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3D Dynamic Modeling of Transition Zones

Edina Koch, Péter Hudacsek

Abstract**—**In railways transition zone is present at the boundaries of zones with different stiffness. When a train rides from an embankment onto a stiff structure, such as a bridge, tunnel or culvert, an abrupt change in the support stiffness occurs possibly inducing differential settlements. This in long term can yield to the degradation of the tracks and foundations in the transition zones. A number of techniques have been proposed or implemented to provide gradual stiffness transition at the problem zones, such as methods to ensure gradually changing pad stiffness, application of long sleepers or installation of auxiliary rails in the transition zone. Aim of the research presented in this paper is to analyze the 3D and the dynamic effects induced by the passing train over an area where significant difference in the support stiffness exists. The effects were analyzed for different arrangements associated with certain differential settlement mitigation strategies of the transition zones.

Keywords**—**Culvert, dynamic load, HS small model, railway transition zone.

I. Introduction

RAILWAY transition zones are always present at the boundaries between regions of different stiffness. Fig. 1 shows this problem and relates it to another one; namely the differential settlement between these two zones. According to [1], the key factor for reducing the maintenance costs in railways consists of defining an optimum vertical stiffness below the track and maintaining it. This is clearly a problem in transitions between embankment and bridges or tunnels. One of the objectives of the transition is to provide a gradual stiffness variation as shown in Fig. 2.

ERRI [2] indicates that the factors influencing the behavior of the track in transition zones can be: (1) external to the track (axle loads, weather conditions, speed and vibrations), (2) geotechnical issues (sub-grade and soil conditions), (3) structural conditions (bending stiffness, lateral movements and interaction between track and bridge) or (4) related to the track design and layout (stiffness, location of track dilation devices or presence of CWR).

A number of different solutions for transition zones have been proposed and applied. These transitions are built to smooth the stiffness variation between the "soft" approach section and the "stiff" section over the structure. Transitions based on smoothing the stiffness variation on the "soft" side include the use of oversized sleepers, varied spacing sleepers, underlayments of hot-mix-asphalt, geotextiles, or soil-cement, additional rails, approach slabs, and others [3]-[5].

E. Koch is with the Department of Structural and Geotechnical Engineering at Széchenyi István University, 9026 Győr, Hungary (corresponding author, phone: +3630-5636342; e-mail: koche@sze.hu).

P. Hudacsek is with the Department of Structural and Geotechnical Engineering at Széchenyi István University, 9026 Győr, Hungary.

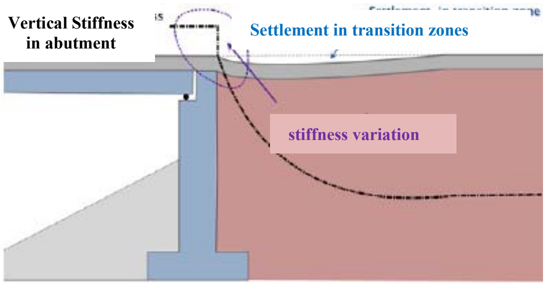

Fig. 1 Stiffness problems

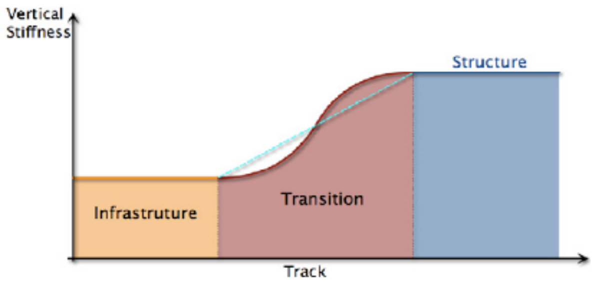

Fig. 2 Transition Solutions

Transitions based on lowering the stiffness on the "stiff" section include the use of soft rail pads under sleeper pads, plastic sleepers or ballast mats [3]-[7]. According to Li and Davis [4], transition zones must address the specific stiffness issues of the corresponding track discontinuities in order to be effective.

The problems associated with the transition zones require a complex analysis. For efficient modelling of the mechanisms resulting in gradual line degradation in the transition zones, understanding the 3D and dynamic effects associated with the problem are essential. To better understand the problem, a 3D numerical model has been developed and presented for time domain analysis.

