Investigating the Effects of Soft Spots on the Functional and Structural Condition of a Railway Track

Mohamed Wehbi, PhD student, department of civil engineering, University of Birmingham, UK.
Dr. Michael Burrow, lecturer, department of civil engineering, University of Birmingham, UK.
Dr. Gurmel Ghatoara, lecturer, department of civil engineering, University of Birmingham, UK.
Dr. Jin Shi, lecturer, School of civil Engineering, Beijing Jiaotong University, China.

Abstract

Overtime railway track starts to deteriorate due to the combined load of the traffic and environment. A major issue concerns the stiffness of the subgrade which has a significant effect on the performance of the track. Subgrade stiffness variation can manifest themselves as sudden changes in the spatial and elastic properties of the subgrade, these are known as soft spots. To investigate these aspects a validated 3-D finite element model of the train-track system was developed to determine track performance, in terms of functional and structural condition as a function of soft spot geometry. It was found that the location of the soft spot of the factors considered is the most influential parameter that affects structural condition of the track. The size of the soft spot was found to be the most influential parameter affecting the functional condition of the track.

Notations

E_{sg}: the stiffness of the subgrade, in MPa
E_s: the stiffness of the soft spot, in MPa.
TQ: track quality, in mm.
E_{Dy}: dynamic stiffness, in KN/mm.
x: the width of the soft spot, in m.
z: the thickness of the soft spot, in m.
y: the length of the soft spot, in m.
r: the depth of the soft spot from the surface of the ballast, in m.
m: the horizontal distance between the centre line of the track and the centre line of the soft spot, in m.

Introduction

The railway track, in figure 1, may be considered to be a structural system which is designed to withstand the combined effects of traffic and the environment so that passengers comfort and safety are kept within acceptable limits and the subgrade is adequately protected. If appropriate and timely maintenance is not carried out, speed restrictions are maybe imposed resulting in financial costs. Variations in the properties of the subgrade may create zones of stiffer or softer materials that can affect the overall track performance (Frohling, 1997 and Berggen, 2007). Long wave stiffness variation may produce low frequency vibrations in the train affecting the passenger ride comfort. On the other hand, short wave stiffness variation may induce high frequency vibrations in the rail leading to local deterioration such as fatigue cracking of the rail and hanging sleepers (Dahlberg, 2007). Examples of short wave stiffness variation are soft spots. These can be described as the presence of a finite area with a low stiffness surrounded by an area with a significantly larger stiffness. To investigate this aspect, a study was undertaken using a 3-D finite dynamic model of the rail track system was used to determine various measures of performance associated with the track as described below.

