Model scale investigations on the deformation of the subsoil under railway traffic

Essais sur modèle sur les déformations du sol sous chargement de trains

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ABSTRACT: In the paper the results of some model scale investigations on the deformation of the subsoil under railway traffic will be presented. To investigate the stability of the rail track alignment investigations in respect of the deformation of the subsoil were made at the Institute of Geotechnics at Darmstadt University of Technology. For the deformation behaviour of the subsoil a difference is made between uniform and non-uniform settlements, where the last mentioned are especially of importance with respect to the driving behaviour and the travelling comfort.

RÉSUMÉ: Ci-dessous les résultats de plusieurs essais sur modèle sur les déformations du sol sous chargement de trains sont présentés. Dans le comportement de la déformation du sol une différence entre des tassements régulier et des tassements irréguliers est faite. Les tassements irréguliers ont une importance sur le confort et le mouvement des trains. Avec les recherches il était possible de trouver une configuration de la rigidité du système avec laquelle seulement de tassements réguliers subissent.

1 INTRODUCTION

In the case of repeated loading of a track under railway traffic uniform and non-uniform settlements can occur. As long as the settlements are uniform, they are uncritical for the railway traffic. In contrast to the uniform settlements the non-uniform, permanent settlements, that can occur at a crossover to an artificial building but also if inhomogenities in the subsoil are existent which are not recognised or considered during the building process, are critical. If there are permanent settlements of the subsoil it is very significant for the practice to know, if non-uniform settlements can develop under railway traffic even in case of at first homogeneous subsoil.

2 MODEL SYSTEM

To examine the phenomenon of non-uniform settlements a simplified model that admits irreversible settlements is used. The real system is simplified as an elastic slab which is located on a homogeneous halfspace of sand. In the model the slab replaces all the elements of the track that are able to transfer bending moments along the longitudinal axis of the track. The halfspace of sand is the idealisation of the subsoil, so that the deformations of the subsoil are time independent, i.e. the material of the subsoil is non viscous. Another assumption of the model is, that the low velocity of the moving load avoids effects of inertia, i.e. the examination is limited to a certain extent on static effects.

The simplified model to examine the phenomenon of the uniform and non-uniform settlements is schematically shown in Figure 1 in cross and longitudinal section (Katzenbach et al., 1999).

For the description of the displacements of superstructures on a granular halfspace a constitutive model is used for the subsoil which is described by Dietrich (1977). The non-linear stress-strain relation of a grain in the granular halfspace can be described by the following power function:

$$\varepsilon \sim \left(\frac{\Delta\sigma}{\gamma\cdot z}\right)^{\mu} \qquad \mu > 1 \tag{1}$$

where ε = strain; $\Delta\sigma$ = stress increment; γ = unit weight of the soil; z = depth; μ = material parameter.

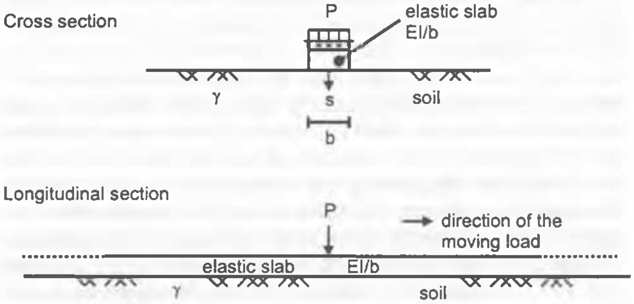

Figure 1. Sketch of the simplified system.

The settlements of the elastic slab, shown in Figure 1 can be described by the following function:

$$s = f\,(x, N, p, l, d, b, EI/b, \gamma, K_0, \not{g}) \tag{2}$$

where s = settlements; x = position of the load; N = number of loading; p = load of the train; l = length of the train; d = distance between the trains; b = width of the track; EI/b = bending resistance over the width of the track; γ = unit weight of the soil; K_0 = coefficient of earth pressure at rest to express the virgin configuration; $\not{g}$ = granulometry of the soil, which characterises the grain size distribution respectively the statistic description of the grains.

The bending resistance of the track respective to the width of the track and the unit weight of the soil are replaced by the so-called elastic length of the elastic slab, which is particularly suitable for an infinite elastic slab, because the elastic length contains only cross-sectional dimensions of the elastic slab beside the unit weight of the soil and the Young's modulus.

$$l_E = \sqrt[4]{\frac{EI}{\gamma\, b}} \tag{3}$$

where l_E = elastic length; EI/b = bending resistance over the width of the track; γ = unit weight of the soil.

