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NUMERICAL MODELING OF HIGH SPEED TRAIN/TRACK SYSTEM FOR THE REDUCTION OF VIBRATION LEVELS AND MAINTENANCE NEEDS OF RAILWAY TRACKS

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Abstract. *It has been proven that dynamic cyclic loading induced by the circulation of trains at very high speeds (higher than 300km/h) leads to important track vibrations conducting to the deterioration of track geometric quality. Concerning railway track behaviour, its vibration levels are progressively amplified in a repeated process leading to an unwanted increase in track maintenance needs and hence in track life cycle costs.*

Within this framework, it is very important to know how to predict track dynamic response under certain circumstances, that is, to access vibration levels in a specific type of track with certain characteristics. Therefore, having this as concern, a dynamic numerical model of train/track system was built (and validated with real experimental measurements at high and very high speeds) and the influence of increasing train speeds in the level of vibrations reached in different types of tracks may be evaluated, as well as the settlement evolution along the track and throughout millions of cyclic train passages. The implementation in the model of long-term estimations of plastic deformations accumulations is also possible. Thus, the model enables to study the use of certain specific elements and materials, and how their interaction in a multi-element system will confer the ensemble of the track certain dynamic properties that would enhance its performance, in both short and long-run perspectives. In this paper, results from the simulations of different track design solutions are presented, as: softening railpads, applying under sleeper pads or using bituminous subballast as an alternative to granular subballast. Critical analyses on the results obtained in the paper enable to draw recommendations on the mitigation of track vibrations and maintenance interventions, that is, on the possible improvements to be made to ballasted high-speed track design considering its maintenance needs.

1. INTRODUCTION

The consequences of travelling at speeds higher than 300km/h present some concerns in terms of railway track geometry deterioration, and thus in track maintenance costs, due to the known increase of track vibration levels. In order to study this problem and investigate improved track solutions, it would be important to have a model that, in a whole, could turn out possible to perform short and long-time dynamic simulations for analysis of high speed track responses.

The model described in this paper is a finite elements model that fully takes into consideration dynamic interaction between the train and track with all its components, even so, with very low computation time. This is possible because a modal sub-structuring method is applied so as to achieve model reduction, assuming that a track can be longitudinally cut into several cross-section slices, which are considered dynamically equal and periodically repeated, enabling to decrease significantly the number of the system's degrees of freedom (dofs). Therefore, it is able to calculate a track with hundreds of meters long with low computation time. The complete model, called Dynavoie, is the junction of a vehicle model and the global model of the track, which results from the assembly of repeated slices along x direction. Model is described hereafter in the paper.

Nevertheless, before this model could be used for application, a validation process for comparison with real measurements had to be undertaken in order to assure confidence in high speed calculations. This is presented hereafter and in further detail in [1].

Furthermore, the paper also shows the numerical evaluation of the impact of different track design solutions, such as applying soft railpads, or under sleeper pads (USP), or bituminous subballast (instead of the conventional granular layer), on track responses when speed increases, essentially trying to confirm enhanced dynamic behaviour and reduction of track vibrations. Moreover, for some track dynamically improved solutions, track settlement progression along time was also numerically evaluated.

2. NUMERICAL MODELLING OF HIGH SPEED TRAIN/TRACK SYSTEM: SHORT AND LONG-TERM PREDICTIONS

2.1. Description of dynamic numerical model of train/track system

As referred previously, Dynavoie model is conceived based on the fact that the track is a periodic structure. A modal substructure reduction method [2] is applied and the reduction basis is built computing a series of harmonic static displacements obtained as responses of the model to a vertical load applied on the rail. The reduction method proposed in [3] for structures with cyclic symmetry is here extrapolated to longitudinal periodic structures like the railway track [1, 4]. The modal reduction basis is set up through modal analysis of the reference slice. The slice model is built using 3D finite elements techniques and takes into account the models of the rail, sleepers, fastenings and railpads, ballast and subballast layers and all other layers of soil including the subgrade soil foundation. Then, the assembly is done assuring continuity of static displacements inter-slices.

The several phases for building the complete train/ track model in Dynavoie are the following: Phase 1: Building the reduction basis (harmonic static responses; add some extra modes of vibration; assure mass and stiffness orthogonality; add the rail head 24 dofs deformation and the rail contact guide; assure displacements continuity inter-slices using a special inter-slice superelement); Phase 2: Determination of the damping matrix; Phase 3:

Assembling superelements to form global track model; Phase 4: Building train model (or moving load); Phase 5: Wheel/rail contact consideration; Phase 6: Time solving equation of motion to obtain track response.

