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Study on the Applicability of Dynamic Stability Evaluation Criteria by Comparison of Trackside Measurement Results of Different Track Structures

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Abstract: Countries such as Korea adopt design codes, evaluation criteria and specifications from standards originating abroad; this leads to a lack of distinction of the separate applications of dynamic stability evaluation parameters between various track structures of different track moduli. This paper discusses the applicability of the dynamic stability evaluation method of railway track structures by assessing 10 different types of railway track sections of a newly constructed railway operation line (5 ballasted and 5 concrete type track structures) by field instrumentation testing. Parameters of track support stiffness (TSS), wheel load fluctuation, derailment coefficient, and rail displacement are measured. The respective results are first compared to the standard criteria (design specification) and comparisons between the different track types are presented as ratios. Findings show that while all of the tracks satisfy the design specification requirements, each track type measurement result varies by a noticeable degree, particularly when comparing between concrete and ballast type track structures. Results of the study demonstrate that using the same dynamic stability evaluation criteria can lead to an incorrect assessment of the track performance evaluation of track structure, and a separate evaluation parameter for ballasted and concrete track structures is required.

Keywords: dynamic amplification factor; total spring constant of track; field measurement; railway system management; railway maintenance; different track structures

1. Introduction

Countries with a relatively short history of railway infrastructure development reference other international standards for design and maintenance of tracks. In the Middle East and South East Asian countries, the International Union of Railways (UIC) codes have been adopted as their own standards. For example, the Korean Railway Code (KRC), the representative design specification code for both ballast and concrete track structures is mostly drafted by adopting the Union of Railways (UIC) or the American Railway Engineering and Maintenance-of-Way Association (AREMA) code. It is common knowledge in the academic field of railway engineering that, due to the respective environmental conditions and the difference in the types of components used in the various countries, the evaluation criteria and the methods are different case by case, nor are they fully theoretically consolidated. Cai et al., discuss an estimation method of static track modulus using elastic foundation models and outline the difference of the proposed method and the various existing methods for calculating track modulus [1]. Van Dyk et al., outline many of the significant dynamic factor calculation methods applied in the different nations and their respective evaluative metrics [2]. Kouroussis provides a review of the structural monitoring methods upon investigating the gauges and sensors used for field instrumentation [3]. Le Pen discusses a new track support stiffness (TSS) evaluation method without relying on wheel load data, and instead calculating the TSS using rail displacement and train speed [4]. A paper by Sadeghi et al. is one of the few existing studies that attempts a similar purpose as this study, where current practices of track analysis of ballasted tracks are reviewed and compared [5]. The study discusses the theoretical limitations of some existing standards, and that there is a lack of a singular method for analyzing the track dynamic response currently practiced in the U.S., nations using the European Standard (CEN) codes, and Australia [6].

Review of existing studies clearly illustrates that there are different methods for calculating the respective parameters for dynamic stability evaluation of railway track structures, and each new method is developed and proposed to take into account an environmental or technical factor that was not previously taken into account [7]. One such issue that is not often discussed is the application of the same evaluation criteria for different track structures of different track moduli, such as is the case in Korea. This is particularly problematic considering the differences between concrete and ballast track structures, where the track support stiffness is considerably different between the two different structure types, but the evaluation criteria for satisfactory track stability performance requirement (safety limit) is the same [8]. Different nations account for different properties in their standard specifications and design codes, and numerous studies discuss inclusion of new factors in the calculation of track parameters. This serves as an indication that while detailed performance evaluations exist, they are not necessarily consolidated or they are not being employed where necessary, and detailed studies on this issue have not been conducted in the railway academic field [9]. While it is a given fact that the respective national standards and specifications cannot all take into account the differences in the track properties and incorporate them into the evaluation regime, an actual investigation and comparison of ballasted track structures and concrete track types should be conducted to confirm how much of the difference in their properties affect our understanding of their track performance [10]. In light of this issue, this paper conducts an experimental study by trackside measurement through field instrumentation of track structures with different components and modulus properties. Properties of vertical and lateral wheel load and rail displacement, as well as stress and sleeper displacement are measured, and these factors are used to calculate the track support stiffness, derailment coefficient, and wheel load fluctuation for the six different types of track structures, all with varying component structure and/or characteristics. Results of the measurements are compared and the values are compared as ratios.

2. Theoretical Discussion

In the following section, the individual parameters and factors evaluated through the trackside measurement analysis are briefly reviewed. Next, the effect of the difference in track moduli to the reviewed parameters is outlined, and the importance of investigating the different outcomes of the parametric evaluation is discussed.

2.1. Key Dynamic Stability Evaluation Parameters Review

2.1.1. Derailment Coefficient and Wheel Load Fluctuation

The derailment coefficient is defined as the ratio of lateral pressure (the force exerted by the wheels on the rail at a horizontal direction) and the wheel load (force exerted on the rail at vertical direction) of a railroad vehicle. The lateral force is commonly expressed as Q, while the vertical rail load expressed as P, and the derailment coefficient is expressed Q/P. When the lateral force increases or the vertical wheel load decreases, the deviation coefficient (Q/P) increases, resulting in the increase in the probability of derailment.

$$\frac{\mathrm{Q}}{\mathrm{P}} = \text{Derailment Coefficient}(\mathrm{Q}/\mathrm{P})$$

where:

Q: Lateral wheel load (kN);
P: Vertical wheel load (kN).

During the train operation, the hunting oscillation movement of the wheels, in addition to the specification load of the vehicle, exerts a vertical force and lateral force on the rail simultaneously. The analysis of the derailment coefficient is divided into a static analysis and a dynamic analysis. The static analysis in the state shown in Figure 1 holds the following equation considering the force balance at the contact point.

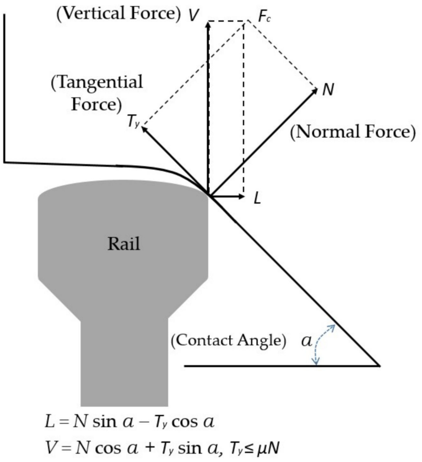


Figure 1. Interaction forces between the wheel and rail.