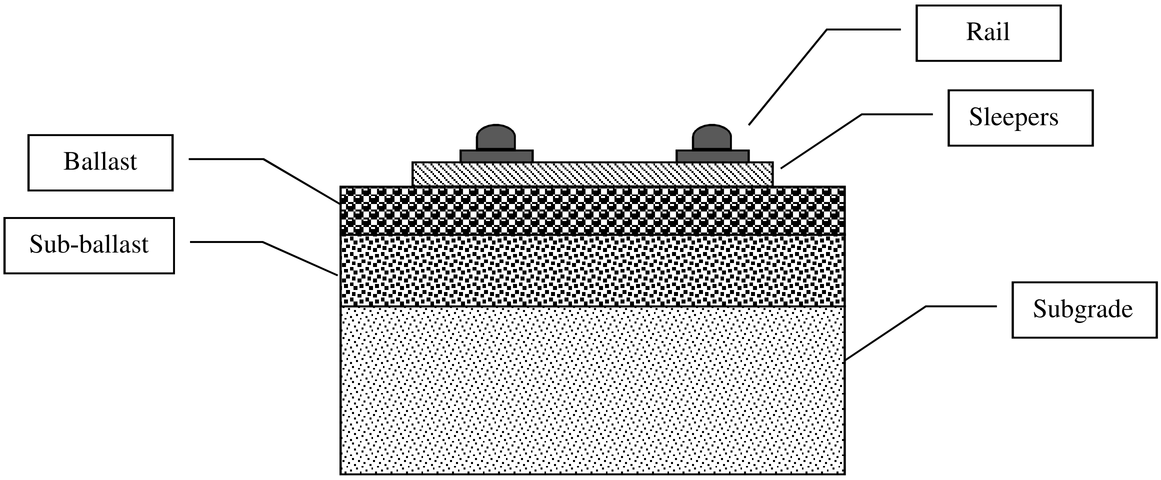

Figure 1: Railway track

Modelling a soft spot

An existing FEM of the rail track system was adopted (Shi et el, 2013) using ABAQUS explicit software and it comprises of a total 47555 elements and 64452 nodes constructing a track of 40 metres resting on a typical UK substructure (Burrow, 2007) (see figure 2). Also the train was modelled as shown in figure 3 and table 2. The model it was configured to simulate soft spot with low elastic stiffness surrounded by a stiff subgrade as shown in figure 4 and 5. The dimensions (*x, y, z*) and location (*r, m*) of the soft spot were changed for each scenario one at a time as shown in table 3.

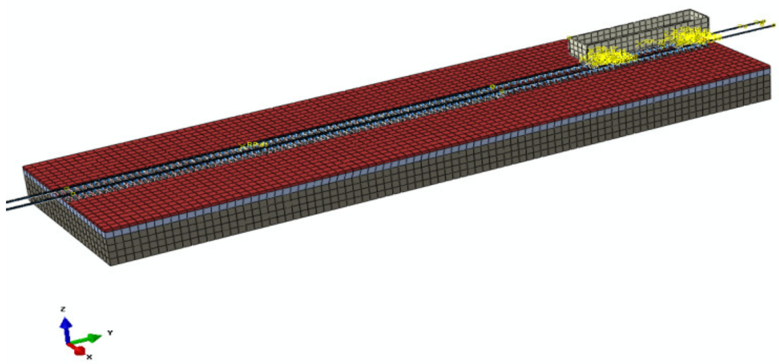

Figure 2: FE dynamic track model

Table 1: FEM specifications (after Shi et al, 2013)

Specification	Value
Track length	40 m
Train length	11 m
Train speed	80 Km/hr
Number of axles	4
Wheel load	125 KN
Rail stiffness	210 GPa
Rail density	7830 Kg/m^3
Rail Poisson ratio	0.3
Sleeper spacing	0.6 m
Sleeper stiffness	35 GPa
Sleeper density	2600 Kg/m^3
Sleeper Poisson ratio	0.22
Sleeper's dimensions	2.5 m, 0.25 m, 0.16 m
Ballast thickness	0.3 m
Ballast stiffness	180 MPa
Ballast density	1650 kg/m^3
Ballast Poisson ratio	0.27
Sub-ballast thickness	0.7 m
Sub-ballast stiffness	50 MPa
Sub-ballast Poisson ratio	0.28
Sub-ballast density	1800 Kg/m^3
Subgrade thickness	typically 3 m
Subgrade stiffness	Varying
Subgrade density	1800
Subgrade Poisson ratio	0.3
Soft spot Stiffness	20 MPa
Soft spot density	2100 Kg/m^3

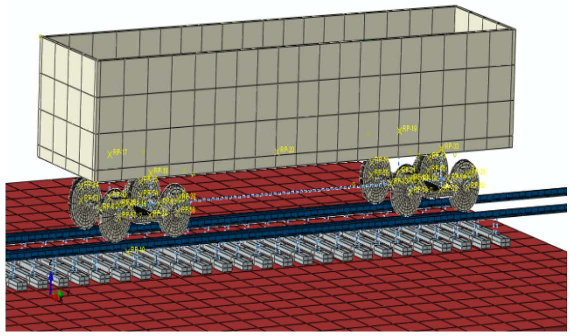

Figure 3: Vehicle Model

Table2: Vehicle specification (after Shi et al, 2013)

Specification	Value
Mass of car body *(M_c)*	91400kg
Inertia of car body *(J_c)*	1.33×10^5 kg·m^2
Mass of frame *(M_f)*	1786kg
Inertia of frame *(J_b)*	420kg·m^2
Mass of wheel *(M_f)*	1257kg
Primary suspension stiffness	13MN/m
Primary suspension damping	3×10^5 Ns/m
Secondary suspension stiffness	4.4 MN/m
Secondary suspension damping	4×10^3 Ns/m

