Non-destructive assessment of railway substructure

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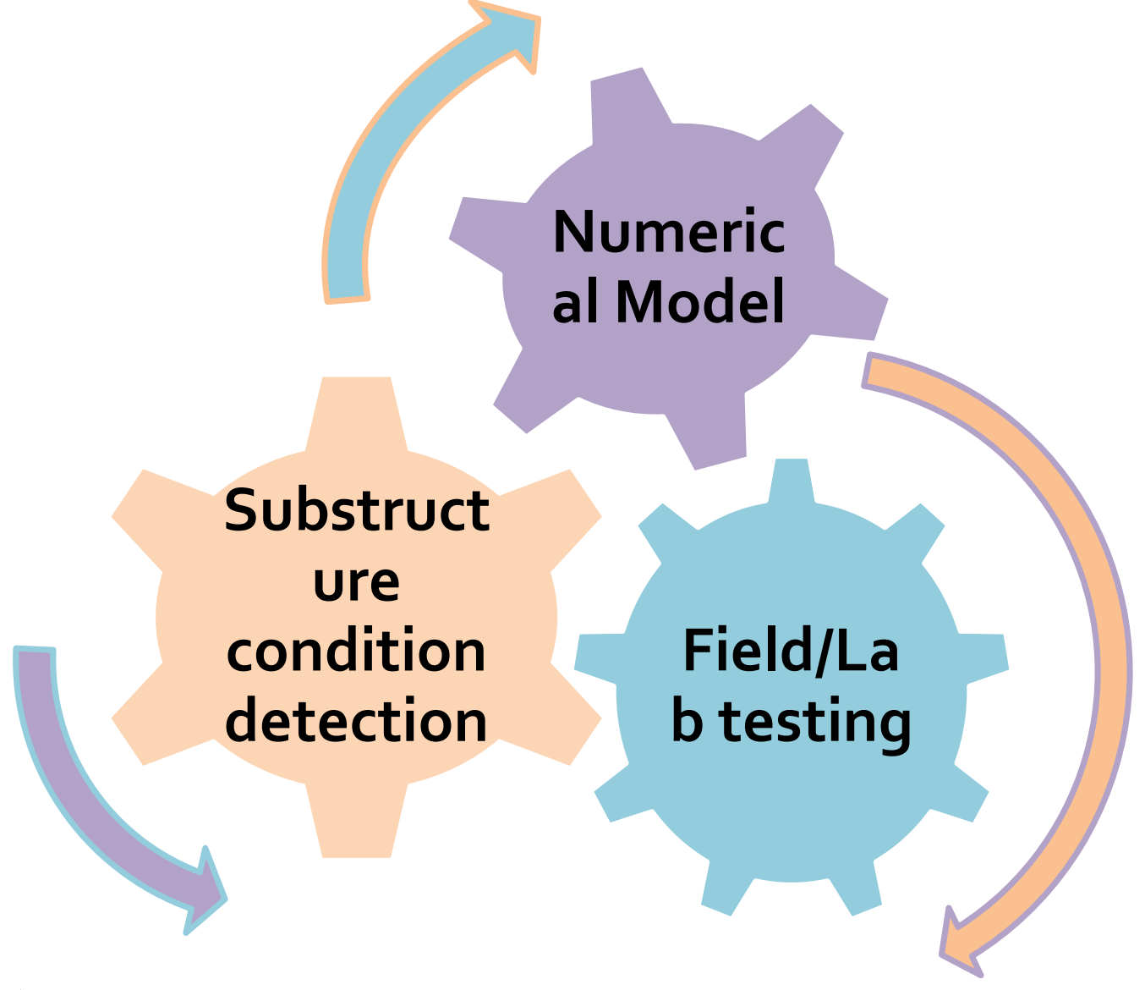
1. PROJECT OVERVIEW

The presence of uneven distribution of railway ballast stiffness and thickness along and across the railway track has several negative side effects. The directly affected areas and the ones in proximity will have an increase in settlements and reduction in bearing capacity. In addition, if soft subgrade is present underneath the affected ballast area, the negative effects will be enlarged and the total life span of the affected railway section will be greatly reduced.

