Coupled Three-Dimensional Analysis of the Slab Foundation for the Magnetic Levitation Transportation System (TRANSRAPID) in Germany

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Abstract

A 292 km long, very high speed magnetic levitation transportation system (MAGLEV) is planned between Hamburg and Berlin, as part of the German TRANSRAPID transportation system. The MAGLEV system will reach a maximum speed of 250 km/h in conurbations and up to 450 km/h elsewhere.

The foundation construction is one of the most important parts of the MAGLEV system, since only very small settlements and deflections can be tolerated. The guideway including station facilities, estimated to cost approximately 7 billion DM ($ 4 billion) is also a major part of the total system investment. The design challenge is to set up a safe and economic foundation system that meets the technical requirements.

This paper presents the results of complex static and dynamic numerical simulations carried out in three dimensions to assess the likely extent of elasto-plastic deformation of the slab foundation. The simulations consider hydro-mechanical coupling and full soil-structure interaction. Dynamic loads on the structure were determined by modeling the complete passage of a TRANSRAPID train and the results used in the design computations. The loads imposed on the structure include centrifugal forces due to curvature of the track and acceleration forces due to braking and accelerating, in addition to the vertical load.

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The calculations reveal that significant amounts of plastic deformation should be anticipated under these extreme loading conditions. The pore water pressures under the foundation slab may change dramatically. In parts of the foundation, the transient pore water pressure may decrease almost to zero, whereas in other parts of the foundation it may increase to approximately 250% of the steady state value.

The results of the simulations illustrate both the potential of and the need for complex numerical modeling in order to correctly dimension and optimize foundation constructions for high-speed transportation systems, such as the TRANSRAPID or the more classical European ICE high-speed trains. Two different numerical codes (FLAC^{3D} and ANSYS) were used independently for quality assurance, to verify the results, and to increase their acceptability to the design and construction engineers.

1. Introduction

The 292 km-long Magnetic Levitation Transportation System (TRANSRAPID), planned to link the major German cities of Hamburg (population 2 million) and Berlin (population 5 million) is intended to reduce the travel time between the two cities to one hour. Approximately 131 km of the track will be elevated and 161 km at ground-level. The maximum speed of the train will be 250 km/h in conurbations and up to 450 km/h elsewhere. The total cost of the project will reach 10 billion DM (Fechner, 1996 and MPG, 1996). The estimated costs for the guideway are in the order of 7 billion DM ($ 4 billion) including station facilities. The technical requirements of the system are extremely high. The maximum diametral clearance of the guide way that can be balanced is 5 mm, which imposes strict tolerances with respect to settlements and deflections along the system. The ground surface along the planned guideway consists mainly of settlement-sensitive formations, including loose and medium dense sand, clays, peat and weak lignite. The groundwater table is approximately two meters below the surface. Several slab foundation and combined pile-slab-foundation options have been examined for the guideway frame, based on classical engineering design procedures. (Büchel 1988, Schwindt 1994 and Schwindt 1988) Figure 1 shows the Transrapid on an elevated frame construction.

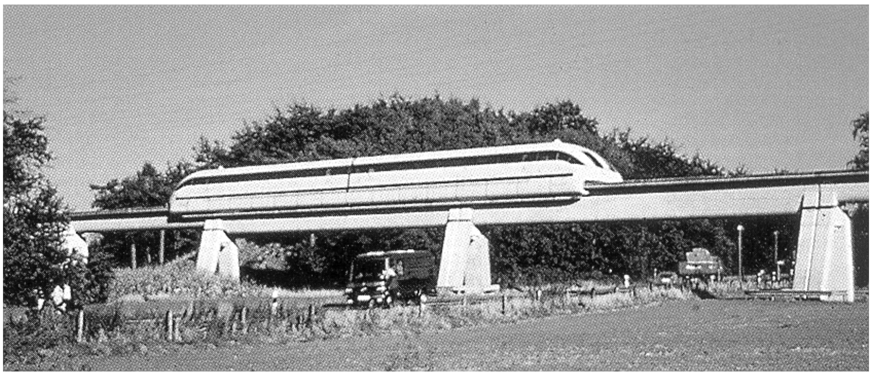

Figure 1. Transrapid on an elevated frame construction.