The load of the train is replaced by a quantity, in the following called system length, which has the dimension of a length. It is defined as follows:

$$l_P = \left(\frac{P}{\gamma\, l_E^2} \right)^{\frac{\mu-1}{2(\mu+1)}} l_E \qquad (4)$$

where l_P = system length; P = load of the train; γ = unit weight of the soil; l_E = elastic length, μ = material parameter.

The "width ratio" is defined as the following dimensionless system parameter:

$$\beta_P = \frac{b}{l_P} \qquad (5)$$

where β_P = width ratio; b = width of the track; l_P = system length.

With the "width ratio" the classification of a system between the limiting cases of the "rigid track" and the "elastic track" takes place. The actual width ratio for the slab-track is about 0,4 and for the conventional ballast track about 0,9 (Katzenbach et al., 2000).

For the examination of the plastic deformations of the subsoil a circular testing device was planned in which a moving load runs in circles. Because of the supposition that the moving load has an influence on the initiation of waves the moving load must run in one direction. This requires a circular testing device as shown in Figure 2 (Heineke et al., 2000). Therefore different assumptions must have been taken. The form of the settlement-mould under a train is a function of the load and the length of the train. For the simulation it is important, that at least one preferably several settlement-moulds along the track axis can appear. Because of the limited geometric dimensions of the testing device investigations for the plastic deformations are carried out for a short train. This means, that the length of the train is not of any importance and the load of the train can be reduced to a single load related to the width of the track. Furthermore long intervals between trains were assumed, so that the following train has no influence on the passing train and vice versa. Due to these two conditions the settlement-mould will be shorter which enables to choose a smaller diameter of the circular testing device.

Figure 2 shows the circular testing device on the left hand side and a detail of the loading system on the right hand side. The deformations induced by the loading roller are measured by a dial gauge in combination with a gauge to measure the angle, which is fixed on the vertical axis in the middle of the testing device.

For the comparison between the different model scale tests and to see if on an initially uniform subsoil non-uniform settlements can occur, the testing container must be filled for each test in the same way. Figure 3 shows the filling of the testing container with the sand trickle installation (Arslan et al., 1998) on the left hand side and the installation of a special sand hoover to obtain a smooth surface on the right hand side.

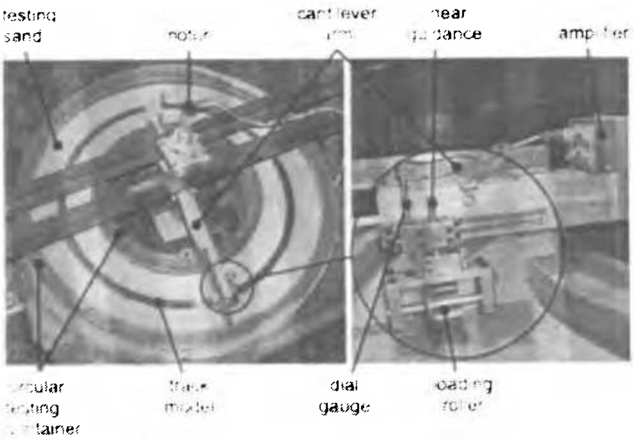

Figure 2. Photo of the testing device with a detail of the loading system.

Figure 3. Photo of the filling of the testing container (left) and the leveling of the surface with a special sand hoover (right).

Table 1. Parameter of the performed model scale tests

parameter	b	h	γ	P	E	l_P	β_P
test	[cm]	[cm]	[kN/m³]	[N]	[kN/m²]	[cm]	[-]
HV_3	6.0	0.5	17	60	$1.3\cdot10^6$	18.9	0.355
HV_8	6.0	1.5	17.5	30	$1.3\cdot10^6$	29.2	0.206
HV_10	4.0	1.5	17	30	$7\cdot10^7$	61.6	0.065
HV_11	6.0	1.5	17	30	$7\cdot10^7$	57.6	0.105
HV_12	6.0	1.5	16.8	30	$7\cdot10^7$	57.9	0.103

3 MODEL SCALE TESTS

The successful model scale tests which were carried out and presented in the next chapter are summarized in Table 1. The tests were performed up to 50000 loadings. Because of the low velocity of the loading roller (10 rounds per hour) a single test is running for about 6 months.

4 RESULTS OF THE MODEL SCALE TESTS

Figure 4 shows exemplary some results of the model scale test HV_8 with a width ratio of 0.206. The development of the settlements is shown over the position of the loading roller in the circular testing stage in degrees. It can be seen that the settlements of the model track are uniform at the beginning and that they become more an more non-uniform with increasing number of loading. The settlements are shown up to 50000 loadings.

