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Abstract. In traditional railway networks globally, timber sleepers have been widely adopted since the advent of railway systems. After a certain period of time, timbers tend to degrade and become more and more difficult to seek cost-effective replacement hardwood sleepers. To provide a short-term solution, many rail infrastructure managers use an interspersing method of track maintenance. The interspersed pattern sleeper of railway track, which is a spot replacement of old timber sleeper with concrete or composite counterparts, is often utilised as a temporary maintenance for secondary railway tracks such as low-traffic lines, yards, balloon loops or siding. Reportedly, the performance of interspersed tracks can quickly deteriorate when the tracks are exposed to heavy rains and floods. In many cases, ballast washaway can be often seen. This study is the world first to demonstrate the effects of ballast washaway on the vulnerability assessment of interspersed sleeper railway using nonlinear finite element simulations, STRAND7. Two moving point loads representing an axle load along each rail has been established to investigate the worst-case, potential actions for impaired performance of sleepers and differential settlement of the track. In this study, the emphasis is placed on the effect of ballast washaway on the maximum displacement of rails and the relative track geometries (i.e. top and twist). The maximum bending actions causing the failures of the track components are also investigated. The insight will help track engineers develop appropriate climate change adaptation method and policy for operations of interspersed railway tracks facing extreme rainfall and flooding conditions.

Keywords: Vulnerability, Resilience, Railway, Interspersed Tracks, Ballasted tracks, Flood, Extreme Condition, Washaway

1 Introduction

Over two decades, railway tracks have been built using locally sourced materials such as steel rails, sleepers, fasteners, ballast, formation (capping layer over compacted soil), subgrade and foundation. It is very well-known that the dynamic loading conditions acting on railway tracks stemmed from either passenger or freight trains can induce dynamic behaviour (amplified phenomena above simple static behaviour) of a railway track. This dynamic behaviour is pronounced and can be observed when a train travels over 60 km/h. It is vital to understand the track dynamic responses to diverse loading conditions [1] since excessive irregular responses can lead to train derailments. It is noteworthy that the dynamic loading conditions, which often cause structural cracks in brittle sleepers, densify and pulverise ballast support, are usually the large impact loads due to wheel/rail irregularities (e.g. wheel flats, out-of-round wheels, etc.). For example, a traditional transient waveform pattern of wheel impacts due to a dipped joint can be seen in Fig. 1. Vividly, the amplitude of the impact forces can vary from 200kN to 400kN while the duration may range from 2 to 10 msec. Based on a transient pulse concept (i.e. Duhamel's integral), these impact pulses can be associated with the dynamic excitations with a frequency range from 100 Hz to 500 Hz (f = 1/T: f is the frequency and T is the period). This frequency range can excite the resonances of track components and lead to pre-mature damages, reducing the durability and service lives of track components. In the reality, wheel/rail interaction imposes dynamic forces acting on rail seats. Noting that the dynamic load patterns are dependent on train speed, track geometry, axle load, vehicle type, and wheel/rail defects or irregularities. In practice, railway and track engineers must consider the frequency ranges of static and dynamic loadings to plan and realise the life cycle asset maintenance and management of railway tracks with respect to critical train speeds and bespoke operational parameters [1-10].

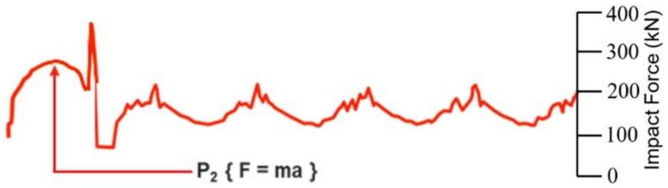


Fig. 1. Example of dynamic impact loading pattern

Timber sleepers have been widely used in railway track systems all over the world, especially in North America, Africa, certain extent in Europe, Australia, and Asia. Their life cycle is estimated to be around 10 to 15 years depending on their applications, service explosures, operation parameters, environmental factors and the level of maintenance quality. Over time, these timber sleepers degrade and require renewals. Partial replacement or spot replacement of timber sleepers by prestressed concrete sleepers is an interesting concept that has been adopted over the world. This temporary method is to maintain track quality and improve short-term solutions that could be agile, cheap, effective and quick. This kind of spot replacement is usually adopted for the second or third class timber tracks or in some countries in the first-class main line. This solution is called "interspersed track". In general, restricted train speeds are regularly adopted when track deteriorates to the condition below the base operation conditions (BOCs) or a reasonably safe condition. By adopting the interspersed method, full operational speed can still be allowed. Moreover, this approach strengthens for enhancement in ability to withstand high velocity operations or to restrain longitudinal rail forces preventing a track buckling [9-11].

Although the spot replacement of aged, rotten timber sleepers is clearly more economical than a complete track renewal or reconstruction, the interspersed track poses some disadvantages. In practice, the spot replacement pays special attention only to old, rotten timber sleepers. The degraded timber sleepers will be removed and then the new stiff concrete sleepers will be inserted onto old and weakened foundation, which has been in services for a very long time. In fact, the track stiffness of the renewed track with spot concrete sleepers is inconsistent as the existing timber tends to be aging too. This track stiffness inconsistency and different track decay rate can be a reason of uneven settlement and foundation failure [9-13]. Based on differential track stiffness, deterioration processes, track component durability and operational parameters, 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 that there is 1 concrete sleeper in every indicated number of sleepers, for instance, 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 exists in a rail network with low operational speeds. 1 in 4 interspersed track is commonly observed and will be the focus in this study. A key reason is that this type of track has various flaws derived from how it is built. These can impair the long-term performance of interspersed railway tracks as shown in Fig. 2 [13]. Fig.2 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 main high-speed link to maintenance junctions.

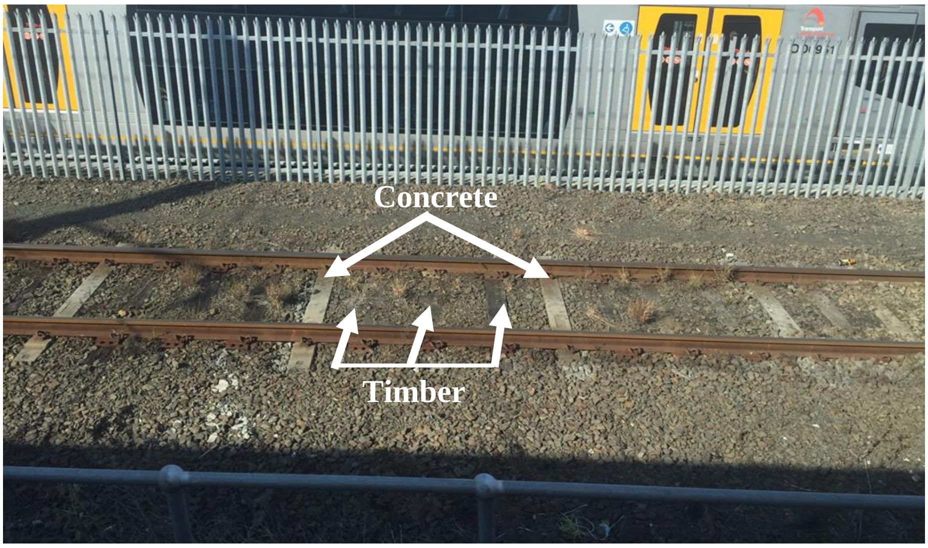


Fig. 2. Example of 1 in 4 interspersed tracks (1 concrete sleeper after 3 timber sleepers – a set of four)

Serviceability of a railway track has become the governing criteria for sleepers made of different material properties in the existing aged track systems. It is important to note that 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 continuously rather than interspersed with other sleepers in between, also referred to as ‘on-face’) [11-13]. This in-face method is advised to improve vulnerability of the track systems. In reality, cost and time constraints have prohibited the in-face installation. Many railway networks have employed on-face installation (spot replacement of concrete sleepers) to retain operational services without disruption from degradations of materials, components and track systems.