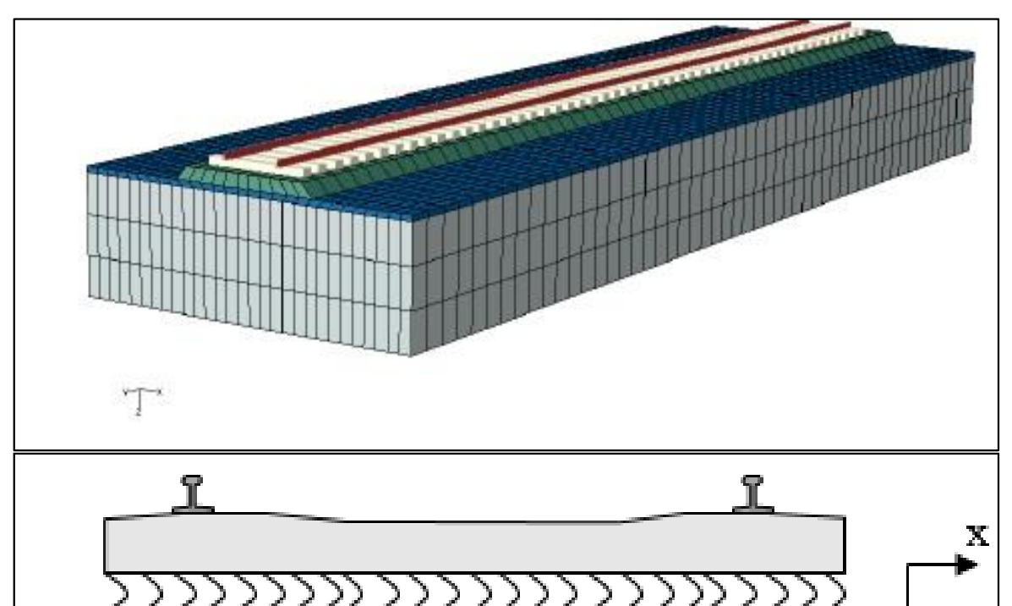
The mentioned severities present in substructure layers will not only affect the behaviour of railway track elements individually, but also response of the whole railway track. These alterations in behaviour of the railway track can be tracked by applying non-destructive, vibration based testing such as impact hammer. If one wants to solve a forward problem, then free vibration characteristics of the railway track are obtained. On contrary, for solving the inverse problem one has to detect the locations with present severities and their extent.

This project is employing impact hammer testing of railway track and its elements for identification of substructure condition. Soft optimisation techniques together with developed numerical models and obtained field and laboratory data are being used for detection of severities and their extent along and across the railway track.

2. METHODOLOGY



- ✓ 1D and 3D numerical models of transverse and longitudinal direction of railway track are used. The 3D model is built from beam and solid elements. Only elastic behaviour is taken into account.



- ✓ The technique consists from exciting the railway track at some points and picking up the accelerations with installed accelerometers on the track. Impact hammer testing is utilized in laboratory and on field. When transient vibrations of railway track are studied in field, the measurements are taken before and after ballast cleaning and tamping.

