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Rolf Katzenbach

Institute of Geotechnics, Technische Universität Darmstadt, Darmstadt, Germany

Marc Ittershagen

Institute of Geotechnics, Technische Universität Darmstadt, Darmstadt, Germany

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SOIL IMPROVEMENT OF SOFT SOIL UNDER DYNAMIC AND STATIC LOADING - CASE HISTORY OF A GEOTECHNICAL FIELD EXPERIMENT UNDER A RAILWAY LINE

Prof. Dr.-Ing. Rolf Katzenbach
Head of the Institute of Geotechnics
Technische Universität Darmstadt
Darmstadt, Germany
katzenbach@geotechnik.tu-darmstadt.de

Dipl.-Ing. Marc Ittershagen
Institute of Geotechnics
Technische Universität Darmstadt
Darmstadt, Germany
ittershagen@geotechnik.tu-darmstadt.de

ABSTRACT

To get informations about the deformation and bearing behaviour of a soil improvement by the use of Lime-Cement Columns under a railway line on soft soil large scale field tests were performed. The tests were observed by various static and dynamic measurement devices and over a period of 3 months 1200 train crossings were recorded. During the test stage the train speed varies from 30 km/h to 90 km/h to analyse the influence of the train speed on the dynamic behaviour and the stabilizing effect of the soil improvement. The measurements show that the large and heavy goods trains are crucial for the maximum dynamic response of the soft soil. The best results were achieved if the Lime-Cement Columns are founded in the good bearing sand layer.

INTRODUCTION

To study and understand the deformation and bearing behaviour of geotechnical constructions large scale tests are a proper method to achieve valuable informations about e.g. the load transfer and the load distribution. The method becomes more relevant if the geotechnical construction is exposed to dynamic loading because only few theoretical models are available and a dynamic design concept for railway lines on soft soil is actually missing.

In conjunction with soil improvement under railway lines some unsolved questions about the impact of the train speed and the train weight on the required depth and arrangement of the soil improvement columns exist. To achieve a technical optimized soil improvement for a railway line on a soft soil layer with a depth of about 10 m large scale filed tests were performed and observed by static and dynamic measurements.

DYNAMIC PROBLEM

During the train crossing the total system consisting of bars, sleepers, ballast and subsoil is set in horizontal and vertical motion. The introduced vibrations are transmitted through the soil body as compression and shear waves and at surfaces as rayleigh waves, Fig. 1 (Woods, 1968). The propagation of these waves is significantly influenced by the depth, the density, the stiffness and the saturation of the soil body.

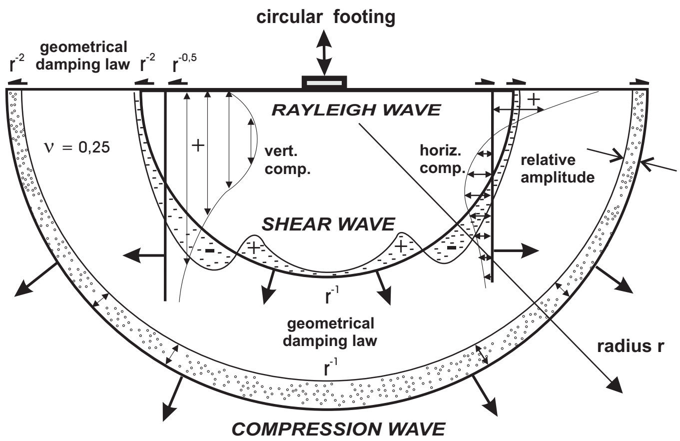


Fig. 1. Distribution of displacement waves from a circular footing on a homogeneous, isotropic, elastic half-space, (after: Woods, 1968).

The described vibrations cause compaction of the ballast, the subgrade and the soft soil and thus enduring deformations of the sleepers and the railway line. The amplitude of the vibration is significantly influenced by the ratio β (Eq. 1) of the activated frequency f_A (Hz) due to the train crossing and the natural frequency f_N (Hz) of the total system. If the activated frequency f_A is equal to the natural frequency f_N (β = 1) the motions for the undamped system becomes infinite.

$$\beta = \frac{f_A}{f_N} \quad [-] \tag{1}$$

Thus vibration problems are likely and possible for a damped system like a railway line, if the activated frequency f_A is in the domain of the natural frequency f_N. The mentioned above frequencies could be estimated by means of equations (2) and (3).

$$f_A = \frac{V}{a} \quad [\mathrm{Hz}] \tag{2}$$

$$f_N = \frac{V_S}{2d} = \frac{\sqrt{\frac{E}{2(1+\mu)\rho}}}{2d} \quad [\mathrm{Hz}] \tag{3}$$

with:

with:	V	= train speed [m/s]
	a	= distance of wheel sets [m]
	V_S	= shear wave velocity [m/s]
	d	= depth of soft soils layer [m]
	E	= modulus of elasticity [N/m²]
	μ	= Poisson's ration [-]
	ρ	= density [kg/m³]

To understand the interaction between the train passing and the dynamic response of soft soil layer both equations are pictured in Fig. 2 for typical soil conditions and train characteristics.