The idea is that the dynamic equation of the problem may be rewritten on the reduced model of a slice through the following expression $\left[M_R\right]\ \ddot{q}_R(t)+\left[C_R\right]\ \dot{q}_R(t)+\left[K_R\right]q_R(t)=\left[T_{slice}\right]^T f(t)$, where $\left[M_R\right]$, $\left[C_R\right]$ and $\left[K_R\right]$ are square matrices that have as dimensions the dofs of the reduced model of the reference slice. After, the global track model is built by juxtaposing the several reduced slice models, making to intervene global matrices of the complete system, $\left[M\right]$, $\left[K\right]$ and $\left[C\right]$. Finally, the vehicle model is built and made to circulate on the global track model by means of an exterior force given by the wheel/rail contact. The vehicle running path is given by indicating the coordinate at the origin (x_0) and the final coordinate (x_f) of the first wheel and also the speed to be considered. Time simulation of a vehicle circulating on the railway track at a certain speed is achieved in Dynavoie by means of Newmark time integration implicit algorithm, with variable and auto-adapted step and assuring unconditional stability. Hence, the wanted responses $q(t)$, and eventually $\dot{q}(t)$, $\ddot{q}(t)$ are obtained after solving the dynamic equation of motion corresponding to the complete model of the global track together with the vehicle model $\left[M\right]\ddot{q}(t)+\left[C\right]\dot{q}(t)+\left[K\right]q(t)=f(x(t),t)$.

With this strategy and the modal reduction method implemented, a significant reduction of the total number of degrees of freedom is gained. To illustrate this, for instance, in the case of a typical track with approximately 2,30m depth and 40 slices, the full (non-reduced) model could have around 0,5 million degrees of freedom whereas the corresponding reduced model only has about 1400 degrees of freedom (350 times lower), implying an enormous reduction in time computing spent in the simulation of a train passage.

2.2. Description of modelling track settlement evolution along time: long-term predictions

From what was previously described about this model, it can be possible to simulate a great number (millions) of circulations in time, allowing also to estimate track long-term differential settlement evolutions. In fact, Dynavoie, is not limited to optimize the design of tracks at very high speeds in order to reduce the level of (short-term) accelerations produced, but it was developed to also evaluate the rhythm of deterioration progression in the track related to the number of passing train axles, by simulating the long-term mechanical process where irreversible permanent track deformations occur with passing tonnage leading to track settlement. This is done incorporating currently known (laboratory tested) settlement laws, see [1] for a synthesis of a literature review on the subject. Consequently, the model allows to establish the maintenance needs over time in a certain track as function of the maximum allowed tolerances.

Settlement predictions using Dynavoie model are performed on a railway track where an initial settlement defect is imposed in the beginning of simulations. This initial defect is represented by a vector which assigns to each slice the corresponding settlement, a vertical displacement dz_{settli}, along the z axis. As referred before, during time simulation, the vertical distance, dz, between the contact point of the vehicle and the rail top is calculated at each time step, as part of the contact management. While the contact force is computed, the progression of settlement is simultaneously brought up to date according to the settlement law introduced in the model.

Taken the example of a Bodin-Guérin law type $\frac{d\tau}{dN} = \alpha \cdot d^{\beta}$, see works of Guérin and Bodin [5, 6] and , where β is a constant exponent serving as an adjustment parameter and α is a coefficient which depends on the hardness of the granular material, which for Guérin's assume $\alpha = 1{,}44 \times 10^{-6}$ and $\beta = 2{,}51$,. In this case, the maximum elastic deflection of sleeper (*d*) is captured during the passage of a bogie by means of a displacement sensor placed inside the modelled sleepers under the rail. Subsequently, the new settlement is taken into account and a new trajectory for the contact points is recalculated.

The flowchart, shown in Figure 1, represents schematically the calculation processes inside Dynavoie, in particular, in the situation of settlement evolution prediction using Bodin-Guérin law type.