II. Modeling Approach

The effect of moving train loads over a culvert has been analysed using the PLAXIS 3D Dynamic package [8]. The culvert itself consists of a square concrete box (2 m by 2 m). Fig. 3 shows a section of the culvert and the soil profile. The top 5-m of the subsoil in the current model was soft silt, resting on 15 m of stiff sand. On top of the soft layer, a sand embankment was built to support the railway line. Height of the embankment was H=0-2-3-4-5 m, with a slope of 1:1.5. The ballast layer was designed with 0.35 m thickness.

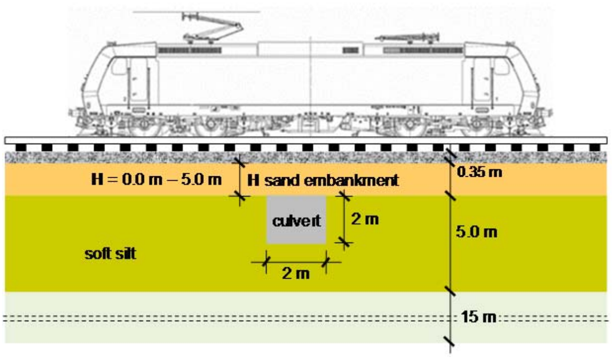

Fig. 3 Longitudinal view of the track passing over the culvert (not to scale)

The length of the model was 96 m, and the width was 45 meters. Standard fixities and absorbent boundaries were applied to model free-field conditions and reduce wave reflections at the boundaries. The rail was modeled by a beam element along 96 m of profile in the Y-direction. The properties of the beam section were selected in a way that it had the same flexural- and tensile stiffness as a 60E1 rail. The standard sleeper, B70, was modeled as a beam element by duplicating the moment of inertia and area. Input properties for rail and sleepers are shown in Table I. A total of 121 sleepers were placed in the model with a center-to-center distance of 60 cm. Fig. 4 shows the PLAXIS 3D model. The moving train was modeled with the LM71 Eurocode load model consisting of eight dynamic point loads of 125 kN vertical force.

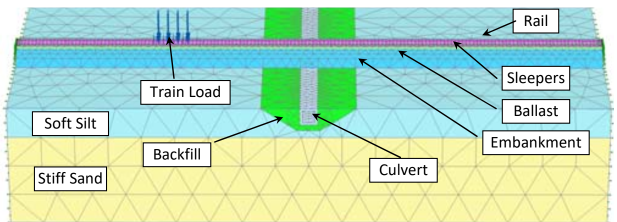

Fig. 4 PLAXIS 3D model

PLAXIS 3D defines dynamic loads using a time-force signal. In the model, every single dynamic point load has its own multiplier. These load multipliers turn on and off when the rolling vehicle passes over it. The dynamic time step changed to simulate different travel velocities (80 km/h and 250 km/h), while the distance between dynamic point loads were held constant. For example, a train with 80 km/h speed passes 80 cm in 0.036 sec; hence, the time interval must be chosen 0.036 sec for the fixed dynamic point loads. The total elapsed time between the first load and the last load 4.32 sec. An additional time of 2.68 sec was considered to allow complete dissipation of the waves induced by the passing train [9].

The following construction phases were defined: 1–initial phase, 2–excavation, 3–placing the backfill material underneath the culvert, 4–construction of the culvert, 5–placing the backfill material at both sides of the culvert, 6–construction of the embankment, 7–placing the ballast, 8–placing the sleepers, 9–placing the rails, 10–moving train (80 km/h and 250 km/h).

A plastic drained calculation condition was chosen in phase 1-9. In phase 10, the dynamic calculation option was selected to model the stress and strain waves and vibrations in the soil. In this phase, all dynamic point loads on the rails were active.