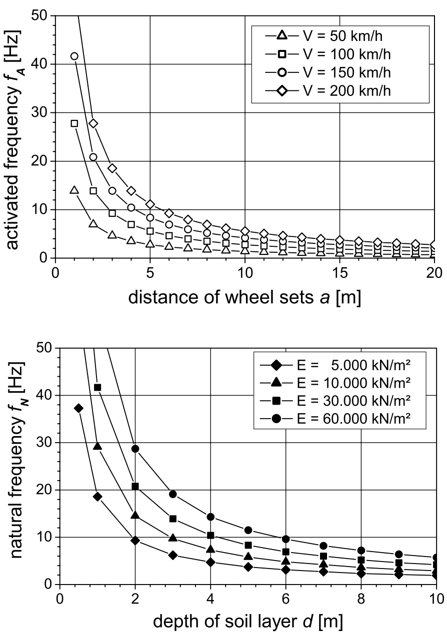
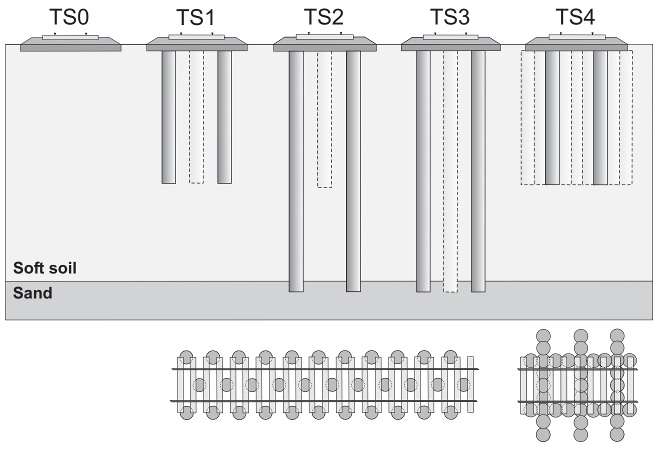


Fig. 2. Activated frequency f_A and natural frequency f_N according to equation (2) and (3).

The analysis of Fig. 2 for typical wheel set distances of $a \geq 5$ m and train speeds up to $V \leq 150$ km/h leads to activated frequencies of $f_A \leq 8$ Hz while the train crossing. If the depth of the soft soil layer with a modulus of elasticity of $E \leq 5.000$ kN/m² is greater $d \geq 3$ m, the natural frequency of $f_N \leq 8$ Hz is in the range of the activated frequency f_A. In this case the motions of the railway line decrease and the deformations become more and more problematically. In general such enduring and sustainable deformations result in speed restrictions down to V = 30 km/h and in some cases in temporary track closings. One way to face the described deformations is to carry out a column shaped ground improvement (increase in elastic modulus E) be means of dry deep soil mixing under the railway line, Holm et al. (2002). In this connection some unsolved questions exist. The aim of the presented large scale tests is to get valuable informations about the influence of the train speed and train weight on the required improvement depth and the column arrangement.

GEOTECNICAL FIELD EXPERIMENT

To investigate the short- and long term deformation and bearing behavior of railway lines exposed to dynamic loading 4 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), SGF (1997). The configuration and the column length installed in test track TS0-TS4 are shown in Fig. 3.



TS0:	Reference track without soil improvement
TS1:	5.9 m depth, single placed
TS2:	10.4 m, 5.9 m depth, single placed
TS3:	11.4 m depth, single placed
TS4:	5.9 m depth, placed in grids

Fig. 3. Geometrical configurations of the ground improvement patterns, TS0–TS4.

