NeTIRail

Needs Tailored Interoperable Railway Infrastructure

Deliverable D2.9

Preliminary transition zone model and detailed modelling plan

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Executive Summary

Transition zones are the locations where discontinuity occurs at the track supports, like where the track reaches the bridges, culverts and tunnels. These locations often need substantial extra maintenance to retain the track geometry and its ride quality. Transition areas are important, however their poor behaviours are still not fully understood [1][2]

Transition zones have higher rate of degradation compared to other parts of the track [3], and the reason behind this problem is the changes in the track alignment which exacerbates the variations in dynamic axle loads applied the track in those areas[4].

Many different suggestions and recommendations currently exist based on careful design and construction to mitigate this problem, however research based on maintenance records of high speed lines indicate that degradation of tracks associated with stiffness variations of the soil is far from being solved [4].

It is hard to understand the fundamental causes behind the performance of transition zones and as much as it is very important to railway infrastructure owners, the behaviour still not fully understood [2].

One of the best options on studying the behaviour of transition zones is to develop a finite element model of these tracks and validate it against real-life measurements of these areas. This report provides the steps on how these finite element models been developed and how they are going to be validated, also a plan is provided how these models will be used to understand the behaviour and give some recommendations to improve the performance of these transition zones.

The method of finite element modelling to study the behaviour of transition zones has been used by different studies, like Coelho et al. [2] or Varandas et al. [3] which used field data obtained from an extensive field survey conducted in two transition zones in Netherlands. Their results show that the forces were vary significantly both in time and space on a transition zones, especially due to the developing of voids under the sleepers. Shan et al. [5] modelled a railway tract subgrade system using finite element methods and studied two different transition zones between the ordinary subgrade and bridges which was used mainly for high speed passenger lines. They have found out that the dynamic response of the track subgrade system changed sharply after the first 3m of the transition zone section, measured from the bridge abutment.

As Coelho et al. [1] pointed out a fair agreement between the experimental and numerical results are necessary. And validated numerical analysis allows the analysis of the behaviour of transition zones at critical train speed and they suggested some recommendations on the shape and combination of concrete slabs and sleepers.

To be able to validate the finite element models, a case study of a transition zone on a new Portuguese railway line been provided from design and construction. The importance of this study was to provide

the results from conventional laboratory and cyclic load triaxial testing on granular materials and in situ mechanical characterization of the different layers are presented. At last the measurements obtained at different substructure level indicated that the design was successful in reducing the settlement and achieving a gradual stiffness increase as a bridge is approached [4].

Within task T2.6.1 we have continued the development of the transition zone finite element models, and a working model has been created and will be used further in the project, in task T2.6.2, to optimise transition zones and identify low cost remedial actions which can be carried out to improve their performance. Remedial actions to be studied further centre around but are not exclusive to sleeper design and spacing.

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1. Introduction

WP2 (tailored track infrastructure, design and maintenance) is a technical work package investigating issues that drive investment and ongoing operational costs. This work package will make contribution to the business case being developed in WP1, and provide technical solutions which will be disseminated to the end users through the training and dissemination activity in WP7 and the decision-making tools within WP6.

The output from this work package will aid evidence based decision making grounded in technical performance of rail infrastructure. WP2 gather the data needed by rail operators and infrastructure managers with the help of research partners, based on their technical expertise. The area of activities as mentioned in the *Project Description* are:

- "Geospatial comparison of rail infrastructure cost and maintenance drivers for high and low density lines. Mapping maintenance data with a Geographic Information System (GIS) and analysis of the data sets in this novel manner will help to reveal the drivers of cost and dependence on line type.
- Application of lean and automotive industry techniques to railway switches and crossings (S&C). Use of lean techniques to identify opportunities in adding value and removing non value adding costs within S&C operations and maintenance, optimised for specific line types.
- Life extension for plain line through preventing corrugation. Optimising fasteners, rail pads and other components to eliminate the root causes of corrugation and extend rail life.
- Tailoring lubrication to duty and climate. Optimising rail and wheel lubrication techniques for different geographical locations and line classifications, helping end users to identify the most appropriate lubrication method for particular traffic and climatic conditions.
- Cost effective transition zone design. Using novel methods for optimising vertical stiffness, reducing a cause of rail failure at the transition from ballasted track to stiffer structures such as bridges. Optimisation of sleeper size, spacing and width will deliver a cheaper solution than the major geotechnical rebuilding currently employed.
- Testing to support these tasks will take place in a lab environment, on the networks of SZ and RCCF, and at the AFER Faurei Test Track.
- Outputs will be in the form of technical solutions (modular infrastructure) and guidelines for operation."

This deliverable provides the details of "***Preliminary transition zone model and detailed modelling plan***". University of Sheffield is the lead partner in this task and undertook the development of the finite element model and will validate this model. After validation this model will be used to study different arrangements of sleepers and also INTADER solution on increasing the distance of stiffness variation area can be examined in the next task. The study on sleepers will be on their mass and dimensions to change the dynamic behaviour of these areas.

The rail industry believes that the ballast is the layer which contribute most in degradation of the track geometry quality, if it's a normal ballasted railway track and resting on good foundations and after the initial stabilization of the supporting layers. Many studies been done to create more efficient rail operations, many empirical relations been proposed over the years to predict the track degradation. The experience from operating on conventional and high speed railway lines (HSLs) has proven that at some locations the track degradation process was faster than normal and demonstrated that using the empirical degradation relationships to predict settlements is invalid. These areas needed more maintenance than expected to re-establish the quality of the track geometry in order to maintain the standard passenger comfort and safety levels. Furthermore, these locations usually correspond to specific points in the track, which show discontinuities in vertical stiffness related to the change in the tracks superstructure (rail, fastening system, sleeper and ballast) or substructure. Measurements carried out between 1992 and 2002 on the Madrid-Seville HSL in Spain reported such occurrences and the results indicated that maintenance work at transitions to bridges or to box culverts was three to six times higher compared to open tracks [4].

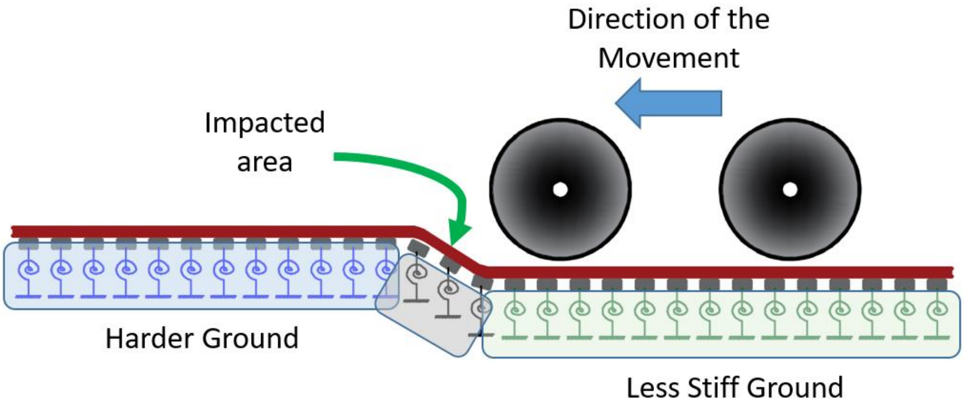


Figure 1 Transition zones less stiff ground to harder ground direction

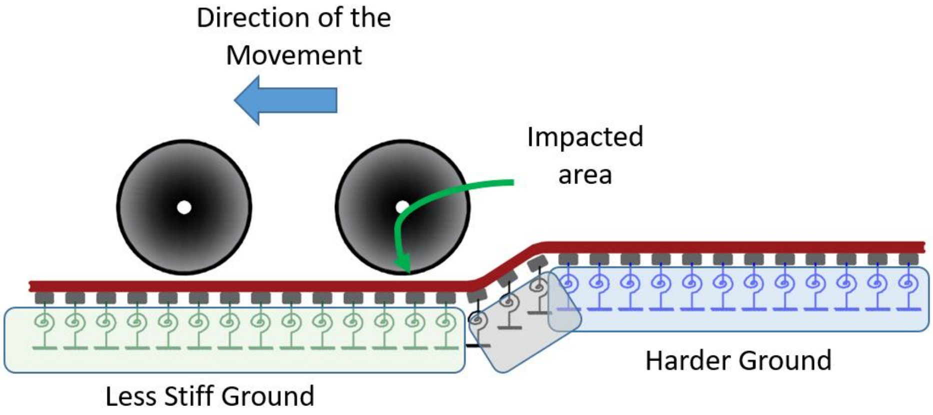


Figure 2 Transition zones harder ground to less stiff ground direction

Figures 1 and 2 show how track can be deformed under the train load and different ground stiffness. The impact location and magnitude also depends on the train direction of motion.