TABLE I
INPUT PROPERTIES IN PLAXIS 3D FOR RAIL AND SLEEPER

Parameter	Sleeper B70	Rail 60E1
Cross section area A (m^2)	0.0513	0.0077
Unit weight γ (kN/m^3)	25	78
Young's modulus E (MPa)	36000	200000
Moment of inertia third axis I_3 (m^4)	0.0253	0.00003
Moment of inertia second axis I_2 (m^4)	0.00024	0.00000513

III. Material Properties

It has been discovered from dynamic response analysis [10], that most soils exhibit nonlinear stress-strain relationships. The shear modulus G (see Fig. 5) is usually expressed as the secant modulus found at the extreme points of the hysteresis loop. The damping factor is proportional to the area found inside the hysteresis loop. The applied terminology of damping usually means the dissipation of strain energy during cyclic loading [14]. From the definition of both physical properties, it is clear that each of them depends on the magnitude of the strain for which the hysteresis loop is determined. Thereby, both the shear moduli and damping factors must be determined as functions of the strain level experienced by the soil [14]. Several studies have shown that the shear moduli of most soils decay monotonically with strain. Cavallaro et al. [11], Mayne and Schneider [12], and Benz et al. [13] suggest that the maxima are at very small strain levels, i.e. less than 10^{-6} to 10^{-5}, which is associated to recoverable strains, the material behavior is almost purely elastic (see Fig. 6). [14]

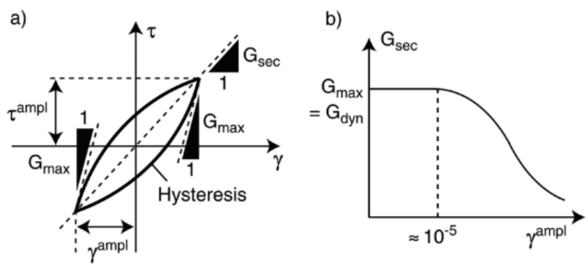

Fig. 5 (a) Definition of the secant shear stiffness G_{sec} of the hysteresis loop, (b) decrease of G_{sec} from its maximum value G_{max} with increasing shear strain amplitude γ^{ampl} [15]

The small strain stiffness implementation in PLAXIS is based on the small strain overlay model [16]. The required parameters are G_0 and $\gamma_{0.7}$. In the absence of experimental data for the determination of these two required parameters, approximations through correlations can be appropriate [14].

To model the soil behavior, the HS-small constitutive model was applied. The ballast layer is modeled by MC, for the concrete culvert Linear Elastic model was applied. Material properties of soil layers are listed in Table II. The Poisson's ratio was ν_{ur}=0.2 for all layers as recommended by PLAXIS [9].

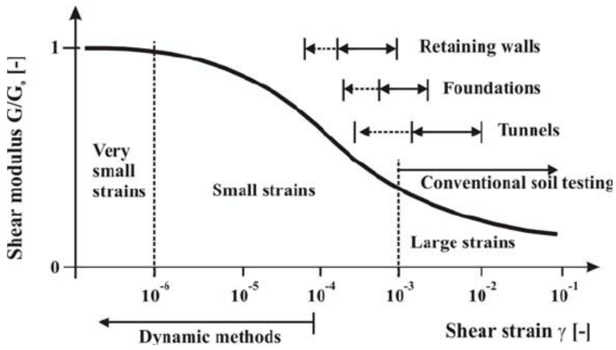

Fig. 6 Characteristic stiffness-strain behavior in logarithmic scale [17], [18]

TABLE II
MATERIAL PROPERTIES OF SOIL LAYERS

parameter	subsoil	backfill / embankment	ballast	culvert
	soft clay	dense sand	gravel	concrete
model	HS-small	HS-small	MC	LE
E (kPa)			100 000	3 10^7
E_{50}^{ref} (kPa)	4 000	36 000		
E_{oed}^{ref} (kPa)	4 000	36 000		
E_{ur}^{ref} (kPa)	12 000	108 000		
G_0^{ref} (kPa)	6 000	100 800		
m (-)	0.70	0.51		
$\gamma_{0,7}$ (-)	0.00279	0.00014		
c'_{ref} (kPa)	10	1.0	10.0	
ϕ'_{ref} (deg)	25	35.5	40.0	
ψ (deg)	0	5.5		

IV. RESULTS

The aim of modeling was to determine the settlement in the culvert transition zone while varying embankment height and train speed. In order to evaluate the settlement due to a moving train, several cross-sections were selected (3 on open track, 5 on backfill and 1 on the culvert) and total displacements were determined on top of the ballast when the moving train was exactly above the cross-section.