Given the high technical requirements, difficult ground conditions and high construction costs (approximately 25 million DM/km, ~$13 million/km), the design of a safe, reliable and economic long-term foundation is a top priority for the project. The initial settlement calculations carried out during the pre-planning and authorization phase, were based on standard, classical engineering design procedures. While these calculations were sufficient to establish the technical feasibility of this part of the system, important aspects of the soil-structure interaction, such as the complete load-deformation response of the ground, the effect of groundwater (especially the dynamically-induced pore water pressures) and the magnitude and extent of the plastic (irreversible) deformations were not investigated. The numerical simulations described in this paper were intended to address these questions.

2. Model set-up and input considerations

The soil profile shown in Table 1, considered to be typical for the Hamburg - Berlin route, was used for the simulations.

Table 1: Soil profile.

Depth below surface [m]	***soil***
0.00 – 8.00	Fine Sand, dense layered
8.00 – 10.50	Fine Sand, dense layered
10.50 – 14.25	Clay, stiff
14.25 – 18.00	Lignite, spongy
18.00 - 25.00	Fine Sand

Figure 2 shows the grid for the complete model, which includes the soil and the lower part of the frame construction shown in Figure 1.

Extensive testing was carried out to verify that the density of the grid (incorporating different element types) chosen for the two numerical codes used [the Finite Element (FEM) code ANSYS, and the Finite Difference (FDM) code FLAC^{3D}] in the (parallel) simulations was adequate. The grid finally used consisted of 88,104 elements and 93,616 nodes.

This level of discretization satisfies the demands of maximum acceptable gridpoint spacing to respond accurately to the frequency content of the dynamic loads imposed on the soil/structure and to the elastic material parameters while determining the stress distributions in the soil/structure with sufficient accuracy. The ground component of the model is 25 m deep and extends 30 m by 40 m laterally. The lower part of the frame construction corresponds to the center pillar of a 62 m long double girder with a gradient height of 7 m. The zoned lower part of the frame construction is shown in Figure 3. The 1.5 m thick slab plate has a lateral extension of 6 m by 8 m. The lower part of the frame construction was assumed to behave as a purely elastic material, using material data for a B30-type concrete (30 MPa uniaxial strength). A parametric study was carried out considering several different elasto-plastic material responses and coupled hydro-mechanical behaviour of the ground. Undrained conditions were assumed in the ground. Both static and fully dynamic calculations were performed.

The following simulations were included in the final calculations.

- Static:
    - elasto-plastic,Mohr-Coulomb behaviour,
- Dynamic:
    - elasto-plastic, Mohr-Coulomb, constant pore water pressure (RF-1)
    - elasto-plastic, Mohr-Coulomb, hydro-mechanically (HM) coupled reponse (RF-2)
    - elasto-plastic, Mohr-Coulomb with additional moving cap (Double-Yield-Model), HM-coupled (RF-3)

All of the elasto-plastic material models obey a non-associated flow rule, with residual strength values and tension cut-off. Volumetric compaction of the sand and variable stiffness during loading and unloading were taken into account by the Double-Yield-Model. Oedometer test results were used to calibrate this model. Figure 4 shows a comparison between measured and numerically calculated values for an Oedometer test.

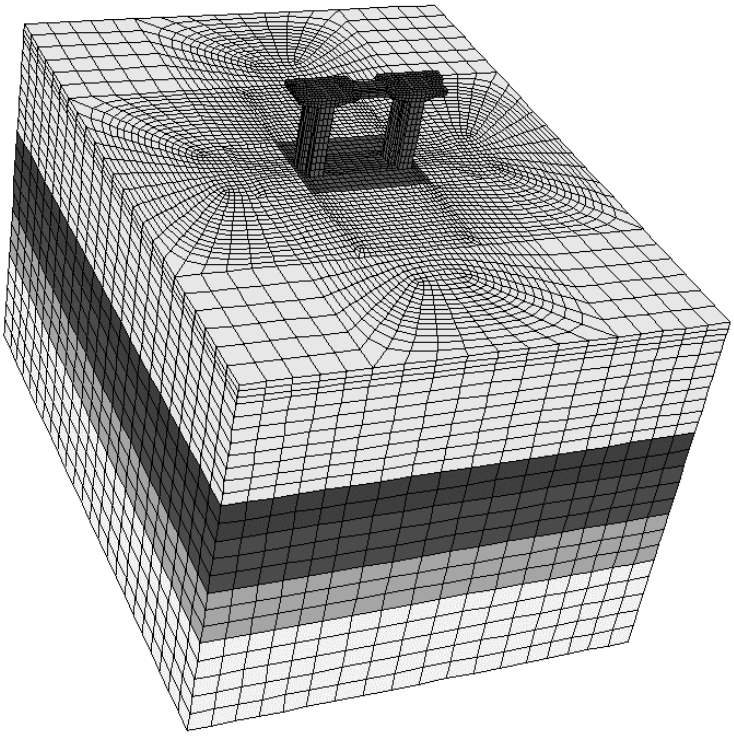

Figure 2. Complete numerical Transrapid model
(soil + lower part of the Transrapid frame construction).