The evaluation principle is the same in multiple countries, but the requirement criteria (safety limit) is different with some nations. Refer to Table 1 for details.

Table 1. Derailment coefficient standard criteria for different nations [11,12].

Nations (Standards or Codes)	Evaluation Criteria of Q/P
Union of Railways (UIC)	≤1.2
German ICE High Speed Train regulation	≤0.8
North American regulation	≤1.0
Korean Railway Code	≤1.2
Chinese Standard (GB5599-85)	≤1.2 (Limit 1, acceptable), ≤1.0 (increased safety margin)
Japanese Railway Construction Standard	≤0.8

With the calculated derailment coefficient from the trackside measurement, the rate of wheel load reduction is generally used to evaluate ride safety with regards to the dynamics of railway vehicles [13]. The static wheel load is determined in accordance to the vehicle's specification weight (static load) where the effect from the vibration or hunting oscillation of the vehicle is not applied. In most cases, this is obtained by the averaged wheel load of the vehicle operating at a speed of about 5 km/h in a flat straight section (the method for deriving static wheel load or quasi static wheel load is different based on national specifications or codes).

The reduction of the wheel weight occurs due to vibration of the vehicle, knitting of the center, incorrect planarity of the track and vehicle, cant and centrifugal force in the curve, and wind pressure. The ratio of the static wheel weight (V) to the wheel weight reduction value (ΔV) is called the wheel load fluctuation ratio; if this value exceeds the allowable limit, there is a risk of derailment. Wheel load fluctuation is calculated with the following equation, and is calculated as an absolute value:

$$\left|Wheel\ load\ fluctuation\ coefficient\right| = \frac{\text{Dynamic Load}\left(V_{Dynamic}\right) - \text{Static Load}\left(V_{static}\right)}{V_{Static}} \tag{1}$$

2.1.2. Spring Coefficient and TSS Calculation Methods

Track support stiffness is a measure of the track's stiffness in response to the rail–wheel contact load. According to the Korean Railway Code (KR-C 14080) [14], for sections of the railway track where the track modulus is expected to change, the change in the stiffness over the transition zones should be designed within the allowable value relative to the speed of the train (refer to Figure 2); additional factors to be taken into consideration are vibration acceleration of the vehicle body, wheel load fluctuation, and yield stress of rail fatigue and upper rail pressure [15].

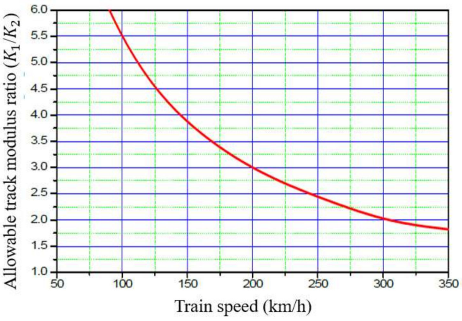


Figure 2. Allowable track modulus change depending on the train speed [8].

The stiffness of the track is derived from the comprehensive spring coefficient from the individual components that comprise the entire track structure. AREMA and the Korean Railway Track Specification (KRTS-VE) uses the spring coefficient (k_s) calculation method, where k is derived by calculating the spring coefficient (stiffness) of the track components/layers to calculate the track support stiffness (TSS).

$$k_{bss} = \frac{1}{\frac{1}{k_p} + \frac{1}{k_r} + \frac{1}{k_{sl}} + \frac{1}{k_{slab}} + \frac{1}{k_{sg}}} \tag{2}$$

where:

k_p: the stiffness of the pad (kN/mm),
k_r: the stiffness of the resilience (if applicable) (kN/mm),
k_{sl}: the stiffness of the sleeper (if applicable) (kN/mm),
k_{slab}: the stiffness of the ballast-less slab (kN/mm),
k_{sg}: the stiffness of the subgrade (kN/mm),
k_{bss}: the stiffness of the ballast-less slab track structure (kN/mm)

$$k_t = \sqrt[4]{\frac{64EI}{d^3}k_s^3} \tag{3}$$

E: modulus of elasticity (GPa),
I: moment of inertia (mm^4),
d: distance of the sleepers (mm),
k_s: stiffness of the track structure (kN/mm),
k_t: track support stiffness (kN/mm).

Korea employs the KR-C 14030 standard for the dynamic stability performance of track structures; it was adopted from the AREMA and UIC codes. For the trackside measurement of TSS, Hooke's law is implemented to calculate the track support stiffness to derive the immediate TSS value/condition of the track structure. Compliant with Hooke's formula, the trackside measurement TSSs is derived using the variables of maximum dynamic wheel load during trackside measurement and the maximum rail displacement (deflection);

$$K_t = \frac{Q_{dyn}}{\delta_{max}} \tag{4}$$

where;

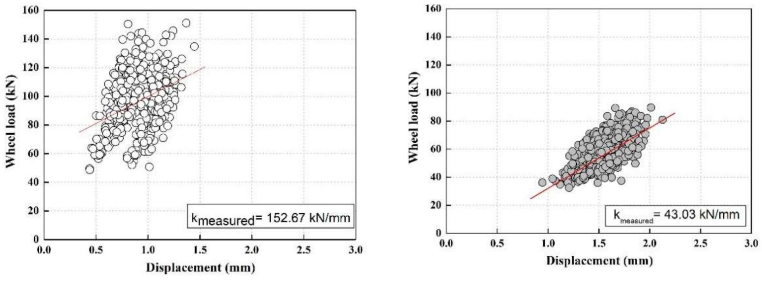
K_t: is the trackside measurement based track support stiffness (kN/mm);

Q_{dyn}: is the dynamic wheel load (maximum value derived from the trackside measurement) (kN);

δ_{max}: is the rail vertical displacement (maximum value derived from the trackside measurement (mm);

