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Kaewunruen, Sakdirat; Ng, Jipong; Aikawa, Akira

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SENSITIVITY OF RAIL PADS ON DYNAMIC RESPONSES OF SPOT REPLACEMENT SLEEPERS INTERSPERSED IN BALLASTED RAILWAY TRACKS

Sakdirat Kaewunruen

The University of Birmingham, School of Engineering, Edgbaston, Birmingham, UK
email: s.kaewunruen@bham.ac.uk

Jipong Ng

The University of Birmingham, School of Engineering, Edgbaston, Birmingham, UK

Akira Aikawa

Railway Technical Research Institute, Tokyo, Japan,

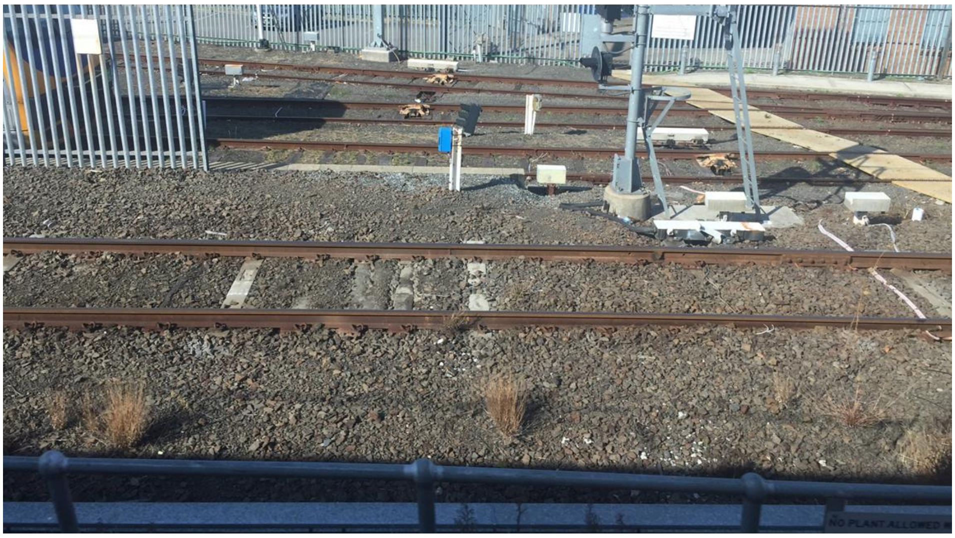
In many countries, timber sleepers have been widely used in railway networks. Over the time, timbers degrade and it becomes more difficult to seek cost-effective hardwood sleepers to replace the deteriorated timber sleepers. To enable a short-term solution, many infrastructure managers adopt the interspersing method of track maintenance. The interspersed pattern sleeper, a spot replacement of old timber sleeper with concrete or composite counterparts, of railway track is often used as a temporary maintenance for secondary railway lines such as yards, balloon loops or siding. It is observed that performance of interspersed tracks can quickly deteriorate after some years due to impact loading condition induced by track stiffness difference. On this ground, a nonlinear simulation of interspersed sleeper railway is conducted using the finite element program, STRAND7, so that the dynamic analysis can be conducted. Two moving point loads representing an axle load along each rail has been established to investigate the worst-case, potential actions for premature damage of sleepers and differential settlement of the track. In this study, the emphasis is placed on the effect of rail pad properties on the dynamic displacement and acceleration of concrete sleepers. The median train speed of 60 km/h and a variety of interspersed patterns have been investigated to identify the causes of track deterioration and track differential settlement. The insight will help track engineers develop a method to control vibration impacts for interspersed railway tracks using resilient rail pads in conjunction with concrete sleepers.

Keywords: Dynamic analysis, ballasted railway track, interspersed track, spot replacement sleeper, railway sleeper

1. Introduction

Timber or wood material has long been manufactured and used as railway sleepers in many parts of railway networks around the world. As the timber sleeper life span is generally around 15-20 years depending on application and maintenance, such timber sleepers are required for maintenance or even a huge replacement at certain point in time. In addition, unless used in low speed traffic operation, timber sleepers require strengthening for structural enhancement in the ability to withstand higher velocity operations or to restrain longitudinal rail forces preventing a track buckling. “Interspersed” is a method that has been adopted as a short-term measure against these problems.