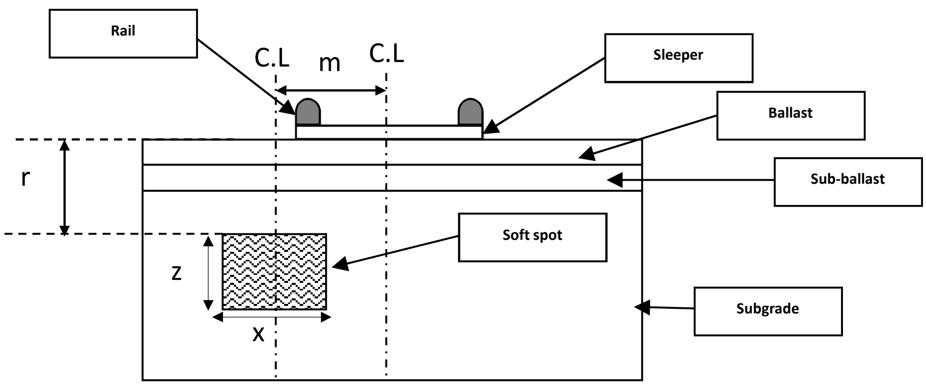

Figure 4: cross-sectional view of rail embankment with a soft spot

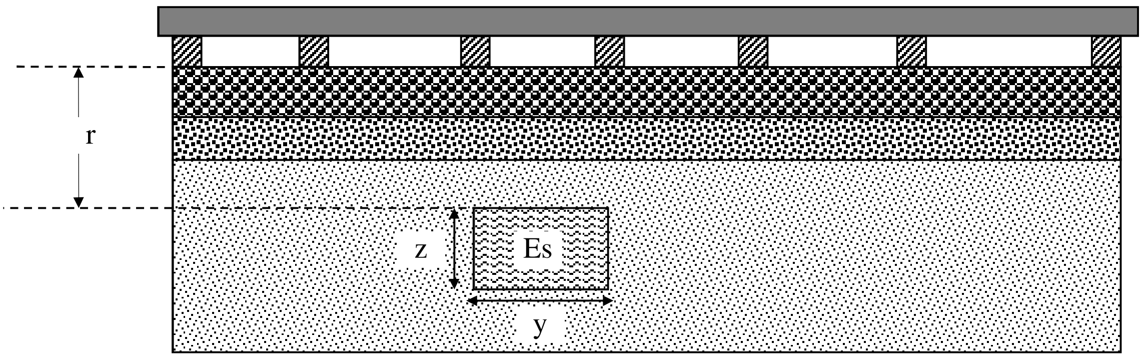

Figure 5: side view of track with a soft spot

Table 3: soft spot scenarios configurations

Scenario	Subgrade stiffness E_{sg} (MPa)	Soft spot stiffness E_s (MPa)	*x* (m)	*y* (m)	*z* (m)	*m* (m)	*r* (m)
S1	20	100	4	3	5	0	1
S2	20	100	4	3	10	0	1
S3	20	100	4	3	15	0	1
S4	20	100	2	3	5	0	1
S5	20	100	8	3	5	0	1
S6	20	100	4	1	5	0	1
S7	20	100	4	2	5	0	1
S8	20	100	4	1	5	0	2
S9	20	100	4	1	5	0	3
S10	20	100	4	3	5	2	1
S11	20	100	4	3	5	4	1

Measure of track performance

To understand the influence of the dimension and location of the soft spot generally two types of measurements are carried out to determine track performance, namely; functional and structural. Functional measurements are associated with the way in which the track performs from the point of view of the user. Relevant measures include horizontal and vertical track geometry/track quality (Cope, 1993).Track quality (*TQ*) can be calculated as the standard deviation of vertical profile of the rail. It is desired to keep the value of track quality as low as possible. On the other hand, the measurements of structural condition are associated with the structural integrity of the track and include track dynamic stiffness (Berggen, 2007), and concerned with the long term performance of the track. Dynamic track stiffness (E_{Dy}) is the ratio between the instantaneous dynamic wheel load applied to the corresponding rail deflection at a particular position along the track. It is desired to keep the minimum dynamic stiffness at relatively high value to prevent rail fatigue.