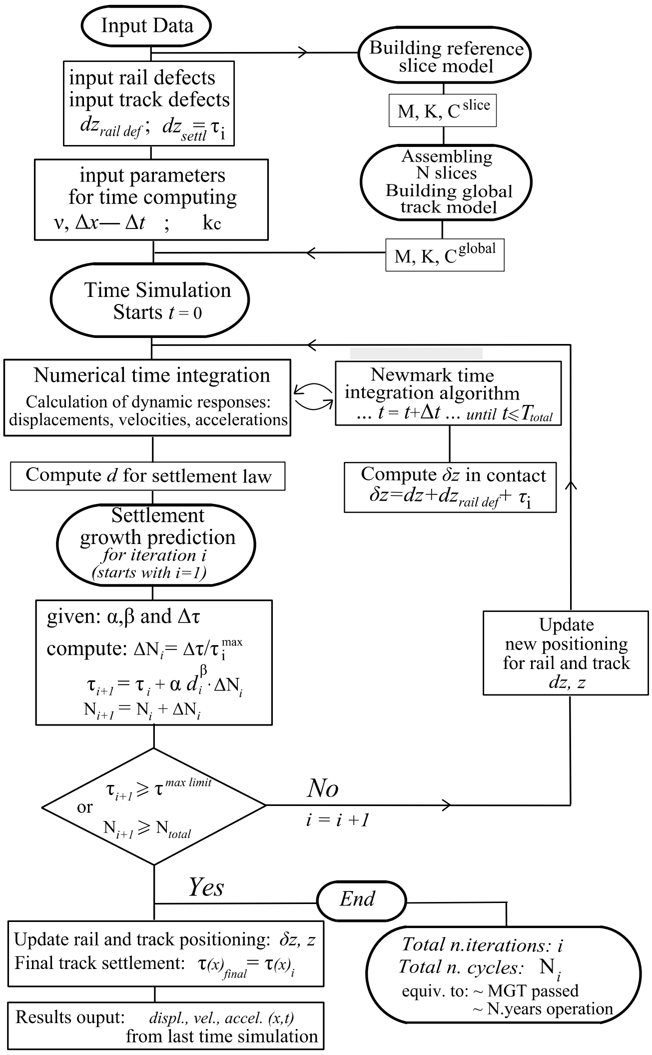

Figure 1: Flowchart with the calculation processes for settlement prediction inside Dynavoie using Bodin-Guérin law in particular, from [1]

Therefore, taking advantage of Dynavoie's capabilities, track settlement inside the model is updated in the following way: $\tau_{i+1}(x) = \tau_i(x) + \alpha \cdot d_i(x)^{\beta} \cdot \Delta N$ where the response of the track $d_i(x)$ also changes in time, with the repositioning of track levelling for each cycle; $d_i(x)$ is the vector of maximum sleeper displacements along the track for each iteration *i*, corresponding to ΔN cycles. Then, as the track settlement growth after N cycles is $\Delta\tau_N$, τ is estimated step by step of ΔN, it is possible to observe settlement evolution, not only longitudinally along the track, in *x*, but also in time (after N cycles, equivalent to certain passing tonnage).

Consequently, with this model, for a given cyclical train passing, the velocity of settlement progression may be evaluated for different track design solutions and different initial track geometric configurations, as well as the passing tonnage required to attain certain admissible maximum defects in the track. Analysis and comparisons are made possible allowing to evaluate certain track design solutions not only in terms of track vibrations reduction but also considering the possible reduction in track degradation along time, and hence in its maintenance needs and costs.

3. TRACK VIBRATIONS IN HIGH SPEED RAILWAY TRACK: EXPERIMENTAL MEASUREMENTS AND MODEL VALIDATION

Since the late 1960's, measurements taken by the Technical University of Munich published by Birmann in [7] and taken by Prud'Homme in the 70's reported in [8], showed that an increase in the travelling speeds from 40 to 200 km/h or from 140 to 300km/h, respectively, produced a significant increase in ballast accelerations.

Furthermore, in [1], a statistical post-treatment was applied to an extensive database resulted from measurements made by SNCF in different French high speed tracks. In particular, the graphic in Figure 2 shows the calculated medians (Acc^{med}) obtained from the maximum values extracted from the sleeper vertical acceleration signals measured during two different campaign tests in two different sections, where approximately 800 train passages were recorded.

These values are represented as function of train speed (in a range of about 200-300km/h) together with the corresponding best fit line (robust linear regression). As it may be noticed, this graphic highlights once more the nearly linear increase of track accelerations with the increasing train speed, as well as their variability in time and their dependence on the track specific characteristics.