Equipment for impact hammer testing

Impact hammer testing of railway track

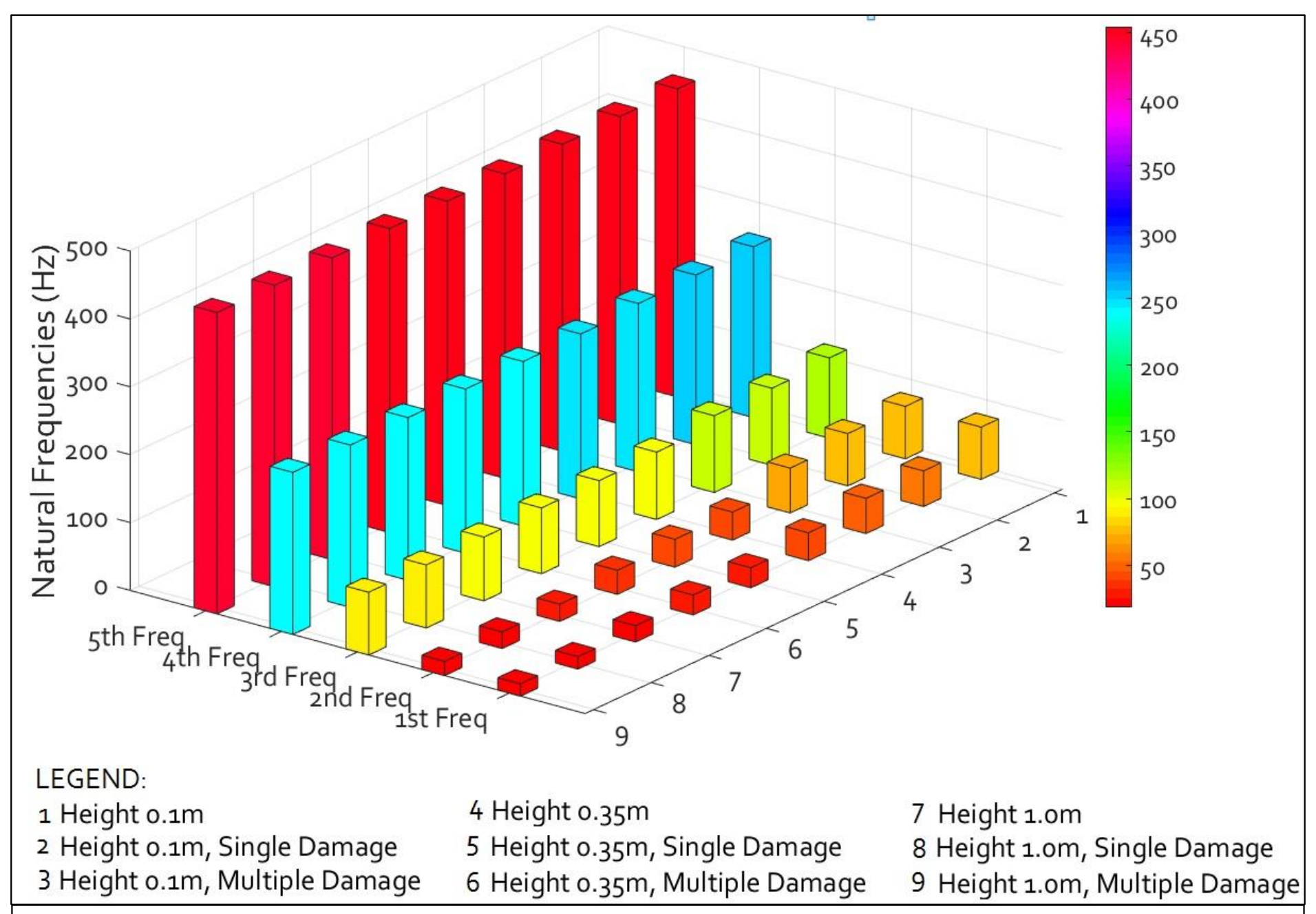
- ✓ The gap after maintenance is two weeks and five months time. When the technique is applied in laboratory setup, railway sleeper is embedded in ballast box and the transient vibrations are acquired for different ballast heights and presence of voids at sleeper-ballast contact.
- ✓ For detection and quantification of present severities in ballast bed and subgrade soft optimisation techniques such as PSO is applied. The algorithm is used in combination with 1D model and laboratory data.