The subsoil in the testing area consists of a soft soil layer with a depth of 10 m and a good bearing sand layer. The average consistency index of the soft soil is $I_C = 0.4$, the average water content varies with depth between w = 0.6–1. The mean mechanical parameters of the soft soil and the sand 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

To observe the dynamic response of the subsoil and the railway structure during the train crossing the test tracks are equipped with multiple measurement devices. The arrangement, the notation and the frequency of registration of the measurement devices is shown in Fig. 4 and Tab. 2.

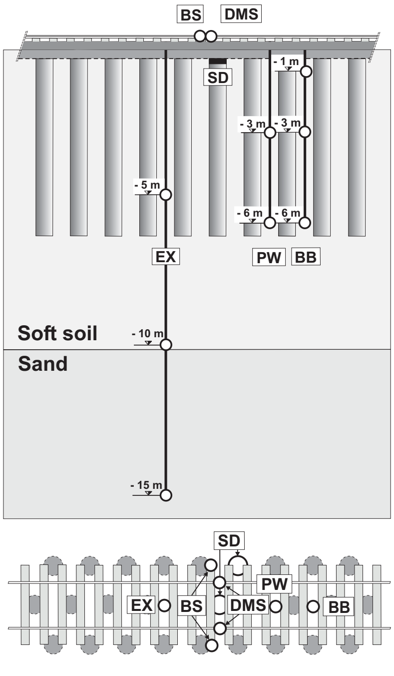


Fig. 4. Arrangement of measurement devices.

During the tests the area was passed for 3 month with 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).

Table 2. Notation, depth and frequency of registration of the measurement devices

Measured value	Notation	Depth	Frequency of registration
Vertical stress	SD 1-1	0.6 m	300 Hz
	SD 1-2		
Pore water pressure	PW 1-1	3.0 m	300 Hz
	PW 1-2	6.0 m	
Acceleration of the sleepers	BS 1-1	surface	2.000 Hz
	BS 1-2		
Acceleration of the ground	BB 1-1	1.0 m	1.000 Hz
	BB 1-2	3.0 m	
	BB 1-3	6.0 m	
Expansion of the bar	DMS 1-1	surface	2.000 Hz
	DMS 1-2		
Deformation of the subsoil	EX 1-1	5.0 m	weekly
	EX 1-2	10.0 m	
	EX 1-3	15.0 m	

RESULTS OF THE GEOTECHNICAL FIELD EXPERIMENT

Measurement of vertical stresses

Fig. 5 shows the increase in vertical stress during the crossing of a 665 m long goods train with a weight of about 2900 t. The train (V = 52 km/h) consists of 32 wagons with 2 and 4 axes. The values given are measured at the centric arranged device in test track TS0 (SD 0-1) and TS1 (SD 1-1).

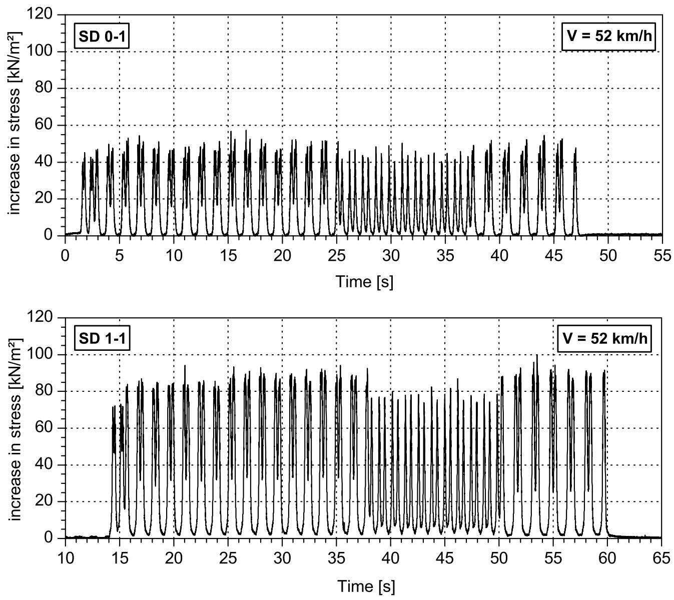


Fig. 5. Increase of vertical stress, TS0 and TS1, V = 52 km/h

The passage of each axe causes a significant increase in stress, between the axes the stress drops back on the initial value. The comparison of the measurement results for test track TS0 and TS1 shows the increase in stress at the top of the Lime-Cement-Columns caused by the higher stiffness of the soil body in this area. Thus a higher part of the dynamic loading is transferred into the columns and the soft soil is being discharged.