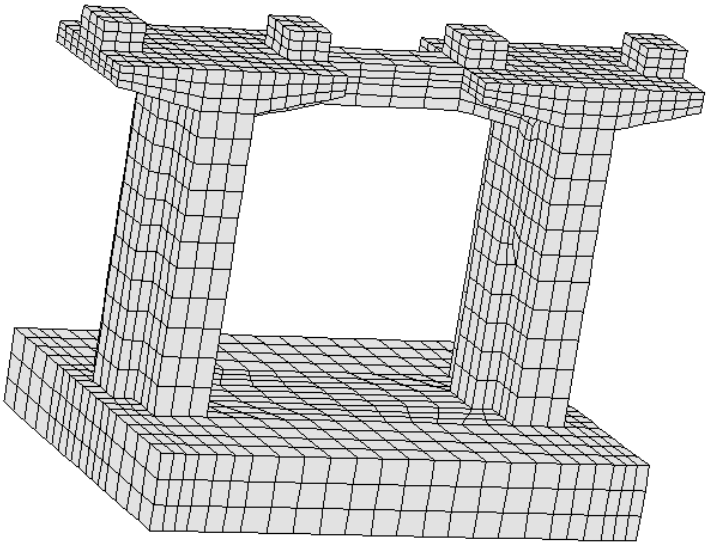

Figure 3. Lower part of the Transrapid frame construction.

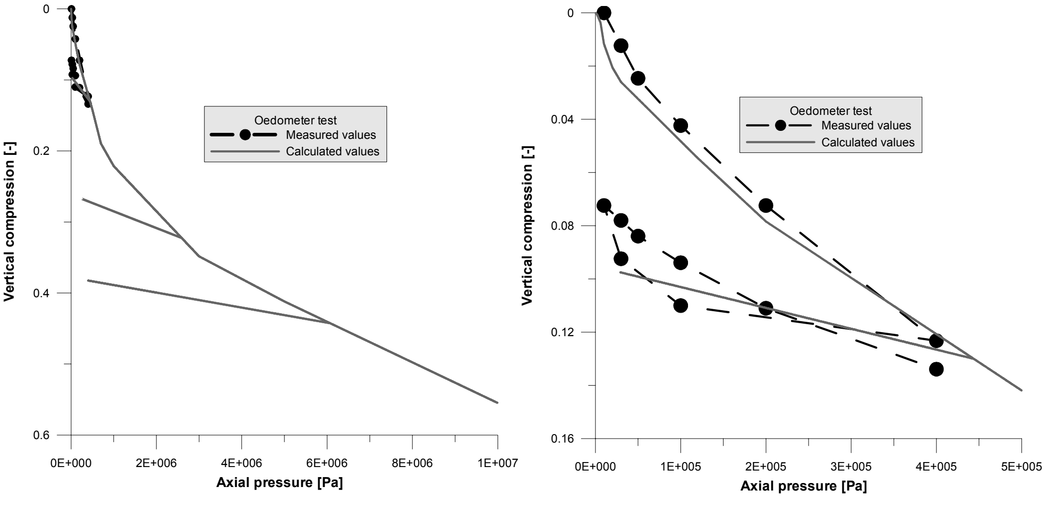

Figure 4. Calculated and measured load-deformation-curves of Oedometer tests.

Extensive elasto-plastic test runs with the code ANSYS (implicit FEM) and FLAC^{3D} (explicit FDM) were carried out to verify the adequacy of the numerical models. A main aim of this test series was to examine the influence of grid density and element types used in the models on the simulation results for the whole model. The system was assumed to exhibit a purely elastic response in this series. This allowed an optimized grid to be designed for the final computations.

The grid was created using the ANSYS pre-processor, which was then transferred to FLAC^{3D} using a specially developed converter, ANSFLAC.
A purely gravitational stress state with an earth pressure coefficient of 0.4 was assumed in all simulations Standard geomechanical far-field boundary conditions were assumed for the ground (static: fixed normal displacements / dynamic: nearly non-reflecting boundaries). Local damping, set at 3% of critical damping, was used.