On the other hands, complexities of climate change and extreme weather conditions have raised an essential concern of risk and uncertainty for railway operators. Extreme weather conditions significantly affect railway operations and safety, such as fatalities, injuries and property damage. It is well known that climate change and extreme weather conditions incur serious challenges to infrastructure systems. However, most research (over 200 journal articles annually) have been focussed only on the development of high-level holistic frameworks for risk reduction, crisis responses, systems resilience, and top-down infrastructure management. There is very little research that has been conducted to understand the true capacity, to identify vulnerability to the transport infrastructures, or to implement real actions to prevent and recover the natural crisis. It has been widely recognized that there is an urgent need to integrate bottom-up consideration of climate change, its vulnerability, its structural integrity, and its extreme weather impacts in policies, design, maintenance and reconstruction of infrastructure systems. Everyday decision makings do not take into account the consequences that could affect the new assets and infrastructures in the future. On this ground, this study is crucial for railway managers, maintainers, and regulators in order to embrace real insights for climate change adaptation and resilience-based measures that mitigate the risks and uncertainty derived from extreme climatic conditions. For example, the climate in South East Asia (such as in Thailand, Indonesia, Malaysia, Vietnam, etc.) is dominated by 2 monsoon regimes namely as northeast monsoon and southwest monsoon. The northeast monsoon circulates during the months of December, January and February, and the period frequently possesses the most flooding conditions. Being in the equatorial zone and tropical country, the average temperature throughout the year is constantly high (e.g. 26 °C) and has a very high humidity due to the high temperature. As a case study, Malaysia also can have a very heavy rainfall season, which is more than 2500mm per year. It is clear that one of the most devastating natural disasters experienced in many continents (e.g. Europe, Asia, Africa, etc.) are floods and their consequential landslides, as illustrated in Fig. 3. These conditions can soften the soil formation underneath the tracks and can also cause washaway when the ballast under the sleepers have been removed by rainfalls and runoffs. This study will thus pay special attention to the risks associated with heavy rainfall and flood.

Hence, this paper aims at investigating the vulnerability of the interspersed railway tracks exposed to flooding conditions. Dynamic responses of the interspersed railway tracks under moving train loads will be considered as the precursor to identify the level of serviceability. Based on critical literature review, this research has never been presented in open literature [14-21]. A class of two-dimensional interspersed track models was created using Timoshenko beams in a finite element package, STRAND7. Dynamic displacement has been evaluated to understand the geometric behaviours of rail over sleeper, rail at midspan, cross level, and twists. The insight into the interspersed track vulnerability will help rail track engineers to manage risks and uncertainty due to flooding conditions and to enable a truly predictive maintenance and improve the reliability of infrastructure asset maintenance and management.

Fig. 3. Washaway of railway tracks occurred in Malaysia East Coast Line railway bridge, which cross Nenggiri River in Kemubu, Kelantan had totally lost due to massive flood in December 2014. (Courtesy: Malaysian Department of Public Works)

2 Methodology and Data

2.1 Track Modeling

Interspersed track models have been established and validated using field data. These models have been adopted in this study. In the model, a two-dimensional Timoshenko beam model has been employed and found to be one of the most suitable options for modeling rails and concrete sleepers [21]. Using the numerical and experimental modal parameters [22], the finite element models of railway tracks can be fully calibrated. Fig. 4 illustrates the finite element models in three-dimensional space for an in-situ 1:4 interspersed railway track with different types of sleepers. Using a general-purpose finite element package STRAND7, the numerical model included the beam elements, which take into account shear and flexural deformations, for modeling the sleeper and rails. Each sleeper consists of 60 beam elements and each rail consists of 200 beam elements. The 60kg rail cross section and sectional parameters (Area: 17,789.9 mm2; Second moment of Area: 43.2 x106 mm4) were used [21]. The trapezoidal cross-section was assigned to the concrete sleeper elements in accordance with the standard medium duty sleepers (204 mm top-wide x 250 mm bottom-wide x 180 mm deep) [22]. The rectangular cross-section was assigned to the timber sleeper elements in accordance with the standard timber sleepers (230 mm wide x 130 mm deep) used in Australia [22]. The rail pads at railseats were simulated using a series of spring-dashpot elements. The novelty in this study is the realistic model of the support condition, which has been simulated using the nonlinear tensionless beam support feature in STRAND7. This attribute allows the beam to lift over the support while the tensile supporting stiffness is omitted, especially when the support is deteriorated unsymmetrically. The tensionless support option can correctly stimulate the ballast characteristics in real-life tracks [21].

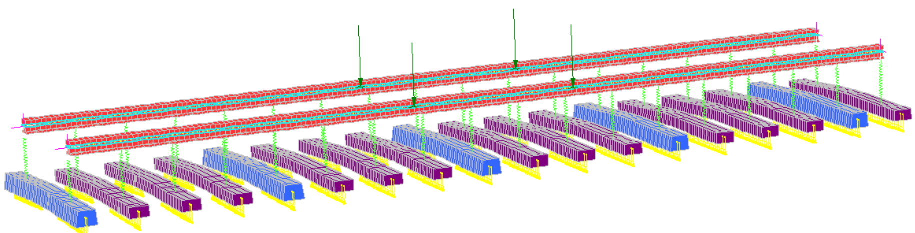


Fig. 4. Validated 1:4 interspersed track model (blue: concrete sleepers; and purple: timber sleepers). The model is subjected to a moving train axle (two wheel sets).

2.2 Engineering properties

Engineering properties of each element are tabulated in Table 1. Table 1 shows the geometrical and material properties of the finite element model. All dimensions are given in millimetres. The partial support condition, which has been reported to be more suitable for standard gauge tracks, has been adopted for this study. Spring – dashpot model of rail pad is used. For the envelope study, four separated forces with a constant magnitude of 100kN have been used to imitate the loading condition of a passenger train bogie (2 per each rail, 2 meters apart). This load magnitude has been used for benchmarking purpose [21-23]. The non-dimensional analyses have then been carried out to investigate the dynamic responses in terms of maximum displacements and cross level (inferring track twists) over train speed and over frequency domain.

Table 1. A summary of engineering parameters in the model

Parameters	Range	Unit	Remarks
Length	l_r=10.8	m	*standard gauge is 1.435m.
Gauge	g=1.5	m	*1.5m is distance between wheel loads.
Modulus	E_r=2.0000e5	MPa	
Poisson's ratio	v_r=0.25	-	
Rail pad stiffness	$k_p = 17$	MN/m	

2.3 Risk explosures to flood and washaway conditions

When a railway track is exposed to flood and washaway conditions, the formation strength and capacity will be undermined. The severity of strength reduction depends on the duration of rainfalls and runoffs. In most cases when water ponding exists, total track inspection cannot be adequately conducted, making it a very dangerous situation to operate any train. In an event of heavy rainfall (e.g. 2 hours continuously), a flash flood can incur. Any flash flood along railway corridors can weaken the formation, resulting in a very low to nil track modulus. The location with low level of terrains will often suffer this problem and sometimes lead to track mud pumping overtime. In practice, engineers may not be able to observe this problem until the severity and damage scale is large.

In a case that the gradient or vertical slope of railway tracks and corridor is steep, the runoffs can cause erosion of formation and cause ballast washaway. This event will completely eliminate the ballast and track formation that support the track systems. The severity of this incident depends on the volume and the speed of runoff and whether any water-borne debris exists. If the railway corridor has been properly designed (e.g. with a crossfall tapering towards the drainage), the ballast washaway might occur partially (e.g. only half of track support) but the scale of damage might be large (e.g. a large number of sleepers are affected). If the flood condition exists, rail engineers may not be able to observe the affected zone until major damages incur such as land slide, derailments, etc. For instance, land slip could also occur as illustrated in Fig. 5. Initially, loss of track support will occur, followed by tension cracks and land slips. Track engineers are generally unable to observe or notice occurrences of the loss of track support.

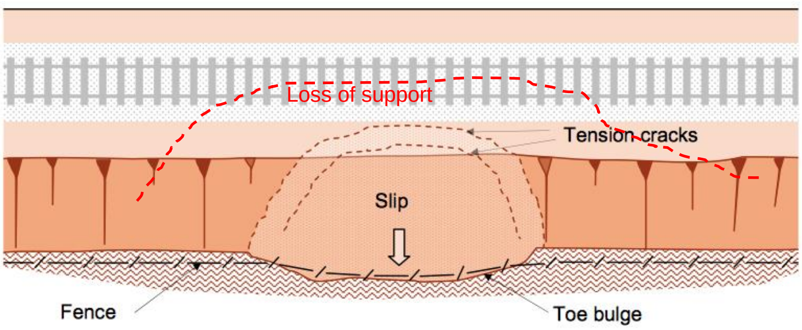


Fig. 5. Risks of heavy rail falls and runoff, and flood conditions.