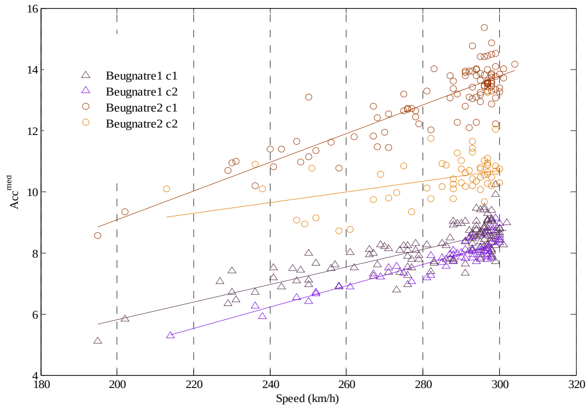

Figure 2: Acc^{med} (m/s^2) as function of the train speed with robust linear regression obtained from sleeper accelerations, [1]

The model was submitted to a process of validation with experimental measurements which was of major importance to assure the correct evaluation of track responses at very high speeds. Essentially, experimental measurements which were used in the validation process came from instrumented track sections in high speed lines in France, Spain and Belgium. A total of five experimental track sites were used: Beugnâtre, Ressons, Lapalud, Guadalajara and another one in the Paris-Brussels line. The first two track sites belong to the

North high speed line (Paris-Lille) and Lapalud site is in the Mediterranean high speed line (Paris-Marseille), while the Guadalajara site is in the Madrid-Barcelona high-speed line. Additionally, experimental measurements made in the full scale Track box facility in the CEDEX laboratory were also used to contrast with numerical results. Track responses recorded at speeds reaching maximum values of up to 308, 317 or 390km/h could be analysed, coming respectively from France, Belgium field measurements and from Track box laboratory in Spain.

The main parameters that could be extensively validated within comparisons were: rail displacements and efforts (shear, moment), sleepers' reactions, railpad deformation, track displacements, track pressures and vibrations as accelerations or velocities at different track levels. Examples of some comparisons between measured and calculated accelerations made during validation are exposed in both graphics of Figure 3, where time signals were obtained by simulation of Beugnâtre high speed track case. Main attention was paid on vibrations, mainly on sleepers and inside the track.

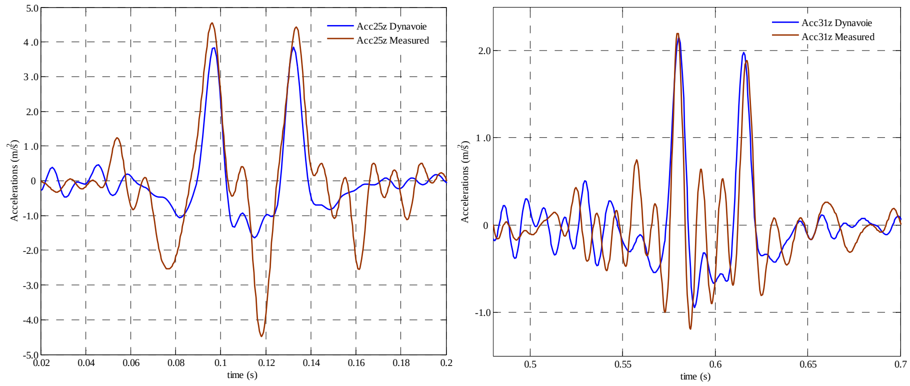

Figure 3: Time signals of vertical accelerations calculated and measured on sleepers (left) and inside platform layer (right) at Beugnâtre track section at 300km/h, in [1]

4. IMPROVED BALLASTED HIGH SPEED TRACK DESIGN SOLUTIONS

The design of track solutions for an enhanced dynamic performance should pass by either increasing the superstructure elasticity or raising the substructure bearing capacity. Therefore four track design solutions can be established: using softer railpads; introducing under sleeper pads (USP); introducing ballast mats (UBM); introducing bituminous subballast (instead of granular subballast). These solutions may be applied (usually alternatively and not simultaneously) at different levels of the track, descending in depth inside the track, from the first measure, under the rail, to the fourth under the ballast layer, a total of three intervention levels may be attained, as it is represented in Figure 4.