For almost a century studies have been conducted on railway dynamics. Knothe and Grassie [6] have reviewed the history behind of modelling of railway vehicle-track interaction. In 1926 Timoshenko [7] started to study the dynamic of vehicle-track to find out the effect of wheel flats. Also in the last century hundreds of papers and reports on dynamics of vehicle-track been published [8].

Finite element analysis has become more popular in geotechnical practices to control and optimise the engineering tasks. Specially finite element models are very useful to study the behaviour of the track [9]. As the engineering problems are usually complex, there is always a need to simplify the problem when simulations are used to save time and money. To understand the dynamic behaviour of transition zones, they need to be analysed, including the displacement, acceleration and stress distribution of each part of these transition areas [10].

In this study 3D & 2D finite element models were developed to study the behaviour of transition zones under passing of high speed trains. No field test were conducted for this work, however another study which been done on a new Portuguese railway [4] is going to be used to validate these models.

Time domain and frequency domain are the two different methods which can be used to analyse the finite element models. Frequency domain is simplified solution for wheel/rail interaction. It builds a relationship between the external force and receptance at different frequencies by avoiding the complicated differential equations and using mathematical transformation under set of assumptions. First person who used the frequency domain solution to analyse the dynamic behaviour of the track was Timoshenko [7] and he introduced the concept of receptance for a continuously supported Euler beam. Sato [11] calculated the receptance of an Euler beam on a separate layer of rigid sleepers for the first time. Grassie et al. [12] have introduced a system and studied the dynamic response of railway track using a frequency domain modelling technique [8].

Time domain modelling uses the time instead of frequencies to solve the wheel/rail interaction. The advantage of this method is the ability to solve the vehicle/track interaction using wheel/rail contact to give displacement, velocity, accelerations and forces generated in the model on all different components. In this method frequencies of different parts can be calculated based on displacement and time relationship. There are many researches which either contribute or use time domain finite element modelling. The models developed before 1980 were simpler compared to recent FE models which was due to the computer limitation at that time. Cai and Raymond [13] could only present 40 sleepers long discretely supported track and 4 dof vehicle model and do the dynamic studies of the vehicle/track interaction [8]. A comparison to the model developed in this study can show how much computer power is increased. The current model presented in this deliverable consists of 6 coaches, 600m long rail, different parts like springs, dampers and pads, different substructures under the track like ballast, sub-ballast, capping layer and different soils. All wheels are in contact with the rail to be able move with the high speed.

2. Development of two different finite element models

Two different finite element models are developed one with higher resolution using solid 3D elements to be able to do stress analysis on smaller parts of the wheel and the rail, also this model is cable of simulate the failure in different areas. The second model is developed using faster 2D elements like beams and shells, this model can give the linear and non-linear deformation results which will be applied to the first high detailed model to check for failures.

ANSYS software was used to develop the model and Ls-Dyna was used to solve the problem. Three different types of elements been used in developments of these two models, a brief description of these elements are provided as follow:

- **SOLID164 Element**

SOLID164 is used for the 3-D modelling of solid structures. The element is defined by eight nodes having the following degrees of freedom at each node: translations, velocities, and accelerations in the nodal x, y, and z directions [14].

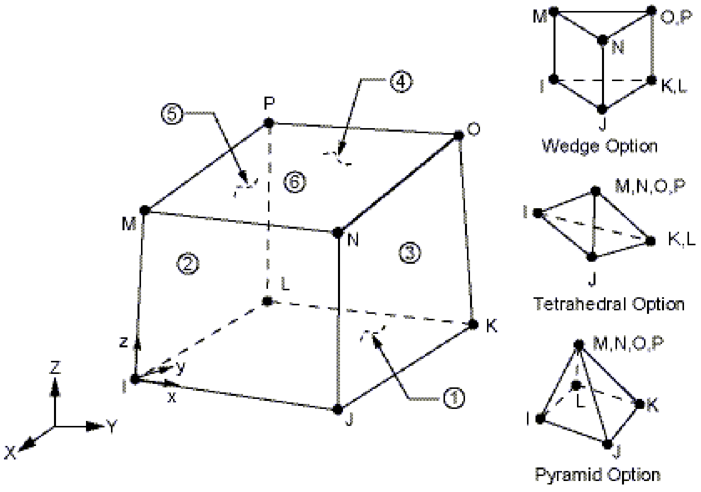


Figure 3 Solid element nodes and arrangement

- **SHELL163 Element**

SHELL163 is a 4-node element with both bending and membrane capabilities. Both in-plane and normal loads are permitted. The element has 12 degrees of freedom at each node: translations, accelerations, and velocities in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes [14].

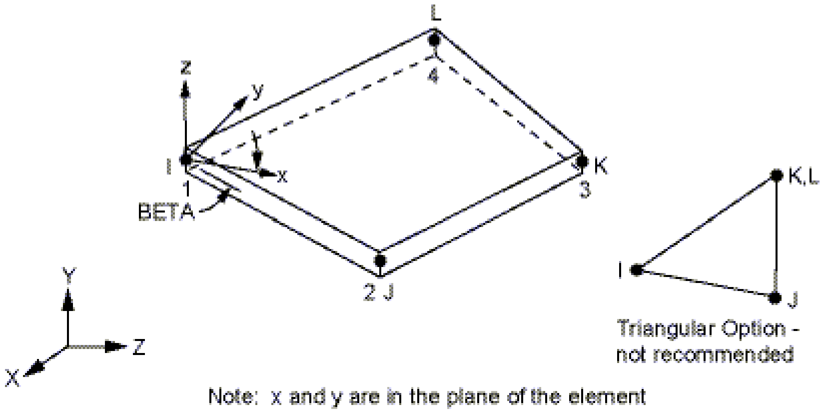


Figure 4 Shell elements nodes and arrangements

- **BEAM161 Element**

It is incrementally objective (rigid body rotations do not generate strains), allowing for the treatment of finite strains that occur in many practical applications. It is simple for computational efficiency and robustness. It is compatible with the brick elements. It includes finite transverse shear strains. However, the added computations needed to retain this strain component, compared to those for the assumption of no transverse shear strain, are significant. The Belytschko beam element formulation is part of a family of structural finite elements that use a "co-rotational technique" for treating large rotation [14].