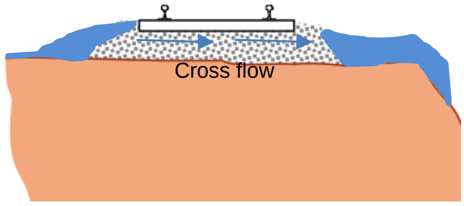


Fig. 6. Cross runoff causing ballast washaway

When a railway track is located in an inclined plane of terrain, cross water runoffs can also cause ballast washaway, as illustrated in Fig. 6. The cross flow can infiltrate the ballast and erode the ballast particles (and potentially formation), causing the ballast washaway (loss of track support), and eventually land slips. When the track system is exposed to a large area with ballast washaway, any operation of a train is reckless.

In this study, a special attention to the initial flood condition when it undermines the track support is considered. This is because, under this situation, engineers and operators cannot inspect the track and observe any problem. In some extent, a service train is operated on the flooded track systems. This study will identify the vulnerability and potential risks when the train services are exposed to such conditions. The emphasis is placed on the interspersed railway tracks since these interspersed methods are often adopted in vulnerable railway corridors and networks.

3 Results and Discussions

Based on the track models, the dynamic responses of the railway tracks (without any damage) under moving train loads can be seen in Fig. 7. It is clear that the train speed influences the dynamic displacements of the track systems. When the train speed increases, the dynamic displacement generally increases. The variance of the dynamic displacement can be observed and is because the dynamic properties or structural periods of track systems can respond differently to different excitation frequencies (i.e. $v = f \times \lambda$ or $f = 1/T$).

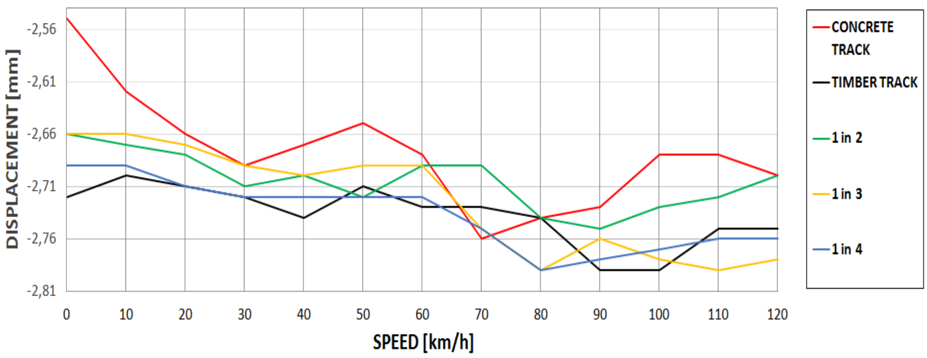
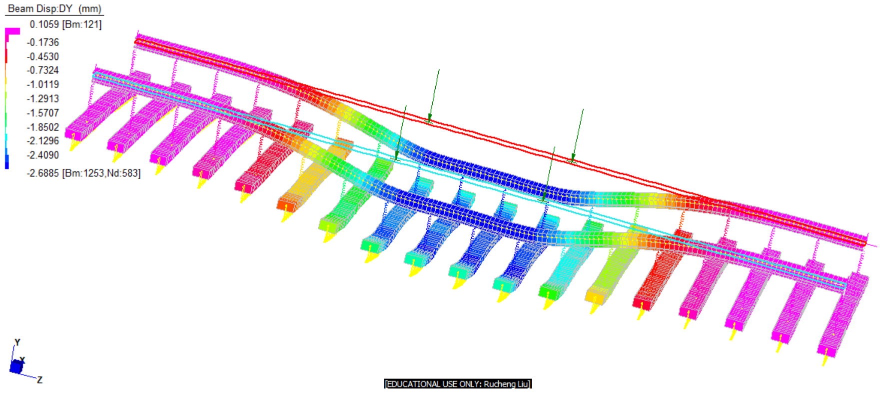


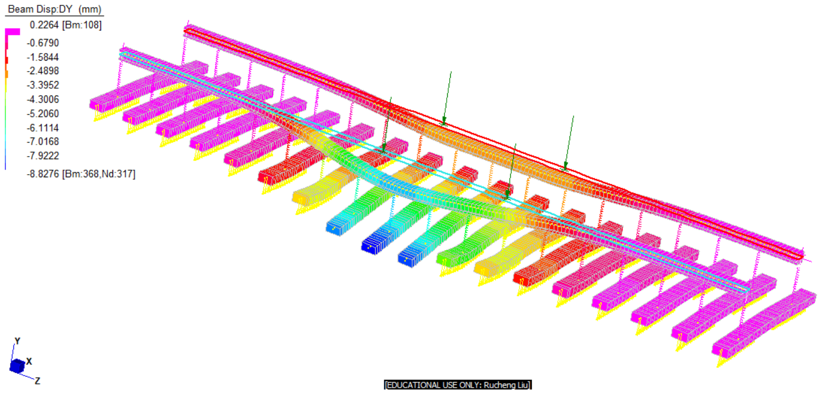
Fig. 7. Dynamic displacements of rails subjected to moving train loads (for track systems with a good track support condition)

For the track systems with a good track support, the symmetry of dynamic displacements on both rails (left and right rails) can be observed. The movement of trains with large rail displacements on interspersed tracks would simply affect the ride comfort of passengers or goods. The symmetrical large rail displacements will commonly cause higher roughness of track geometries, which in turn generally induce higher vibrations (e.g. on-board vibration), louder noises (e.g. rolling noises), and poorer ride comfort.

The analyses into the vulnerability of the 1:4 interspersed track systems have been conducted in comparison with timber-sleepered track systems. Fig. 8 illustrates the dynamic response envelopes of track systems exposed to small-scale and large-scale losses of support conditions. In this study, only half of sleeper support is considered for the effect of floods and washaway condition on the loss of support conditions as the case study.

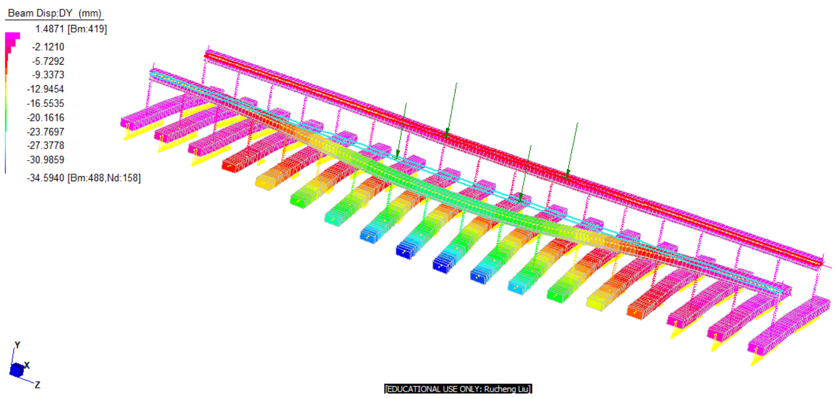


a) timber-sleepered track with full support condition

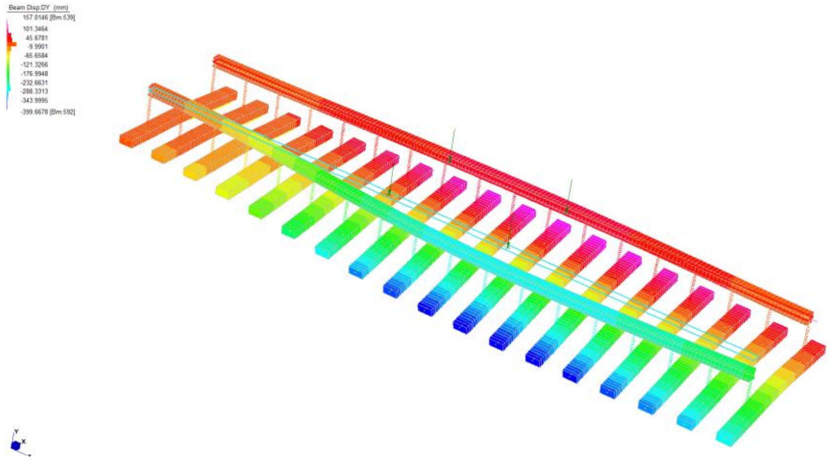


b) timber-sleepered track with small-scale loss of support condition

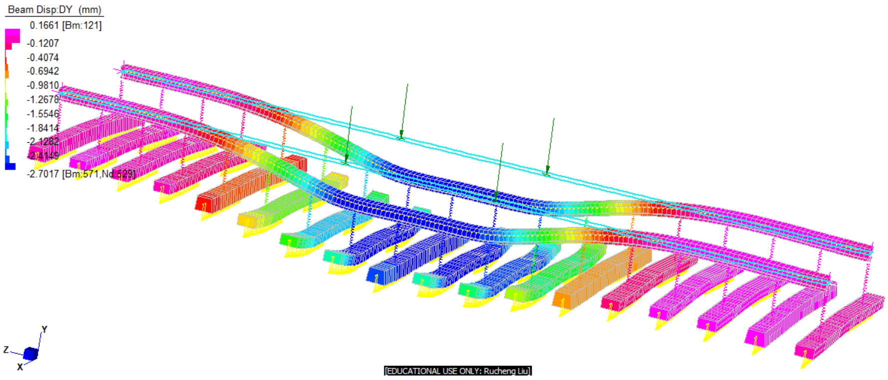
Fig. 8. Dynamic responses to 120km/h moving train loads of track systems exposed to flood and washaway conditions