3. Static Calculations

The static calculations were done for the case where two trains, traveling in opposite directions, passed each other. The estimated added dynamic load advantage factor was included.
The static calculations (maximum loads + added dynamic load advantage factor) were intended to compare the numerical results with those obtained earlier using the classical engineering methods.
Considerable plastic deformation, up to 1/3 of the total deformation, was observed to develop for the assumed loads and soil parameters (Fig. 6). The total deformations were also found to be considerably higher than expected (Fig. 5).
The static results for the load-deformation response of the structure were almost identical for the two codes, ANSYS and FLAC^{3D}.
Following the same comparative procedure for the assumed material behaviours and boundary conditions, it was possible to verify the loads and to establish the adequacy of the grid structure using the two quite different calculational philosophies. This led to a high degree of confidence in the numerical results.

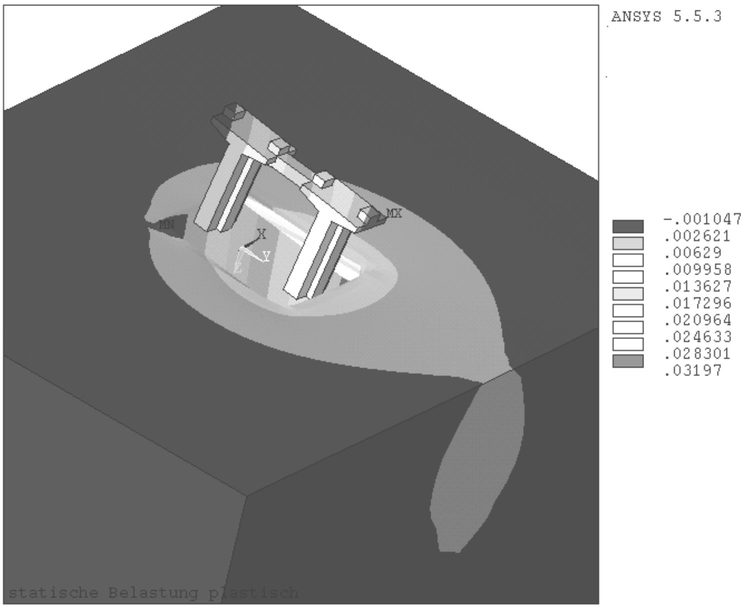

Figure 5. Calculated total ground deformations during passage of two Transrapid-trains (static loading).

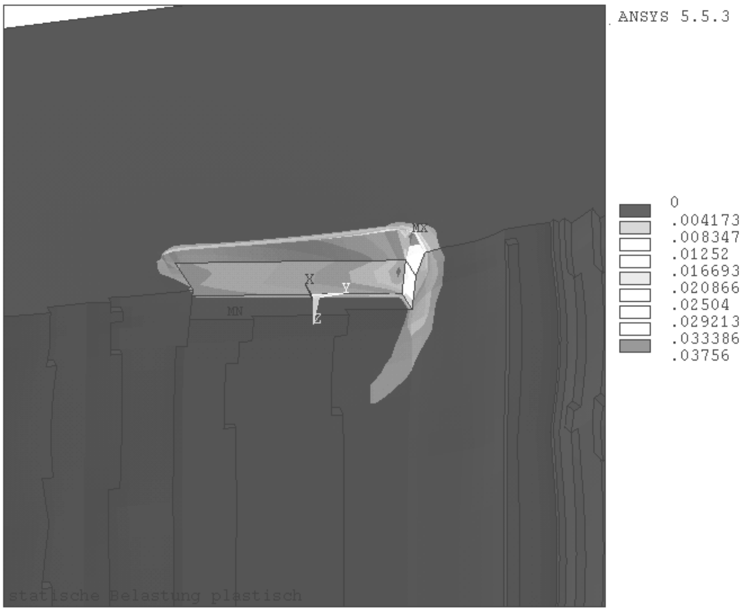

Figure 6. Plastic ground deformations during passage of two Transrapid-trains (static loading).

4. Determination of dynamic loads

The ANSYS code was used to establish values of dynamic loads which act on the lower part of the frame construction during the passage of a Transrapid-train with 2 train sections (train length of 45 m).

The aim of the calculations was to determine the transient load history and frequency content of the load-time-signal in the center pillar. The 62 m long upper part of the frame construction (Fig. 7) was decoupled from the foundation and a transient linear calculation performed.

The loading of the track due to the 15 electromagnets was modeled as a rolling load. The speed of the train was assumed to be 450 km/h. Figure 8 shows the calculated dynamic excitation loads for one of the four suspension points in the frame.

