analyse 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 dynamic measurement results from the experimental investigations.

RÉSUMÉ
Afin d'analyser l'interaction sol- structure d'une voie de chemin de fer sur un sol compressible des expériences et des simulations numériques ont été menées. Le but principal était dans un premier temps d'obtenir des informations sur l'influence de différents procédés d'amélioration du sol, pour ensuite établir outil de conception basé sur les résultats des simulations de cette étude paramétrique. Cet outil serait par conséquent adapté à ces lignes ferroviaires sur sols compressibles. Le présent rapport est principalement consacré à la présentation des résultats des mesures dynamiques obtenues lors des expériences.

1. TRAIN INTRODUCED VIBRATIONS

1.1 Exiting Frequency f_E and Resonance Frequency f_R

During the train passage the ground 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. The velocity of propagation of these waves depends mainly on the shear modulus G, the density ρ, the Poisson's ratio ν and the saturation of the ground. The amplitude of the oscillation is significantly influenced by the ratio of the exiting frequency f_E due to the speed of the train and the resonance frequency f_R of the soft soil layer given by Wu (1994) in Equation 1:

$$f_R = \frac{1}{4H}\sqrt{\frac{G}{\rho}} \quad \text{[Hz]} \qquad [1]$$

If the exiting frequency f_E is equal to the resonance frequency f_R the motions for the undamped system become infinite. This type of deformation behaviour is called resonance case. In a damped system like the natural ground that exhibits geometrical and material (frictional) damping the motions increase rapidly in this case. The resonance problem is relevant for railway lines on soft soil with a layer thickness of H < 10 m because there both frequencies are in the same domain of $f_i \leq 10$ Hz (Figure 1). One method to improve the dynamic behaviour is to reduce the train speed or to increase the dynamic stiffness of the ground by soil improvement.

To investigate the dynamic soil-structure interaction of railway lines founded on very soft soil with and without soil improvement experimental field tests accompanied by measurements are a proper and valuable method.

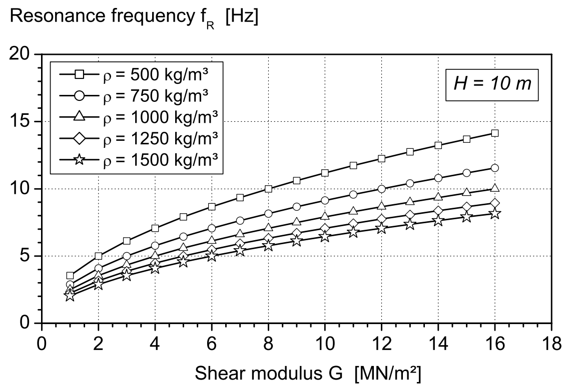

Figure 1. Resonance frequency f_R vs. shear modulus G

1.2 Field Measurements in Sweden

To investigate the impact of a wall shaped soil improvement by Lime-Cement Columns the Swedish National Rail Administration initiated a research project, described in Holm et al. (2002). The subsoil profile below the track system consists of a layer of very soft organic soil named 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. To observe the improving effect of the Lime-Cement Columns on the dynamic response of the ground measurements were performed before (May 2000) and after (December 2000) the column installation. In Figure 2 the amplitude of the measured vertical particle velocities (mm/s) 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 Figure 2 are measured in the middle of the train.

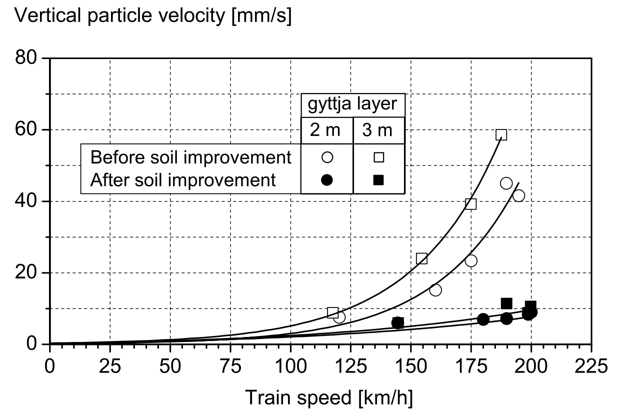

Figure 2. Amplitude of the vertical particle velocity vs. train speed, before and after the installation of wall shaped soil improvement after Holm et al. (2002).