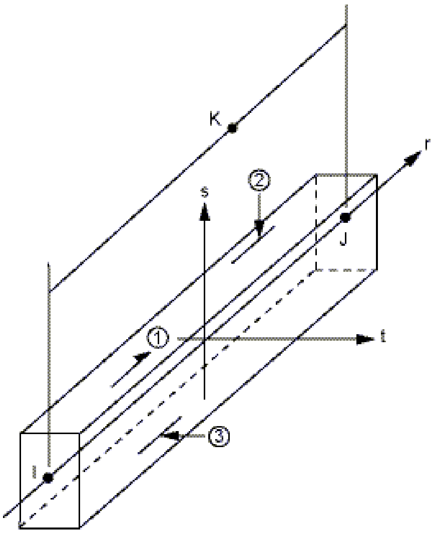


Figure 5 Beam element node and arrangement

These two models can be solved with both Implicit and Explicit methods and to maintain the stability of the solution different control cards are used in the code which made it possible to reach the convergence:

- CONTROL_IMPLICIT_AUTO
- CONTROL_IMPLICIT_FORMING
- CONTROL_IMPLICIT_GENERAL
- CONTROL_IMPLICIT_DYNAMICS
- CONTROL_IMPLICIT_EIGENVALUE
- CONTROL_IMPLICIT_SOLUTION
- CONTROL_IMPLICIT_SOLVER
- CONTROL_MPP_DECOMPOSITION_AUTOMATIC
- CONTROL_MPP_DECOMPOSITION_CHECK_SPEED
- CONTROL_MPP_DECOMPOSITION_CONTACT_DISTRIBUTE
- CONTROL_ENERGY
- CONTROL_SHELL
- CONTROL_CONTACT
- CONTROL_TIMESTEP
- CONTROL_TERMINATION
- CONTROL_DYNAMIC_RELAXATION

And to prevent both models from developing an hour glassing instability HOURGLASS card is included in the code also.

2.1 Building the 3D model, using solid elements

This high resolution finite element model is developed to have the opportunity to study the stress and failure inside different parts of the wheel and rail. However, there is a limitation on running time and PC capacity. Therefore, it is only possible to model one wheel and few meters of the track. Material properties used for this model is *MAT_ELASTIC for all the parts which can be changed to non-linear materials later.

*CONTACT_SURFACE_TO_SURFACE is used between the wheel and the rail to provide the contact between them. Also the contact stiffness's are tuned to give the correct contact force between the wheel and track. Figures below show the model from different angles. Those solid parts in contact had full integration elements to prevent hour-glassing or other kind of instabilities in the model.

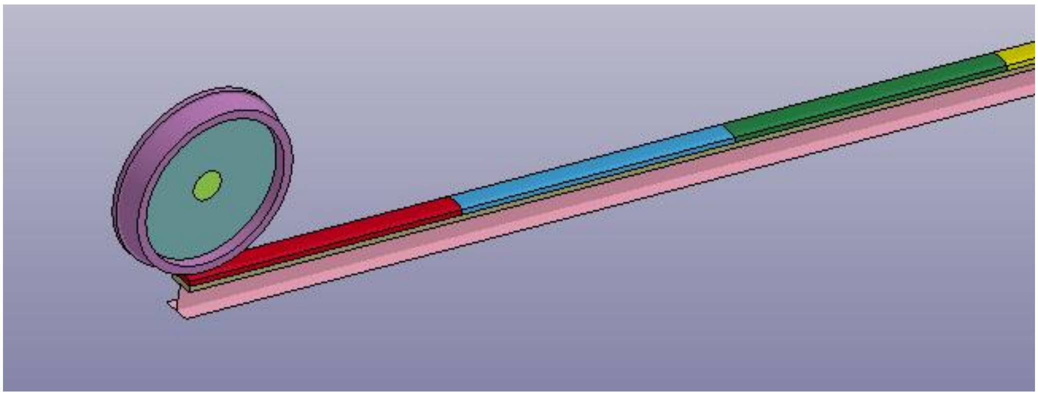


Figure 6 Top view of the wheel on the track, in finite element model

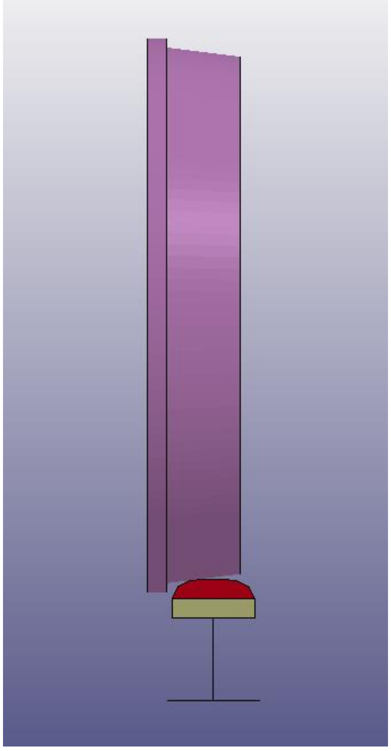


Figure 7 Longitudinal view of the wheel siting on the track, in finite element model

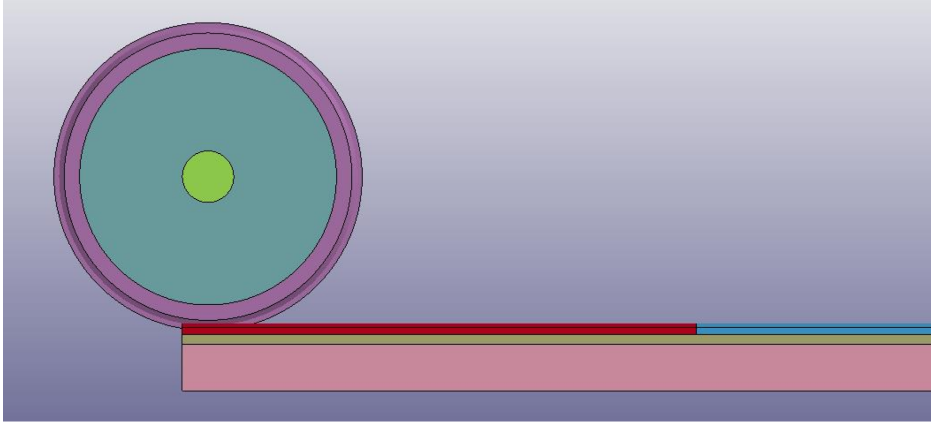


Figure 8 Side view of the wheel siting on the track, in finite element model

2.2 Building the 2D model, using Shell and Beam elements

This model has lower resolution than the 3D model, however it is possible to study the much longer track to around 500 metres length. Also it is possible to model all the layer of the soil which had a height of 9m and length 60m. The first and last 200m parts of the track is made of rigid material *MAT_RIGID, and the 100m track in the middle is elastic and using *MAT_ELASTIC. Also elastic material is used for the shell elements representing the soil in the model. The properties for each part is provided in Table 2. Figure 18 show the details of one vehicle, using different springs and dampers connected to the wheels. *MAT_SPRING_ELASTIC and *MAT_DAMPER_VISCOUS to provide elasticity and viscosity to each wheel, Table 1 provide the parameters.

*CONTACT_AUTOMATIC_BEAMS_TO_SURFACE is used between the wheel and the rail to provide the contact between them. Also the contact stiffness's are tuned to give the correct contact force between the wheel and track. Figures below show the model from different angles. Those shell parts (wheel) in contact had full integration elements to prevent hour-glassing or other kind of instabilities in the model.

