Modeling of railway transition zones under dynamic loading

Modélisation de zones de transition des voies de chemin de fer dans les situations de charge dynamique

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ABSTRACT: Transition zones of railway tracks are intended to provide a smooth transition of the riding train, minimizing the effect of the discontinuities that exist along the track. 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. The differential settlement is especially problematic for high speed rail infrastructure as the "bump" at the transition is accentuated at high speeds. 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. The problems associated with the transition zones require a complex analysis. For efficient modeling of the mechanisms resulting in gradual line deteriorations in the transition zones the understanding of the 3D and dynamic effects associated with the problem seems to be essential. To enhance our understanding regarding the problem a 3D numerical model has been developed and presented for time domain analysis.

RÉSUMÉ : Les zones de transition des voies de chemin de fer sont destinées à assurer une transition en douceur du train en route, en minimisant l'effet des discontinuités qui existent le long de la voie. Lorsqu'un train monte d'un remblai sur une structure rigide, telle qu'un pont, un tunnel ou un caniveau, un brusque changement brusque de la raideur de support se produit, ce qui peut induire des règlements différentiels. A long terme, cela peut conduire à la dégradation des voies et des fondations dans les zones de transition. Le règlement différentiel est particulièrement problématique pour l'infrastructure ferroviaire à grande vitesse puisque la «bosse» à la transition est accentuée à des vitesses élevées. Un certain nombre de techniques ont été proposées ou mises en oeuvre pour assurer une transition de rigidité progressive dans les zones problématiques, telles que des procédés pour assurer une rigidité des semelles progressivement changeante, l'application de longs traverses ou l'installation de rails auxiliaires dans la zone de transition. Les problèmes associés aux zones de transition nécessitent une analyse complexe. Pour une modélisation efficace des mécanismes entraînant une dégradation graduelle des lignes dans les zones de transition, la compréhension des effets 3D et dynamiques associés au problème semble être essentielle. Afin d'améliorer notre compréhension du problème, un modèle numérique 3D a été développé et présenté pour l'analyse dans le domaine temporel.

KEYWORDS: dynamic load, HS small model, transition zone

1 INTRODUCTION

In railways transition zone is present at the boundaries of zones with different stiffness. Fig. 1 shows this problem and relates it to another one, namely the differential settlement between these two zones. According to Insa (2008), the key factor for reducing the maintenance costs in railways consists in defining an optimum level of the vertical stiffness of 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 (1999) indicates that the factors influencing the behavior of the track in transitions zones can be external to the track (axle loads, weather conditions, speed and vibrations), geotechnical issues (sub-grade and soil conditions), structural conditions (static system, bending stiffness, lateral movements and interaction between track and bridge) or related to the track design and layout (stiffness, location of track dilation devices or presence of CWR).

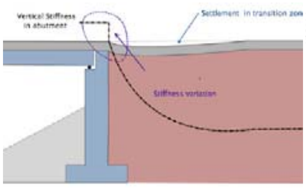

Figure1. Stiffness problems

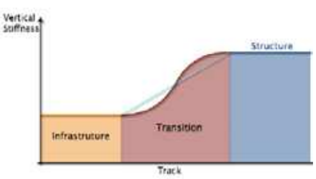

Figure 2. Transition Solutions

A number of different solutions for transition zones have been proposed and applied. These transitions are built to smoothen 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 (Kerr and Moroney, 1993; Li and Davis, 2005; Read and Li, 2006) include the use of oversized sleepers, varied spacing sleepers, underlayments of hot-mix-asphalt, geotextiles, or soil-cement, additional rails, approach slabs, among others. Transitions based on lowering the stiffness on the "stiff" section (Kerr and Moroney, 1993; Sasaoka and Davis, 2005; Read and Li, 2006; Li et al., 2010) include the use of soft railpads under sleeper pads, plastic sleepers or ballast mats. According to Li and Davis (2005), 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 deteriorations in the transition zones the understanding of the 3D and dynamic effects associated with the problem seems to be essential. To enhance our understanding regarding the problem a 3D numerical model has been developed and presented for time domain analysis.