Without the soil improvement the amplitude of vertical particle velocity increases nearly exponential with linear increasing train speed. This trend is an indication for the “high speed phenomenon”. The measured particle velocities before and after the soil improvement clearly demonstrate the strengthening effect of the wall shaped arrangement of the Lime-Cement Columns as soil improvement system.

2. EXPERIMENTAL FIELD TESTS

2.1 Test tracks TS0 – TS4

To investigate the influence of the soil improvement layout under a railway line on soft soil exposed to dynamic loading four different geometrical configurations of ground improvement patterns were installed in a 300 m long testing area in northern Germany. The ground improvement was constructed by Lime-Cement Columns, BRE (2002). The column arrangement installed in the 5 different test tracks TS0-TS4 is shown in Figure 3.

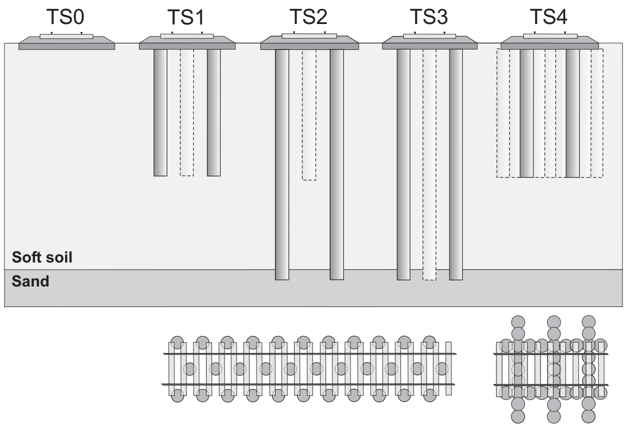

Figure 3. Geometrical configuration of the soil improvement.

2.2 Ground Conditions in the Testing Area

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

Table 1. Mean mechanical parameters of the subsoil

Parameter	Symbol	Unit	Soft soil	Sand
elastic module	E	MN/m^2	≤ 3	30–100
friction angle	φ' / φ_u	°	25 / 0	30 / 0
cohesion	c' / c_u	kN/m^2	5 / 40	0 / 0
density	γ	kN/m^3	14 – 17	18–19

2.3 Layout of the Measurement Program

To observe the dynamic response of the subsoil and the railway structure during operation each test track was equipped with multiple measurement devices pictured in Figure 4.

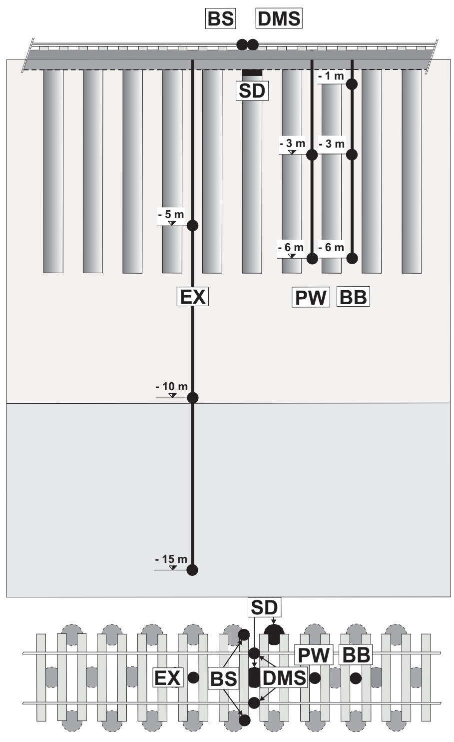

Figure 4. Layout of the measurement devices in TS1.

To get information about the oscillation in the ground triaxial accelerometers (BB in Figure 4) were installed in 1 m, 3 m and 6 m depths below the railway structure. Further on two triaxial accelerometers were fixed at the end of the sleeper

(BS) to record the oscillation of the railway structure. Pore water pressure measurements (PW) were performed in 3 m and 6 m depth and additional vertical stress measurements (SD) in 0.6 m below the railway structure. To determine the axial loading two strain gauges (DMS) were fixed to the bars and to observe the settlement an extensometer (EX) with anchor points in 5 m, 10 m and 15 m below the surface was installed. During the tests the testing 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).

3. RESULTS OF THE EXPERIMENTAL FIELD TESTS

3.1 Vertical Stress Measurements

In Figure 5 the vertical stress measurements during the crossing of a 320 m long freight train with a total weight of about 1900 t is pictured. The train consists of 20 freight wagons with 4 axes and one engine with 6 axes at the front. The values presented are measured at the centre device in test track TS0, the test track without any soil improvement. The train speed varies between 29 km/h and 72 km/h.