In Figure 5 the settlements of 5 different model scale tests are shown. On the vertical axis the settlements related to the system length l_P are shown in dependence of the position of the loading roller in degrees on the horizontal axis. Each curve shows the related settlements for about 50000 loadings of the model system. The curves show that the settlements become more and more non-uniform with an increasing width ratio.

The results of the model scale tests have shown, that the settlements under a uniform track can become non-uniform with increasing number of loading. If there are non-uniform settlements it is of interest as well, if the waves can move in the direction of the moving load. The results in Figure 6 show exemplary for the model scale test HV_3 the moving of local extremes. Therefore the local extreme related to the system length is plotted over the position in the circular testing stage. The parameter beside the measured test values shows the number of loading. It can be summarized, that if there are non-uniform settlements and that waves occur, the local extremes move in the driving direction of the loading roller, that corresponds with the increasing values of the position of the loading roller. With increasing values of the width ratio this phenomenon is intensified.

The development of the mean settlements related to the system length over the number of loading shows, that the mean settlements increase with the number of loading in a logarithmic way (Figure 7). Arslan et al. (2000) also found in cyclic triaxial element tests, that the increment of plastic strain decreases with the number of loading. The settlements become non-uniform with an increasing width ratio and the mean settlements become greater as well, as it is shown in Figure 5.

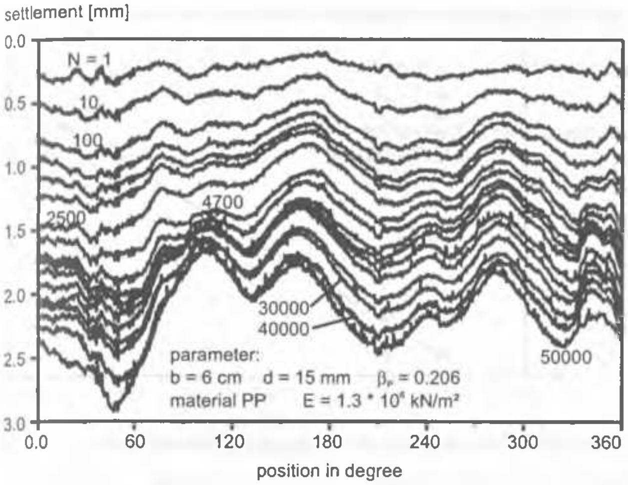

Figure 4. Development of the settlements over the circumference of the testing stage with increasing number of loading.

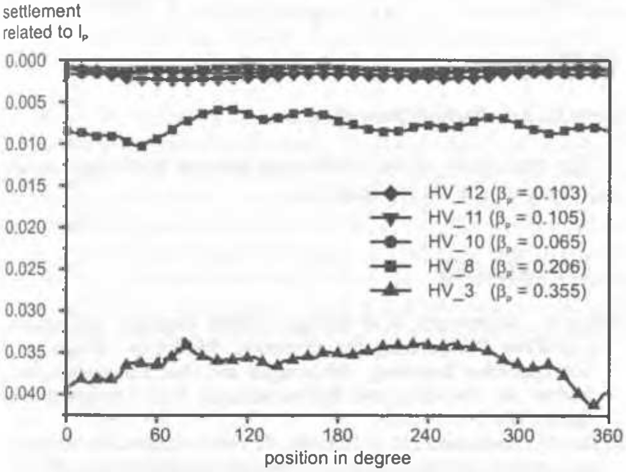

Figure 5. Related settlements of 5 different model scale tests at about 50000 loadings for each test.

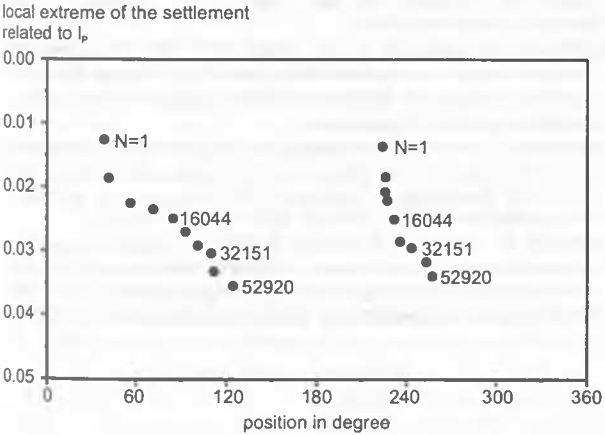

Figure 6. Moving of local extremes for the model scale test.