Measurement of pore water pressure

Fig. 6 and Fig. 7 shows the changes in pore water pressure during the crossing of a 640 m long goods train with a weight of about 2250 tons. The train (V = 30.5 km/h) consists of 31 goods wagons with 2 respectively 4 axes. The values shown are measured in test track TS0 (PW 0-1, PW 0-2) and TS4 (PW 4-1, PW 4-2) in a depth of 3 m and 6 m. All devices are placed in the soil body and not in a column.

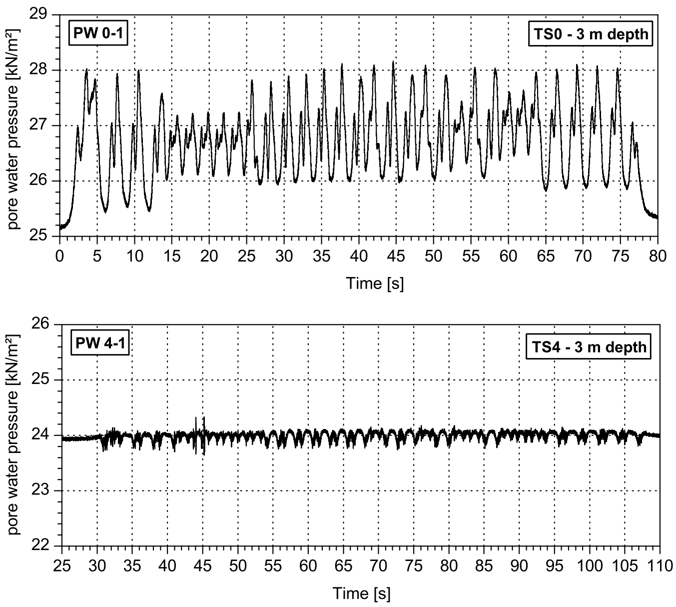


Fig. 6. Changes in pore water pressure, TS0 and TS4, V = 30.5 km/h, depth = 3 m.

The train crossing causes small excess pore water pressures of $\Delta u \leq 3$ kN/m^2. After the train crossing the pressure decreases rapidly to the initial hydrostatic value. The achieved conclusions that the main part of the load is transferred into the Lime-Cement Columns could be confirmed with the measurements in 3 m depth of TS4. At the bottom of the columns in test track TS4 (PW 4-2) in Fig. 5 a slight increase of pore water pressure could be observed due to the load transfer back into the soil body.

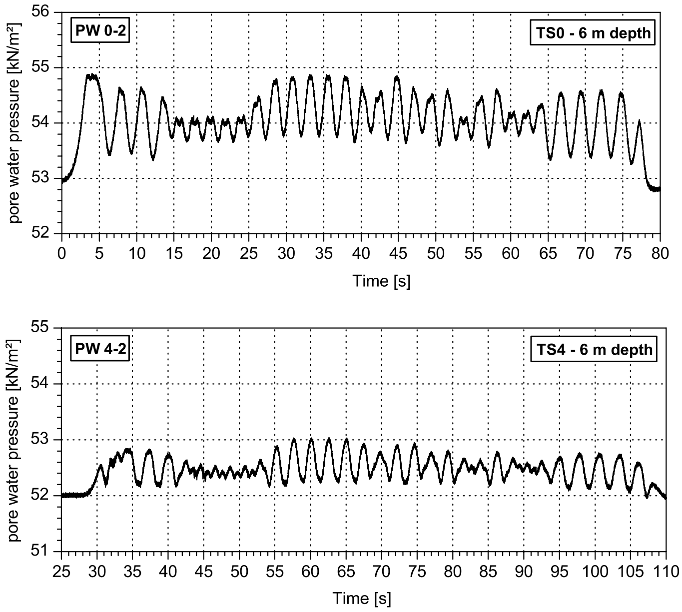


Fig. 7. Changes in pore water pressure, TS0 and TS4, V = 30.5 km/h, depth = 6 m.

Measurement of vibrations at the sleepers

Fig. 8 shows the dynamic measurement results at the sleepers for passenger trains. For railway lines on soft soils the lower part of the frequency domain from 0 Hz – 15 Hz is relevant because in this domain the deformations of the soil are decisive. Consequently, the results under 15 Hz are filtered. In Fig. 6 the quadrat of the Root Mean Square (RMS^2) according to DIN 1311-1:2000-02 (Eq. 4) for the vibration velocities is represented.

$$RMS^2 = \frac{1}{T}\int_0^T x^2(t)\,dt \tag{4}$$

The vibration measurements at the sleepers show the significant decrease in the dynamic response of the system caused by installed Lime-Cement Columns and the associated stiffer subsoil conditions. The exponential fitted curves increase rapidly for the configurations without and with shorter columns TS1 and TS4. For test tracks TS2 and TS3, here the columns are partially and totally founded in the sand, the increase is much slower, in TS3 nearly linear.