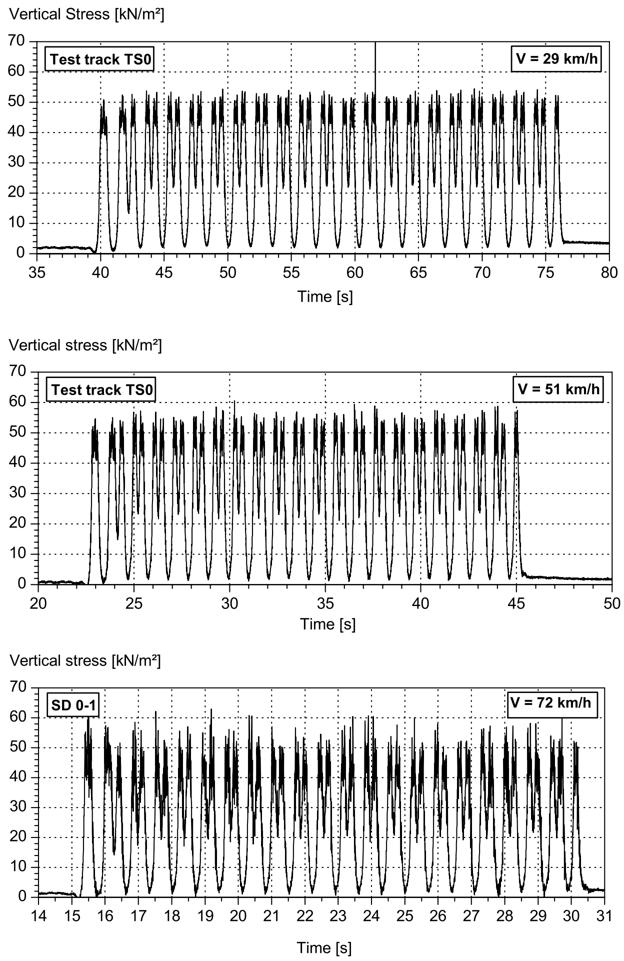

Figure 5. Vertical stress measurements – Test track TS0.

The measurement results show that the vertical stress varies between 50 kN/m² and 60 kN/m². The increase in train speed from 29 km/h to 72 km/h gives no relevant increase in vertical stress. Thus the amplitude of vertical stress is more or less constant. The frequency of the applied load is influenced by the train speed and dominated by the distance of the axes. The exiting frequency thus can be estimated by means of Equation 2.

$$f_E = \frac{V}{a} \quad [Hz] \qquad [2]$$

f_E = Exiting frequency [Hz]
V = Train speed [m/s]
a = Distance of axis [m]

Although the columns in test track TS1-TS4 are different in length there was no intense increase in stress observed over the top at the columns head. The reason therefore is the stiffness of the lime-cement column material of about E = 30-50 MN/m². These columns are named soft to semi-hard columns due to the underlying design philosophy for deep stabilization works, BRE (2002). Within this philosophy the applied load is partly carried by the columns and by the unstabilised soil between the columns. Thus an intense load concentration is not expected and desired.

3.2 Pore Water Measurements

In Figure 6 the vertical stress and in Figure 7 the correspondent pore water pressure measurements in a depth of 3 m and 6 m for a 640 m long freight train with a total weight of 2250 t is pictured.

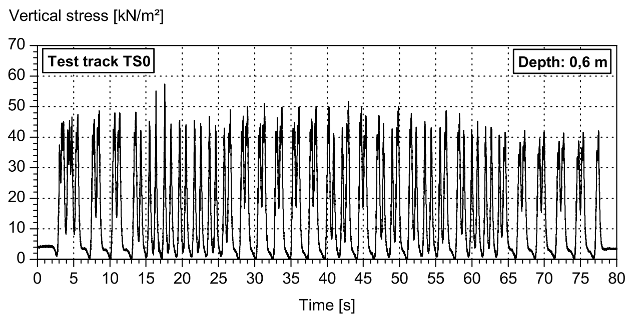

Figure 6. Vertical stress measurements – Test track TS0.

The train consists of 31 freight wagons with 2 and 4 axes and the train speed is 32 km/h. At the top there is one engine with 6 axes.