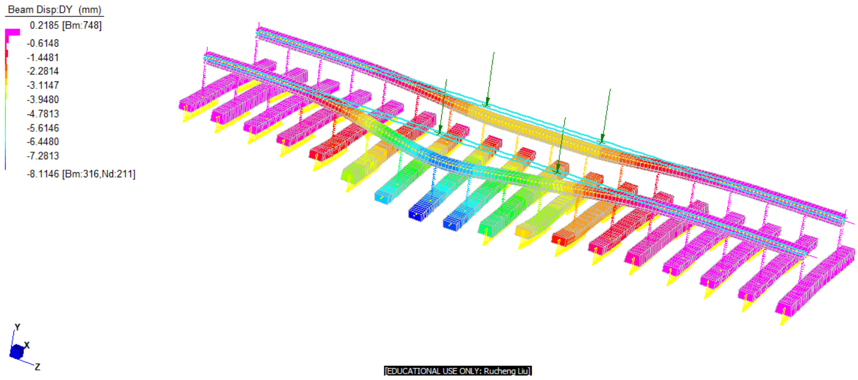
c) timber-sleepered track with large-scale loss of support condition



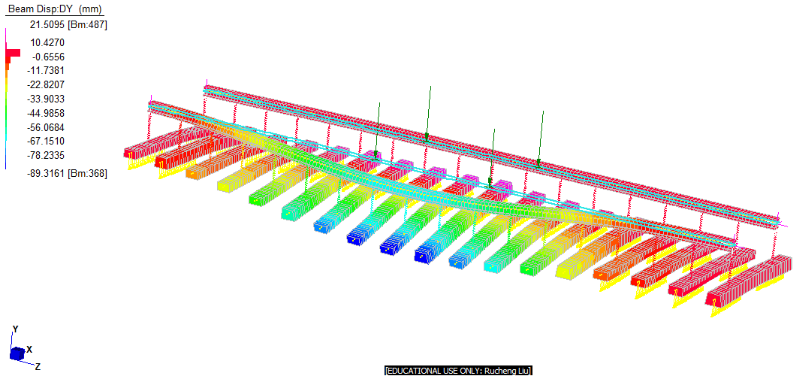
d) timber-sleepered track with full-scale loss of support condition



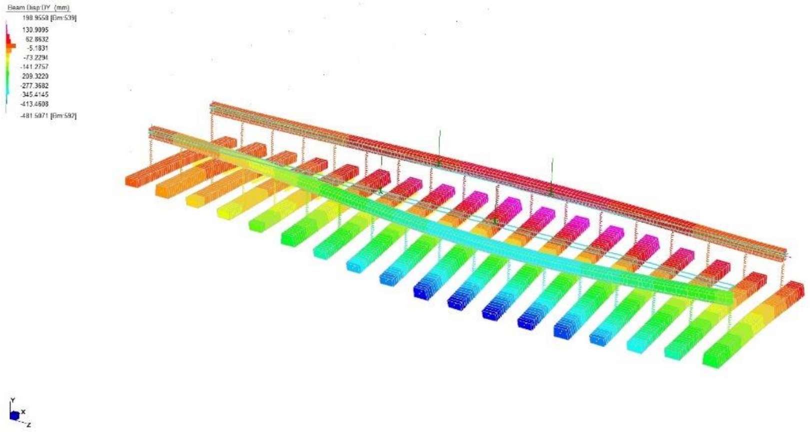
e) 1:4 interspersed track with full support condition



f) 1:4 interspersed track with small-scale loss of support condition



g) 1:4 interspersed track with large-scale loss of support condition



h) 1:4 interspersed track with full-scale loss of support condition

Fig. 8. Dynamic responses to 120km/h moving train loads of track systems exposed to flood and washaway conditions

Track Geometry									
Wide Gauge	Tight gauge	Short Twist		Track Speed (Normal / Passenger) km/hr					
		2.7m DO NOT USE	2m	20/20	40/40	60/60	80/90	100/115	115/160
<21	<10	<16	<12	N	N	N	N	N	N
21 – 22	10	16 – 18	12 –13	N	N	N	N	P3	P2
23 – 26	11 - 12	19 – 21	14 - 15	N	N	N	P3	P2	P1
27 – 28	13 – 14	22 – 23	16	N	N	P3	P2	P1	E2
29 – 30	15 – 16	24 – 25	17 – 18	N	P3	P2	P1	E2	E2
31 – 32	17	26 – 27	19 – 20	P2	P2	P1	E2	E2	E2
33 – 34	18	28 – 29	21 - 22	P1	P1	E2	E2	E2	E1
35 – 37	19 – 20	30 – 31	23	E2	E2	E2	E2	E1	E1
>37	>20	>31	> 23	E1	E1	E1	E1	E1	E1
Long Twist				Track Speed (Normal / Passenger) km/hr					
Not in a Transition		In a Transition		20/20	40/40	60/60	80/90	100/115	115/160
13.2m DO NOT USE	14m	13.2m DO NOT USE	14m						
<29	<31	<32	<34	N	N	N	N	N	N
29 – 33	31 – 35	32 – 36	34 – 38	N	N	N	N	P3	P2
34 – 38	36 – 40	37 – 41	39 – 43	N	N	N	P3	P2	P1
39 – 43	41 – 46	42 – 46	44 – 49	N	N	P3	P2	P1	E2
44 – 49	47 – 52	47 – 52	50 – 55	N	P3	P2	P1	E2	E2
50 – 56	53 – 59	53 – 59	56 – 62	P2	P2	P1	E2	E2	E2
57 – 60	60 – 64	60 – 63	63 – 66	P1	P1	E2	E2	E2	E1
61 – 66	65 – 70	64 – 69	67 – 72	E2	E2	E2	E2	E1	E1
>66	>70	>69	>72	E1	E1	E1	E1	E1	E1

Fig. 9. Maintenance limits of track twists (adopted from Base Operating Condition, BOC, from Transport for NSW, Australia). Note: N is normal condition; P3 is a situation needed to repair within 3 months; P2 is a situation needed to repair within 28 days; P1 is a situation needed to repair within 7 hours; E2 is a situation needed to repair within 24 hrs; E1 is a situation needed to repair immediately.

It is clear from Fig. 8 that the train loads incur the difference in dynamic rail displacements on left and right rails. This difference at a position is often referred to as 'cross level'. When a train bogie or a train body travels over the differential cross levels, the twists in the train body or bogie can incur. These twists can cause train derailments. The twist on train body is often called 'long twist' while the twist on train bogie is called 'short twist'. These twist limits can be illustrated in Fig. 9 (adopted from a maintenance standard of Transport for NSW, Australia). If the track twists reach E2 and E1, this situation is at danger and requires emergency actions. The train could derail when travel over E2/E1 conditions.

The dynamic twists of the interspersed track systems considering the losses of support conditions are shown in Fig. 10. The short twist is determined using 2m , while the long twist is based on 14m cord. The twist results have been correlated with the risk colours shown in Fig. 9 (green is normal, light blue is P2, dark blue is P1, yellow is E2, red is E1).