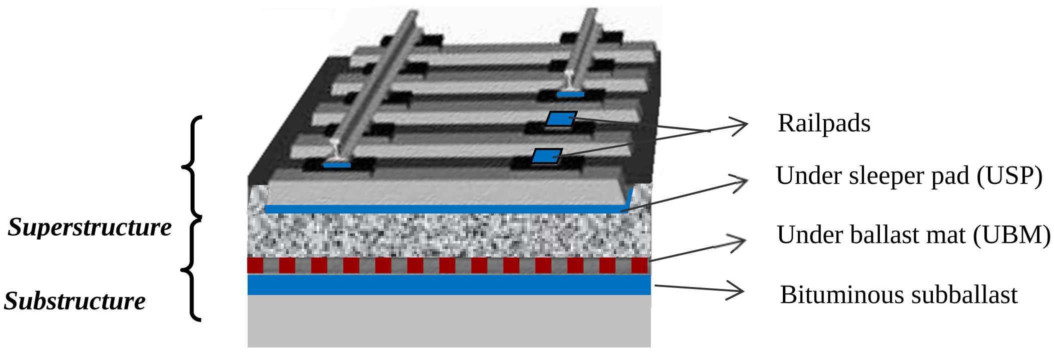

Figure 4: Schematic representation of different alternative track design solutions for enhanced dynamic performance of high speed tracks

The first three track solutions are all design alternatives which involve the insertion of new damping materials to increase track resiliency and the first two that were initially conceived to attain low ballast track maintenance needs. Another type of design solution can be achieved by increasing track substructure bearing capacity, incorporating stiffer and more durable materials between the subgrade and the ballast layer. This is the case of the fourth solution, indicated in Figure 4 of using a bituminous subballast, see [9] for more details on this track solution.

The third track design solution consists on placing ballast mats (UBM) under the ballast layer. These mats are normally used to reduce structure borne noise or in particular zones where ballast is damaged and in zones of important stiffness variations as in bridges and tunnels transitions. On the contrary of the other interventions, the use of under ballast mats revealed to only reduce vibrations in the substructure (see [1]), that is, under the ballast layer, while simultaneously amplifying sleeper and ballast accelerations, which is undesirable. Therefore, for high speed track design optimization in the point of view of reducing track vibrations and maintenance, the interest will be focused only on the first, second and fourth solutions, discarding ballast mats application.

4.1. Evaluation of the interest of using improved design solutions to reduce track vibrations

A comparative analysis between certain track design solutions which were found to be more dynamically favourable was undertaken in order to evaluate their interest in reducing track vibrations, in relative terms.

The conventional track taken as reference (hereafter identified as Track B) comprises a UIC60 rail, monoblock sleepers and railpads with vertical stiffness of 100kN/mm. The track includes the consideration of ballast and subballast layers (both with h=0,30m and E=100MPa) and subgrade soil (with h=0,60m and E=75 MPa), completing a total of three supporting layers.

First of all, in order to evaluate the benefits of using under sleeper pads (USP), numerical results obtained in this track are compared with the ones calculated in the situation where pads with 70kN/mm were introduced under the sleepers, see image of track model in Figure 5.

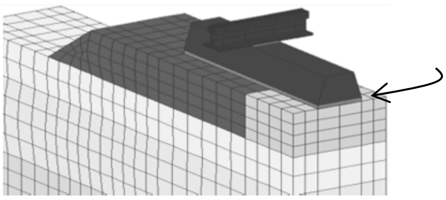

Figure 5: Part of the model in Dynavoie showing a sleeper with USP

Comparisons of both solutions with and without USP, are shown in Figure 6 through the curves of ballast displacements and accelerations for a train speed of 300km/h. It may be deduced that the use of USP fades the actuation of the two bogie axles, as the usual discharge between both axles almost disappears. Hence, in the FFT graphic of Figure 6, it may be noticed that there isn’t a relevant peak for the frequency axle’s passage (around 28Hz) for that track case. On the other hand, it may be deduced that sleeper passing frequency (around 139Hz) is undertaken with more energy by the track with USP than without USP. Above all, this reflects the great influence that the use of USP has on the dynamic behaviour of a high speed track, significantly modifying spectra characteristics mainly for low frequencies.