Results

The analysis was carried out as it was described earlier to determine the effect of changing the size and location of the soft spot and the results are shown in figure 6 and 7. From these it can be observed that for most cases the structural and function condition of the track start to decrease as the size of the soft spot starts to increase. Similar observation can be also noted as the soft spot location moves closer to the rail. When the width (*x*) and length (y) of the soft spots exceeds the length and width of the train, the deterioration starts to diminish.

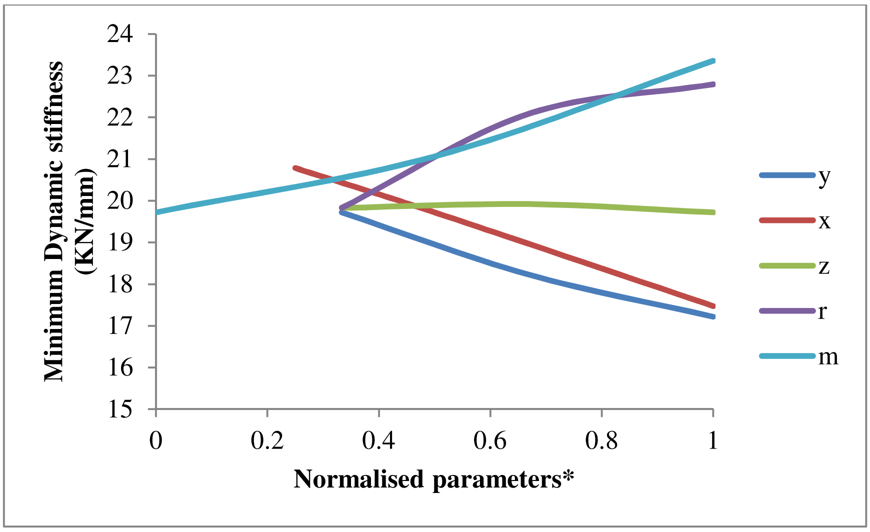

Figure 6: structural condition of the track vs. size and location of the soft spot

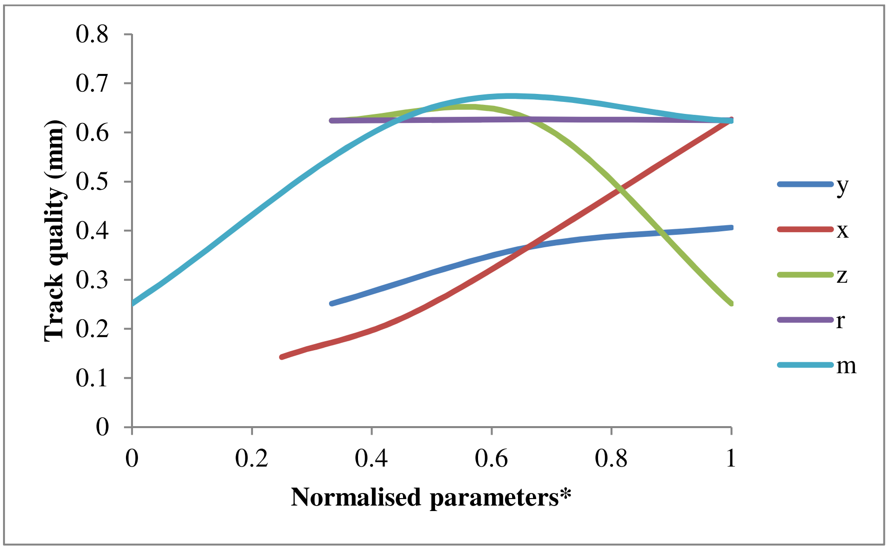

Figure 7: functional condition of the track vs. size and location of the soft spot