Signal analysis of the results reveals two dominate frequencies: one of approximately 1 Hz generated by interaction of the loads generated by the two trains as they pass, the other of approximately 4 Hz, associated with the frequency of the electromagnets. Passage of the trains takes 0.85 s, so calculations were carried out for 1.5 s. Depending on the value chosen for global damping, the maximum dynamic loads exceeded the static loads by a factor of up to 1.5.

It should be noted that, if information on the mass and stiffness of the upper parts of the frame construction is provided and included in the simulation of the train passage, information on resonance behaviour, critical train velocities and added dynamic loading factors These questions were not part of the current modeling task.

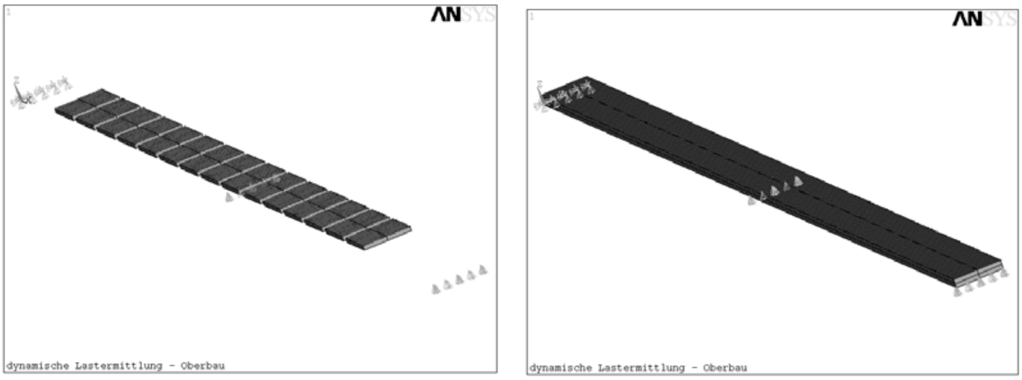

Figure 7. Finite element-model of the frame (left) and load distribution produced by the electromagnets (right) for the maximum load amplitude during passage of the Transrapid train.

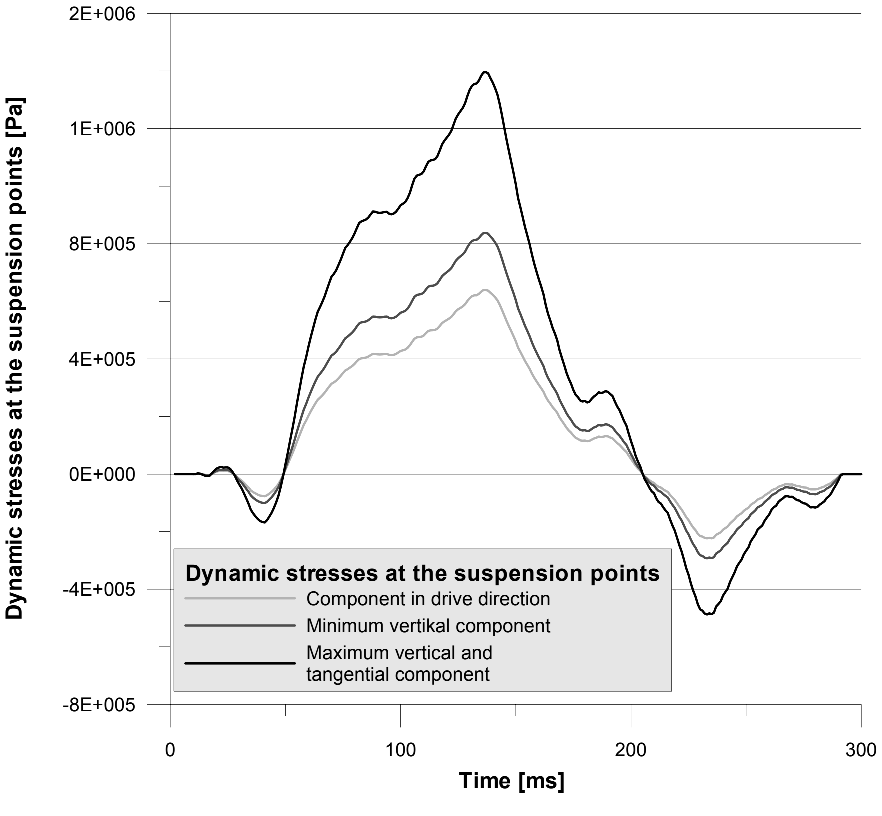

Figure 8. Variation of dynamic excitation stresses [Pa] for one load suspension point.