Ballast Box for experimental assessment

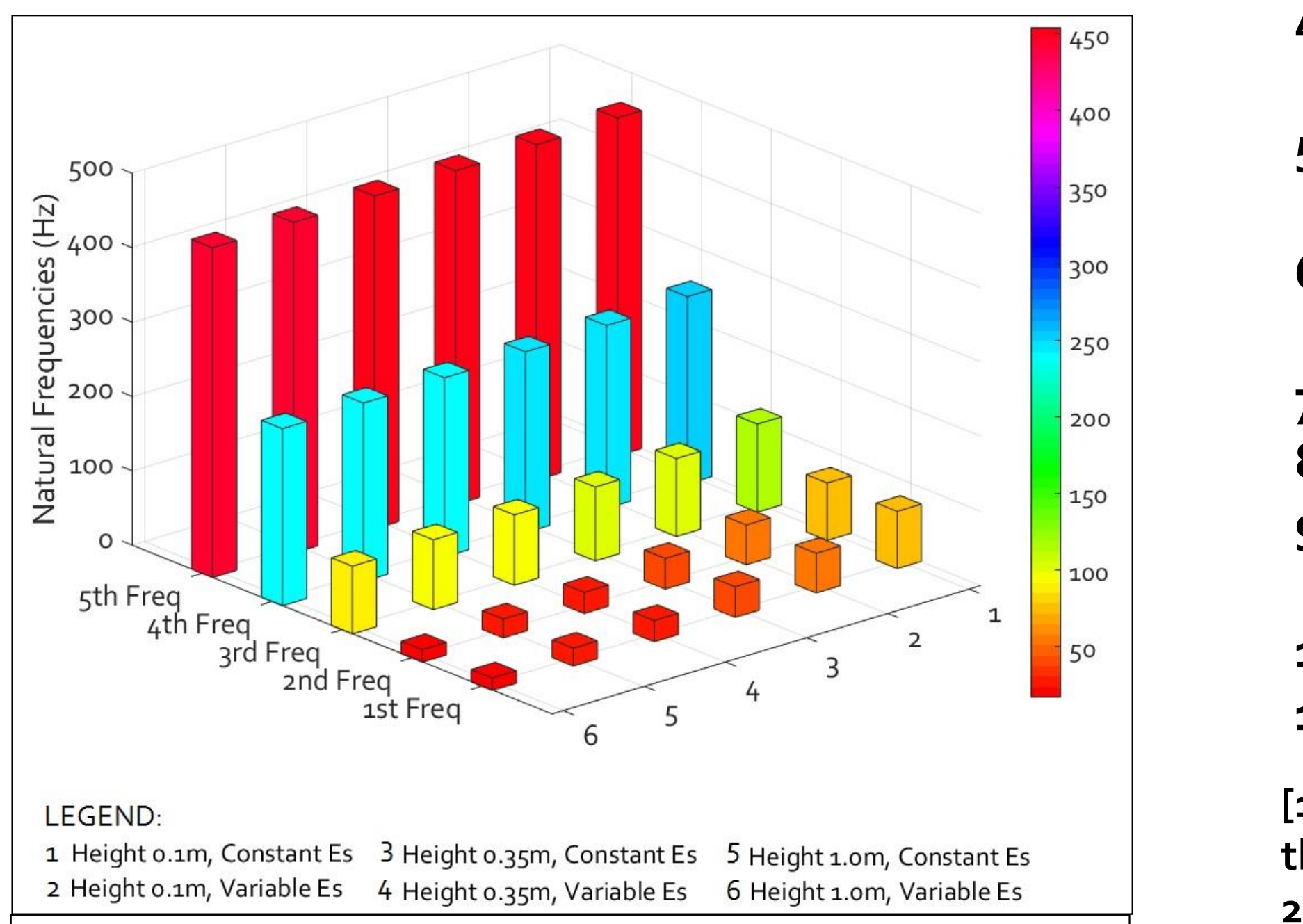
2. RESULTS

2.1 VIBRATION CHARACTERISTICS OF RAILWAY SLEEPER FOR ASSESSMENT OF BALLAST CONDITION[1,3]

For introduced variability in ballast height from 0.1m to 1.0m, the changes in frequencies were apparent. As the ballast thickness increased, the natural frequencies of the sleeper decreased. By adding other changes such as induced damage and variability of ballast modulus, the reduction in natural frequencies was intensified. As ballast height increased on one side, the variability of elastic modulus with height prevails and influences the reduction in natural frequencies the most, but on the other side for remote heights of ballast, induced damage along the sleeper predominates. Variabilities in ballast height had great influence on vibration modes. When the variability of ballast modulus with height is considered, a swap occurred between translational and rotational mode of the sleeper. The same scenario occurred for variable ballast modulus.