An interesting observation can also be seen as the thickness of the soft spot (*z*) increases the function and structural condition start to improve. With the increase of soft spot thickness (*z*) the accumulated deflection will increase and a punching effect starts to manifest at the surface of the soft spot. As a result the stressed area will increase reducing the resultant deflection which translates into an improvement in the overall condition of the track. Also as the soft spot get closer to the rail, i.e a decrease in (*r, m*), the soft spot starts to experience

*The dimensions and the location are normalised by the maximum value of each parameter higher stress amplitudes resulting in a decrease in the structural condition of the track. On the other hand, the functional condition of the track starts to worsen as the value of the horizontal distance (*m*) between the soft spot and the rail reaches 2m and then the condition starts to improve beyond that value. The reason for this is that at 2m distance the soft spot only affects one rail creating differential displacement between the two wheels of the axle.

In order to facilitate the predication of track quality and dynamic stiffness a regression analysis was carried out as suggested by Hamby, 2000 to try to relate track quality and dynamic stiffness as a function of the size and location of the soft spot. The resulting are shown in equation 1 and 2 and figure 7. The models had correlation factors (R^2) more of than 0.92. To determine the most parameter influential parameter the models coefficients were then converted to coefficients weightings using equation 3 and compared against each other; the higher the coefficient weighting the more important the parameter is.

$$E_{Dy} = C_1\,(x) + C_2\,(y) + C_3\,(z) + C_4\,(r) + C_5\,(m) \qquad \text{(equation 1)}$$

$$TQ = C_1\,(x) + C_2\,(y) + C_3\,(z) + C_4\,(r) + C_5\,(m) \qquad \text{(equation 2)}$$