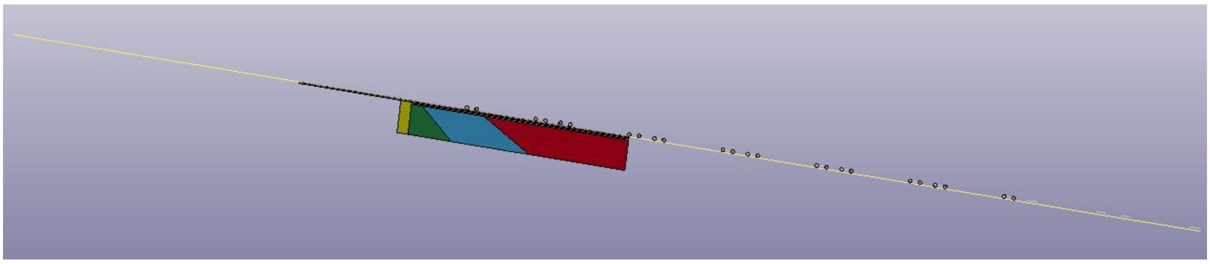


Figure 9 Full length of tract, 2D finite element model

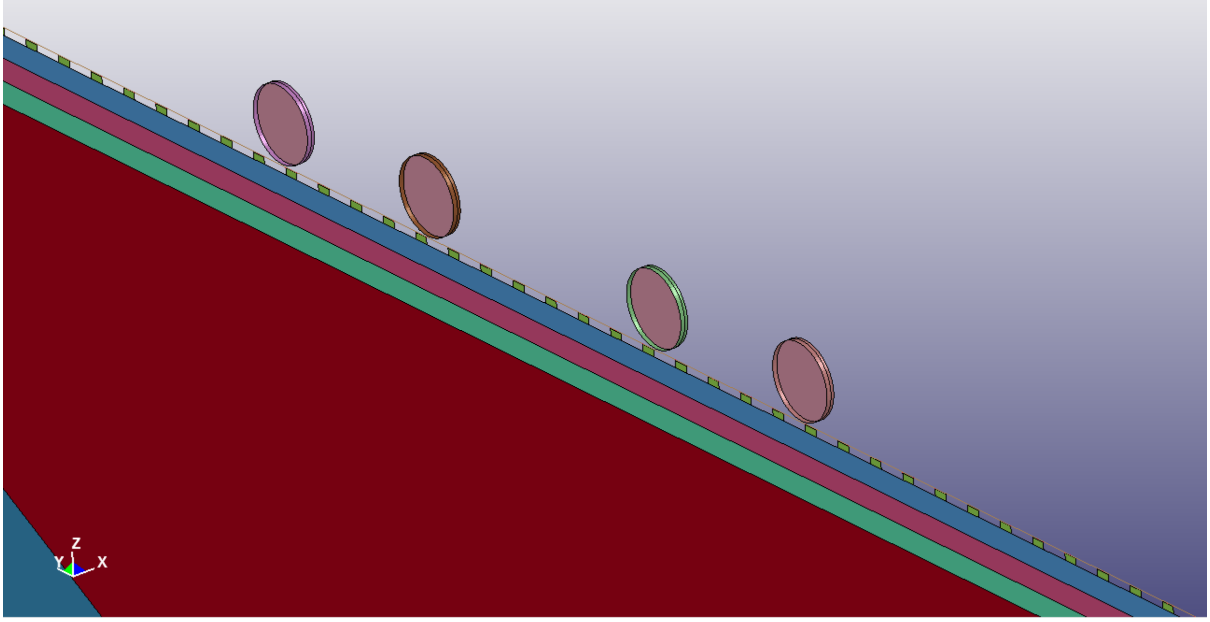


Figure 10 Top view of four wheels on the track, different layers of the soil and sleepers

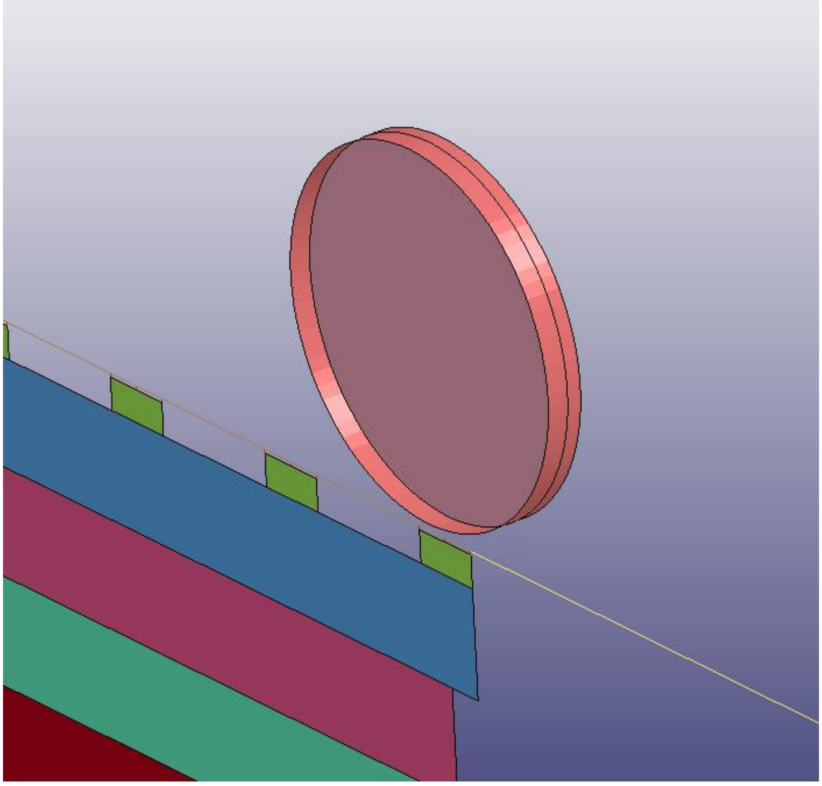


Figure 11 Zoomed in view of one wheel made by shell elements moving on the track

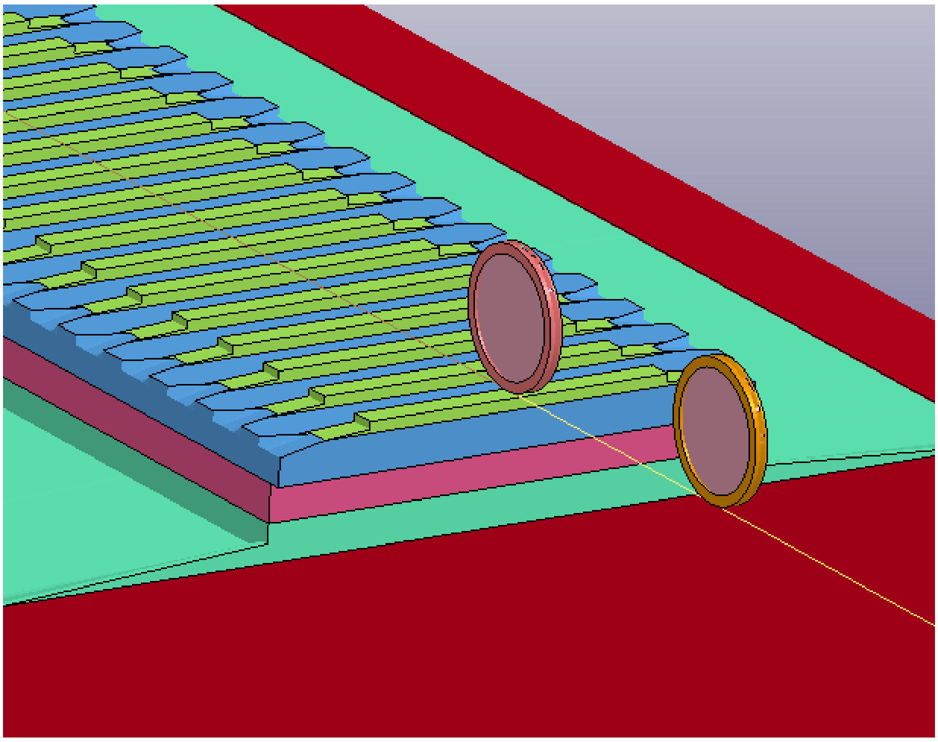


Figure 12 Extrude version of 2D model showing the thickness of the shell elements