Interspersed railway track can be built by re-sleepering old and rotten timber sleepers and replace it with concrete sleepers [1-6]. Due to differential track stiffness, deterioration process, and operational parameter, many patterns of interspersed railway tracks have been introduced i.e. 1 in 2, 1 in 3, 1 in 4 and so on (which mean there is 1 concrete sleeper in every indicated number of sleeper such as 1 in 4 mean 1 concrete sleeper in every 4 sleepers including the concrete itself). It is important to note that this type of railway track mainly existed in a third class track (low volume traffics) with low operational speeds. The key reason is that this type of track has various flaws derived from how it is built. The replacement of old timber sleepers is frequently done over old and soft existed formation, which has been in services for so long, by installing new stiff concrete sleepers in its existing place. This can result in soil foundation failure, track stiffness inconsistency (as it made up of both concrete and timber sleepers), and different track decay rate [7-11]. These can impair the long-term performance of interspersed railway tracks as shown in Figure 1. Figure 1 shows the conditions of interspersed railway tracks in low-speed operation (<25 km/h). The tracks have been commissioned between 2006 and 2008 and have served as a link to maintenance junctions. The photos were taken in April 2016 during a site visit. This provides clear evidence that there is a need to further suppress the vibrations in the interspersed tracks. Especially at the concrete sleepers, the effects of rail pads used to help attenuate impacts should be investigated to extend the life of sleepers.



(TOP)

(BOTTOM)

Figure 1: Deteriorated interspersed railway track (Top: mud pumping, and Bottom: ballast pulverisation and ballast dilation)

A critical review on the loading conditions acting on railway tracks for either passenger or freight trains shows that dynamic behaviour of a railway track is vital to understand the track dynamic responses to diverse loading conditions [12-13]. A critical loading condition, which often causes structural cracks in brittle sleepers, densifies and pulverises ballast support, is the large impact loads due to wheel/rail irregularities. For example, a common transient waveform pattern of wheel impacts due to an out-of-round wheel can be seen in Fig. 1. Clearly, the magnitude of the impact forces varies from 200kN to 400kN while the duration is ranging from 2 to 10 msec. Based on a transient pulse concept, these impact pulses are associated with the vibration excitation frequency range from 100 Hz to 500 Hz (f = 1/T: f is the frequency and T is the period). This frequency range can resonate with track components and lead to pre-mature damages. In the real world, wheel/rail interaction generates dynamic forces acting on a rail seat. The dynamic load patterns are dependent on train speed, track geometry, axle load, vehicle type, and wheel/rail defects or irregularities. Track engineers must consider the frequency ranges of static and dynamic loadings in life cycle asset maintenance and management of railway tracks with respect to critical train speeds and bespoke operational parameters [14-16].

It is important to note that serviceability limit state has become one of the key governing criteria for sleepers made of different material properties in the existing aged track systems. These criteria include the ability of sleepers to absorb impact loading and the resilient fastening to attenuate dynamic contents. In this study, this short-term mitigation measure is sometimes called ‘spot replacement’ or ‘intersperse method’. The design and work method for interspersing technique has not been fully analysed. In addition, a general recommendation (e.g. by Australian Office of Transport Safety Investigations) is to perform concrete sleeper installation only ‘in-face’ (i.e. the practice of installing the same sleeper type constinuously rather than interspersed with other sleepers in between, also referred to as ‘on-face’) [3-4]. Therefore, this paper aims at investigating the potentials of rail pads to help suppress vibrations of concrete sleepers mounted in the interspersed railway tracks. Based on critical literature review, this research has never been presented in open literature [3-6]. The insight into this practice will help rail track engineers to enable a maintenance technique to mitigate damage and to improve reliability of infrastructure assets.