2 MODELING APPROACH

In this paper the effect of moving train loads over a culvert has been analysed using the Plaxis 3D Dynamic package. The culvert itself consists of a square concrete box (2 m by 2 m). Figure 3 shows a longitudinal section of the culvert and the soil profile. The top 5m of the subsoil in the current model was soft clay, 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=0-2-4m, with a slope of 1:1.5. The ballast layer was designed with 0,35 m thickness.

The length of the model was 96 m and the breadth was 45 meters. Standard fixities and absorbent boundaries were applied to model free field conditions by the reduction of reflections from the boundaries. The rail was modeled with a beam element along 96 m of profile in Y direction. The properties of the beam section were selected in a way that it had the same flexural- and normal stiffness as a UIC60 rail. The standard sleeper B70 was modeled as a beam element by providing the moment of inertia and area. Input properties of rail and sleepers are shown in Table 1. 121 sleepers were placed in the model with a center-to-center distance of 60 cm. Figure 4 shows the PLAXIS 3D model. The moving train was modeled with the LM71 Eurocode load model consisting of eight dynamic point loads with 125 kN.

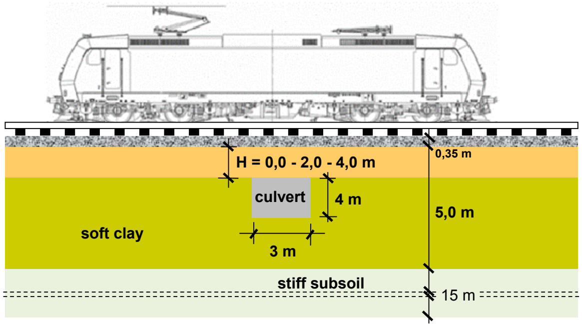

Figure 3. Longitudinal view of the track passing over the culvert (not to scale)

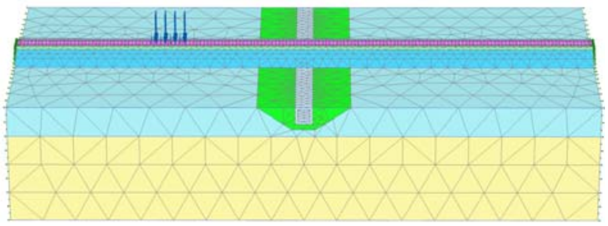
Figure 4. Plaxis 3D model

A dynamic multiplier is defined as a time-force signal in PLAXIS 3D. In the model, every single dynamic point load has its own multiplier. These load multipliers turn on and off the present point loads simulating the loads imposed by the rolling vehicle. For the simulation of different travel velocities (80 km/h and 250 km/h) the dynamic time step has been changed, 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 moments the first load enters the model and the last load leaves is 4.32 sec at 80 km/h. An additional time of 2.68 sec was considered to allow complete dissipation of the stress waves induced by the passing train.

Table 1. Input properties in PLAXIS 3D for rail and sleeper

Parameter	Sleeper B70	Rail UIC60
Cross section area A (m^2)	0,0513	0,0077
Unit weight γ (kN/m^3)	25	78
Young'smodulus 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

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.

A plastic drained calculation type 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.

3 MATERIAL PROPERTIES

It has been discovered from dynamic response analysis (Seed & Idriss, 1970), that most soils exhibit curvilinear stress-strain relationships. The shear modulus G (see Figure 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. 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. Several studies have shown that the shear moduli of most soils decay monotonically with strain. Cavallaro et al. (1999), Mayne & Schneider (2001), and Benz et al. (2009) 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 Figure 6).

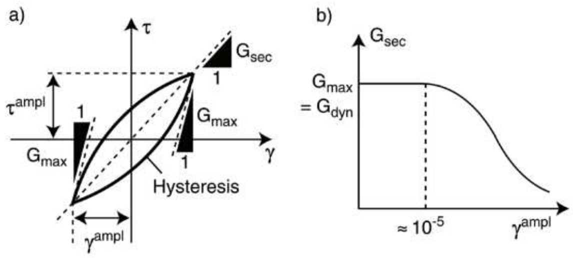

Figure 5. a) Definition of the secant shear stiffness G_{sec} of the hysteresis loop, b) decrease of G_{sec} from its maximum value G_{max} with increasing shear strain amplitude γ^{ampl}