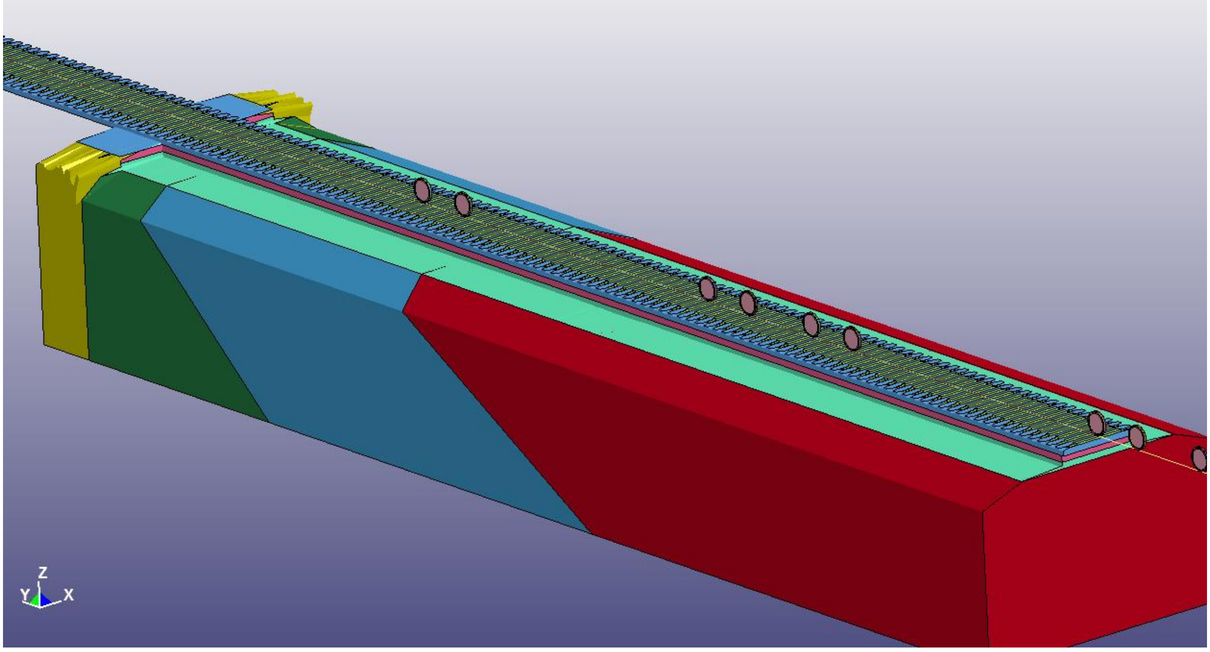


Figure 13 Full extrude version of the whole transition zone

3. Validating with measurements at Portuguese South Main Line

For the purpose of validation, a case study of transition zone at the southern approach of the new railway bridge over Sado river, located in the Portuguese South Main Line (coordinates: 3823.7780N, 835.6700W) in the 29 km-long Alcácer bypass, is chosen [4].

This line was opened in late 2010, allowing mixed traffic, with maximum axle loads of 250 kN and maximum speeds of 220 km/h for the Portuguese tilting passenger trains (Alfa Pendular). It comprises a single track with Iberian gauge (1.668 m) using continuously welded UIC60E1 rails, 2.6 m long mono block concrete sleepers (spaced 0.6 m), Vossloh W14 fastening system with elastomer rail pads Zw700/148/165 (static stiffness of 50–70 kN/mm, measured under a load between 18 and 68 kN, as provided by the manufacturer) [4].

The southern part of the bridge deck is a composite structure with a concrete slab supported by a steel plate girder with multiple spans of 37.5 m. The last span rests on a counterfort abutment in reinforced concrete, founded on ten 21 m-deep piles, with a large opening at the front. The natural foundation of the transition zone consists mostly of mono granular fine grained sands that provide good foundation conditions to the track [4].

The transition zone includes a backfill, about 9 m high, that was constructed using materials with better performance (higher stiffness and lower plastic deformation) than the embankment soils. The backfill comprises two zones, forming a wedge-shape with the geometry depicted in Figure 15. The first zone is located behind the abutment and comprises layers of cement bound mixture (CBM), with binder content (BC) of 5%. The other zone is located between the CBM and the embankment with soils. It comprises unbound granular material (UGM): a well graded crushed limestone aggregate with min./max. particle sizes of 0/31.5 mm [4].

Figure 14 Side view of the transition zone before construction and general view of the track [4]

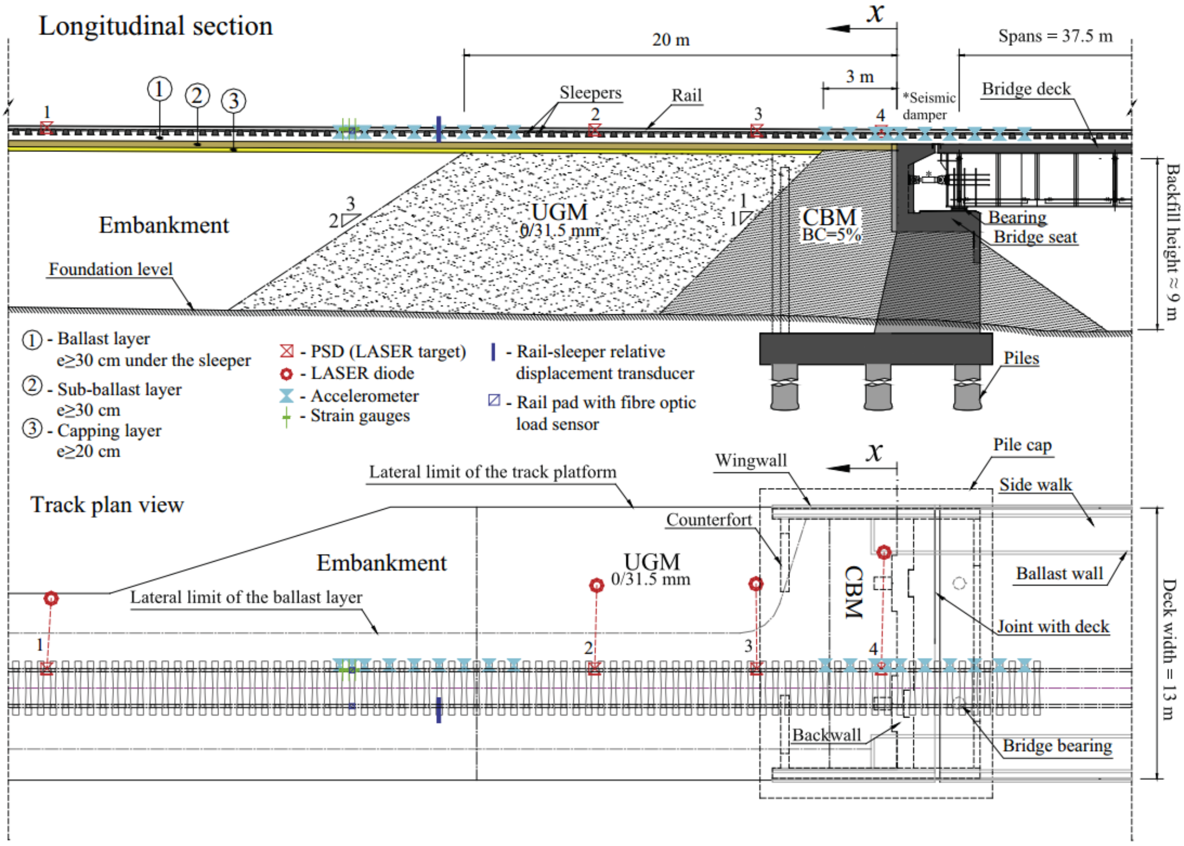


Figure 15 Schematic longitudinal profile and plan view of the transition zone [4]

A minimum ballast thickness (e) of 0.30m under the sleepers was established both for track on embankment and on the bridge. To analyse the response of the track along the transition zone when the Alfa Pendular trains passed by, the measurements been carried out in two separate occasions: (i) October 18th, 2011; (ii) April 19th–20th, 2012. It was possible to record 4 and 8 trains, respectively in each period, with speeds of about 220 km/h. The monitoring comprised various types of transducers connected to a single acquisition system [4].