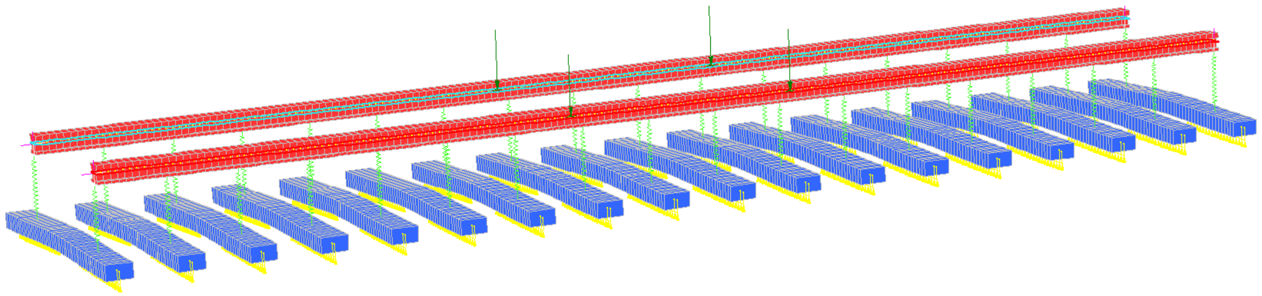
2. Nonlinear-FEM of Interspersed Tracks

2D Timoshenko beam has been chosen for track structure idealisation as a beam model since it has been found to be one of the most suitable options for modelling rail and concrete sleeper [17] due to its ability to reflect the deep-beam-like structural behaviours. For both rail track and sleepers, they are idealised using beam elements in finite model so shear and flexural deformation can be included in computation [18]. The rail pads at the rail seat are simulated by using series of spring dash-pot elements. In order to replicate ballast supports, non-linear tensionless beam support is used. The tensionless support can correctly demonstrate ballast under the sleeper as this attribute allow beam to lift over the support while the tensile support is omitted [6]. This tensionless support creates nonlinear boundary conditions for the tracks as the support contacts are derived from the convergence of iterations to match ballast-sleeper deformation. For the train loading on the rail track, it is simplified to 2 points loads (1 axle) with 100kN in magnitude, 2m apart (common passenger bogie centre), on each side of the rail track (4 point loads in total as equivalent to a bogie), to enable envelop analysis (maximum responses for design purpose). Figure 2 shows the illustration of the models.

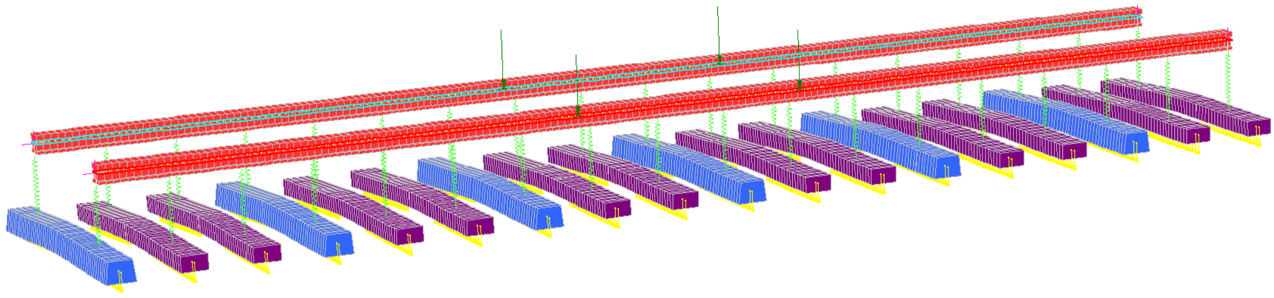
The numerical simulation is conducted using non-linear transient dynamic solver in Strand7 to enable tensionless capability of ballast using properties in Table 1 [19]. The nonlinear iteration (Newton Raphson) has been used to compute the ballast contact and support. The model has been validated earlier using experimental parameters, field data and previous laboratory results [20-22]. In this study, the train speed of 60 km/h has been considered as this speed is a common median speed for suburban rail network (i.e. on average from 50 km/hr in London, 55 km/hr in Tokyo, to 55-60 km/h in Sydney) [23-25].

Table 1: Engineering properties of the reference sleeper used in the modelling validation

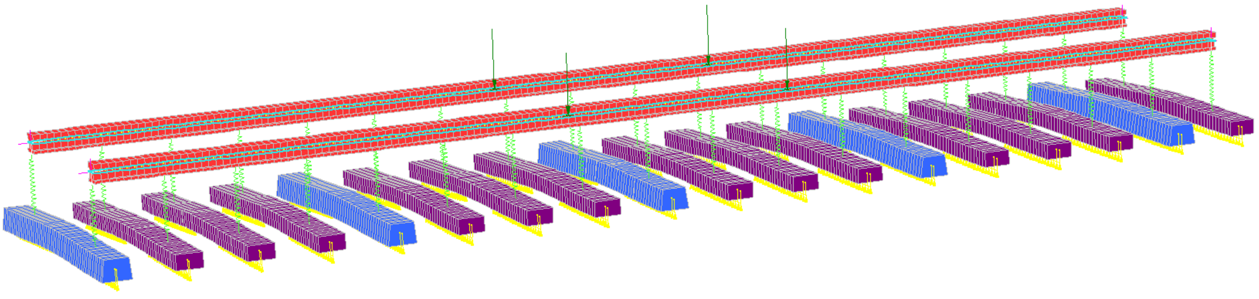
Parameter List	Characteristic value	Unit
Flexural rigidity	$EI_c = 4.60$, $EI_r = 6.41$	MN/m^2
Shear rigidity	$\kappa GA_c = 502$, $\kappa GA_r = 628$	MN
Ballast stiffness	$k_b = 13$	MN/m^2
Rail pad stiffness	$k_p = 17$	MN/m
Sleeper density	$\rho_s = 2,750$	kg/m^3
Sleeper length	$L = 2.5$	m
Rail-centre distance	$G = 1.5$	m
Rail gauge	$g = 1.435$	m