The development of the mean settlements with the number of loading can be described by the following mathematical function:

$$\frac{s_M(N)}{l_P} = \frac{s_{M1}}{l_P} + a \cdot \ln\left(\frac{N-1}{1000}+1\right) \qquad (6)$$

where: s_M = mean settlement; N = number of loading; l_P = system length; s_{M1} = mean settlement after first loading; a = constant to be determined out of the tests.

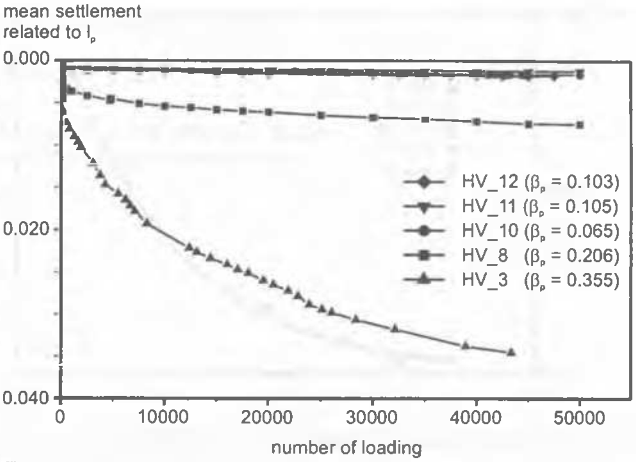

Figure 7. Development of the mean settlements related to the system length with increasing number of loading.

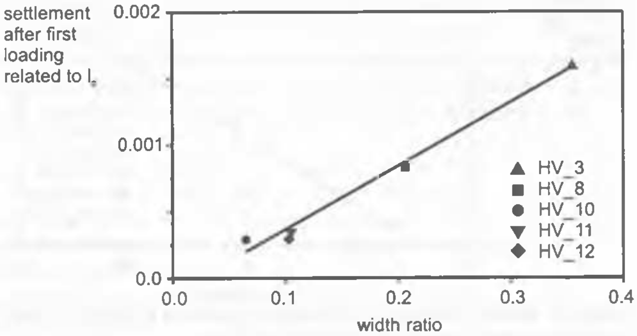

Figure 8. Relation between the settlement after the first loading and the width ratio.

In this equation the knowledge of the mean settlement after the first loading and of the constant a is necessary to determine the mean settlements in function of the number of loading. Therefore a relation between these two mentioned parameters in dependence of the width ratio has been carried out.

Figure 8 shows the relation between the settlement after the first loading related to the system length over the width ratio for the presented model scale tests. It can be seen, that there is a linear relation between the settlement and the width ratio.

For the constant a subjected to the width ratio an exponential relation has been found. The mathematical description is as follows:

$$a = 0.0002 \cdot e^{10.3 \cdot \beta_P} \qquad (7)$$

where: a = constant; β_P = width ratio.

Figure 9 shows the relation between the constant a and the width ratio. The constant a grows in an exponential way with increasing values of the width ratio. With the knowledge of the width ratio the mean settlements can be determined for a rail track system on a subsoil consisting of a granular material by determination of the constant a and the mean settlement after the first loading as input for equation (6).

Another relation with the width ratio was found for the differential settlement after 50000 loadings. The model scale tests show, that the differential settlement is nearly constant after 50000 loadings. The relation shows, that track systems with a low value of the width ratio, i.e. rigid systems, have nearly uniform settlements and that with increasing values of the width ratio the differential settlements grow in a linear way (Figure 10).

Another criterion for the waviness of the track system is the standard deviation of the mean settlements over the circumference of the circular model track. Figure 11 shows the development of the standard deviation related to the system length in relation to the number of loading. The curve parameter is the width ratio. The graphic shows, that the standard deviation increases

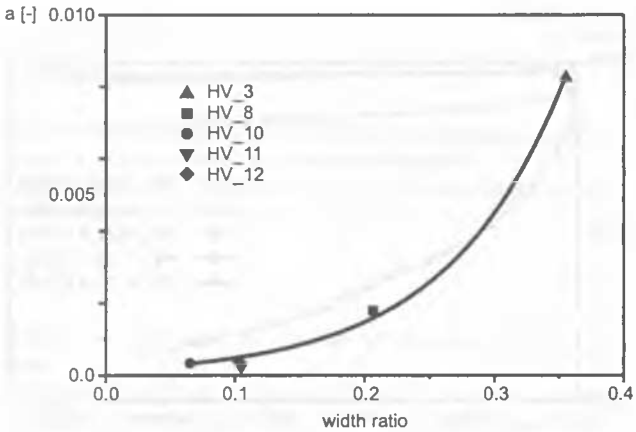

Figure 9. Relation between the constant a and the width ratio.