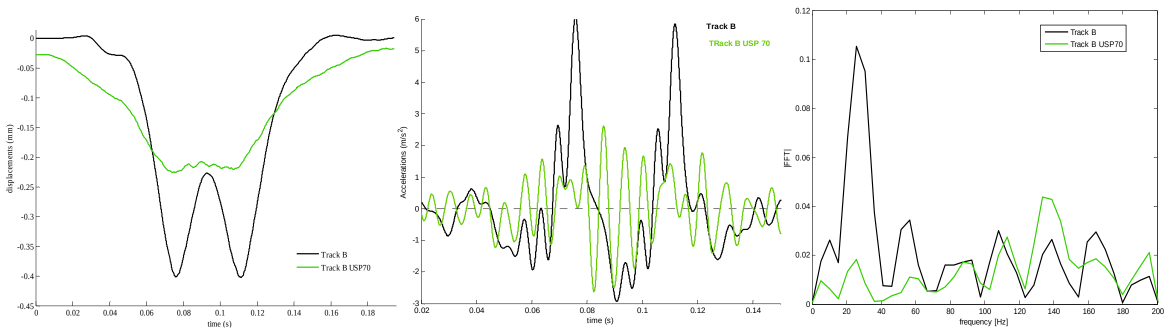

Figure 6: Displacements and acceleration time signals on ballast (left, centre) and FFT of ballast vibrations (right) in Track B with and without USP for a train speed of 300km/h

From the previous figure, it may be concluded that for this specific track, the insertion of USP is very effective at very high speeds for accelerations in ballast and supporting layers. Moreover, the use of softer USP even increases this benefit. However, it must be taken into account that, when using USP, while ballast vibrations are reduced, maximum accelerations obtained in the rail and sleepers may be increased to some extent, depending on the USP stiffness. Therefore, this indicates that the use of USP in a track should be carefully planned for each particular situation.

It should be referred that currently the introduction of USP is more often made in tracks with stiffer railpads (as 500 kN/mm), hence with higher vertical stiffness (than the tracks tested here) and also in bridge-abutment transitions, as a method to improve dynamic behaviour of existing tracks. In these cases, the use of USP is a very effective solution leading also to very significant accelerations' decrease and considerable reduction in maintenance needs.

With the purpose to evaluate the effectiveness of track vibrations reduction, the analysis undertaken compares three different track design solutions based on the conventional Track B (with granular subballast and 100kN/mm railpad, as reference), which are: Track B with softer railpad of 60kN/mm; Track B with USP of 70kN/mm and Track B with bituminous subballast. In this last situation, numerical calculations performed are applied to Track B where the granular subballast of 0,30m thickness is replaced by a 0,12m thickness layer of bituminous material with a Young modulus of 6000MPa.

A sum-up of the results obtained for these solutions are briefly exposed in Figure 7 in terms of maximum accelerations calculated at different levels inside the track for different train speeds.

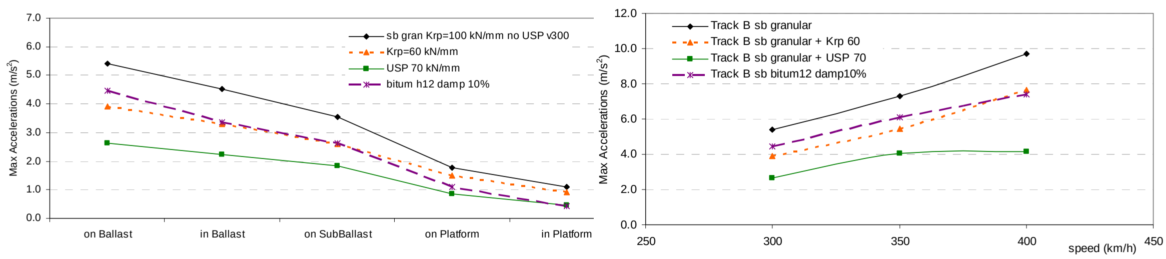

Figure 7: Maximum accelerations at different levels of Track B at speeds of 300km/h (*left*), and ballast maximum accelerations for several train speeds (*right*), comparison of four different solutions: conventional granular subballast using either railpad of 100 (—) or 60kN/mm (¨), with USP of 70kN/mm (—) and with bituminous subballast (---), [1]

For this particular comparative case, using conventional Track B as reference, from the observation of the graphics, it stands out that vibrations in the track are reduced for all three design solutions tested, the highest decrease being achieved with the USP solution, at all speeds. In fact, the solution which has demonstrated to have better dynamic performance is the solution of placing under sleeper pads, except for sleeper vibrations.