2.2. Effect of Different Track Conditions and Types on the Parametric Evaluation

As is shown in the above discussions of the parameters, the effect of the dynamic load is a factor for consideration in all of the calculations. The spring coefficient that comprises the track modulus denotes the supporting strength of the track, and is measured by the factor of wheel load during track side measurement. In most cases for the trackside measurement of TSS, Hooke's law is used, in consideration that the track is considered as a beam element to calculate the track support stiffness. The TSS is derived using the variables of maximum dynamic wheel load during trackside measurement, and the maximum rail displacement (deflection). In this regard, Lee compares the TSS between ballasted and concrete slab tracks [16]. Based on the measured wheel load and vertical displacement of ballasted and concrete slab tracks, the averaged TSS values of 152.67 kN/mm for the ballasted track (Figure 3a) and 43.03 kN/mm for concrete tracks (Figure 3b) are derived (Refer to Figure 3 for the comparison). This is a measurement of the track support stiffness at the wheel-rail contact point, therefore, it is reasonable to consider that while the overall track modulus for the concrete track should be higher in theory, these values can be seen to be reasonable only when considering that the fastener spring coefficient of the respective track types would affect the measurement results. Ballasted tracks employ high spring coefficient fasteners and rail pads to compensate for the softer ballast layer, and concrete tracks use rail fastener and pad types with low spring coefficients to counteract the effect of the concrete layer's high stiffness. Other similar studies in Korea indicate that the average TSS values of ballasted track structures are approximately in the range of 130~160 kN/mm, while ballast-less slab track TSS values range over a wider extent, between 60~120 kN/mm [17]. Refer to Figure 3 below for details:



(a) (b)

Figure 3. Track support stiffness (TSS) comparison of ballasted and ballast-less slab tracks: (**a**) TSS of the evaluated ballasted track, and (**b**) TSS of the evaluated ballast-less slab track [17].

These findings and results indicate that an investigation of the respective parameters for dynamic stability evaluation is required. The problem is not the variance between the TSS obtained by measurement, as it has already been well established that the behavior of the ballasted and ballast-less tracks are different (Ginnakos provides an extensive study on this subject matter) [18,19]. The problem is that despite this difference in the properties, the evaluation parameters and criteria is the same for both ballasted and ballast-less tracks between different structure types (railway bridges, tunnel structures, earthwork tracks, etc.) of the same track types [20–22]. Furthermore, as far as the trackside measurement method is concerned there are also numerous studies and experimental results that take into account the environmental effects on the dynamic stability and the field instrumentation conditions [4,23]. Lewis et al. indicates that humidity and temperature may be relevant factors when studying parameters about the wheel/rail interface friction condition, and investigates the effect of humidity and temperature on the railhead contamination on the performance of friction modifiers [24]. Henrick discusses that wind pressure is also a key factor that affects the hunting movement of the vehicle, particularly in either curved rail structures or in tunnels [25] and can drastically change the evaluation results of a track's measured wheel load. In open areas, rain would affect concrete and ballasted tracks differently, as ballasted tracks would be subjected to fouling and concrete tracks would be subject to cracking, which in turn would affect the dynamic performance evaluation of the track. However, the these factors are not considered enough in the adopted international standard codes and regulations such as have been adopted in Korea, China, Southeast Asia and the Middle East [26]. The effect of environmental factors in measurements and on different track structures is a subject worth continued discussion, as there is admittance that there are far too many variables to quantify the environmental factors as a numerical coefficient in the dynamic stability criteria [27].

2.3. Investigation into the Applicability of Korean Dynamic Stability Evaluation Criteria

This study demonstrates the application of the track performance evaluation method currently practiced in Korea in the form of the Korean Railway Code (KR-C 14030), a standard adopted from the old and new American Railway Engineering and Maintenance-of-Way Association (AREMA) and parts of the Union of Railways Code (UIC). Evaluation is conducted on 10 different tracks, 5 of them having different ballasted track structures, and 5 of them having different concrete track types (comprised of different track components). The subsequent sections outline the evaluation criteria described in this code; these criteria are applied to all types of high speed tracks, both ballasted and concrete. The parameters do not include instructions on how to consider differences of track properties and components; only included are the methods on how to calculate the performance levels of each parameter. The investigation into the result comparison of various types of track structures should be able to contribute towards our understanding of the applicability of today's dynamic stability evaluation methods and criteria.

3. Trackside Measurement through Field Instrumentation

3.1. Trackside Measurement Site Condition

The trackside measurement for the dynamic stability evaluation was conducted on 5 different types of ballasted track structures, and 5 types of ballast-less (hereby referred to as concrete tracks) track types. Specifications of the respective test beds are outlined in Table 2. Track sites were selected from newly opened sites (from 2018–2019) for high-speed passenger transportation lines in Korea under the assumption that the tracks have undergone minimal degradation effects such that cracks and rail conditions would not affect the measurement results. In the case of ballasted track structures in Korea, the superstructure design specification of high speed tracks is compliant with the identical format, with exceptions for sleeper spacing in certain cases [16]. For the concrete track structures, design specifications with regards to component usage usually varies, all the while ensuring that safety design requirements are met [6,16–18].

Table 2. Track specifications (ballasted tracks).

Characteristics	Ballasted Tracks (B)				
	B-Type 1:	**B-Type 2:**	**B-Type 3:**	**B-Type 4:**	**B-Type 5:**
Cumulative Tonnage (MGT)	2.5	4.7	1.4	2.8	0
Structure Type	Earthwork	Earthwork	Tunnel	Turnout	Bridge
Curvature (R)	Straight	Straight	Straight	Straight	Straight
Rail Type	60 kg	60 kg	60 kg	60 kg	60 kg
Fastening System Type	E-clip	E-clip	E-clip	E-clip	E-clip
Fastener Spring Coefficient	124.8	125.8	125.8	125.8	125.8
Sleeper Type	PC sleeper	PC sleeper	PC sleeper	PC sleeper	PC sleeper
Sleeper Spacing	625	625	625	625	625

For each track type, 20 separate measurements were conducted and 5 sets of ranges in intervals of 10 km/h from 120~170 km/h were selected such that the measurements can be derived at incremental intervals in accordance with increasing speed. Only straight line track sections were considered, to reduce the effect of the variables of cant and curvature during comparative analysis, and track condition factors (Φ) of 0.3 were selected. In the Korea's case, ballast structures are constructed with the same fastening systems for high speed tracks (Tables 2 and 3 for details).

Table 3. Track specifications (concrete tracks).

Characteristics	Concrete Track (C)				
	C-Type 1:	**C-Type 2**	**C-Type 3:**	**C-Type 4:**	**C-Type 5:**
Cumulative Tonnage (MGT)	0	0.2	0	2.1	3.4
Curvature (R)	Straight	Straight	Straight	Straight	Straight
Rail Type	60 kg	60 kg	60 kg	60 kg	60 kg
Fastening System Type	E type Elastic Fastening	B type Elastic Fastening	Rail Floating	L type Sleeper Floating	P type Sleeper Floating
Fastener Spring Coefficient	16.24	18.71	6.72	15.65	17.16
Sleeper Type	RC Block	Precast Slab Panel	-	RC Block	PC sleeper
Sleeper Spacing	625	625	630	625	620

Trackside measurement was conducted for only one specific vehicle type throughout the entire investigation (KTX-Sancheon). KTX operates in the site where field measurements were performed; it is composed of 18 passenger trains. Test trains without passengers were measured to reduce variability in the results. Specifications of the KTX are outlined in Table 4.