5. Results of dynamic hydro-mechanical coupled calculations

Selected results of the dynamic hydro-mechanical coupled calculations RF-1, RF-2 and RF-3 are shown, in summary form, in Table 2 below.

Table 2. Summary of most important calculation results.

	RF-1	***RF-2***	***RF-3***
Maximum dynamic displacement at the lower boundary of the foundation slab [mm]	4.0	3.5	13.5
Maximum residual displacements at the upper boundary of the lower part of the frame construction after train passage [mm]	2.2	2.0	11.0
Maximum dynamic inclination at the lower boundary of the foundation slab during train passage [mm/m]	0.90	0.87	3.5
Maximum residual inclination at the upper boundary of the lower part of the frame after train passage [mm/m]	0.33	0.30	1.7
Maximum dynamically generated pore water pressure increase / decrease at the lower boundary of the foundation slab during train passage [%]	----	144 / 100	233 / 100

Plastic deformations extend locally and temporarily to a depth of up to approximately 15 m below the surface. Shear and volumetric failure are dominant. Nearly all of the dynamic movements in the ground have been attenuated after approximately 1.5 s for most of the simulations. In the case RF-3 the ground vibrations show a small decay only. This is due to a resonance-like behavior in the first soil layer, which is a consequence of reflections produced by the strong stiffness contrast at the first discontinuity layer. Figures 9 to 14 show examples of time varying displacement components and pore water pressures at the four corners A, B, C and D of the slab foundation, and below the center of the slab foundation Undrained conditions were assumed in view of the short loading times.

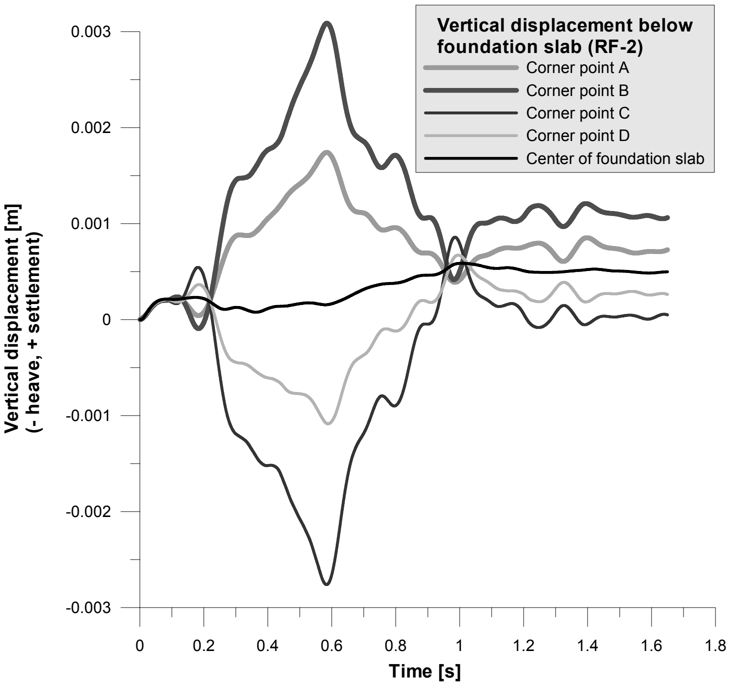

Figure 9. Vertical displacements [mm] of selected observation points at the lower boundary of the slab foundation as a function of time (Case RF-2).

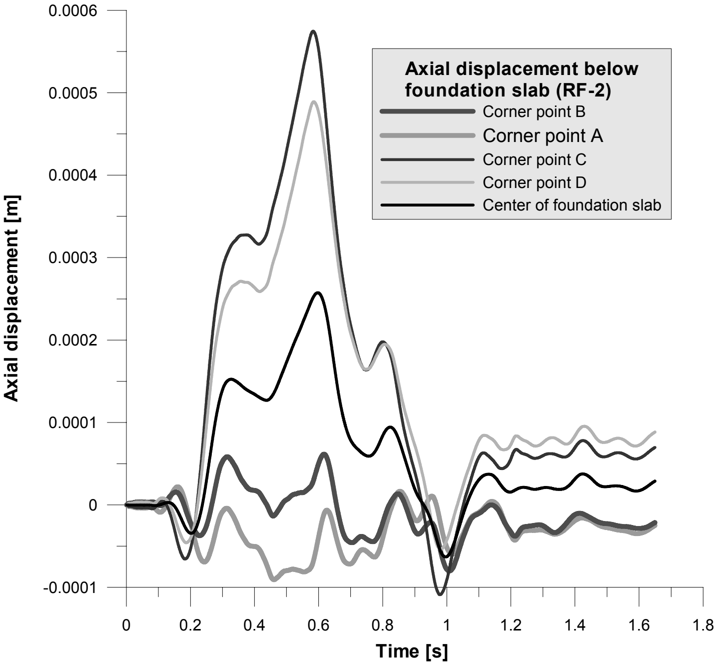

Figure 10. Horizontal displacements [mm] at selected observation points on the lower boundary of the slab foundation in the direction of the train as a function of time (Case RF-2).