a) Timber track



b) 1:3 interspersed track

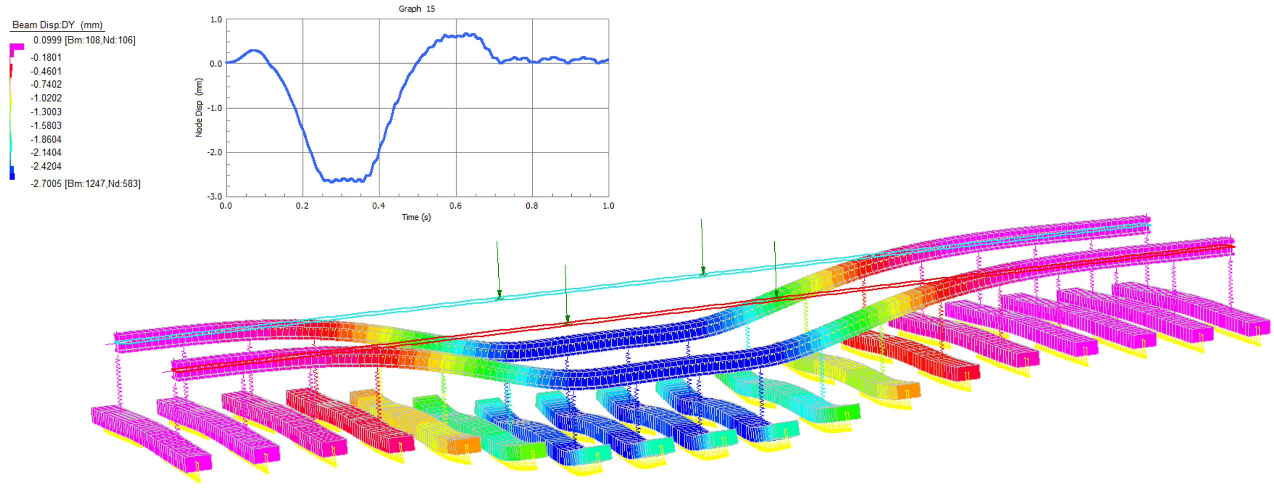


c) 1:4 Interspersed track

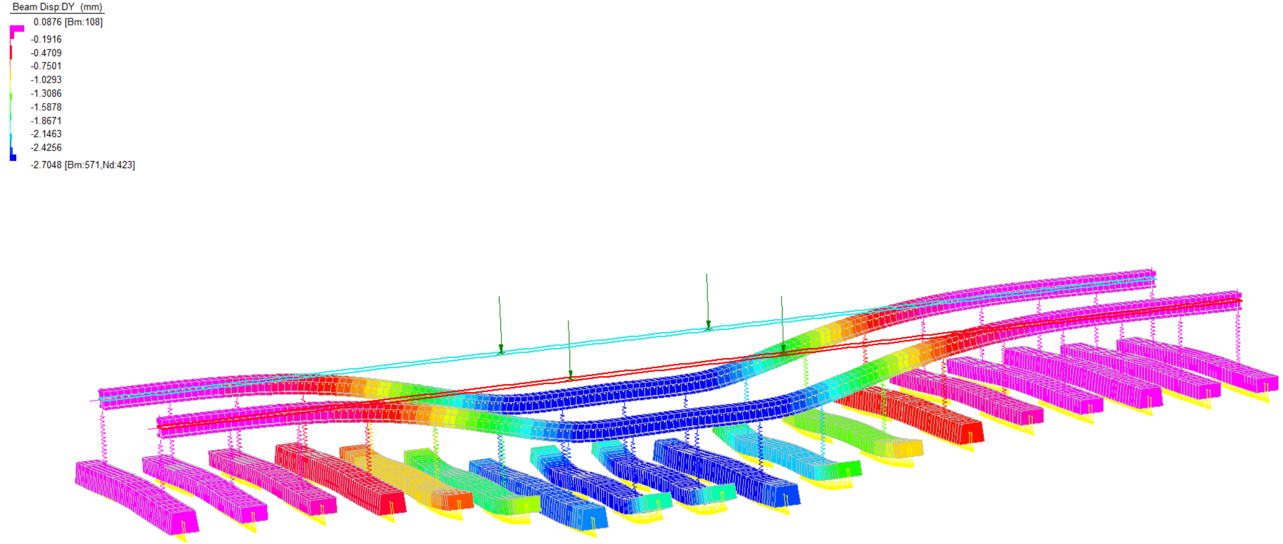
Figure 2: NFEM of Tracks

3. Results and Discussion

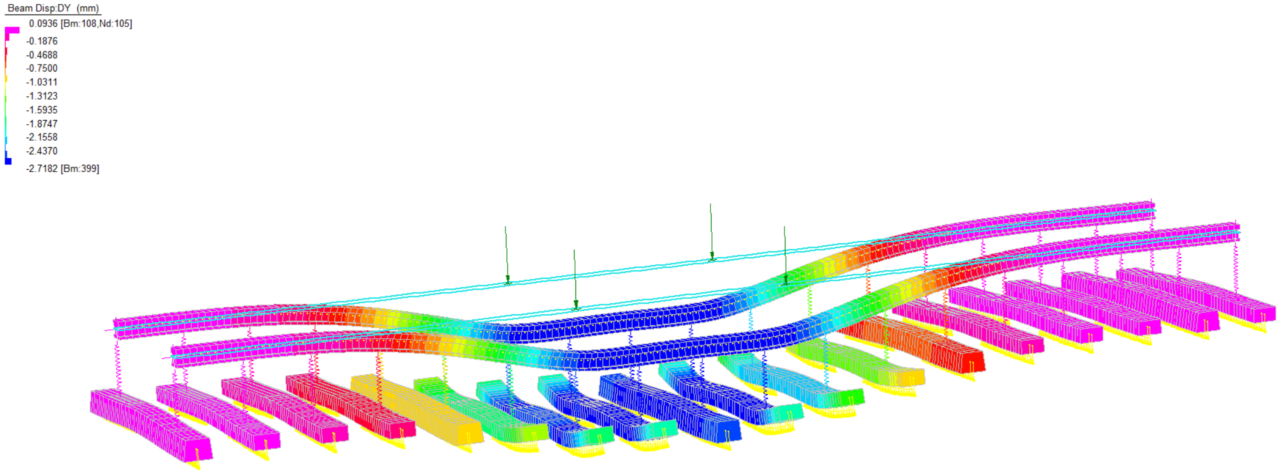
The dynamic responses of sleepers interspersed in ballasted railway tracks to moving loads can be seen in Figure 3.



a) Timber track (Box: time domain of sleeper displacement)



b) 1:3 interspersed track



c) 1:4 Interspersed track

Figure 3: Dynamic responses of railway tracks

It is clear that timber tracks tend to deform over larger area under the same moving load due to its lesser stiffness. As the concrete sleepers are much stiffer than timber counterparts, the track skeleton tends to redistribute the load to the stiffer element. It can be seen that the 1:4 interspersed track has the highest track deformation and the highest deformation is centred around stiff elements (concrete sleepers). Considering the sleepers' responses, it is clear that timber sleepered tracks deform vertically lower than interspersed or concrete sleepered tracks. The concrete sleepers in either plain or interspersed tracks tend to deform significantly more at their mid span. Such the deformations can cause centerbound problems or the issue with cracks at the mid-span of sleepers. This issue is commonly found in railway tracks with poor maintenance (high level of ballast densification and fouling) [22]. On this ground, the use of interspersed system will gradually accelerate the centerbound problems in railway lines.

The dynamic effects of rail pads on the maximum displacement and uplift responses of sleepers can be seen in Table 2. It is clear than the interspersed tracks have higher uplift deformation. The relative uplifts of the sleepers tend to cause deteriorations of railway tracks over time, such as ballast breakage, excessive dilation and densification, which can cause further track differential settlements. However, it is also found that rail pads do not play a key role in maximum displacements of concrete sleepers. This is because concrete sleepers tend to have much higher stiffness than timber. On the other hand, Figure 4 demonstrates the insertion loss in concrete sleepers. It is quite clear that softer rail pads tend to suppress vibrations of concrete sleepers. However, the rail pads play little role for 1 in 3 interspersed track in comparison with 1 in 4 interspersed track.