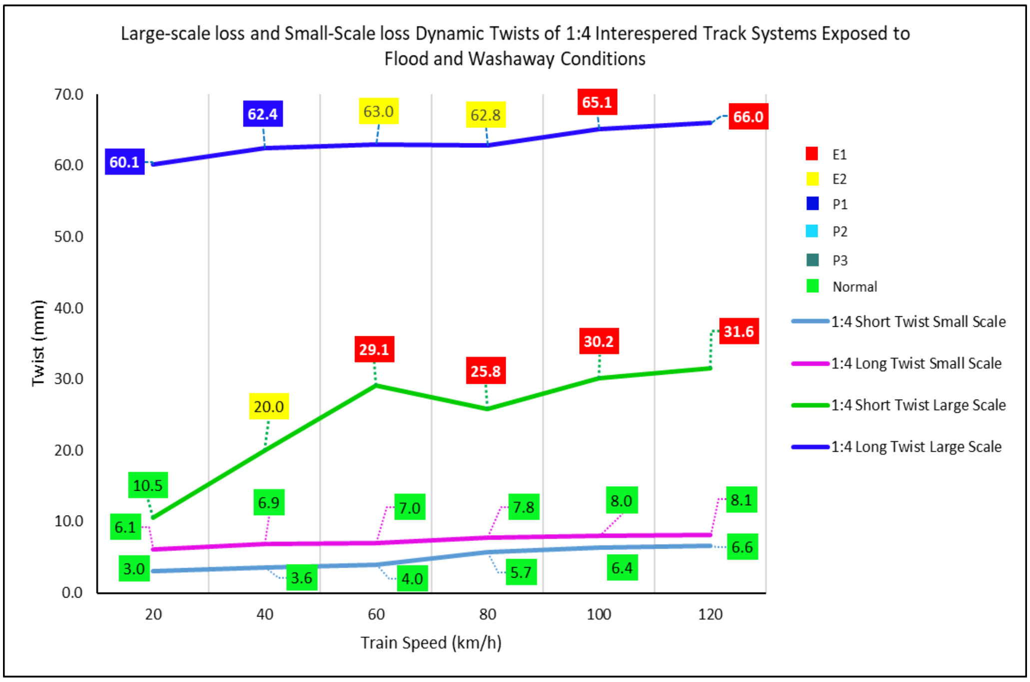


Fig. 10. Dynamic twists of 1:4 interspersed track systems exposed to flood and washaway conditions (unit in mm.). Colour backgrounds are correlated with risk profiles defined in Fig.9.

From Fig. 10, it should be noted that N is normal condition; P3 is a situation needed to repair within 3 months; P2 is a situation needed to repair within 28 days; P1 is a situation needed to repair within 7 hours; E2 is a situation needed to repair within 24 hrs; E1 is a situation needed to repair immediately. This implies that when the 1:4 interspersed track is exposed to large scale loss of support condition, it could be very dangerous to operate a train above 40 km/h. In fact, it will still be at risk when a train travels at 20 km/h since the long twist defect could derail the train, especially when the train could also have certain defects (e.g. stiff bogies, deflated suspensions, etc.). On this ground, it is clear that rail operators should be very careful in train operations when the railway tracks become vulnerable due to flood and washaway conditions. In order to mitigate this issue, engineers should consider applying ballast bond solutions to enable free drainage whilst reinforce the ballast particles [24]. This insight will help track engineers develop appropriate climate change adaptation method and policy for operations of interspersed railway tracks facing extreme rainfall and flooding conditions.

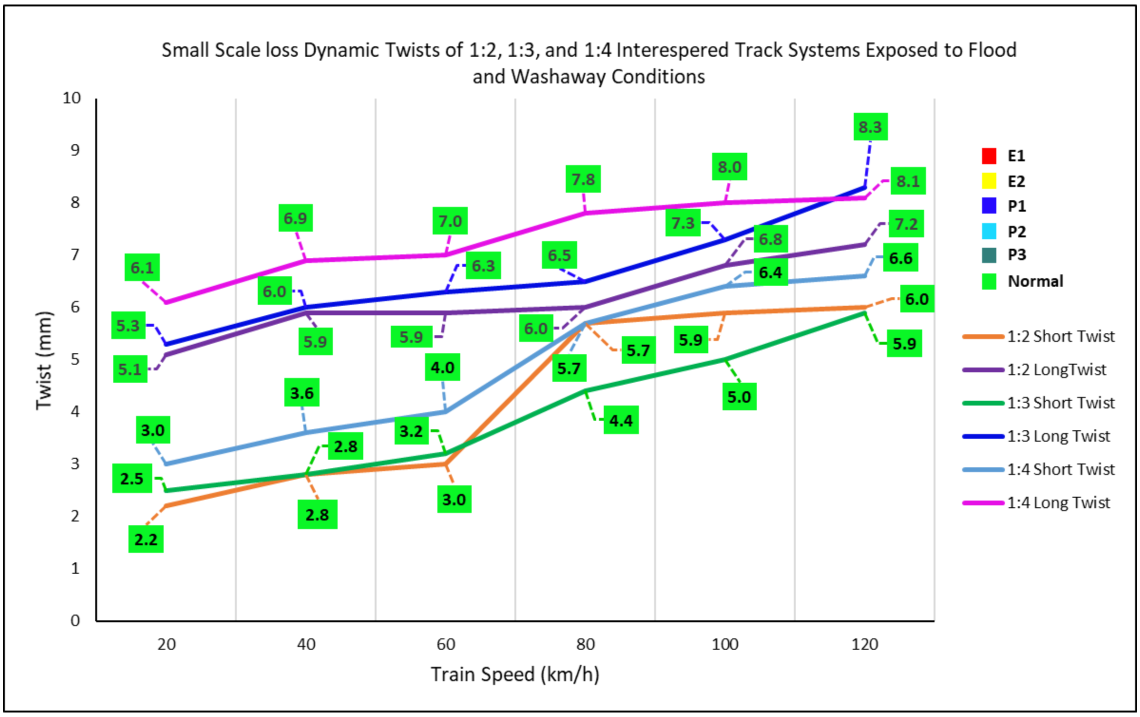


Fig. 11. Small-scale loss dynamic twists of 1:2, 1:3, and 1:4 interspersed track systems exposed to flood and washaway conditions (unit in mm.). Colour backgrounds are correlated with risk profiles defined in Fig.9.

According to Fig. 9, the dynamic response for interspersed track 1:2, 1:3, 1:4 exposed to small-scale loss from Fig. 11 will not cause any issue in terms of short and long twist. It is safe to operate the train on a small-scale loss track even at 120 km/h. Nevertheless, the situation might change if the train not in a favourable state.

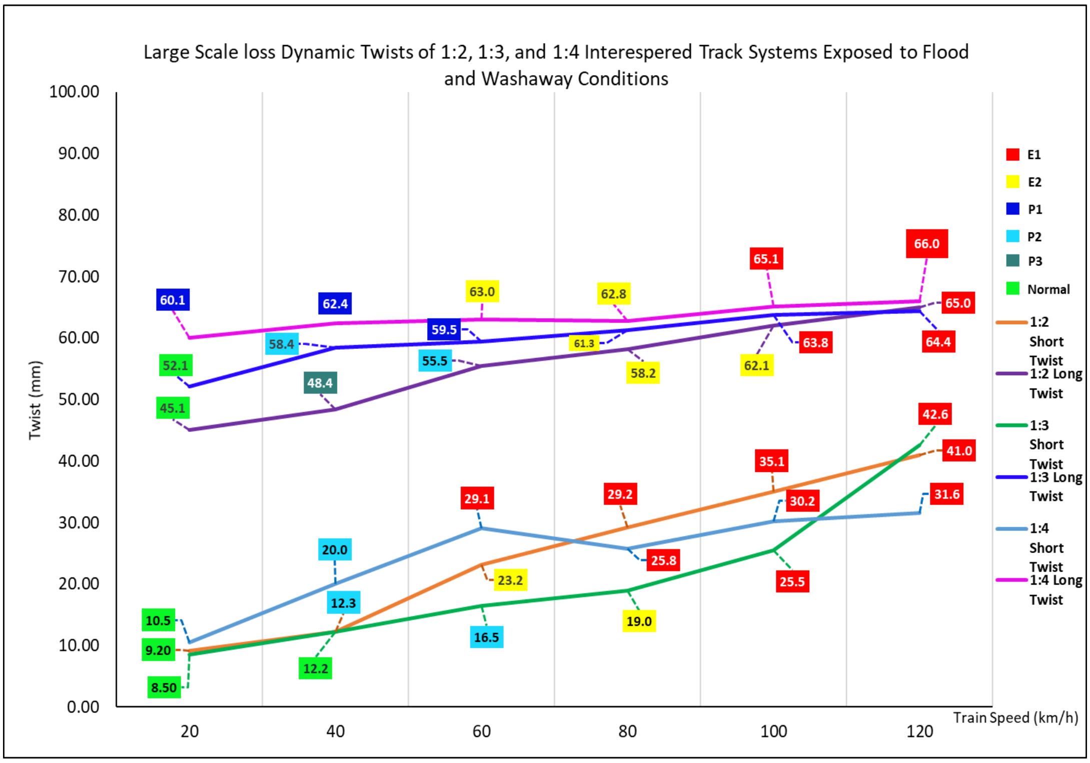


Fig. 12. Large-scale loss dynamic twists of 1:2, 1:3, and 1:4 interspersed track systems exposed to flood and washaway conditions (unit in mm.). Colour backgrounds are correlated with risk profiles defined in Fig.9.