Table 4. Test train (KTX Sancheon) specification.

Photo	Item	Specification	Item	Specification
	Division	KTX-Sancheon	Full length (mm)	2970
	Control method	VVVF-IGBT	Max. speed (km/h)	305
	Vehicle formation	PC1-T1-T2-T3-T4-T5-T6-T7-T8-PC2	Design max. speed (km/h)	330
	Weight	Curb weight: 403 ton Full weight: 434 ton	Gauge (mm)	1435
	Whole length (m)	201.00	Design wheel load (kN)	85

3.2. Dynamic Stability Evaluation Criteria

Table 4 below outlines the railway track dynamic stability evaluation criteria compliant with the Korean Rail Code 14030 (KR-C 14030) that was used to conduct the performance comparison analysis of the tracks measured in this study. Refer to Table 5 for the calculation method and requirement criteria for the evaluation parameters.

Table 5. Dynamic stability evaluation criteria.

Evaluation Parameter	Calculation Method	Requirement Criteria
Derailment Coefficient	$\frac{Lateral\ Wheel\ Load}{Vertical\ Wheel\ Load}$ - Maximum Value: 1.2	Allowable Limit - 100%: ≦ 0.8 - 0.10%: ≦ 1.1
Wheel Load Fluctuation/Reduction	$\frac{V_{static}-V_{dynamic}}{V_{static}} = \lvert WLF \rvert$ - V_{static}= 85 kN: Static Wheel Load	Allowable Limit - 100%: ≦ 0.5 - 0.10%: ≦ 0.8
Rail Stress	σ	≦200 MPa
Rail Vertical Displacement	mm	Concrete track: 3 mm Ballast track: 4 mm

3.3. Field Measurement Method

Field Instrumentation and Installation

The following field instrumentation equipment were used: 1- and 2-axis strain gauges (for vertical and lateral wheel loads), a data acquisition system, and lateral-vertical displacement transducers (LVDT) were used. In Table 6 the specification of equipment is outlined;

Table 6. Field instrument equipment list.

Category	Type	Model	Manufacture Co.	Measurement Item and Purpose
Sensor	2 axis-strain gauge	FCA-5-11-1L	Tokyo Sokki	Vert./lateral Wheel load
	1 axis-strain gauge	FLA-5-11-1L	Tokyo Sokki	Bending stress in rail
	Dis. transducer	CDP-10 (10mm)	Tokyo Sokki	Vert./lateral dis. of rail, Vert. Dis. of sleeper
Measurement instrument	Data acquisition device for dynamic responses Bridge box Laptop	MGC plus SDA-810 (8ch) DB-120 (1 ch, 8 ch) Windows 10	HBM Tokyo Sokki Kyowa Samsung	Data acquisition and collection

3.4. Trackside Measurement Method

For measuring the wheel load and the lateral wheel load, as shown in Figure 4, strain gauges are attached at an angle 45° to the neutral axis of the rail bottom and web of the rail at a position 100 mm from the center between the sleepers. The sampling rate is set to 1200 Hz. For the dynamic response of the track, vertical and lateral rail displacement and vertical sleeper displacement are measured using the LVDTs. The field instrumentation installation overview is shown in Figure 4 below.

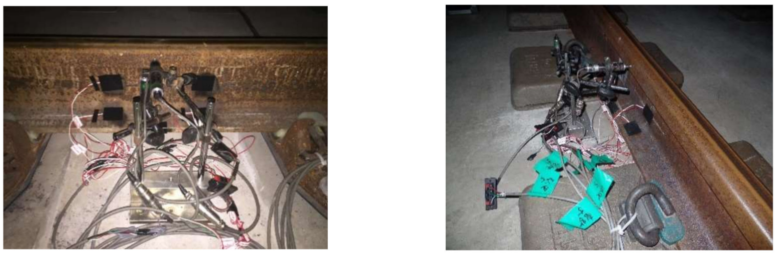
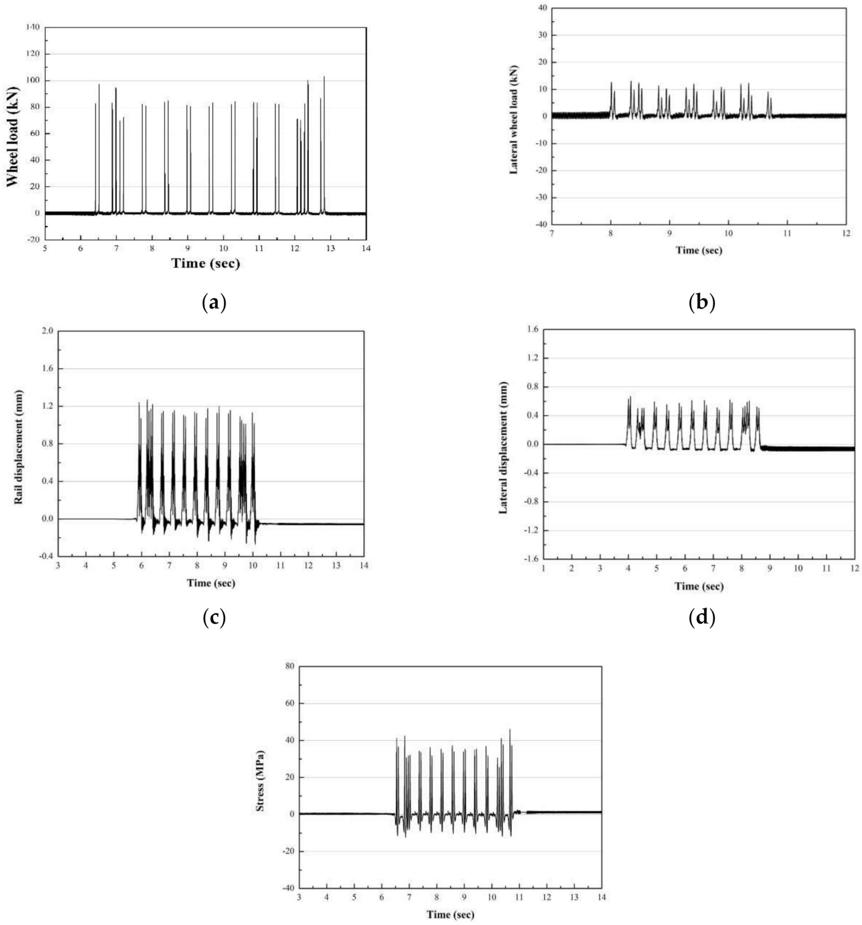


Figure 4. Strain gauge and LVDT installation image.

