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Site Investigations on the Lateral Movement of Skewed Prestressed Concrete Sleepers (PCS) Subjected to Rail Dynamic Loading

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***Abstract* — Prestressed concrete sleepers (PCS) are crucial for preserving track stability under dynamic train loads. This study compares the dynamic load behavior of a skewed PCS (placed at a minor angle with one rail seat spacing of 0.67 m instead of the conventional 0.70 m) to a non-skewed PCS. Vibration measurements were taken on an operational Malaysian railway line during commuter train passages (six-coach trains traveling at 30-40 km/h) at a curve track. The Integrated Electronic Piezo-Electric (IEPE) sensor installed on the edges of PCS recorded accelerations in three axes, which were then converted to movement (mm). The lateral movement derived from the skewed sleeper is compared against that from an adjacent normal sleeper. The results show that under identical strain, the skewed PCS has larger lateral movements than the non-skewed PCS. This larger movement indicates that lateral movement (skew) has a stronger influence on load distribution and track compliance. The findings shed light on how non-uniform sleeper placement influences dynamic track response, contributing essential data that is useful for railway maintenance and design in ensuring safety and performance on tracks with uneven sleeper alignment.**

Keywords—Prestressed Concrete Sleepers (PCS), Skewed conditions, Lateral movement, Dynamic loading, Commuter train, KTMB.

I. INTRODUCTION

The rails, pads, fasteners, and sleepers that make up a railway track's superstructure rest on the ballast, sub-ballast, and subgrade that form the track's substructure. Sleepers sustain the rails, maintain appropriate gauge, and distribute wheel loads to the ballast. Prestressed concrete sleepers (PCS) are commonly utilized due to their high strength, long lifespan, and low maintenance requirements. Their weight and stiffness stabilize the track against passing trains. Increasing train speeds and axle loads can cause more severe dynamic forces on sleepers, leading to faster track degradation. According to a recent comprehensive assessment, increasing load demands and frequent vibrations can accelerate the accumulation of damage in concrete sleepers, emphasizing the importance of optimum sleeper designs and maintenance techniques [1].

The field investigation was conducted on the mainline track near the route of Abdullah Hukum KTM Komuter Station in Malaysia. Standard gauge (1.435 m) prestressed monoblock concrete sleepers are spaced 0.70 m center-to-center on the selected track segment. A specific "skewed" sleeper was identified within this segment, where one end was affixed closer to its neighbor than is customary. In particular, the center-to-center distance to the adjacent sleeper along one track was a mere 0.67 m, in contrast to the standard 0.70 m on the opposite rail. This geometry indicates that the sleeper was slightly rotated with respect to the track axis, resulting in a skewed orientation. As a point of comparison, a neighboring sleeper with regular alignment and spacing was selected. Both sleepers were immersed in crushed ballast (rock) and were in similar condition. Keretapi Tanah Melayu Berhad (KTMB) personnel also supervised the site investigations as per requirements like safety and operational guidelines. Figure 1 shows differences between skewed and non-skewed Prestressed Concrete Sleeper (PCS) conditions.

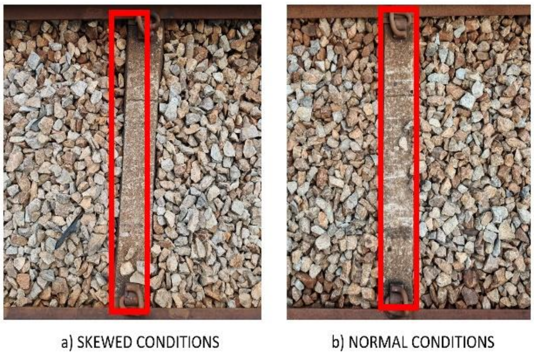

Fig. 1. Differences between skewed and non-skewed PCS conditions.

II. LITERATURE REVIEW

Dynamic loading conditions and support irregularities have a significant impact on sleeper performance. For instance, even a small void or loss of ballast support under a sleeper can induce high-impact dynamic forces. Field and simulation studies have shown that an “unsupported” sleeper (hanging void) can experience dramatically increased impact loads; one study reported up to ~70% higher sleeper–ballast contact force for a sleeper with only a 1 mm gap under it [2]. This impact force not only overburdens the sleeper but also accelerates ballast deformation and subsidence. Nabochenko *et al.* [3] found that minor impact vibrations lead to substantially increased ballast settlement compared to standard cycle loading, illustrating how dynamic variables might exacerbate track degradation. Another important geometric factor is the spacing and alignment of sleepers. The lateral track stability is significantly diminished when the typical sleeper spacing is reduced from 0.6 m to 1.0 m, as Sañudo *et al.* have observed a 40% reduction in resistance [4].

The results indicate that unequal placement of sleepers, as well as other non-uniform geometries, can influence track rigidity and load distribution. El-Sayed *et al.* conducted numerical experiments that examined the effects of combined vertical and lateral loading on concrete sleepers, demonstrating that lateral forces, such as those encountered on curved or misaligned tracks, can substantially affect sleeper bending moments and stress distribution [5]. In addition, a recent simulation study varied the loading frequency on a concrete sleeper and observed notable changes in its vibrational response and stress under higher-frequency cycles [6]. It is evident that the dynamic response of sleepers is influenced by load magnitude, geometry, loading frequency, and train speed.