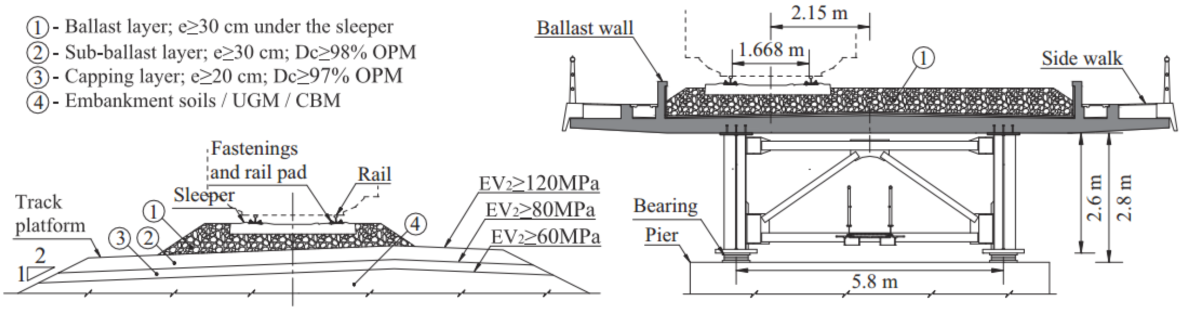


Figure 16 Track cross sections on earthworks and on the bridge [4]

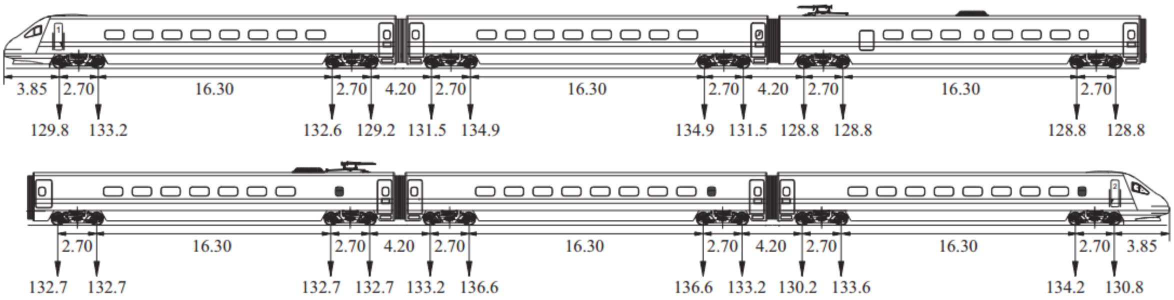
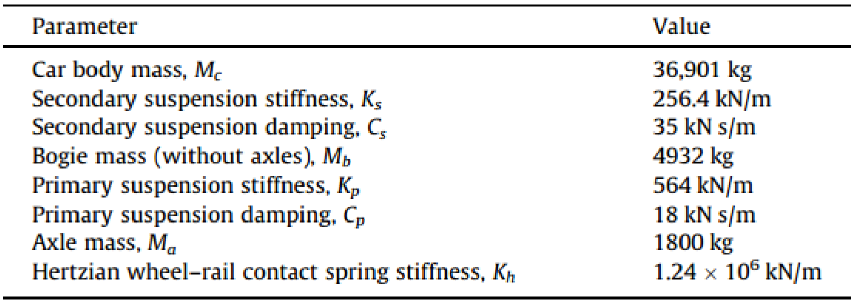


Figure 17 Train configuration: distances between axles (in m) and approximate loads (in kN) [4]

Table 1 Characteristics of the coach model [4]



Parameter	Value
Car body mass, M_c	36,901 kg
Secondary suspension stiffness, K_s	256.4 kN/m
Secondary suspension damping, C_s	35 kN s/m
Bogie mass (without axles), M_b	4932 kg
Primary suspension stiffness, K_p	564 kN/m
Primary suspension damping, C_p	18 kN s/m
Axle mass, M_a	1800 kg
Hertzian wheel–rail contact spring stiffness, K_h	1.24×10^6 kN/m

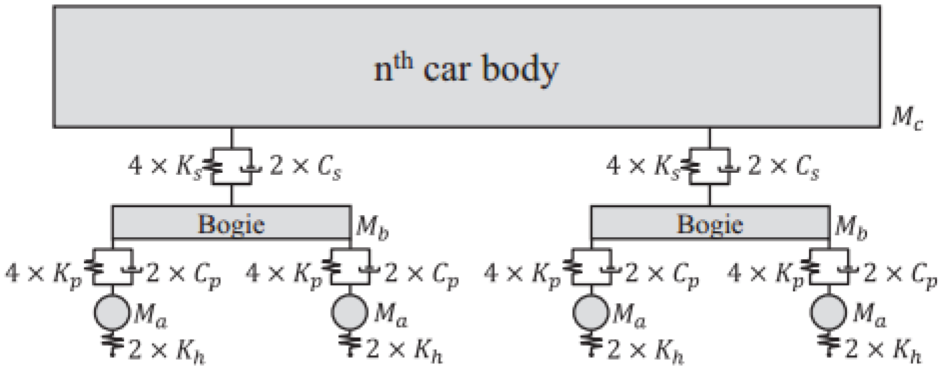
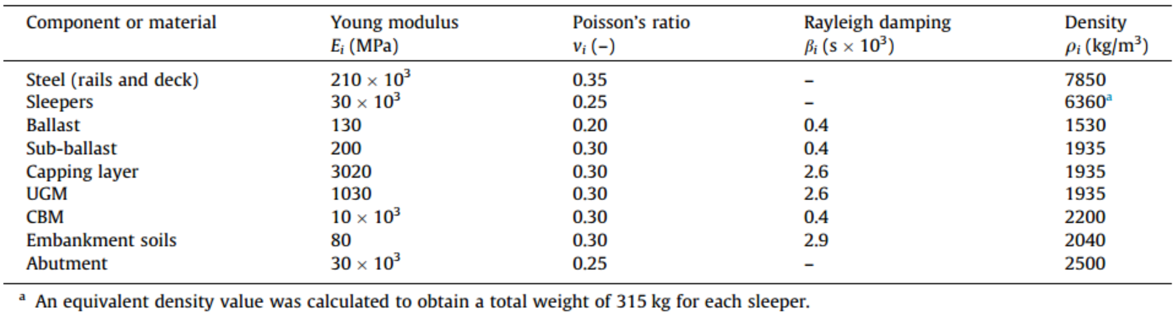


Figure 18 Model of one of the 6 coaches of the train (see parameters in Table 1) [4]

Table 2 Properties of the materials of the track and its substructure [4]



Component or material	Young modulus E_i (MPa)	Poisson's ratio ν_i (–)	Rayleigh damping β_i (s × 10^3)	Density ρ_i (kg/m^3)
Steel (rails and deck)	210×10^3	0.35	–	7850
Sleepers	30×10^3	0.25	–	6360[a]
Ballast	130	0.20	0.4	1530
Sub-ballast	200	0.30	0.4	1935
Capping layer	3020	0.30	2.6	1935
UGM	1030	0.30	2.6	1935
CBM	10×10^3	0.30	0.4	2200
Embankment soils	80	0.30	2.9	2040
Abutment	30×10^3	0.25	–	2500

[a] An equivalent density value was calculated to obtain a total weight of 315 kg for each sleeper.

3.1 Initial comparison between measurements and finite element results

Figure 19 provides the measurements from both before and after the bridge transition zones, the maximum deformation was around 0.8mm. Rail and sleeper relative displacement was around 0.2mm, which is mainly in the rail pads. This means the ground deformation was around 0.6mm maximum. Finite element results showed a similar behaviour to the real measurements and maximum ground deformation was around 0.55mm, results from the same location is provided in Figure 21.