A result example for vertical rail displacement is shown in Figure 4 The elastic modulus of the rail, using a general value of 60 kg/m rail steel ($E = 2.1 \times 10^3$ MPa) is applied.

3.5. Field Measurement Result Comparison

To compare the track performance and track dynamic stability of a total of six track structures, the wheel load, lateral wheel load, and the vertical and lateral rail displacement were measured for determining the dynamic response of the test train. Test results were organized in accordance to the interval of increasing speed (as close as possible based on the measured samples). Among the results, the measurement data of each track structure of similar speed band are presented as examples for each factor in Figure 5.



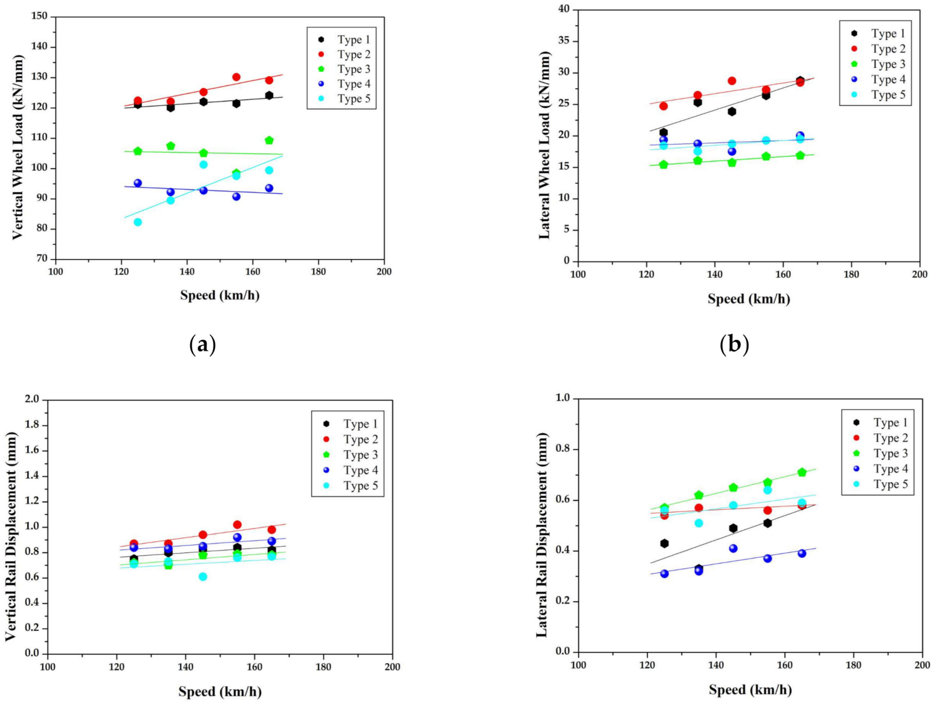
(**a**) (**b**)

(**c**) (**d**)

(**e**)

Figure 5. Data for the respective measurement factors (examples): (**a**) wheel load data sample, (**b**) lateral wheel load data sample, (**c**) vertical rail displacement data sample, (**d**) lateral rail displacement data sample, and (**e**) stress data sample.

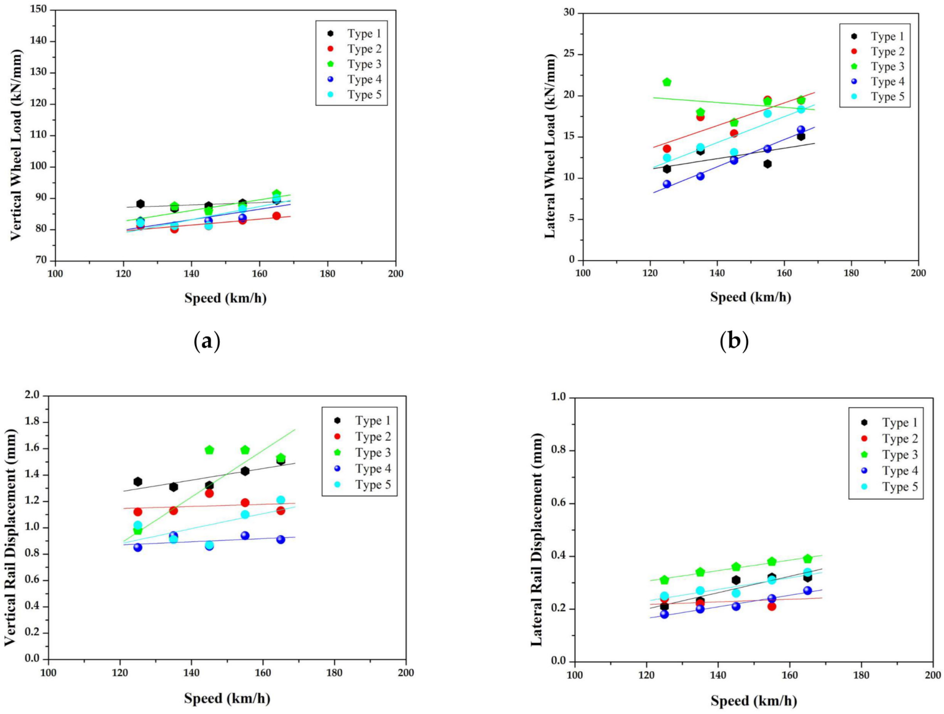
The field measurement results for the ballasted track structure types and the concrete track structure types are shown in Tables 7 and 8 respectively, and are displayed in graphs in the subsequent Figures 6 and 7, respectively. Among the 20 measurements taken from the field trackside measurements, the speed of the train was recorded (upon provision by the control center), and was classified in accordance to the speed ranges, increasing in increments of 10 km/h. Only the peak values among the measurement results were averaged.



(**a**) (**b**)

(**c**) (**d**)

Figure 6. Trackside measurement result comparison for ballasted track types: (**a**) wheel load, (**b**) lateral wheel load, (**c**) vertical rail displacement, and (**d**) lateral rail displacement.