The pore water pressure measurements in Figure 7 reveals that only a small amount of the dynamic loading is transferred in the fluid phase. For the test track configuration TS0 without any soil improvement the additional pore water pressure is 2-3 kN/m². The additional pore water pressure decreases with increasing depth due to the load distribution.

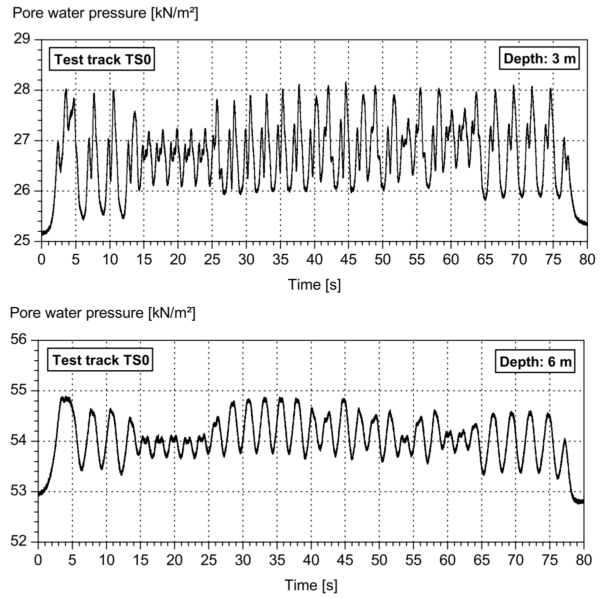

Figure 7. Pore water measurements – Test track TS0.

At constant depth the freight wagons with 2 axis, in Figure 7 located between Time = 15 s and 25 s, causes the half additional pore water pressure compared to the wagons with 4 axes although the load amplitude in Figure 7 is nearly constant. The reason for this is the very close distance of the double wheel sets at the 4 axes freight wagons.

In Figure 8 and 9 the measured pore water pressure in a depth of 3 m for test track TS2 and TS4 are pictured.

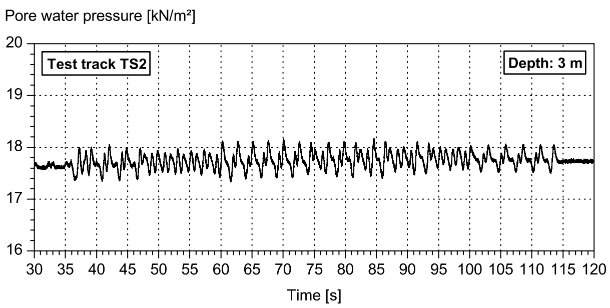

Figure 8. Pore water measurements – Test track TS2.

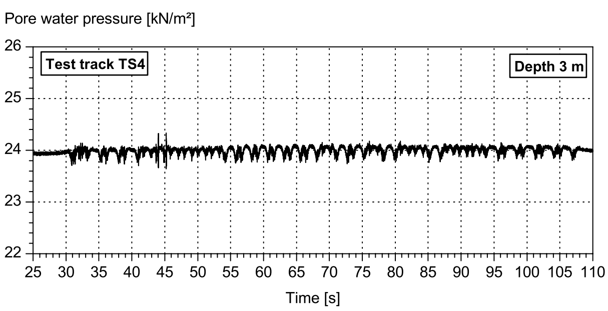

Figure 9. Pore water measurements – Test track TS4.

Compared with test track TS0 in a depth of 3 m the measured pore water pressure in test track TS2 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 (SGF 1997). The highest hydraulic permeability thus is observed in test track TS4 were the columns are placed in grids.

3.3 Vibrations of the Sleepers

To observe the oscillation of the track structure triaxial accelerometers were fixed at the end of the sleeper. Figure 10 shows the dynamic measurement results for passenger trains. The calculated velocities are filtered by f < 15 Hz because this frequency domain is relevant for the deformations of the soil, Jones et al. (1996), Madshus et al. (1996). In Figure 10 the Root Mean Square (RMS) values (Equation 3) calculated from the vertical oscillations are presented.

$$RMS = \sqrt{\frac{1}{T}\int_0^T x^2(t)\,dt} \qquad [3]$$

Also pictured for every test track are best fitting curves with an exponential function. The curve fitting was done by the Least Square Failure method.