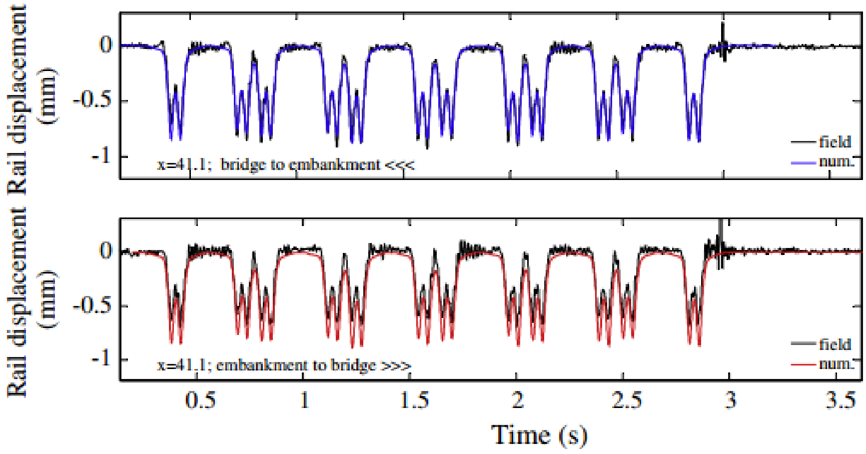


Figure 19 Rail displacements at position 1 in plan track [4]

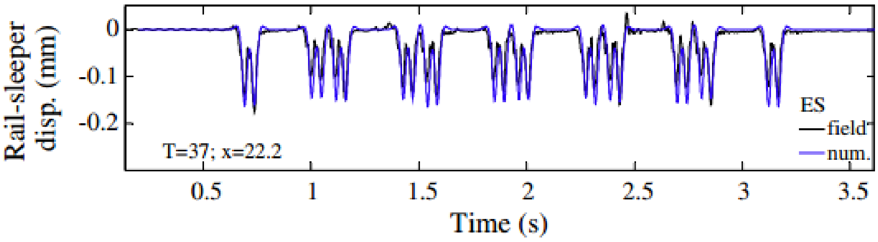


Figure 20 Rail sleeper relative displacement at position 1 [4]

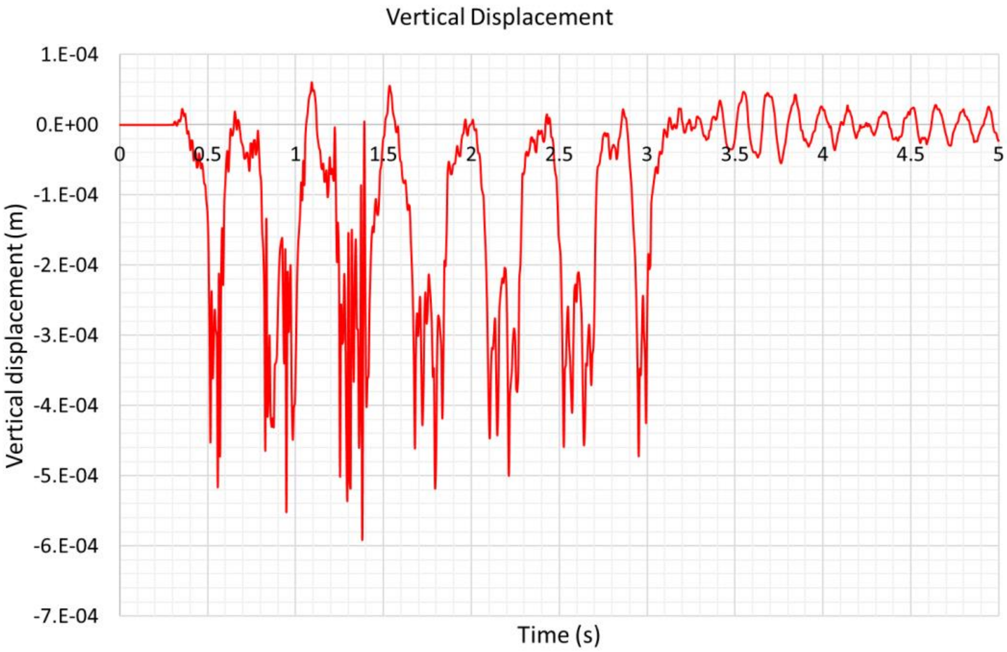


Figure 21 Vertical displacement of the tract at the same position as the measurements

Figure 22 shows the deformation of the soil at different locations, as expected embankment had the maximum deformations compare to the bounded layers and bridge abutment.

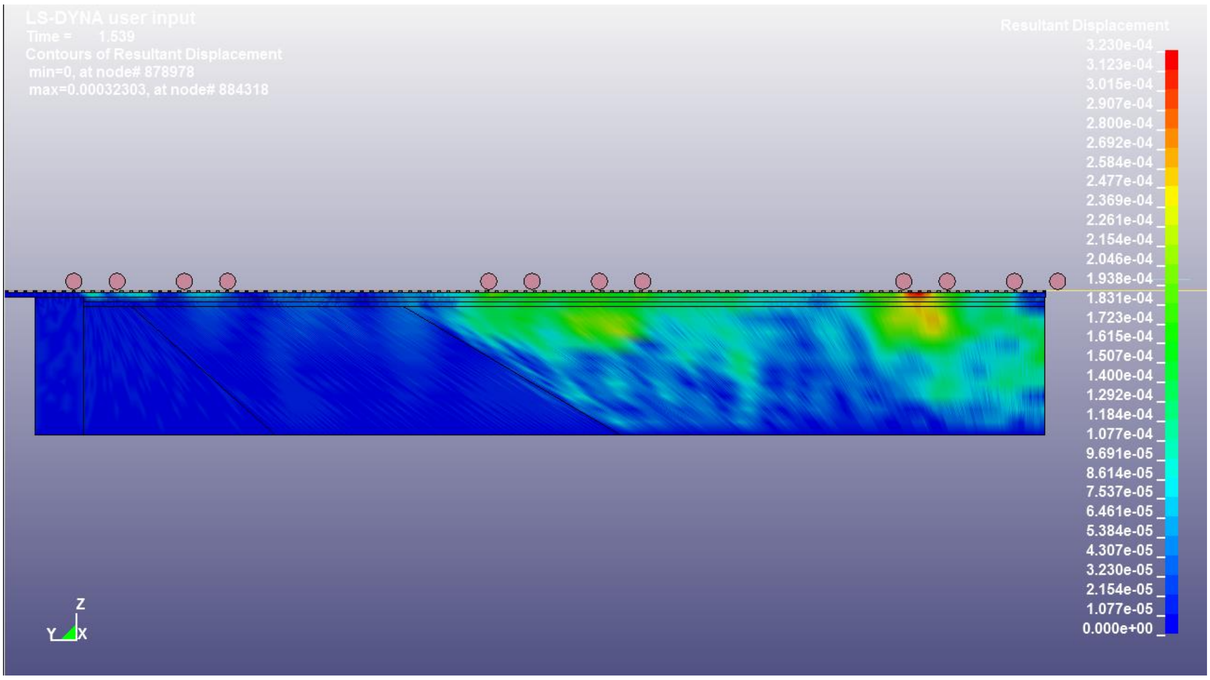


Figure 22 Vertical deformation predicted by the 2D finite element model

4. Conclusion

At this stage of study the model been developed and it is close to be validated, the next stage before validation is adding the rail pads between the sleepers and the track. After this stage next task 2.6.2 “Predictive and cost effective transition zone design (M13-M33)” will continue by validating, refining and apply the models developed in T2.6.1. SZ will contribute with on-site experimental testing of substructure and superstructure to validate the modelling results of track stiffness. Task duration allows for defining the validation site and required instrumentation while simultaneously finalising the modelling plan in T2.6.1.

Also INTADER will also support with providing some information and measurements about transition zones in Turkey (an example of a transition zone in Turkey is presented in Appendix A). After the validation, different types of parametric studies will be performed to help with understanding the behaviour of these transition areas and how it is possible to extend track life in those areas. One suggested method is changing the dynamic behaviour of these regions by changing the sleeper’s shapes and masses, as mass has a big role in impact and fast dynamic.