(**a**) (**b**)

(**c**) (**d**)

Figure 7. Trackside measurement result comparison for concrete track types: (**a**) wheel load, (**b**) lateral wheel load, (**c**) vertical rail displacement, and (**d**) lateral rail displacement.

Table 7. Average values of maximum dynamic response by passing train for ballasted track structures.

Railway Structures	Speed (km/h)	Wheel Loads (Averaged Peak Values)		Displacements (Averaged Peak Values)	
		Vertical (kN)	Lateral (kN)	Vertical Rail (mm)	Lateral Rail (mm)
B-Type 1:	120~130	121.16	20.54	0.87	0.54
	130~140	120.09	25.33	0.87	0.57
	140~150	122.03	23.87	0.94	0.58
	150~160	121.45	26.43	0.85	0.56
	160~170	124.15	28.78	0.98	0.58
B-Type 2:	120~130	122.44	24.71	0.72	0.57
	130~140	122.12	26.47	0.70	0.62
	140~150	125.25	28.73	0.78	0.65
	150~160	130.21	27.32	0.79	0.67
	160~170	129.12	28.49	0.78	0.71
B-Type 3:	120~130	105.72	15.42	0.75	0.43
	130~140	107.44	16.06	0.80	0.33
	140~150	105.09	15.74	0.83	0.49
	150~160	98.47	16.74	0.84	0.51
	160~170	109.28	16.88	0.82	0.58
B-Type 4:	120~130	95.21	19.36	0.84	0.31
	130~140	92.24	18.74	0.83	0.32
	140~150	92.72	17.51	0.85	0.41
	150~160	90.74	19.27	0.92	0.37
	160~170	93.52	20.03	0.89	0.39
B-Type 5:	120~130	82.33	18.46	0.71	0.56
	130~140	89.47	17.54	0.73	0.51
	140~150	101.30	18.74	0.61	0.58
	150~160	97.55	19.26	0.76	0.64
	160~170	99.43	19.48	0.77	0.59

Table 8. Average values of maximum dynamic response by passing train for concrete track structures.

Railway Structures	Speed (km/h)	Wheel Loads		Displacements	
		Vertical (kN)	Lateral (kN)	Vertical Rail (mm)	Lateral Rail (mm)
Type 1	120~130	88.26	11.12	1.35	0.21
	130~140	86.81	13.31	1.31	0.23
	140~150	87.58	12.22	1.32	0.31
	150~160	88.46	11.74	1.43	0.32
	160~170	89.39	15.08	1.51	0.32

Table 8. *Cont.*

Railway Structures	Speed (km/h)	Wheel Loads		Displacements	
		Vertical (kN)	Lateral (kN)	Vertical Rail (mm)	Lateral Rail (mm)
Type 2	120~130	81.13	13.57	1.12	0.24
	130~140	80.14	17.41	1.13	0.22
	140~150	81.17	15.44	1.26	0.21
	150~160	82.97	19.52	1.19	0.21
	160~170	84.42	19.44	1.13	0.27
Type 3	120~130	88.81	21.65	0.98	0.31
	130~140	87.52	18.01	0.92	0.34
	140~150	85.89	16.75	1.59	0.36
	150~160	87.37	19.32	1.59	0.38
	160~170	91.42	19.49	1.53	0.39
Type 4	120~130	82.68	9.28	0.85	0.18
	130~140	81.27	10.23	0.94	0.20
	140~150	82.82	12.14	0.86	0.21
	150~160	83.74	13.55	0.94	0.24
	160~170	89.81	15.89	0.91	0.27
Type 5	120~130	82.19	12.49	1.02	0.25
	130~140	81.22	13.75	0.91	0.27
	140~150	81.30	13.15	0.87	0.26
	150~160	86.55	17.83	1.10	0.31
	160~170	90.03	18.34	1.21	0.34

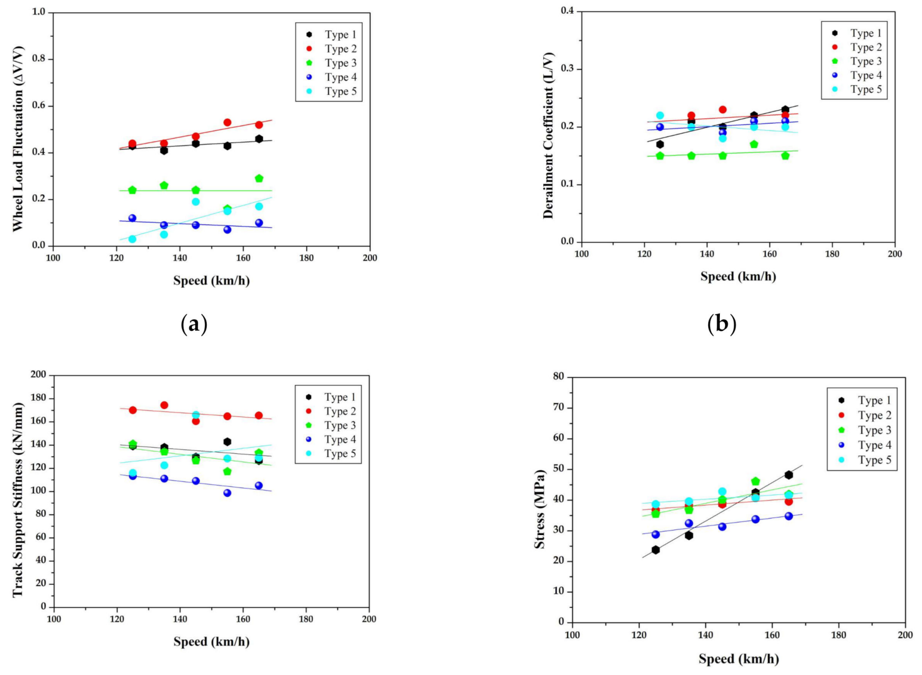
With regard to the ballasted tracks, the above measurement results show varying indications that the measurement result values differ. Regression lines have been provided for the series of Figures 5 and 6 only for the purpose of visually aiding the general trend of the changing parameters in accordance with increasing speed. While some exceptions are present, in general the values for all measurement parameters were shown to increase as the speed of the train increased as well. For the load parameters (vertical and lateral wheel loads) track Types 1 and 2 show the highest range on average compared to the other types of track structures. The vertical displacement results indicate that structures where the track substructure is of an earthwork type may be subject to receiving higher wheel-rail contact load than those of the other track types due to the different track modulus properties. The higher lateral displacement perceived in Track Type 3 (tunnel structure) is estimated to be due to the enclosed wind pressure affecting the hunting oscillation, resulting in higher displacement measurement than those of the other structure types. The precise cause and effect should be further investigated and cannot be provided in the scope of these measurement results, but it was confirmed that despite the same design specification, as well as all the track structures being relatively new with minimal cumulative tonnage recorded, a variance in the measurement results can be derived.