Fig. 7 shows the deformed mesh of a model. One can see the effect of the moving train as it pushes the embankment into the soft subsoil.

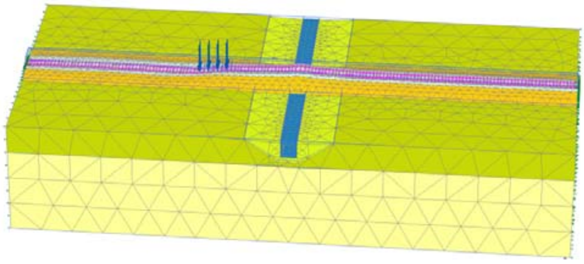

Fig. 7 Deformed mesh of a model

The influence of train speed and embankment height on track settlement is summarized in Fig. 8. It can be established that a higher speed causes greater settlement and the higher the embankment, the lower the settlement due to the moving train. The difference is not much; especially in case of low embankment height due to the softness of the subsoil.

Fig. 9 shows the vertical velocity for five checkpoints in different layers on open track (A: +3.35 m-top of the ballast, B: +2 m in the embankment, C: ±0.0 m-top of the subsoil, D: -1.5 m in the subsoil, E: -5 m in the subsoil). Results relate to the case of 3.0 m high embankment and 80 km/h train speed. Velocity amplitudes are smaller as you go deeper, which is matched to the engineering expectation. The highest velocity belongs to checkpoint A that is located on top of the ballast. The checkpoints B, C, D, and E show smaller velocities as the wave goes deeper in Z-direction.