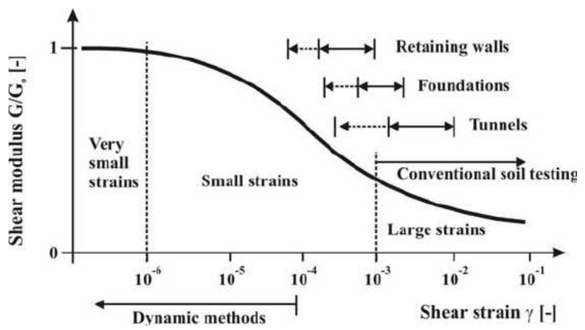

Figure 6. Characteristic stiffness-strain behavior in logarithmic scale

The small strain stiffness implementation in PLAXIS is based on the small strain overlay model (Benz et al., 2009). Parameters G_0 and $\gamma_{0.7}$ are required input parameters. At the absence of experimental data for the determination of these two required parameters, approximations through correlations can be appropriate.

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. Soil basic and advanced properties in models are listed in Table 2. The applied Poisson's ratio for all layers in the HS-small model is the default value given by PLAXIS (ν_{ur} = 0.2).

Table 2. 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 E+7
E_{50}^{ref} (kPa)	10 000	36 000		
E_{oed}^{ref} (kPa)	10 000	36 000		
E_{ur}^{ref} (kPa)	32 000	108 000		
G_0^{ref} (kPa)	22560	100 800		
m (-)	1,0	0,51		
$\gamma_{0,7}$ (-)	0,0001	0,00014		
c'_{ref} (kPa)	5	1,0	10,0	
ϕ'_{ref} (deg)	22	35,5	40,0	
ψ (deg)	0	5,5		

4 RESULTS

The aim of modeling was to determine the settlement in the culvert transition zone investigating the effect of embankment height and train speed. In order to evaluate the settlement due to moving train, several cross-sections were located (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.

Figure 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.

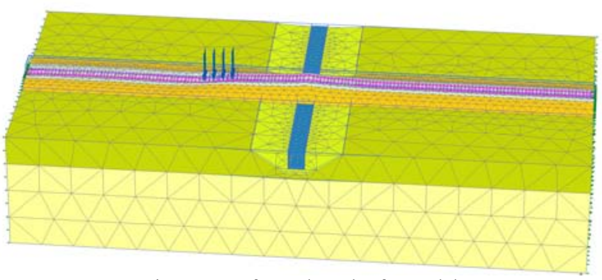

Figure 7. Deformed mesh of a model

The influence of train speed and embankment height on open track is summarized in Figure 8. It can be established that higher speed causes higher settlement and the higher the embankment the lower the settlement due to the moving train.

Figure 9 shows the vertical velocity for five checkpoints in different layers on open track (A: top of the ballast, B: top of the subsoil, C: -2 m in the subsoil, D: -5 m in the subsoil, E: +2 m in the embankment). 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 E, B, C and D show smaller velocities as the wave goes deeper in Z-direction.

Figure 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.