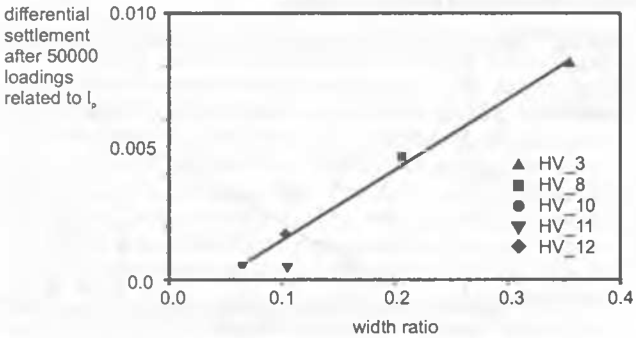

Figure 10. Relation between the differential settlement after 50000 loadings related to the system length and the width ratio.

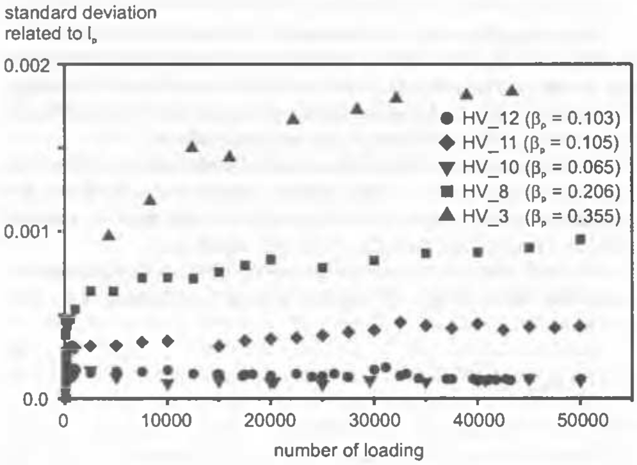

Figure 11. Development of the standard deviation of the mean settlements related to the system length with increasing number of loading.

with the number of loading. The value of the standard deviation reaches an asymptotic value. That means, that the non-uniform settlements grow until they reach a certain waviness and then the waves do not grow any more.

For the relation shown in Figure 11 the following mathematical description of the function has been found:

$$\frac{st(N)}{l_P} = b \cdot \ln\left(\frac{N-1}{10}+1\right) \tag{8}$$

where st = standard deviation; N = number of loading; l_P = system length; b = constant.

The Graphic in Figure 12 shows the linear growing of the constant b with the width ratio. This shows in the same way as for the mean settlements, that with the knowledge of the width ratio the waviness of a track system on a subsoil consisting of a granular material can be determined with equation (8).

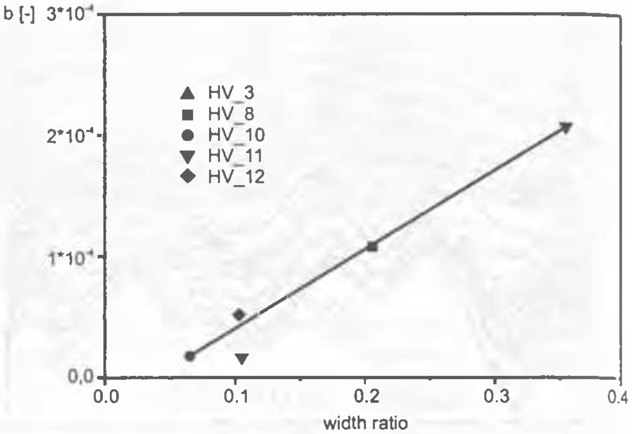

Figure 12. Relation between the constant b and the width ratio.

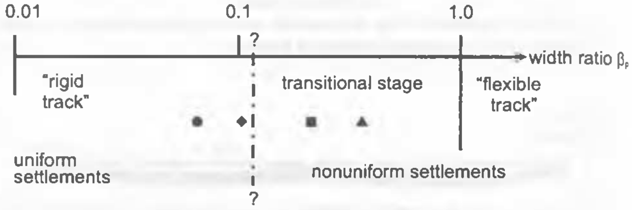

Figure 13. Area limits of the width ratio.

The area limits of the width ratio and the performed model scale tests are shown in Figure 13.

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