The measurements demonstrate the speed dependent increase of the vertical oscillations at the end of the sleepers. The poorest result was achieved in test track TS0 without any soil improvement. The measured values for the two test tracks with shorter Lime-Cement Columns, test tracks TS1 and TS4, are obviously lower. The best results were detected for test track TS2 and TS3 where the columns are founded in the good bearing sand layer.

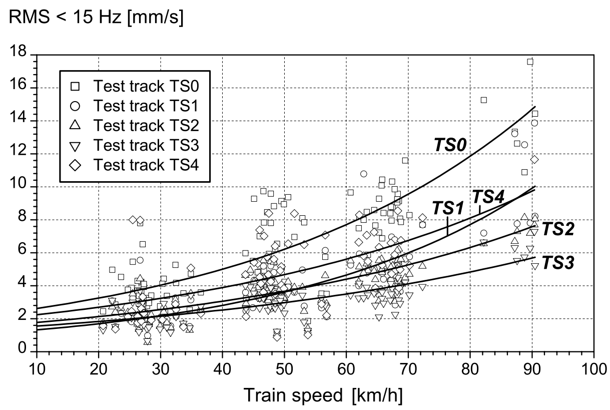

Figure 10. RMS of the velocities of the vertical oscillations measured at the end of the sleepers for passenger trains.

The mentioned decrease in the dynamic response of the track system is caused by the higher stiffness of the Lime-Cement Columns and the associated higher stiffness of the total layer.

3.4 Vibrations of the Ground

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 effective compression wave velocities $V_{C,eff}$ and afterwards converted into the amplitude of shear strain γ by means of Equation 4.

$$\gamma = \frac{V_{C,eff}}{V_S} \qquad [4]$$

$V_{C,eff.}$ = Effective compression wave velocity [m/s]
V_S = Shear wave velocity [m/s]

The shear wave velocity in the soft soil of V_S = 70 m/s was measured in situ. In Figure 11-13 the results for the freight trains for different train speeds in test track TS0, TS1 and TS2 are presented.

To compare the results best fitting curves with an exponential function according to Equation 5 are added.

$$\gamma(z) = \gamma_0 \times e^{-bz} \qquad [5]$$

In Figure 11 (TS0) the amplitude of shear strain γ decreases with increasing depth z. Compared to test track TS1 and TS2 the values close to the surface are obviously greater and thus connected with a greater rate of long term deformation. For the both test tracks with short (TS1) and long (TS2) Lime-Cement Columns the shear strain is approximately equal.

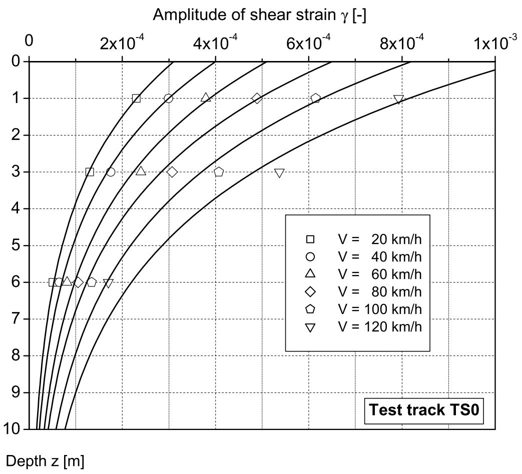

Figure 11. Amplitude of shear strain vs. depth – test track TS0.

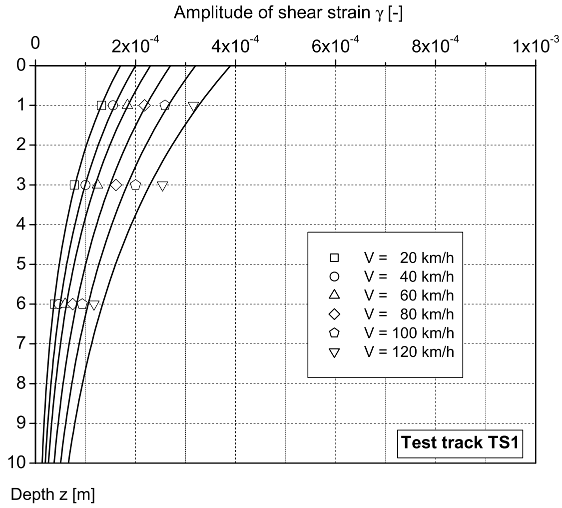

Figure 12. Amplitude of shear strain vs. depth – test track TS1.