With regard to the concrete tracks, measurement results for the Type 3 (floating rail) structure was conspicuously higher than the results of the other structure types, and Type 4 (L type sleeper, floating) structure was the lowest, on average. Results for Types 1, 2 and 5 varied without a distinct patter, indicating that further investigation is required to understand the proper relation dynamic between the track structure characteristic and the parameter measurement results, but it was evident with track

Types 3 and 4 that a consistent difference in the measurement is also present among concrete type track structures.

3.6. Dynamic Stability Performance Result Comparison

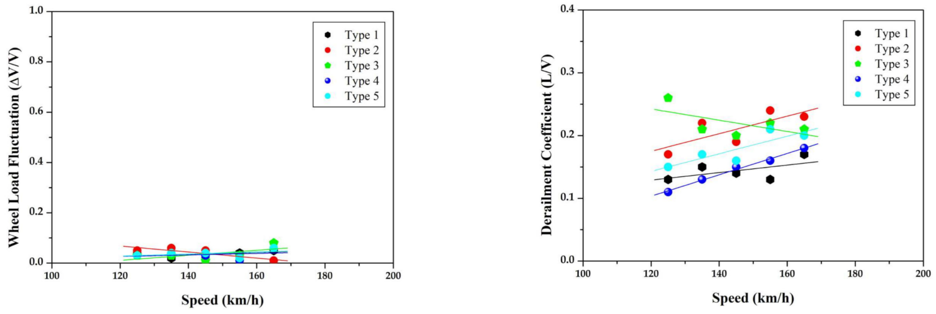
Based on the averaged peak measurement results, dynamic stability performance evaluation was conducted in accordance with the following criteria; wheel load fluctuation, derailment coefficient, track support stiffness, and stress. Calculation of the criteria was conducted in compliance with the outlined methods found in KR-C 14030 (Table 4). The results for the ballasted track structure types and the concrete track types are outlined in Table 9 (linked with Figure 8) and Table 10 (linked with Figure 9) respectively.



(**a**) (**b**)

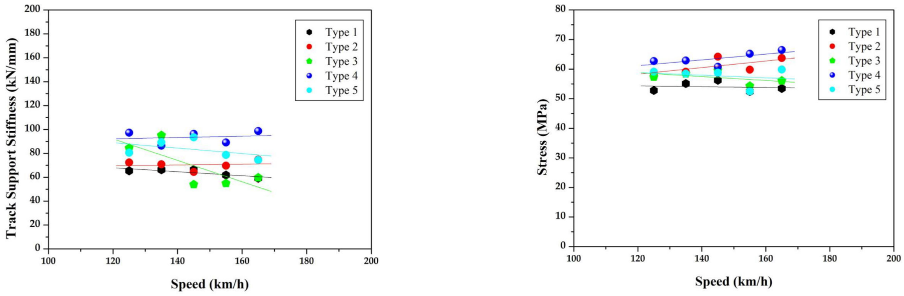
(**c**) (**d**)

Figure 8. Dynamic stability evaluation result comparison: (**a**) wheel load fluctuation, (**b**) derailment coefficient, (**c**) track support stiffness, and (**d**) rail stress.



(**a**) (**b**)

Figure 9. *Cont.*



(**c**) (**d**)

Figure 9. Dynamic stability evaluation result comparison for concrete track types: (**a**) wheel load fluctuation, (**b**) derailment coefficient, (**c**) track support stiffness, and (**d**) rail stress.

Table 9. Calculation result of track performance and dynamic stability according to railway structures per vehicle speed ranges (ballasted track structure types)**.**

Railway Structures	Speed (km/h)	Track Performance and Dynamic Stability per Vehicle Speed			
		Wheel Load Fluctuation [1]	Derailment Coefficient [2]	Track Support Stiffness (kN/mm)	Stress (MPa)
Type 1	120~130	0.43	0.17	139.26	52.78
	130~140	0.41	0.21	138.03	55.12
	140~150	0.44	0.20	129.82	56.23
	150~160	0.43	0.22	142.88	52.41
	160~170	0.46	0.23	126.68	53.47
Type 2	120~130	0.44	0.20	170.06	58.52
	130~140	0.44	0.22	174.46	59.12
	140~150	0.47	0.23	160.58	64.23
	150~160	0.53	0.21	164.82	59.82
	160~170	0.52	0.22	165.54	63.72
Type 3	120~130	0.24	0.15	140.96	57.34
	130~140	0.26	0.15	134.30	58.42
	140~150	0.24	0.15	126.61	59.62
	150~160	0.16	0.17	117.23	54.32
	160~170	0.29	0.15	133.27	56.09
Type 4	120~130	0.12	0.20	113.35	62.71
	130~140	0.09	0.20	111.13	62.89
	140~150	0.09	0.19	109.08	60.78
	150~160	0.07	0.21	98.63	65.18
	160~170	0.10	0.21	105.08	66.47
Type 5	120~130	0.03	0.22	115.96	59.12
	130~140	0.05	0.20	122.56	58.45
	140~150	0.19	0.18	166.07	58.78
	150~160	0.15	0.20	128.36	52.48
	160~170	0.17	0.20	129.13	59.87

(1) Calculated as absolute value; (2) Calculated using Equation (1).

Table 10. Calculation result of track performance and dynamic Stability according to railway structures per vehicle speed ranges (concrete track types).