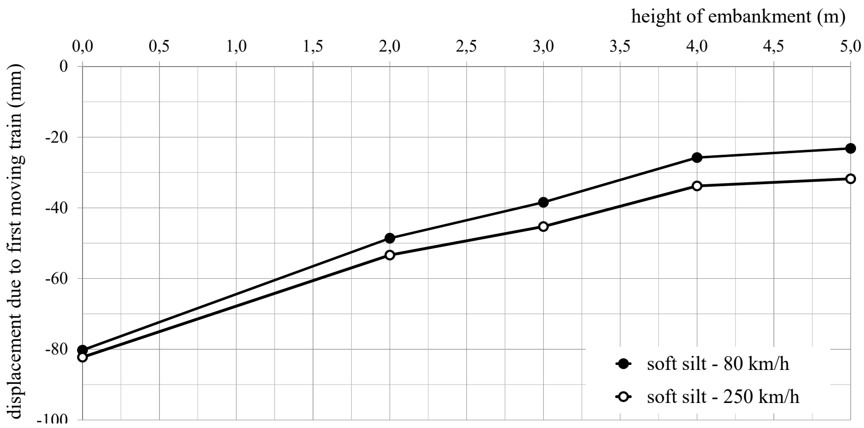

Fig. 8 Relationship between embankment height and settlement

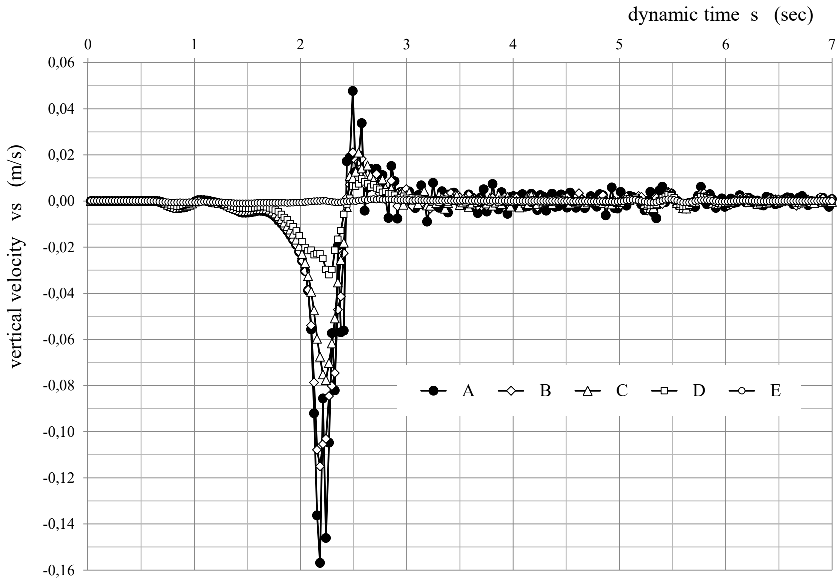

Fig. 9 Vertical velocity vs dynamic time at 80 km/h

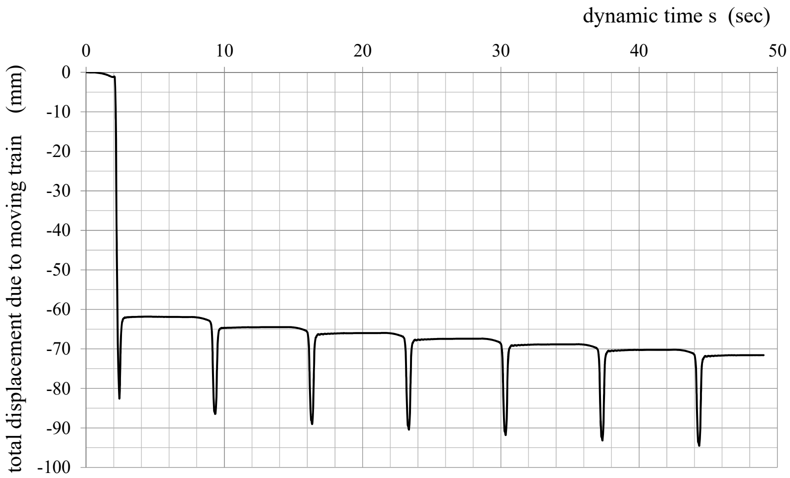

Fig. 10 Settlement of open track due to repetitive moving load

Fig. 10 presents the result of total displacements due to repetitive moving load. The same load model run seven time on the 96-m long model with the speed of 80 km/h. One can state that the first moving load causes high immediate settlement, the residual one is much lower. The incremental settlement between two load steps slightly decreases as the running step increases.

Fig. 11 shows the total displacement in a longitudinal section of the transition zone when the train approaches to the backfill zone. Red colour means higher settlement. The effect of moving train is clear. The displacement decreases with depth. The residual settlement on the open track is less than the immediate.

Fig. 12 shows the total displacements (construction and moving train) for seven checkpoints in different layers (open track: A: top of the ballast +2,35 m, B: top of the subsoil, C: -3,0 m in the subsoil; backfill zone: D: top of the ballast +2,35 m, E: top of the backfill, F: -3,0 m in the backfill zone, G: top of the ballast above the culvert).

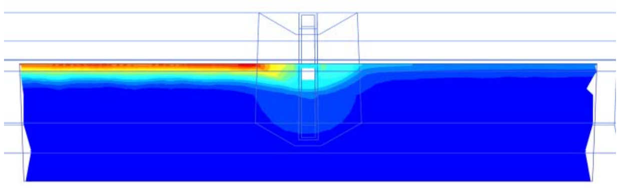

Fig. 11 Longitudinal section of transition

Based on Fig. 12, the following observations can be stated:

– the greatest displacement on open track occurs on top of the ballast (A),
– in the backfill zone, the displacement reduces

significantly (D),

- the “bump” is conspicuous when the load is directly above the culvert (G),
- reduction of the settlement with the depth is obvious (B-C and E-F),
- at -3 m in the subsoil, the effect of passing train is definitely decreased (C).

Fig. 13 shows the peak extra displacements due to the first passing of the train along the longitudinal profile for four different cases, varying the embankment height and train speed. The following could be stated:

- the highest settlement due to the passing train on open track occurs in the case of no embankment at 250 km/h train speed,
- the lowest settlement on open track occurs in the case of 2 m embankment at 80 km/h train speed,
- differential settlement between the open track and culvert is the highest in the case of no embankment and 250 km/h train speed,
- case of no embankment and 250 km/h needs the longest transition,
- shapes of settlement curves change in the backfill zone due to the stiffest backfill material.