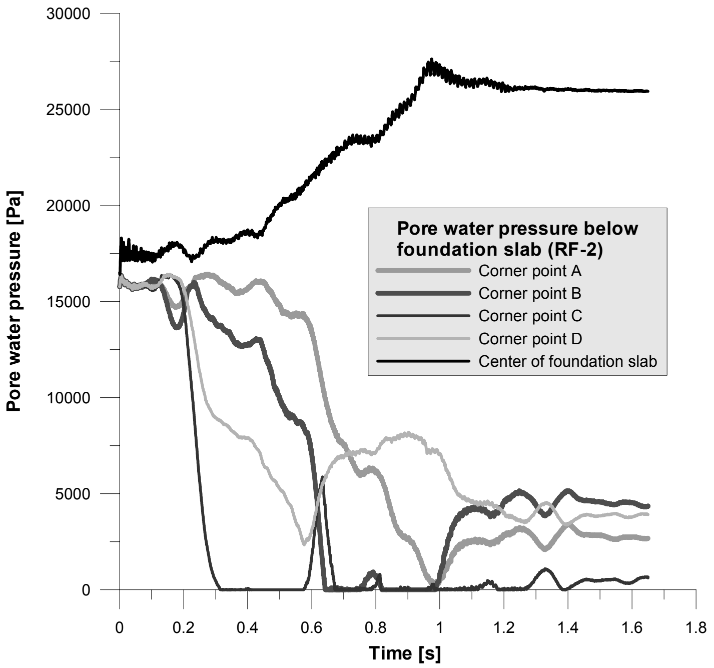

Figure 11. Pore pressure [Pa] of selected observation points on the lower boundary of the slab foundation as a function of time (Case RF-2)

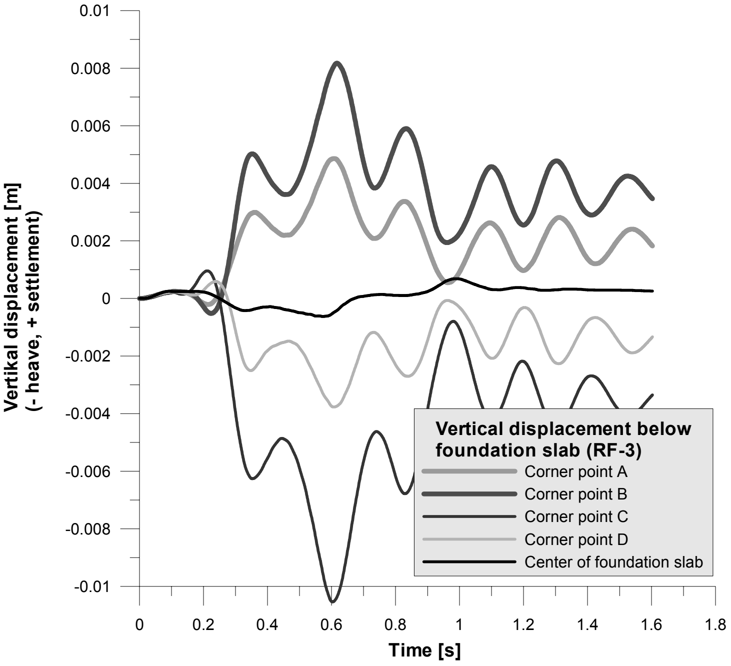

Figure 12. Vertical displacements [mm] of selected observation points on the lower boundary of the slab foundation as a function of time (Case RF-3).