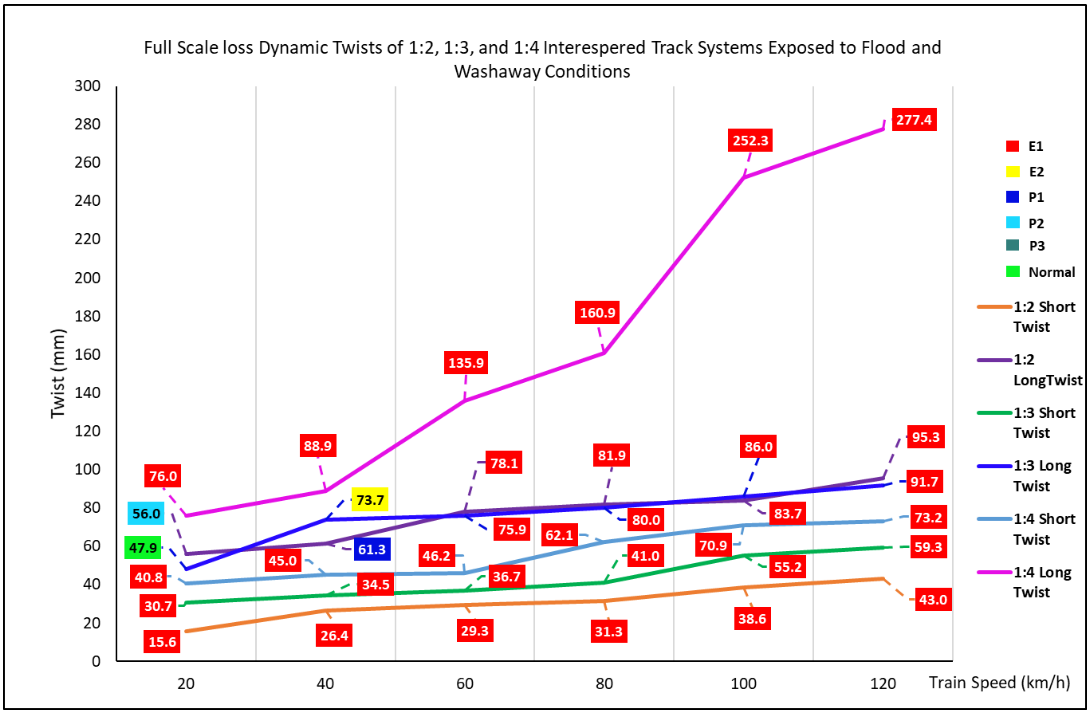


Fig 13. Full-scale loss dynamic twists of 1:2, 1:3, and 1:4 interspersed track systems exposed to flood and washaway conditions (unit in mm.). Colour backgrounds are correlated with risk profiles defined in Fig.9

Based on Fig. 12, it is relatively dangerous to operate above 60km/h on interspersed track 1:4 exposed to large-scale loss. Immediate repair is needed to ensure the safety of the train operation since the dynamic twist could lead to train derailment The interspersed track 1:2, 1:3, 1:4 exposed to large-scale loss is very vulnerable to dynamic twist where the train only allowed to operate not more than 40 km/h.

In Fig. 13, the figure shows Interspersed track exposed to full-scale loss is very dangerous for the trains to operate even with a vigilant monitoring. Even at speed of 20 km/h will cause short twist which lead to E1 situation (immediate repair). In short, immediate maintenance should be carried as it is impossible for a train to utilize its functionality as it's only allowed to operate below than 20 km/h. This will definitely affect the operation of the rail service. Moreover, the ballast support and sleepers might expose to several defects such as structural cracks and pulverized ballast. In addition, the interspersed track known to has inconsistent track stiffness which cause uneven settlement and foundation failure resulting in track deterioration overtime. Hence, it is crucial for the rail operators to take immediate action and come up with a truly predictive track maintenance to improve the reliability of infrastructure asset maintenance and life cycle management.

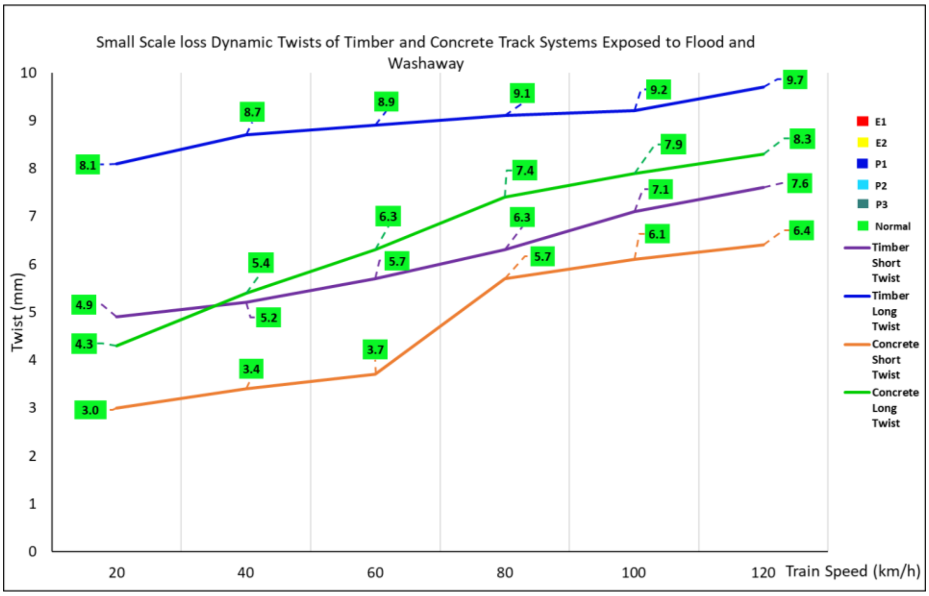


Fig. 14. Small scale loss dynamic twists of timber and concrete track systems exposed to flood and washaway conditions (unit in mm.). Colour backgrounds are correlated with risk profiles defined in Fig.9.

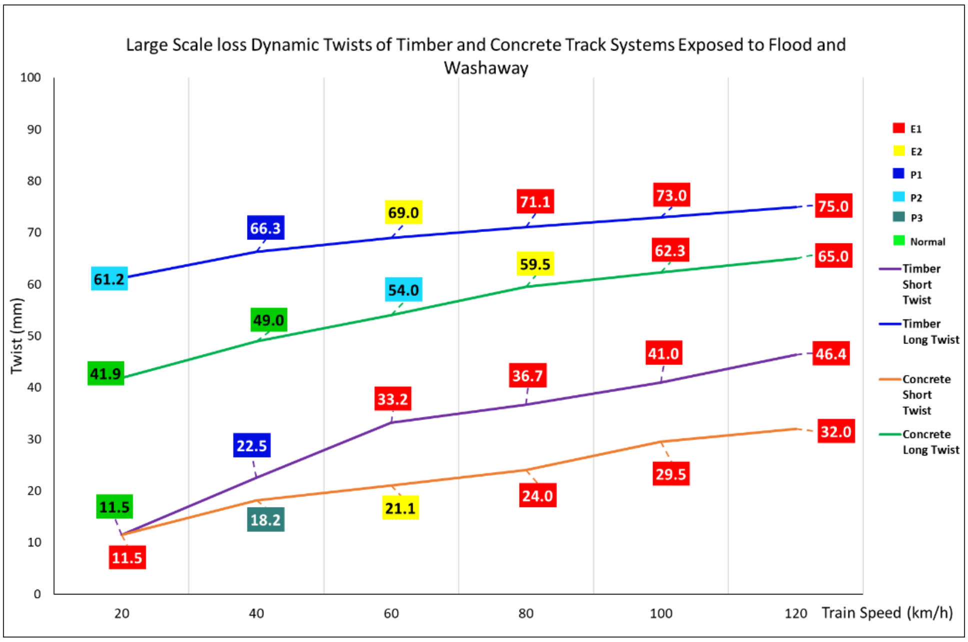


Fig. 15. Large scale loss dynamic twists of timber and concrete track systems exposed to flood and washaway conditions (unit in mm.). Colour backgrounds are correlated with risk profiles defined in Fig.9.