Countermeasures and innovative technologies are being investigated to enhance track performance under dynamic loads. The utilization of under-sleeper pads (USPs) is one method to alleviate impact pressures. The use of elastic pads beneath sleepers, as per the field-validated estimates of Ngamkhanong and Kaewunruen reduces flexural deflection and impact acceleration, which leads to a decrease in the contact forces transmitted to the ballast [7]. The development of "smart" PCS with embedded sensors is a revolutionary technique. Xu *et al.* recommended the integration of fiber optic sensors with PCS to continuously monitor stresses and deflections during operation [8]. By monitoring rail seat loading, fracture, and differential settlement in real time, the self-sensing sleepers demonstrated the ability to provide essential information for preventative maintenance practices.

Despite these advances, there remain important knowledge gaps in how non-standard sleeper configurations affect dynamic behavior. In particular, the influence of lateral sleeper movement or skewed installation has not been evaluated through in-situ measurements. Such skewed conditions may occur in special track layouts (e.g., turnouts or curved alignments) or due to construction tolerances, which may result in unequal weight distribution and increased lateral stresses on the sleeper.

This work fills the gap by performing field experiments on a skewed PCS and a normal PCS under identical traffic conditions to assess the impact of lateral misalignment on sleeper deflection and load response. Vibration data were collected from an operating railway and analyzed to compare the lateral deflection behavior of the skewed against the standard sleeper. The outcomes provide empirical insight into dynamic load redistribution caused by sleeper skew, which can inform maintenance decisions and design guidelines for tracks with irregular sleeper alignments.

III. METHODOLOGY

To capture their dynamic response under train loads, a portable vibration acquisition system was used. High-sensitivity Integrated Electronic Piezo-Electric (IEPE) accelerometers were rigidly attached (glued) to the end of the PCS, parallel to the first tendon at the rail seat section. The sensors were oriented to record accelerations in the lateral (Z) axes of the sleeper. A multichannel data logger (Sirius-M) with a sampling rate suitable for rail vibration (in the order of kHz) was connected to record the Z-axis acceleration signals from the skewed and normal sleeper. During the measurement sessions, regular commuter trains (six-coach) passed over the instrumented track, typically operating at 30–40 km/h due to safety and speed restrictions on the curved track, ensuring consistent loading conditions. Each train passing exerts a sequence of wheel stresses on the two monitored sleepers, producing vibration data recorded by the accelerometers. A multitude of train passes was documented to guarantee the consistency of the observations. Meanwhile, Fig. 2 illustrates the experimental setup of the equipment installed on site.

Fig. 2. Equipment setup on site.

IV. RESULTS AND DISCUSSIONS

The raw acceleration time histories were processed to evaluate sleeper movements. Since the movement of a sleeper under dynamic load is directly related to acceleration (by double integration over time), the Z-axis acceleration data from each sensor were used to compute movement-time profiles. Prior to integration, the acceleration signals were filtered to remove any DC bias and high-frequency noise, minimizing drift in the calculated movement. A numerical integration was then performed twice (once to obtain velocity and a second time to obtain displacement). The resulting movement time history represents the vertical motion of the sleeper relative to its static equilibrium position as the train wheels pass. This acceleration-integration technique for measuring movement has been applied in previous studies and shown to reliably estimate track movements [9, 10]. For each train pass, key response metrics were extracted from the movement signals, including the peak vertical deflection at the rail seat and the movement waveform shape. The skewed sleeper's response was directly compared to that of the normal sleeper under the same train loading event. In particular, differences in peak movement magnitude and movement profile were analyzed to discern the impact of the skewed geometry. To account for any variability between passes, multiple events were averaged or examined, confirming consistent behavior. After that, all data processing and analysis were conducted using Dewesoft software that comes in a bundle with the Sirius-M device, which is compatible and capable of exporting to an Excel file.

The lateral movement behaviors of skewed and normal prestressed concrete sleepers (PCS) are evidently distinct in field investigations conducted at the curved track segment. The impact of sleeper skewing on lateral movement characteristics was evaluated by comparing the measured lateral movements of both skewed and normal sleepers under dynamic loading conditions from a six-coach commuter train traveling at 30 – 40 km/h.

Movement measurements taken at the site of investigation reveal that lateral movements of skewed sleepers were significantly higher than those of normal sleepers. The skewed sleeper showed notable lateral movements with a minimum of 1.46 mm and a maximum of 2.97 mm. By the lowest movement, the normal sleeper's lateral movements were somewhat less, which is 0.098 mm, and by the maximum, which is just 0.13 mm. These notable differences in movement magnitudes suggest that under the same stress conditions, skewed sleepers undergo a far higher degree of lateral movement.