4.2. Evaluation of the interest of using improved design solutions to reduce track maintenance needs

Afterwards, using the same three different track design solutions for which dynamic short-term responses, as track vibrations, were already confirmed to be reduced, a comparative analysis of numerical long-term settlement evolution predictions is undertaken. The purpose is to evaluate the interest of these dynamically improved track solutions to also delay track maintenance needs.

Thus, settlement computations were carried out in Dynavoie reproducing each track case. The same punctual settlement of 3,0mm is initially imposed and several cyclic calculations with settlement evolution are made until a 5,0mm defect is reached in the track, after accumulated train passages at a speed of 300km/h. Figure 8 shows the fatigue curves numerically obtained in the point of each track where settlement progression is faster. In these curves, maximum track settlement is plotted against the accumulated number of cycles simulated.

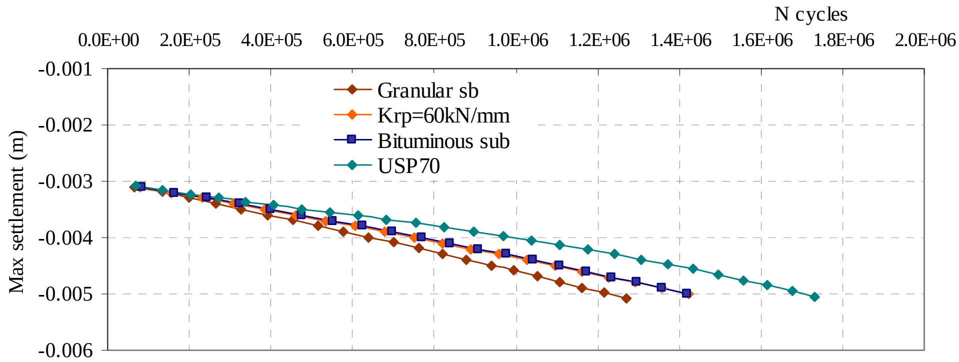

Figure 8: Settlement progression curve in one point of the track for cyclic passages at 300km/h: comparative cases for conventional track and with different design.

From the estimated settlement curves obtained, it could be deduced that all design solutions have delayed the progression of the defect comparing with the conventional track with granular subballast and 100kN/mm railpads stiffness. The track solution which presents the slowest settlement increment rate is the one which applies pads under the sleepers. Also, it may be noticed that for a train speed of 300km/h and in this case study in particular, the use of bituminous mixtures in the subballast layer delays track deterioration, very similarly to the use of softer railpads, when comparing with a conventional track with granular subballast layer.

5. CONCLUSIONS

This paper presents a dynamic train/track model which has been developed and validated in order to predict track vibrations induced by high speed trains. Using modal substructure method, model reduction is attained and time simulation of a train passage can be made with very low computation time when comparing to other existing models. This big reduction in calculation time becomes an enormous advantage when it comes to simulate repeated train passages so as to be able to estimate settlement progression along the track during its life time. Hence, this model turns out possible to perform simultaneously short and long-time dynamic simulations for analysis of track responses, in space and time. Furthermore, this paper also presents the results obtained from some simulations carried out with this dynamic model (validated with experimental measurements in high speed lines) in order to evaluate the impact that different track design solutions may have on track dynamic responses when speed increases and the corresponding track settlement progression along time. Track design solutions that were tested were: applying soft railpads, or under sleeper pads, or bituminous subballast (instead of the conventional granular layer). From the three track design cases analysed, short-term results revealed reduction of track vibrations. Moreover, from what was possible to investigate and infer concerning long-term simulations, lower accumulation of plastic deformations throughout train running cycles could be deduced for the three cases in comparison with the reference conventional track. Hence, for the particular track case considered, certain enhanced design solutions could be suggested in order to reduce track vibrations and the number and frequency of maintenance interventions. Therefore, the model presented allows to improve track dynamic behaviour and to extend its lifetime, upgrading its design and leading to the consequent savings in maintenance costs which can consist in an important supporting tool for life-cycle cost analyses of a particular railway infrastructure.

Currently the model is being applied and further tested to evaluate other case studies for track enhanced dynamic short and long term behaviour in other railway lines.

Acknowledgements

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