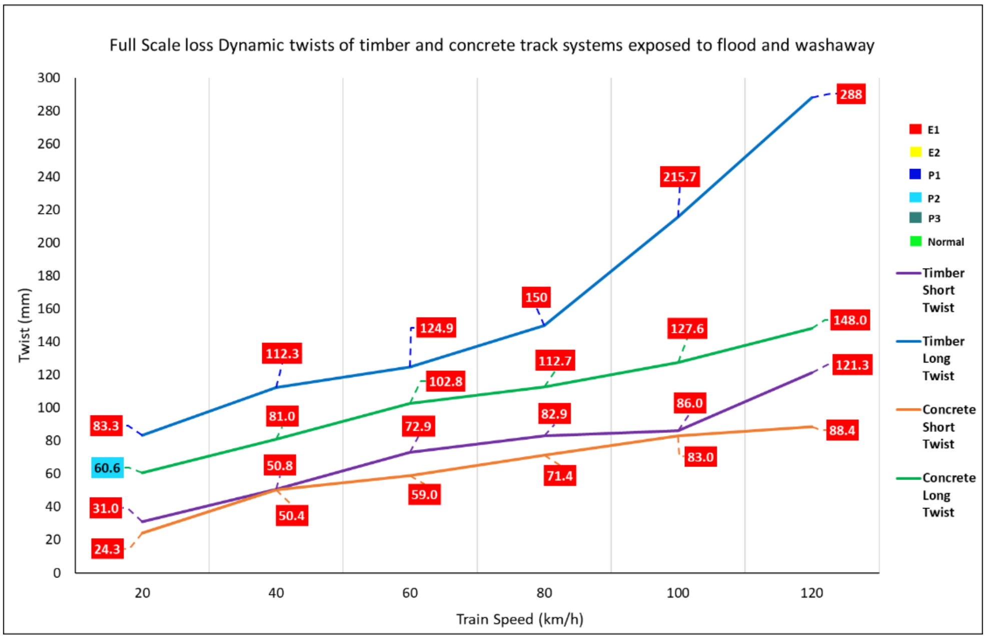


Fig. 16. Full scale loss dynamic twists of timber and concrete track systems exposed to flood and washaway conditions (unit in mm.). Colour backgrounds are correlated with risk profiles defined in Fig.9.

From Fig. 14, small-scale loss will not cause any issue even if the train operated at 120 km/h. However, looking at large-scale (Fig. 15) and full-scale loss (Fig. 16), timber sleepers long twist reading's reach up to 288.0 mm (full-scale loss) when the train operates at 120 km/h. This is due to the difference between timber and sleepers in terms of properties and geometry resulting in difference of dynamic twist data. Full-scale loss is extremely unsafe for a train to operate on and the track engineers must carry on an immediate repair (E1 situation) as the strength formation and capacity of the rail completely diminished.

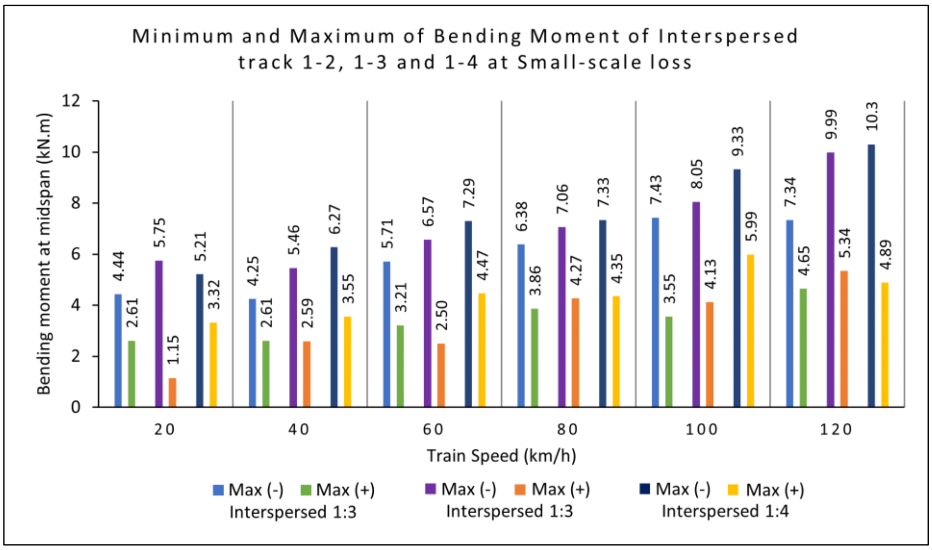


Fig. 17 Minimum and maximum of bending moment of interspersed track 1-2, 1-3 and 1-4 at small-scale loss

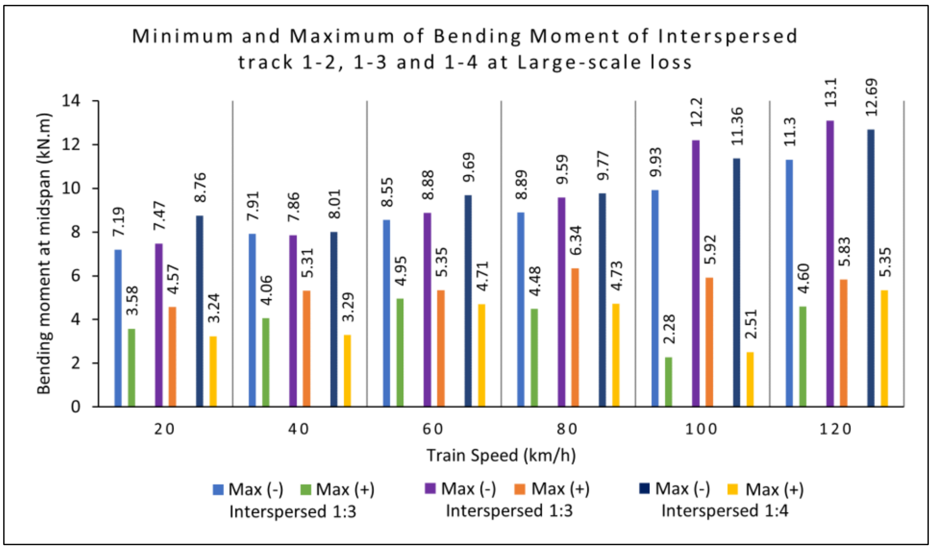


Fig. 18. Minimum and maximum of bending moment of interspersed track 1-2, 1-3 and 1-4 at large-scale loss

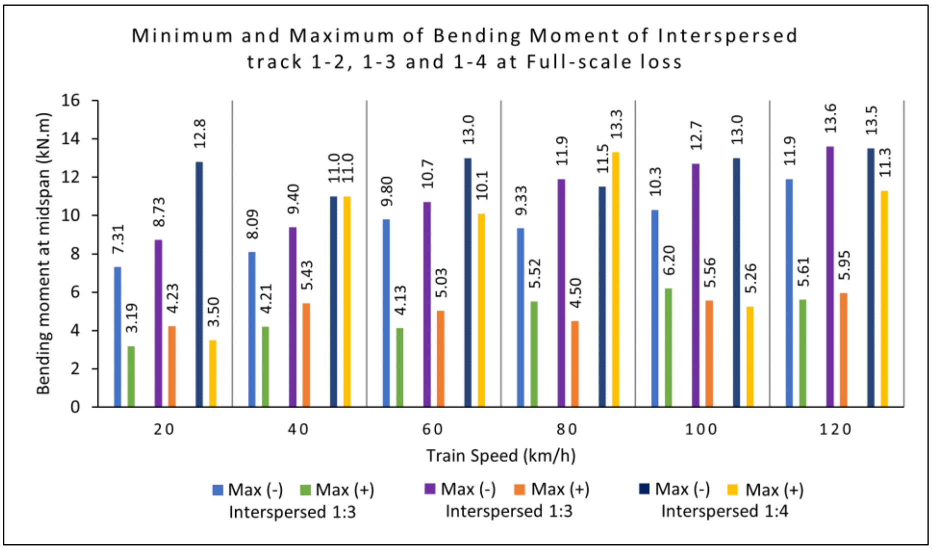


Fig. 19. Minimum and maximum of bending moment of interspersed track 1-2, 1-3 and 1-4 at full-scale loss