5. References

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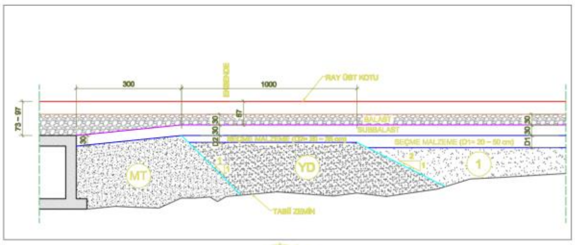
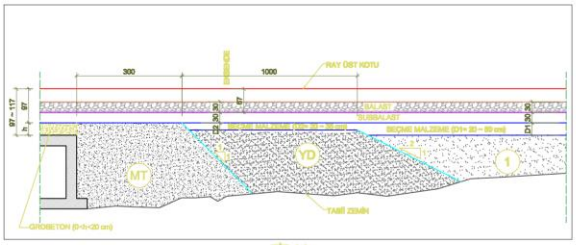
6. APPENDIX A

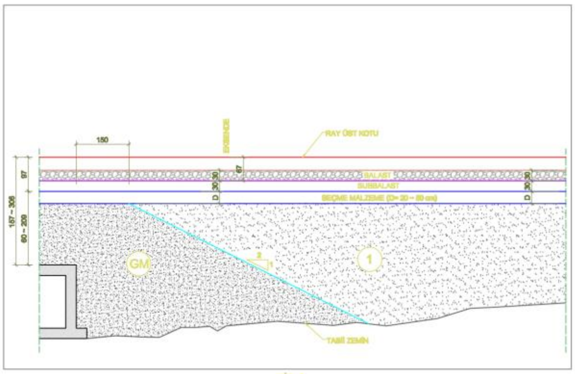
This picture shows examples of different transition zones provided by INTADER.



TİP 1-a
ÖLÇEK: 1/100



TİP 1-b
ÖLÇEK: 1/100
(TABAN KALINLIĞININ YETERLİ KALINLIKTA OLMADIĞI YERDE)



TİP 2
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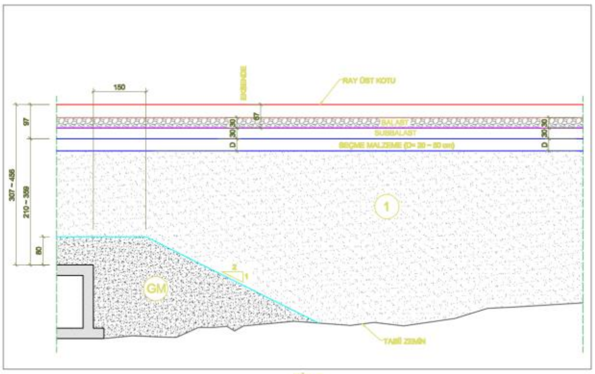

TİP 3
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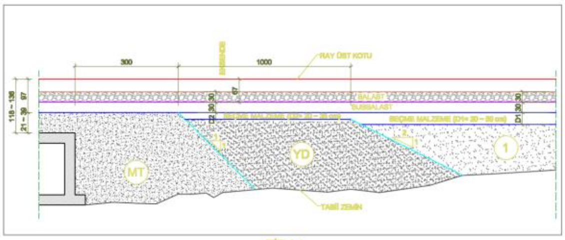
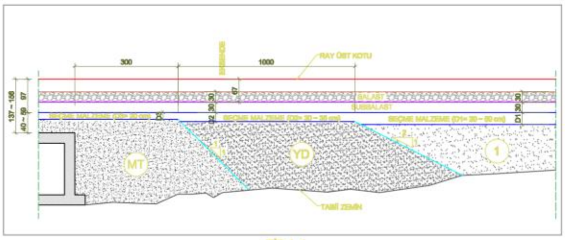
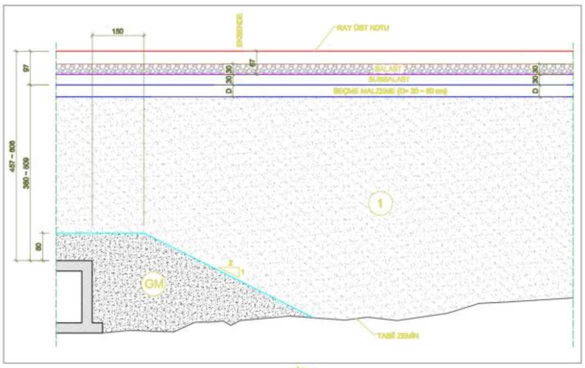


TİP 1-c
ÖLÇEK: 1/100



TİP 1-d
ÖLÇEK: 1/100



TİP 4
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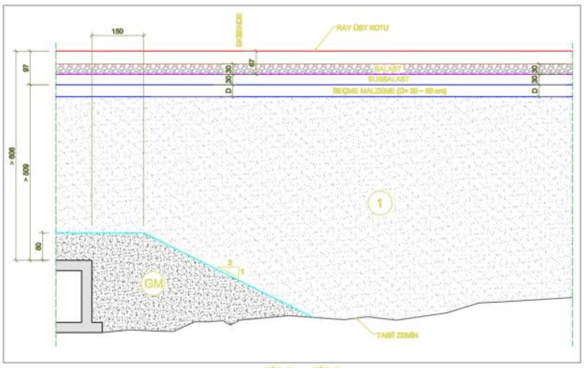
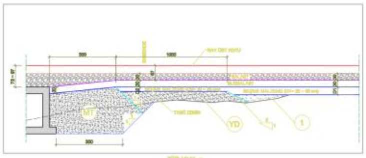
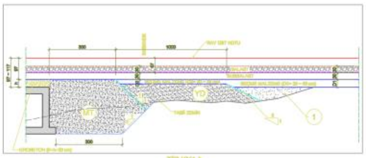


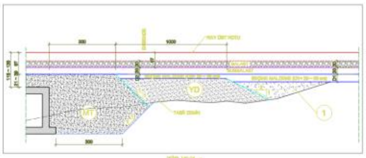
TİP 5 ve TİP 6
ÖLÇEK: 1/100



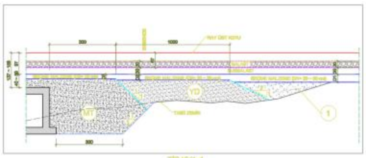
TİP KY1-a



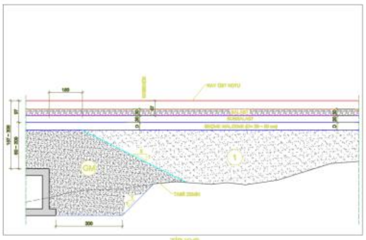
TİP KY1-b



TİP KY1-c



TİP KY1-d



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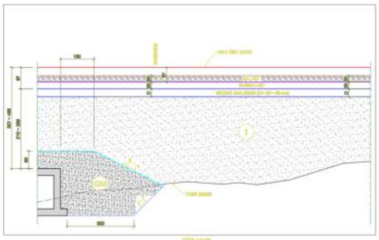
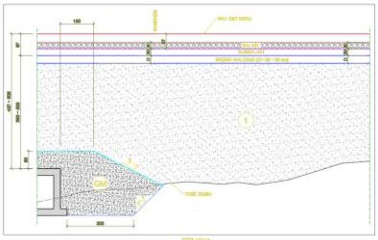


TİP KY3



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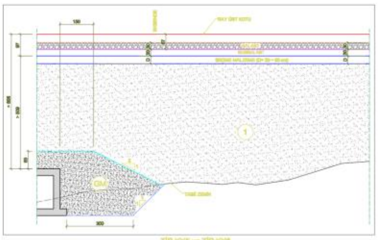
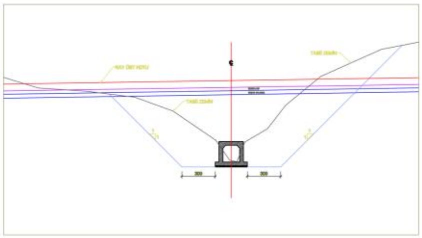


TİP KY5 ve TİP KY6



TİP TY1