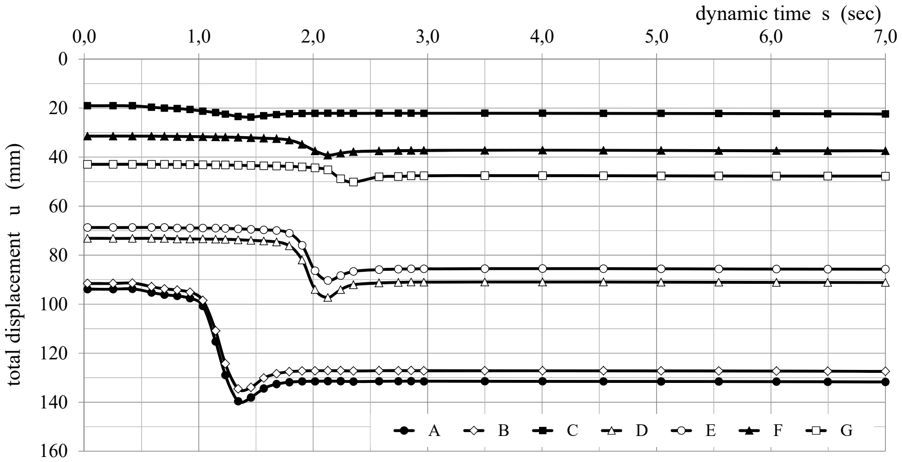

Fig. 12 Total displacement in different checkpoints

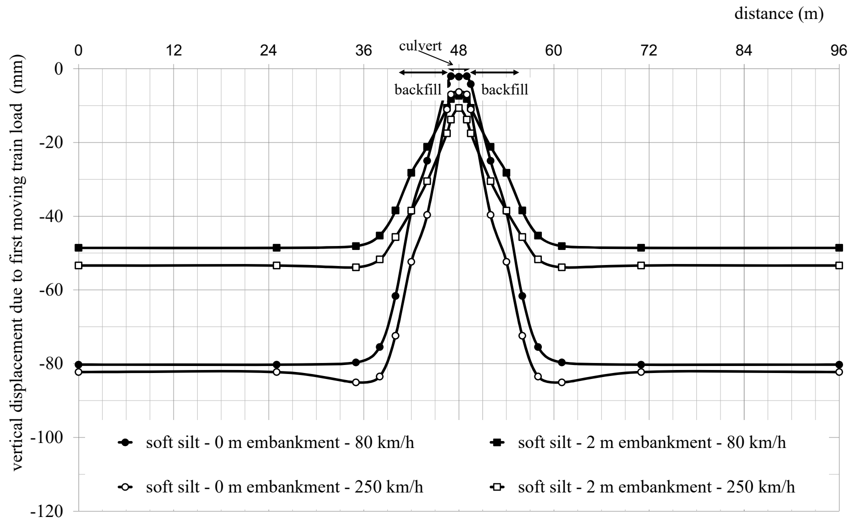

Fig. 13 Settlements of different models

V. Ground Improvement for Reducing Differential Settlement

The second part of our research was to investigate how reduce the differential settlement between the two different stiffness structures (embankment and culvert) and how provide a gradual stiffness variation. For this purpose, the 2.0-m height embankment and 80 km/h train speed model was analyzed.

The basic results of the model were

- settlement on open track was 95 mm after placing the rails,
- moving train caused almost 50 mm extra settlement,
- the differential settlement (due to the extra settlement)

between the two different stiffness structures was about 40 mm,
- necessary length of the transition was 2.5 times longer than the length of the backfill zone.

For achieving the design criteria where settlement is less than 20 mm on open track and transition is smooth between the open track and the culvert, ground improvement is recommended before starting construction One of the solutions is deep-mixing stabilization of the subsoil.

The goal of deep-mixing is to improve the soil characteristics, e.g. increase the shear strength and/or reduce the compressibility, by mixing the soil with some type of chemical additives that react with the soil. The improvement occurs due to ion exchange at the clay surface, bonding of soil particles and/or filling of voids by chemical reaction products [19].