Natural frequencies for variable ballast height and induced single and multiple damage



Natural frequencies for variable elastic modulus and ballast height

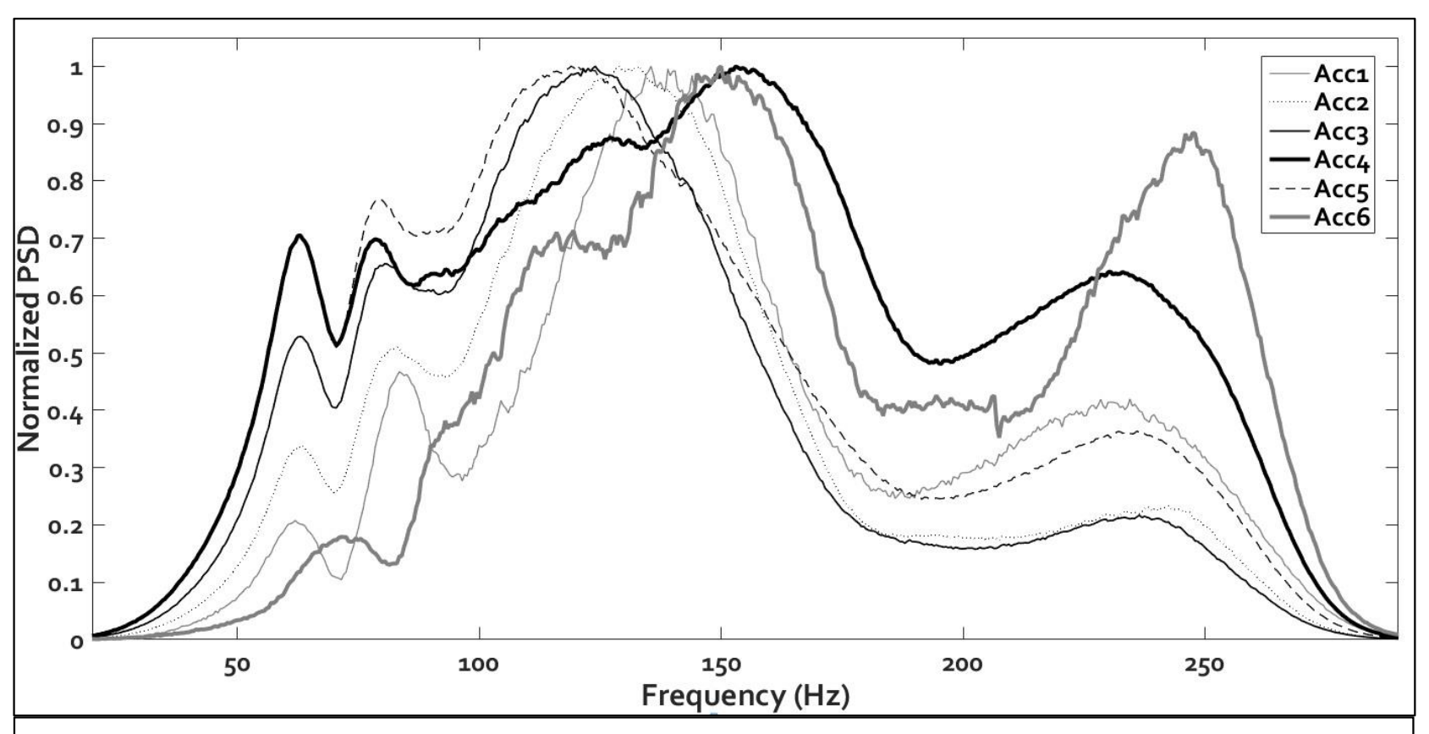
Condition	Feature	Foundation Type	Natural Frequencies (Hz) 1	2	3	4	5
Healthy Foundation	-	Winkler	41.14	41.27	99.35	243.79	450.35
Damaged	Single		29.46	41.20	97.37	243.29	450.13
	Multiple		29.16	35.50	97.17	242.68	449.81
Healthy Foundation	-	Vlasov-Leontiev	41.16	41.27	99.35	242.95	448.59
Damaged	Single		29.56	41.12	97.27	242.49	448.40
	Multiple		29.27	35.41	97.07	241.86	448.06