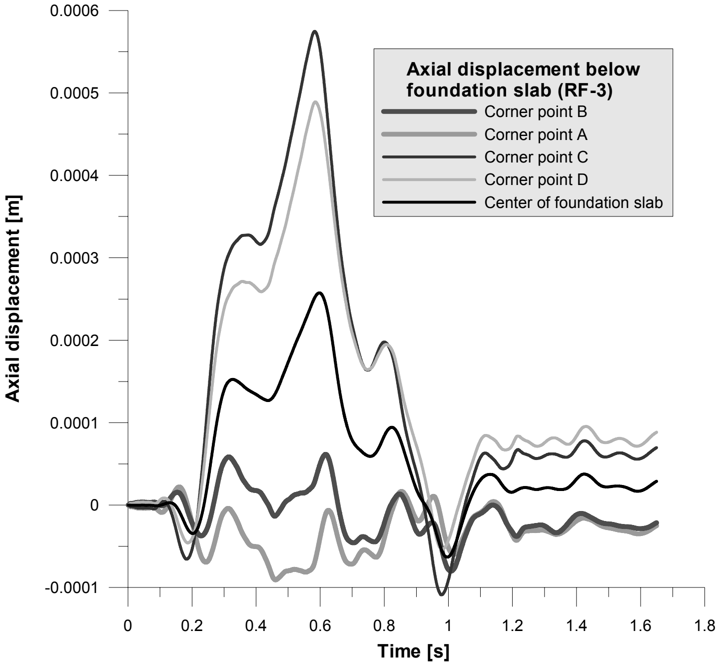

Figure 13. Horizontal displacements of selected observation points on the lower boundary of the slab foundation [mm] in the train direction as a function of time (Case RF-3).

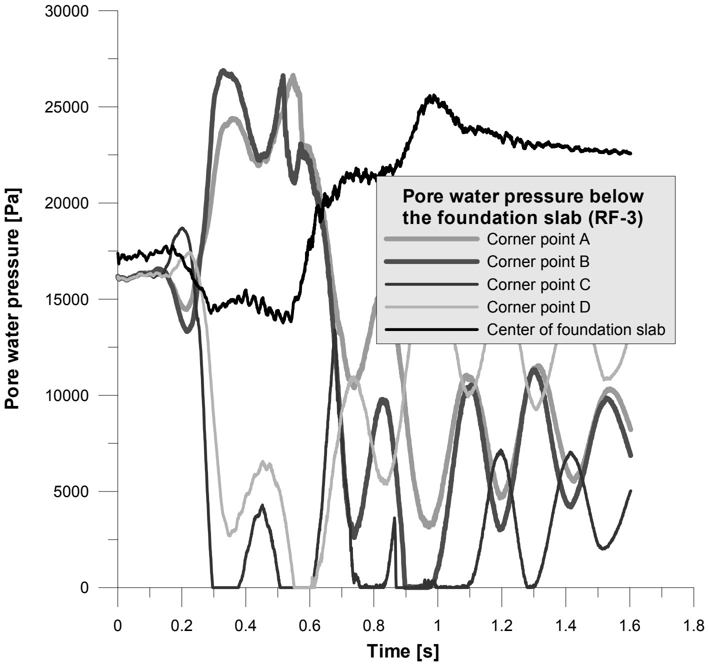

Figure 14. Pore pressure development [Pa] at selected observation points on the lower boundary of the slab foundation as a function of time (Case RF-3).

6. Discussion of results

The numerical simulations described above demonstrate the feasibility of complex geotechnical 3-dimensional hydro-mechanical coupled calculations to study practical problems. In the case discussed, dynamic loading and soil structure interaction of the foundation for a high-speed train system is the particular problem but other problems of comparable complexity can be analyzed. The simulations indicate that the complete three-dimensional load-deformation behaviour and soil-structure interaction can be investigated.

The extent and magnitudes of dynamically-generated pore pressures, plastic regions and possible areas of failure have been identified and evaluated. A realistic representation of the behavior of ground was achieved by including the following aspects of the problem:

- 3D simulation,
- full hydro-mechanical coupling,
- dynamic generation of pore pressures,
- non-linear static calculations,
- non-linear transient dynamic simulation (real-time),
- elasto-plastic material behavior, including a moving cap,
- realistic dynamic excitation in all 3 spatial directions.

Consideration of these factors allow more realistic simulations with respect to the following design issues

- serviceability limits,
- ultimate limit state design,
- evaluation of alternative foundation concepts,
- optimization of foundations (including cost optimization),
- reduction of operational risk.

The parameters used in this study correspond to very poor ground conditions with no ground improvement. Combined with the extreme loading conditions the simulations have resulted in large plastic deformations. These deformations can be reduced considerably with application of ground improvements and /or alternative foundation concepts. Further numerical simulations should include cyclic loading with a high number of train passages in order to assess the long-term behavior of the system.

7. References

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