$$CW_n = C_n / (C_1 + C_2 + C_3 + C_4 + C_5) \qquad \text{(equation3)}$$

Where: *x, y, z, r, m* are soft spot parameters

C_1 *to* C_5 are regression coefficients

CW_n: nth parameter coefficient weighting

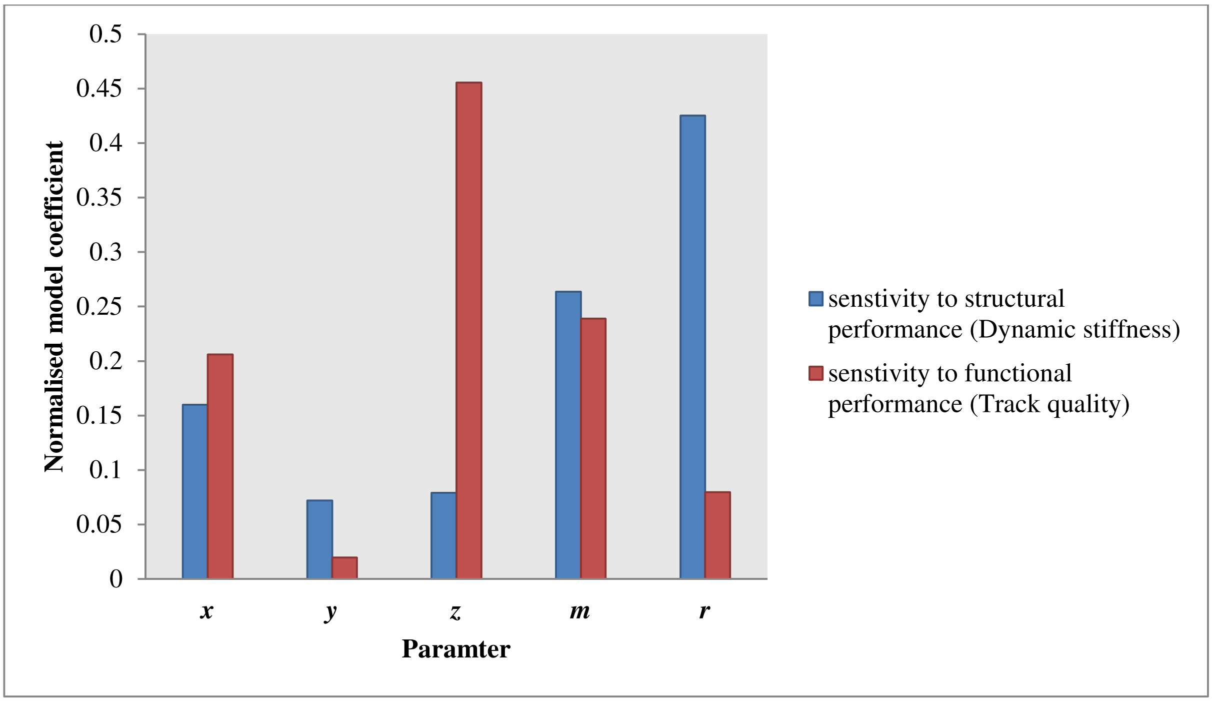

Figure 8: regression coefficients

From figure 8, it can be observed that the location (*r, m*) of the soft spot has a significant effect on the structural condition on the track; however, the size (*z, x*) of the soft spot is the most influential parameter that affects the functional condition of the track.

Discussion

Soft spots have significant effects on the overall condition of the track. However, there are number of analysis uncertainties in the analysis that need to be addressed including:

1. Elastic modelling: the behaviour of the substructure in the FE model is assumed to be linear elastic; however, previous studies have suggested that it should be modelled as a nonlinear stress-dependent material accompanied with field validation to provide a more accurate representation of the track's dynamic behaviour (Burrow el at, 2007).
2. Smooth rail surface: in the FE model it was assumed to have a perfectly smooth rail with no irregularities. In reality the presence of rail irregularities is unavoidable which has a significant impact on the dynamic load. Therefore modelling rail as smooth may provide underestimated results.
3. Performance indicators: in the analysis, track quality and dynamic stiffness were used to assess the functional and structural, respectively. Those two indicators may not provide a complete understanding of the overall condition of the track and other indicators such as the stress and ride comfort may provide different outcomes.
4. Regression analysis: due to the nonlinearity of the results described earlier multi-regression models were used to understand the influence of each parameter on the overall condition of the track. The results obtained from this method were in a reasonable agreement with the literature (Gonzalez, nd), however, other techniques such as regression Decision Trees and Nonlinear Multiple Regression Analysis maybe used to reinforce those findings.

Conclusions

While it is recognised that it is important to carry validations to the model, the following can be concluded from this study:

1. The overall condition of a railway track starts worsens as the soft spot size increases.
2. The functional and structural conditions of a railway track start to improve as the soft spot get further away from the rail.
3. The location of the soft spot is the most influential parameter in terms of the structural condition of the track.
4. The size of the soft spot is the most influential parameter in terms of the functional condition of the track.

References

Berggren, E. (2009), *Railway track stiffness,* Royal Institute of Technology, Stockholm

Burrow, M. (2007). Track Stiffness Considerations for High Speed Railway Lines. Centre for Railway Research and Education, School of Engineering, University of Birmingham, UK, Paulo Fonseca Teixeira, Head of Railway Division

Burrow, M.P.N., Chan, A. H.C, and Shein, A. (2007). Falling weight deflectometer based inverse analysis of ballasted railway tracks. Geotechnical Engineering, Proceedings of the Institution of Civil Engineers. 160 July 2007 Issue GE3. pp 169–177.

Cope, G. H., Ed. (1993), British Railway Track: Design, Construction and Maintenance. Loughborough, The Permanent Way Institution.

Dahlberg, T.(2010). Railway Track Stiffness Variations – Consequences and Countermeasures International Journal of Civil Engineering, 2010; 8 (1) :1-12. URL http://ijce.iust.ac.ir/browse.php?a_code=A-

Frohling ,R. (1997). Deterioration of railway track due to dynamic vehicle loading and spatially varying track stiffness. From http://upetd.up.ac.za/thesis/available/etd-01122009-160350/

Gonzalez, P, Cuadrado, M, Romo, E. (nd) Small structures in the core (nucleus) of the embankment in high-speedlines. Effects on the variation of the global stiffness of the track and design recommendations. Funacon Caminose De Hierro. Madrid.

Hamby, D. (2000). A comparison of sensitivity analysis techniques. Savannah River Technology Centre. Westinghouse Savannah River Company.

Shi, J., Burrow, M. & Chan, A. (2012), "Measurements and simulation of the dynamic responses of a bridge-embankment transition zone below a heavy haul railway line", *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol., no. pp. 254-268.