Natural frequencies for different foundation types and induced damage

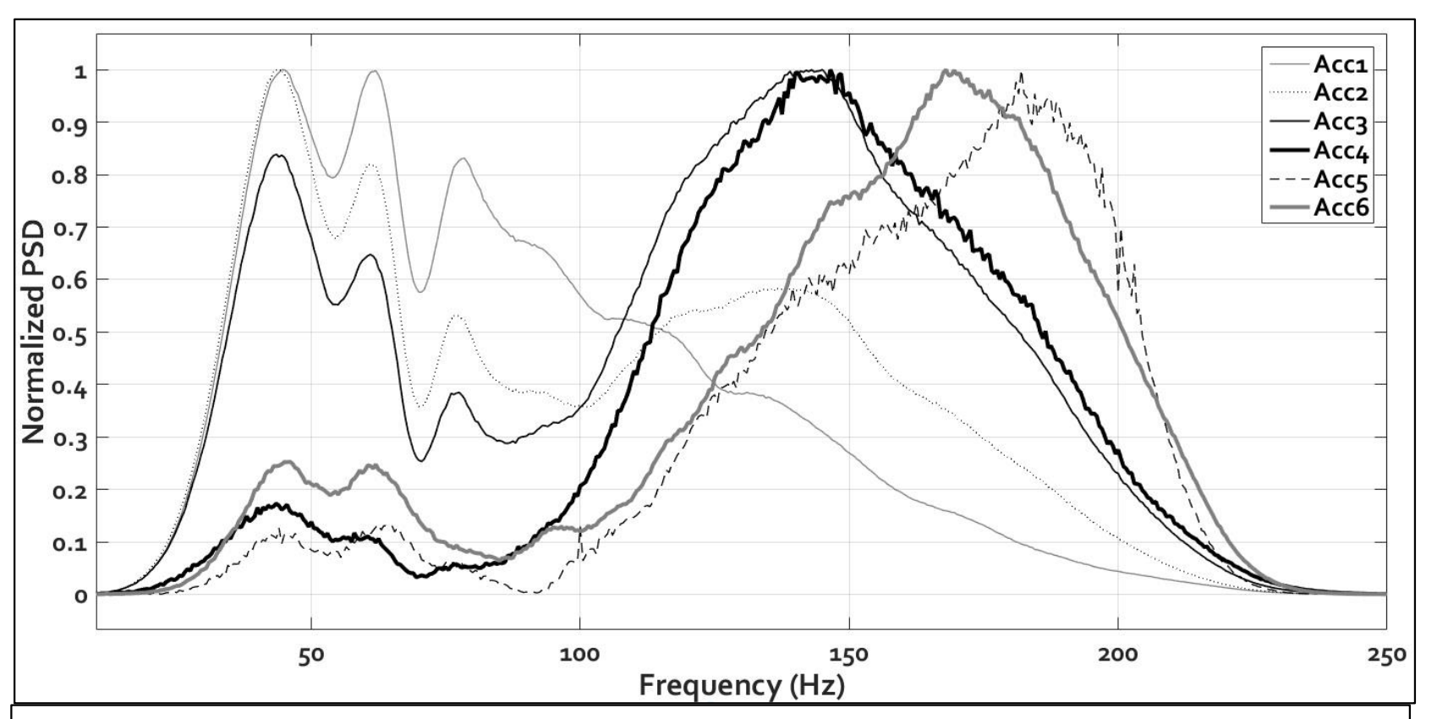
Both foundation types showed similar results for "healthy" case and induced single and multiple damages in the ballast bed. Since the parameter k_1 is assumed to be equal to subgrade coefficient k_W, no great discrepancies were observed in natural frequencies or mode shape curves.

2.2 TRANSIENT VIBRATIONS OF RAILWAY TRACK-IN SITU APPROACH[2]

Impact hammer testing of a railway track was used to obtain the PSD and FRF function of different track elements for inactive railway line in Wellingtonbridge in Republic of Ireland. First test location of interest was an embankment with timber sleepers whereas second location had concrete sleepers with bedrock positioned close to the surface. The lower frequency range (below 300 Hz) was the frequency range of interest, since substructure condition is of great importance. Plotted PSDs and FRFs for the sleepers and rail showed that high damping is present in the system.