One type of treatment namely partial mass stabilization was evaluated; 1.8-m diameter equivalent columns were placed in 3.0×3.0-m square grids. Young's modulus for the columns was Eref=20 000 kPa, the unconfined compressive strength was qu=300 kPa and the value of Poisson's ratio was ν = 0.2.

Fig. 14 shows the PLAXIS 3D model. Fig 15 shows the peak displacements for the first passing of the train along the longitudinal profile for both cases, without treatment and with treatment of subsoil. The following could be stated:
- the settlement on open track is reduced drastically,
- settlement reduction is significant on the backfill zone,
- the smooth transition is visible,
- differential settlement between the open track and culvert was less than 10 mm.

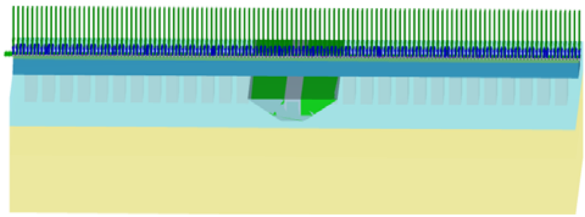

Fig. 14 PLAXIS 3D model with the partial mass stabilization

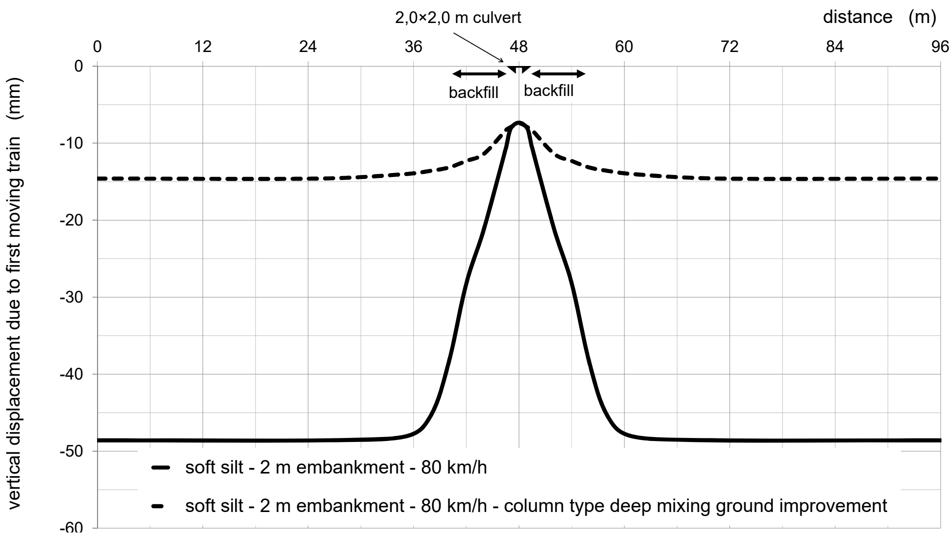

Fig. 15 Reduction of differential settlement

VI. Conclusions

The presented results show that the real life problem of a train travelling in a transition zone can be modelled in PLAXIS 3D. The current paper focuses mainly on the modelling itself, and the results presented here are only a subset of a larger parametric study. It is clearly illustrated that the influences of the different parameters (such as the speed of the vehicle and the height of the embankment) can be modelled efficiently. The presented experience in dynamic 3D modelling of the problem allowed us to make design recommendations for the required length of the transition zone in different soil conditions and different types of structures. The effect of the train velocity on the settlements has been demonstrated. This increment however is not associated with the increased dynamic factor but probably the higher rate of accumulated strains due to a more rapid impact and a same rate of energy dissipation. The extra peak settlement in the approach zone at high speed passing is probably also due to the accumulation of dynamic strains partially caused by the reflections from the culvert.

Based on the cyclic response analysis that has also been presented here, one may conclude that the model is capable to produce predictions on the long term behavior of the track. The experienced incremental settlement is due to plastic deformations of the soil mass which supposed to cease after a number of cycles. To test this hypothesis, a higher pass numbers will be tested shortly. For the analysis of shakedown like behavior different soil model with cyclic degradation capability should be implemented.

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