These findings prove the susceptibility of sleeper alignment to dynamic stresses, as they align precisely with the existing research. Misaligned sleeper orientation disrupts the optimal distribution of dynamic loads and generates uneven stress distributions that exacerbate lateral movements. Table I shows the comparison of lateral movement between skewed PCS and normal PCS for 6 coaches commuter train that passed through the site investigations. Meanwhile, Table II shows the types of trains passing through skewed and non-skewed PCS.

Table I. Comparison of lateral movement between skewed and non-skewed PCS.

Type of Prestressed Concrete Sleeper (PCS)	***Highest Movement (mm)***	***Lowest Movement (mm)***
Normal PCS	0.13	0.098
Skewed PCS	2.97	1.46

Table II. Types of trains passing through skewed and non-skewed PCS.

Type of Train	***Speed (km/h)***	***Axle Load (tons)***
Fast Train	120	16
Good Train	90	20

One important factor affecting these notable lateral movement variations is the dynamic loading generated by passing trains. Particularly in skewed sleepers, because of their unequal support conditions, cyclic and recurrent loads aggravate movement under dynamic conditions. The obtained data shows a continuous trend: each commuter train passage generates a larger lateral movement reaction in the skewed sleeper than in the properly oriented sleeper. Such dynamic impacts exacerbate the sleeper's movements, subsequently accelerating ballast degradation and sleeper deterioration. In accordance with the KTMB Permanent Way Manual (Rev. 2/2024), all ballast used in Malaysian tracks is required to comply with strict specifications, including a minimum depth of 300 mm for main lines, a safe bearing pressure at formation level of 200 kPa for most main lines, material properties such as Wet Attrition Value (max 6%), Crushing Value (max 30%), Impact Value (max 25%), Flakiness and Elongation Index (both max 50%), and Cleanliness (foreign particles ≤ 1% by weight), and Grading requirements (e.g., 100% passing 63 mm sieve, 70% – 80% passing 50 mm)[11].

The geometry of the testing site significantly influences the recorded differential lateral movements. In curved track sections, trains generate increased lateral forces as a result of centrifugal effects, thereby elevating the lateral load requirements on sleepers and track structures. Lateral pressures have a considerable impact on skewed sleepers because their misalignment exacerbates uneven load distribution. This study shows that skewed sleepers in curved segments experience compounded pressures due to lateral forces caused by passing trains and geometric misalignment.

Moreover, the configuration of the commuter train (six coaches) also plays a crucial role. Longer trains produce sequential and repetitive loadings, hence increasing cycle load conditions and hence the dynamic responses in track components. Multiple coaches passing constantly generates repeated loading cycles at predictable intervals, hence emphasizing cumulative effects on skewed sleepers. As such, every coach who passes the skewed sleeper increases lateral movement amplitudes, hence progressively raising structural degradation sensitivity. Figures 3 and 4 show lateral movement against time for each commuter train passing through the skewed and non-skewed PCS.

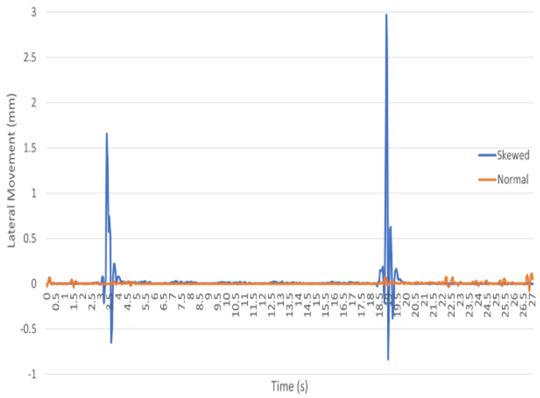

Fig. 3. Differences of lateral movement against time for highest movement.

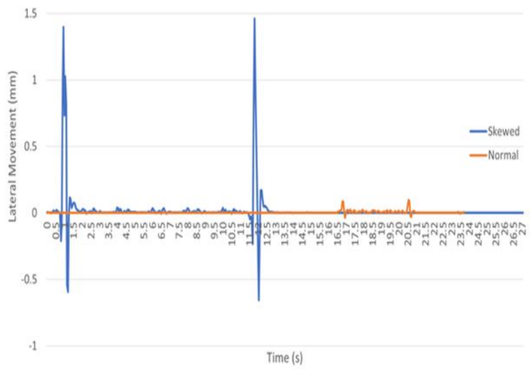

Fig. 4. Differences of lateral movement against time for lowest movement.

V. CONCLUSION

This study examined the lateral movement characteristics of skewed prestressed concrete sleepers (PCS) in response to dynamic forces from a six-coach commuter train traversing a curved railway track. Field measurements revealed significant disparities: skewed sleepers exhibited considerably greater lateral movements (ranging from 1.46 mm to 2.97 mm) compared to regular sleepers (ranging from 0.098 mm to 0.13 mm). The results indicate that irregular installation significantly affects lateral load distribution and the dynamic response of sleepers. The heightened lateral movement in skewed sleepers shows an uneven weight distribution and poses a risk of deterioration at the sleeper-ballast contact, jeopardizing the track's long-term stability and safety. Proactive maintenance and meticulous sleeper alignment procedures are crucial for the durability and dependability of railway infrastructure.

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