Railway Structures	Speed (km/h)	Track Performance and Dynamic Stability per vehicle speed			
		Wheel Load Fluctuation (1)	**Derailment Coefficient** (2)	**Track Support Stiffness (kN/mm)**	**Stress (MPa)**
Type 1	120~130	0.04	0.13	65.38	23.78
	130~140	0.02	0.15	66.27	28.45
	140~150	0.03	0.14	66.35	38.71
	150~160	0.04	0.13	61.86	42.42
	160~170	0.05	0.17	59.20	48.21
Type 2	120~130	0.05	0.17	72.44	36.75
	130~140	0.06	0.22	70.92	38.21
	140~150	0.05	0.19	64.42	38.65
	150~160	0.02	0.24	69.72	40.82
	160~170	0.01	0.23	74.71	39.52
Type 3	120~130	0.03	0.26	84.50	35.48
	130~140	0.03	0.21	95.13	36.75
	140~150	0.01	0.20	54.02	40.14
	150~160	0.03	0.22	54.95	46.08
	160~170	0.08	0.21	59.75	41.82
Type 4	120~130	0.03	0.11	97.27	28.75
	130~140	0.04	0.13	86.46	32.42
	140~150	0.03	0.15	96.30	31.27
	150~160	0.01	0.16	89.09	33.72
	160~170	0.06	0.18	98.69	34.74
Type 5	120~130	0.03	0.15	80.58	38.61
	130~140	0.04	0.17	89.25	39.57
	140~150	0.04	0.16	93.45	42.81
	150~160	0.02	0.21	78.68	40.63
	160~170	0.06	0.20	74.40	41.52

(1) Calculated as absolute value; (2) Calculated using Equation (1).

In the above calculation process for both ballasted and concrete track structures/types, the analysis dynamic stability performance evaluation results show that all 10 types of track structures, for both ballast and concrete structure types, meet the design specification requirements outlined in KR-C 14030. However, the difference between the range of results when comparing the ballasted versus the concrete structure types was clearly different, with the exception of the derailment coefficient, where for both classifications of tracks, the range was safely within 0.1~0.3. The minimal variance can be seen between the different track types/structures in between the ballasted and concrete track types, it was shown that for ballasted track structures, wheel load fluctuation, track support stiffness, and stress values were higher than those for the concrete track types. Ballasted tracks Type 1 and 2 particularly stood out in that the values were nearing the safety limit (≤1.2, referring to Table 1). As far as the inter-comparison between the track classifications is concerned, some types showed relatively high slopes of change in their performance in accordance with increasing speed, in particular for the concrete track types. Ballasted track structures, while having results higher in value, show in general consistent performance throughout the increasing speed ranges, but track Types 1 and 2 show an increasing trend of derailment coefficient, and Type 1 shows a higher increasing trend with the stress parameter. These factors can serve to indicate that certain track types may be more subject to performance change due to increasing speed of the trains than others.

For easier comparison purposes, the peak values for the respective track structures/types of the two classes of tracks were derived among the 5 different speed conditions (from 120 to 170 km/h). With the exception of the track support stiffness, as there is no standard criteria for maximum track support stiffness in the KR-C 14030 railway track performance evaluation criteria, the evaluation parameters for wheel load fluctuation, derailment coefficient and stress were compared to the maximum limits outlined in the specification code. The results are shown in Table 11 for ballasted track structures and in Table 12 for concrete track types.

Table 11. Evaluation results of track performance (ballasted track structures).

Track Structures	Wheel Load Fluctuation (Max: 0.8) (%)	Derailment Coefficient (Max: 1.2) (%)	TSS (Peak TSS) (kN/mm)	Stress (Max 200 MPa) (%)
Type 1	57	19	142.88	28
Type 2	66	19	174.46	32
Type 3	36	14	140.96	30
Type 4	15	18	113.35	33
Type 5	24	18	166.07	30

Table 12. Evaluation result of track performance (concrete track types).

Track Structures	Wheel Load Fluctuation (Max: 0.8) (%)	Derailment Coefficient (Max: 1.2) (%)	TSS (Peak TSS) (kN/mm)	Stress (Max 200 MPa) (%)
Type 1	6	14	66.35	24
Type 2	7	20	74.71	20
Type 3	10	22	95.13	23
Type 4	7	18	98.69	17
Type 5	8	17	93.45	21

As can be seen in the results, the two classes of track structures show high variance between one another, but amongst the structure and types, the differences are low, but not completely negligible. For instance, Type 1 and Type 2 ballasted track structures are up to 57~66 percent of the maximum allowed wheel load fluctuation rate. Based on the limited information given, one could surmise that the cause of this difference is due to the higher overall stiffness at the rail and wheel contact point, supported by the spring constant of the substructure of the track, but again with only the evaluation results, it is difficult to understand the precise reason. The derailment coefficient was similar between all types and classes of tracks, where the range was between 14~20% of the maximum allowed coefficient, and this was the same with the case of the stress parameter, ranging between 17~33% of the maximum allowed stress limit.

The conventional state of the track performance assessment regime does not perform additional analysis or inquiry into the difference in the figures of these evaluation results (unless the analysis results pass the maximum limit), and additional clauses or instructions are not found in the KR-C 14030 or other design code specifications or standards. The difference in the evaluation result values, particularly between the ballasted and concrete track structures, is no coincidence. The reasons for the differences can be estimated as was attempted in some of the sections in the above, but it is clear that there is currently a strong limitation in the adopted design code and the evaluation criteria. The results of this study lead to proposing that further investigation of the correlation between the track structure properties and track performance is required, and that current evaluation methods and criteria found in the adopted national standards and design codes undermine the importance of this factor.

4. Conclusions

This study showed the limitations of conventional track performance (dynamic stability) evaluation methods currently used as part of internationally adopted national standards and design codes. In particular, the method outlined in KR-C 14030, an adopted code from the international standards and codes found in AREMA and UIC, was investigated. Dynamic stability evaluation results of 10 different railway tracks of a newly constructed railway line, 5 ballasted track structures (2 earthwork, 1 tunnel, 1 turnout and 1 bridge) and 5 concrete structure types (with different component characteristics) were analyzed and compared, and comparison showed unsurprising results of significant variance between the ballasted and concrete railway tracks, and minimal but non-negligible difference between the types and structures within the track classes. The differences in the track structure moduli and spring constants of the components shows that they have varying performance properties, despite all the tracks being able to meet the standard specification requirement. From an operations safety perspective, this may not pose a significant problem, but the results of the study nonetheless outline that current adopted standards do not provide any instructions or methods for distinguishing the characteristic features of each track type. In particular, the wheel load fluctuation and track support stiffness of the ballasted track structures are relatively higher than those of any of the concrete track types. While there is still no risk of derailment or immediate structural failure, the results indicate that over time, a higher probability of safety risk may be found in ballasted track structures. It has been made clear with the above findings and results that there is still a requirement for further improvement of the adopted codes, as a precise assessment of the track conditions and performance is not yet possible with the parameters and criteria outlined in the code, and consideration of the track properties in the evaluation of track dynamic stability performance is required. This study will need to improve by including further investigation of different tracks in different nations, and comparison with other theoretical evaluation methods put into practice, in the hopes of providing a reliable evaluation method applicable to all railway track types and structures.

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