Table 2: Effects of rail pads on dynamic displacement envelop

Track Type	**Rail Pad Stiffness**	**Displacement envelop (mm)**					
		At rail seat			At mid span		
		Front Uplift	Displacement	Rear uplift	Front Uplift	Displacement	Rear uplift
Timber	-	0.27	2.66	0.65	0.49	2.50	0.59
1:3 Interspersed	800MPa	0.67	2.61	0.52	0.67	2.64	0.52
	600Mpa	0.67	2.61	0.52	0.67	2.63	0.51
	400MPa	0.67	2.62	0.51	0.67	2.63	0.51
	200MPa	0.67	2.62	0.49	0.67	2.62	0.50
1:4 Interspersed	800MPa	0.51	2.66	0.66	0.51	2.71	0.66
	600Mpa	0.52	2.67	0.66	0.51	2.70	0.66
	400MPa	0.51	2.67	0.66	0.51	2.69	0.65
	200MPa	0.51	2.67	0.64	0.51	2.68	0.64

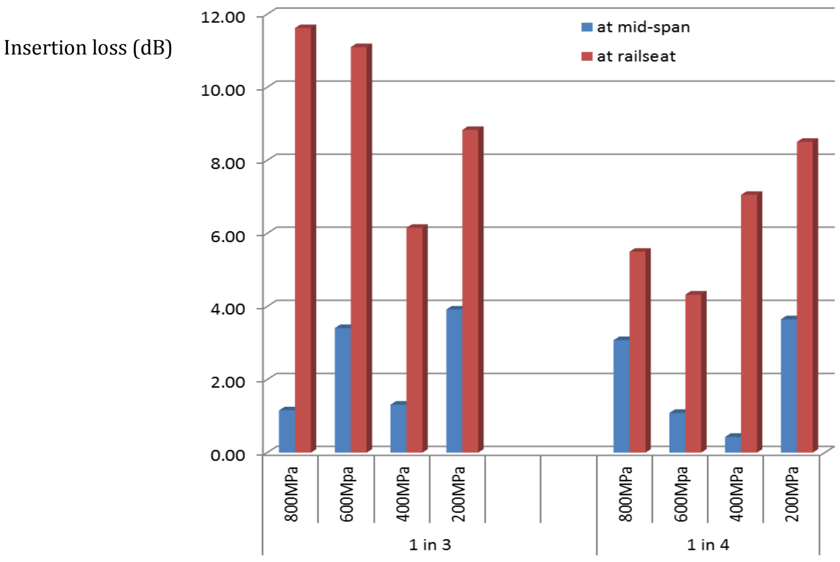


Figure 4: Insertion loss in interspersed railway track due to rail pad stiffness (RE: timber sleepers)

4. Conclusion

A short-term solution to maintain aging timber tracks is to replace rotten and decayed timber with new concrete sleepers. This technique is often called ‘interspersing’ in practice. This construction technique has been used in railway industry in many countries around the world. Such practice is common for secondary or third class tracks where operations are not excessive and the train speeds are moderate. However, the practices can cause excessive track maintenance over time. This is because a cluster of timber sleepers with mixed quality could deteriorate faster than the others and the replacement by concrete sleepers could induce inconsistent track stiffness differentials and aggravate ride comfort and loading conditions acting on the track. This paper is found to be the first to investigate dynamic responses of the interspersed track to a moving train load in order to understand the root cause of rapid track deterioration and to evaluate the value of using resilient rail pads in the interspersed track systems. A nonlinear finite track models in three-dimensional space have been established and validated in the past. This study makes use of the validated models and extends it for parametric studies. The parametric studies into rail pad sensitivity have revealed the key insights into the track behaviours:

- Rail pads have little influence on the displacement of spot replacement sleepers. They slightly increase the displacement at rail seats but decrease the deformation at the mid-span of concrete sleepers.
- The relative dynamic uplift responses of concrete sleepers, which is the main cause of rapid track deterioration such as track mud pumping, ballast pulverisation and ballast dilation, are hardly affected by rail pad stiffness. This implies that using softer rail pads do not significantly improve the life cycle of interspersed track systems.
- The use of rail pads can provide insertion losses to the concrete sleepers. However, it is found that the optimal stiffness of rail pads is train-speed dependent. In this study, only 60 km/h train speed was simulated. Future studies will consider the dynamic effect of train speeds in order to develop insertion loss spectra and to identify optimal rail pad stiffness for each type of interspersed tracks.

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