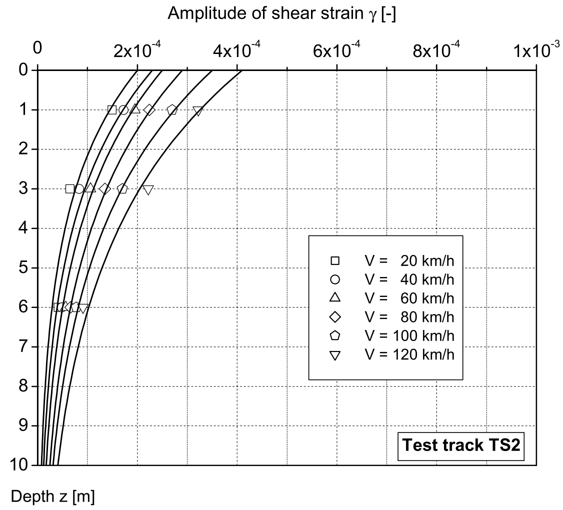

Figure 13. Amplitude of shear strain vs. depth – test track TS2.

In Figure 14 the results for the device in a depth of 3 m are plotted against the train speed for freight trains. Within this view test track TS4 brings out the best results but all variants with a soil improvement lead to a clear decrease in the amplitude of shear strain and thus a lower rate of long term deformation is expected.

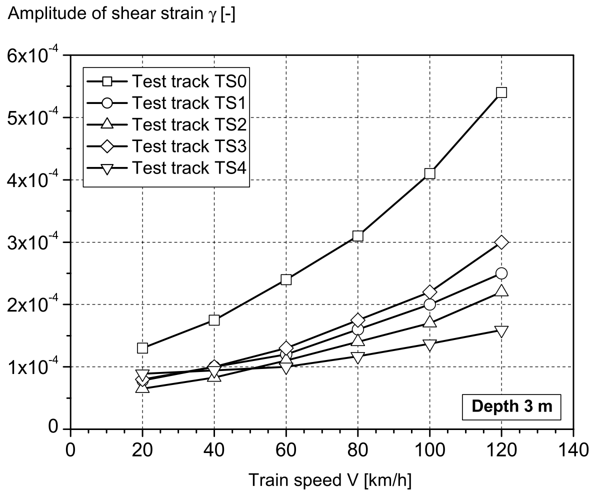

Figure 14. Amplitude of shear strain vs. train speed

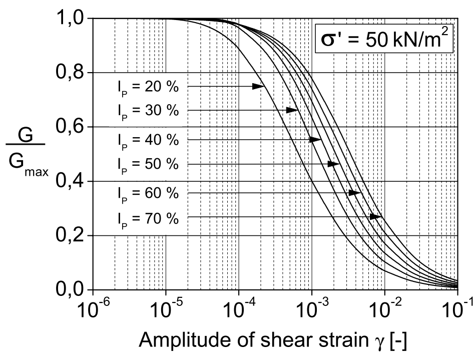

Figure 15. Amplitude of shear strain vs. shear moduli.

After the model calibration deeper layers and varying stiffness and damping properties of the ground could be investigated numerically. The numerical works will result in charts for the predesign of a soil improvement layout.

4. CONCLUSIONS

To investigate the speed dependent dynamic response of the track system and the influence of the soil improvement layout experimental field tests are a proper and valuable method. The measurements demonstrate that the oscillations of the track system and the shear strain in the ground and thus the rate of long time deformation can be reduced significantly when soil improvement is performed. To answer the question which layout should be used for soil improvement the necessary Lime-Cement Column (LC) quantities per meter should be considered. These are for the 30 long test tracks

- TS1: 500 m LC-Columns,
- TS2: 750 m LC-Columns,
- TS3: 860 m LC-Columns,
- TS4: 1510 m LC-Columns.

The quantities are very different for the four column layouts investigated in the field test. A duplication or triplication of the Lime-Cement Column quantity leads not to an equivalent reduction of the measured dynamic response of the track system and the ground. So a technical and economical solution must be achieved that depends on the local project conditions and the tolerable maximum value of the amplitude of shear strain γ in the ground.

5. OUTLOOK

To transfer the achieved knowledge on other ground conditions a numerical model by means of spatial nonlinear dynamic finite element modeling is currently under development. The model takes into account the nonlinear shear strain vs. shear modulus G/G_{max} respectively the nonlinear soil damping relationship based on the approach after Dorby and Vucetic (1987), Figure 15.

6. REFERENCES

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