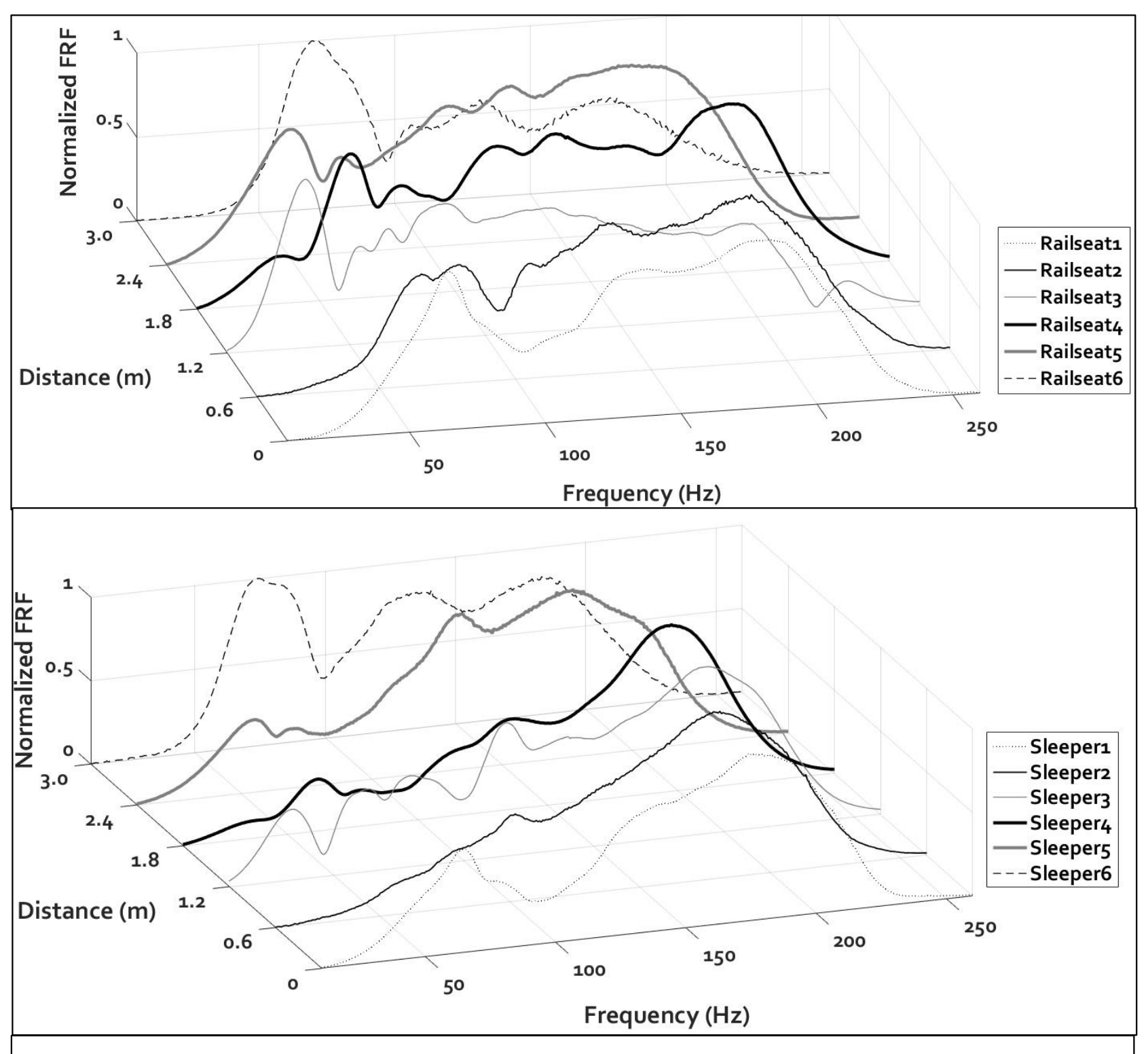


Power Spectral Densities for concrete sleeper for all six channels



Power Spectral Densities for timber sleeper for all six channels

For both sleepers consistency in peaks can be detected in the lower frequency range, under 100 Hz. Above 100 Hz the PSD curves are more shifted with peaks with very broad bandwidth. Moreover, the magnitudes of the frequencies for concrete sleeper are greater than for timber sleeper.