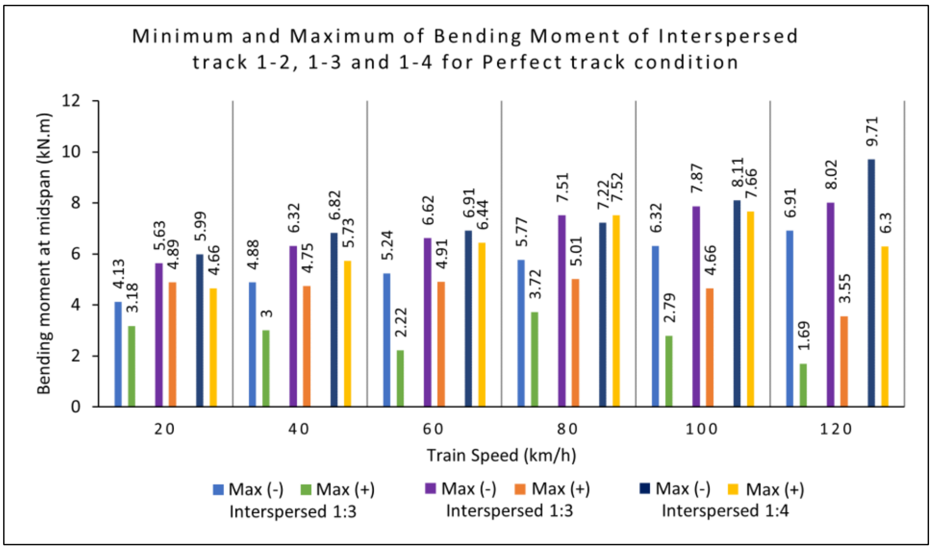


Fig. 20. Minimum and maximum of bending moment of interspersed track 1-2, 1-3 and 1-4 for perfect track condition

The interspersed track 1:2 has better performance in terms of flexural response for small-scale loss (Fig. 17), large-scale loss (Fig. 18) and full-scale loss (Fig. 19) while the bending moment for interspersed track 1:3 is comparable to the interspersed track 1:4 in some cases. For instance, the bending moment of interspersed track 1:3 came out higher than interspersed track 1:4 for large-scale (Fig. 18) and full-scale loss (Fig. 19) but not for small-scale loss (Fig. 17). All in all, this inconsistency of stiffness in interspersed track might influence the flexural response of this track which causing one side hogging of the damaged sleepers (half damaged sleepers).

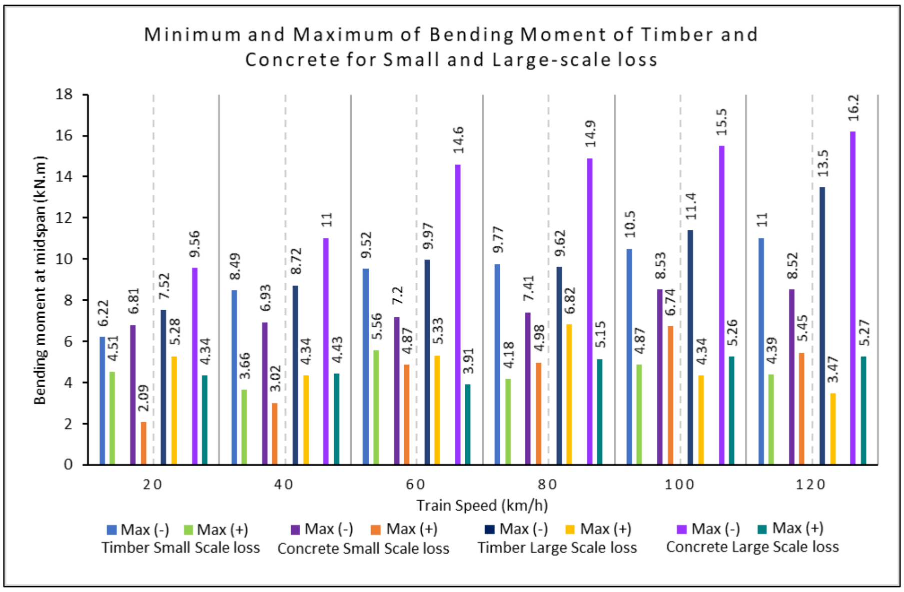


Fig. 21. Minimum and maximum of bending moment of timber and concrete for small and large-scale loss.

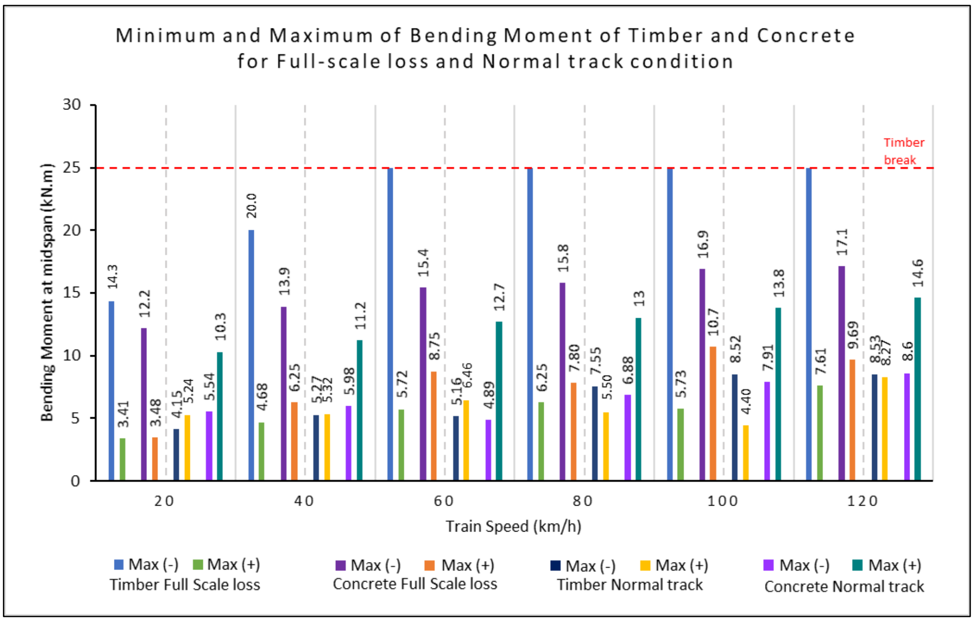


Fig. 22. Minimum and maximum of bending moment of timber and concrete for full-scale loss and Normal track.

In Fig. 22, the maximum bending moment for timber sleepers, full-scale loss, at train speed of 60 km/h, 80 km/h, 100 km/h and 120 km/h, exceeded the maximum value the timber sleepers able to withstand which is 25 kN.m causing the timber sleepers to fail. Full-scale loss has the worst flexural response compared to small-scale loss which is expected to be so. It is highly advisable not to operate the trains on a full-scale loss track which may cause a catastrophic incident.

4 Conclusion

This study identifies the vulnerability in the railway infrastructures exposed to flood and washaway conditions. This study is the world's first to determine the capability of operating trains over vulnerable track systems. A special track system, called the interspersed track, is used as case studies. Nonlinear finite element analyses of interspersed track systems have been established. A clear novelty in the model is the adoption of tensionless support condition that can mimic the actual ballast condition. It is very important to realistically simulate the actual ballast condition when the track is vulnerable and the asymmetric instabilities occur. This study considers the loss of support conditions as the consequence of flood and washaway conditions stemmed from extreme weather and climatic events.

The dynamic responses of the interspersed track systems exposed to the extreme weather events have demonstrated the vulnerability of the operations. By considering the risk profiles, the dynamic responses can be instrumental in identifying risks with respect to the operations and track conditions. Dynamic track twists can be derived and employed as the catalyst in vulnerability determination. It is clear that track conditions exposed to flood conditions cannot be easily determined from traditional inspections or observations by engineers, maintainers or operators. On this ground, it is at risk to operate a train over vulnerable track systems. Considering the 1:4 interspersed track systems, it is found that a train should not be operated above 40 km/h when it is suspected that the track suffers from flood and washaway conditions. In an emergency, a train might be able to travel at a low speed (e.g. less than 20 km/h) but vigilant monitoring and control is mandatory. Note that low speed trains could derail in a fail-safe situation if careful monitoring and control is set. However, in general, it is not advisable to operate a train over a vulnerable interspersed track, especially when there is no appropriate monitoring and control measures. A temporary solution to mitigate this issue has been proposed. When heavy rainfalls or extreme weather conditions (e.g. storm, hurricane, or typhoon) are anticipated, engineers and maintainers should develop a solution to reinforce the support condition, for example, by using ballast bonding agents.

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