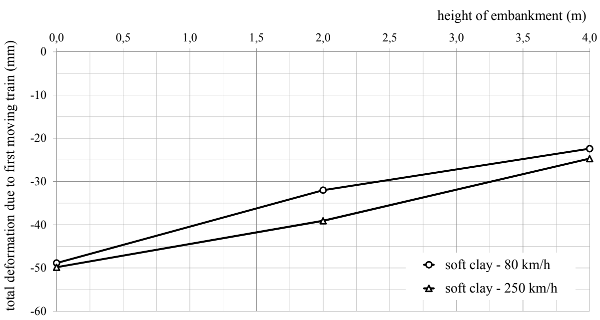

Figure 8. Relationship between embankment height and settlement

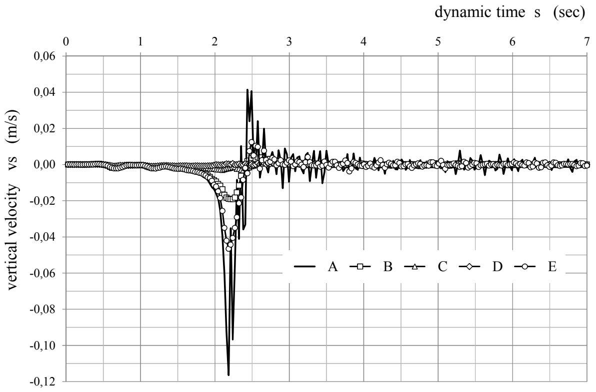

Figure 9. Vertical velocity vs dynamic time at 80 km/h

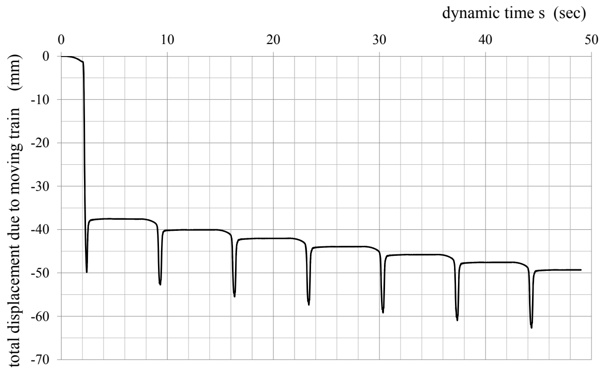

Figure 10. Settlement of open track due to repetitive moving load

Figure 11 shows the total displacement in a longitudinal section of the tranzition 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 open track is less than the immidiate.

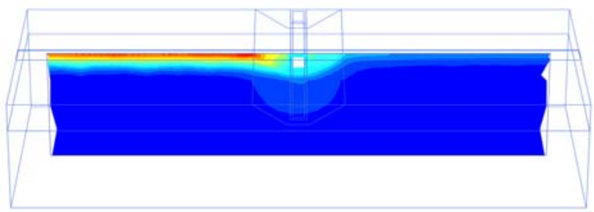

Figure 11. Longitudinal section of transition

Figure 12 shows the total displacements due to moving load for nine checkpoints in different layers (open track: A: top of the ballast, B: top of the subsoil, C: -3,5 m in the subsoil, D: -5 m in the subsoil; backfill zone: E: top of the ballast, F: top of the backfill, G: -3 m in the backfill zone, H: -5 m in the backfill zone, I: top of the ballast above the culvert).

Based on figure 12 the followings can be stated:

- highest displacement on open track occur on top of the ballast (A),
- in backfill zone the displacement reduces significantly (E),
- "bump" is conspicuous when the load is directly above the culvert (I),
- reduction of the settlement with the depth is obvious,
- at -5 m in the subsoil the effect of passing train is marginal.

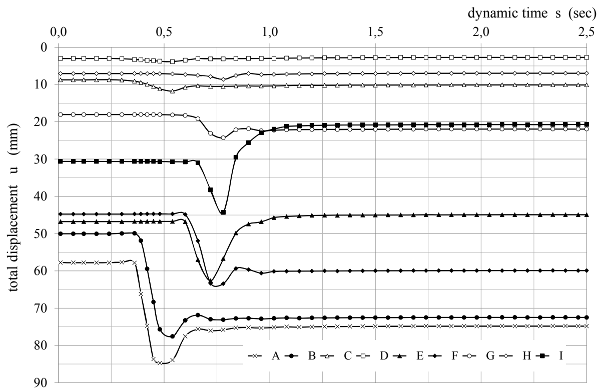

Figure 12. Total displacement in different checkpoints

Figure 13 shows the peak displacements for 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 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.

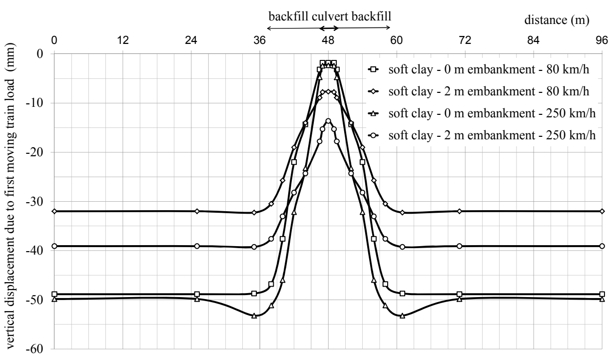

Figure 13. Settlements of different models

5 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 behaviour different soil model with cyclic degradation capability should be implemented.

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