Frequency response functions for six railseats in a row and six sleepers ends in a row

Plotted accelerance functions for six railseats in a row show discrepancies for every FRF plotted. There are distinctive peaks under 100 Hz for all railseats excluding Railseat 5. These peaks occur in the frequency range 30 to 70 Hz. FRF curves above 100 Hz tend to be noisier for all railseats and peak detection is much harder than for the lower frequency range. A rise in the FRF slope for all railseats can be depicted for frequency range from 170 to 200 Hz.

Plotted accelerance functions for six concrete sleepers in a row differ for every sleeper, and the number of peaks in the plotted FRFs is different for every sleeper. Even for various frequency bandwidths, (less than 50 Hz; 50 to 100 Hz; above 150 Hz), the FRFs differ in peak location. However, for frequencies less than 100 Hz an agreement can be made, i.e. all sleepers have an expressed peak in the 50 to 70 Hz range. For frequencies above 150 Hz, all FRFs are consistent for peaks close to 200 Hz, even though the frequency bandwidth is very broad.

2.2 FAULT IDENTIFICATION IN RAILWAY BALLAST BY EMPLOYING PARTICLE SWARM OPTIMISATION

Pseudocode for PSO:

```
1.  Input structural parameters; material properties and boundary conditions. Input characteristics of elastic foundation.
2.  Input measured free vibration data for damaged system.
3.  Input Particle Swarm Optimisation parameters.
4.  Initial swarm. Define random initial particle positions and velocities.
5.  Define particles positions and velocities. Particles positions denote damage location and amount.
6.  Evaluate free vibration characteristics for particles positions.
7.  Evaluate objective function.
8.  Evaluate Error.
9.  Is desired accuracy achieved? Is maximum number of iterations achieved?
10. Yes. End
11. No. Continue to step 5
```

✓ Solving the eigenvalue problem

$$\left(\sum_{e=1}^{N_{el}}\left(\left[k_{TB}\right]^e+(1-\alpha)x\left[k_W\right]^e\right)-\left\{\omega_{PSO,i}\right\}[M_{TB}]\right)\{\phi_{PSO,ij}\}=0$$

$\left[k_{TB}\right]^e$ - Element stiffness matrix of the sleeper.
$\left[k_W\right]^e$ - Element stiffness matrix of ballast.
α - Damage coefficients.
$\left\{\omega_{PSO,i}\right\}$ - Natural frequencies from simulations.
$\{\phi_{PSO,ij}\}$ - Mode shapes from simulations.
$[M_{TB}]$ - Mass matrix of the whole system.
N_{el} - Number of finite elements.

✓ Minimizing the objective function F(α)

$$F(\alpha)=\sum_{i=1}^{N_{fr}}\left(\frac{\omega_{PSO,i}-\omega_i}{\omega_i}\right)^2+\sum_{i=1}^{N_{fr}}\sum_{j=1}^{Ndof}\left(\frac{\phi_{PSO,ij}-\phi_{ij}}{\phi_{ij}}\right)^2$$

N_{dof} - Number of degrees of freedom.
N_{fr} - Number of frequencies considered.
$\left\{\omega_i\right\}\{\phi_{ij}\}$ - Actual frequencies and mode shapes.

[1] E. B. and C. McNally, *"Assessment of Railway Substructures using Impact Hammer Testing"*, in J. Pombo, (Editor), Proceedings of the Third International Conference on Railway Technology: Research, Development and Maintenance, Stirlingshire, UK, Paper 3, 2016, 10.4203/ccp.110.3
[2]E. Balic, D. Hester and C. McNally *Impact Hammer Testing of Railway Track* Bearing Capacity of Roads, Railways and Airfields, Athens, 2017
[3] E. B. and C. McNally, *"Vibration analysis of railway sleeper for assessment of ballast condition"*, submitted for revision to International Journal of Railway Technologies

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