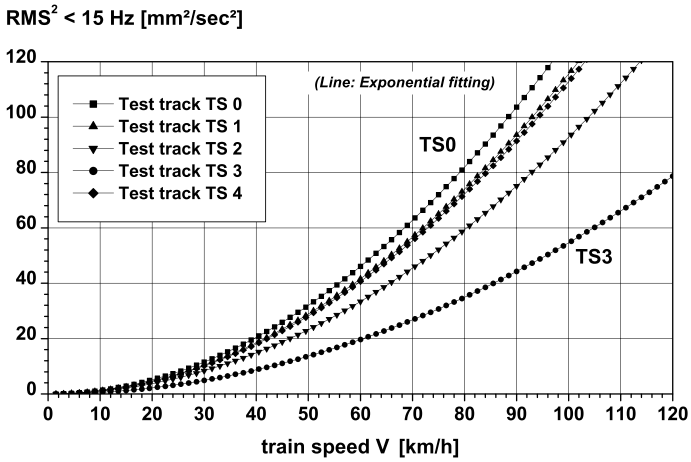


Fig. 8. RMS² for different train speeds, TS0–TS4, passenger trains.

Measurement of vibrations of the ground

To get information's about the dynamic strain level in the soft soil while the train passing, the measurements of the ground accelerations are integrated into effective wave velocities and afterwards converted into dynamic shear strain γ by means of equation (5).

$$\gamma = \frac{V_{eff.}}{V_S} \qquad (5)$$

with: $V_{eff.}$ = effective wave velocity [m/s]
V_S = shear wave velocity [m/s]

The velocity of the shear wave for the soft soil of $V_S \approx 70$ m/s was measured in situ. Fig. 9 shows the converted measurement results in test track TS 0 (Reference track) and TS3 for goods trains and the passenger trains. The values given are measured in a depth of 3 m. To be able to asses higher train speeds particularly for passenger trains the measurement results in Fig. 9 were extrapolated up to V = 120 km/h.

The measurement indicates that for a constant train speed the dynamic shear strain induced by a goods train are significantly higher as for passenger trains and for this reason critical for the assessment of the stabilizing effect of the ground improvement. With increasing train speed the dynamic shear strains rises nearly exponential. The reduction of the dynamic shear strain due to the column shaped soil improvement down to the good bearing sand layer is unambiguous.

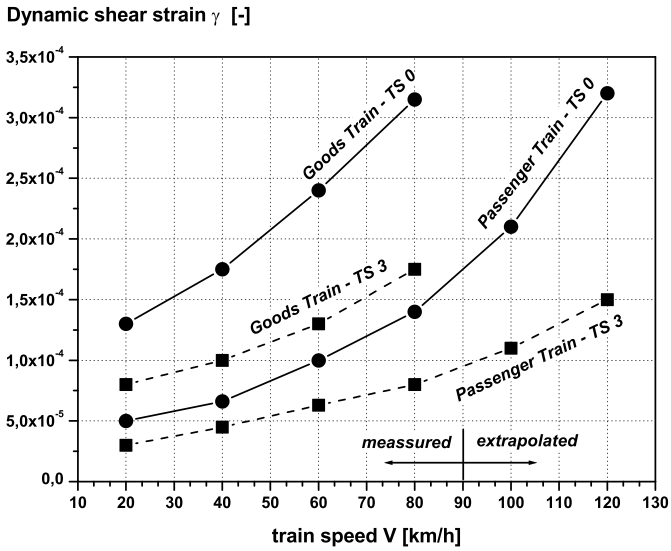


Fig. 9. Dynamic shear strain in the ground for different train speeds, TS0 and TS3, passenger and goods trains.

SUMMARY

To investigate the dynamic response of 4 ground improvement patterns under a railway line experimental field tests were performed. The tests were observed by dynamic measurement devices. Particularly with regard to the vibrations of the ballast and the sleepers the measurements give valuable informations about the effect of the different arrangements of the soil improvement patterns, especially information's about the necessary depth of the columns. The best results were obtained when the Lime-Cement Columns are founded in the good bearing sands. Further on the value of excess pore water pressure could by reduced.

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