Experimental Investigation on Effect of Winged Sleeper on Lateral Resistance of Ballasted Track

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Abstract
Nowadays, the benefits of continuous welded rails and engineers’ tendency toward such types of tracks have increased the importance of railways’ lateral stability. For increasing railways’ stability, lateral resistance development mechanism should be reinforced. One of the methods for reinforcing the passive pressures’ mechanism at sleeper’s end and, therefore, increasing tracks’ durability is the utilization of winged sleepers. In this paper, lateral resistance of conventional and winged sleepers is examined and compared using laboratory and field tests. The tracks’ lateral resistant force was measured by single sleeper push test and track panel loading test. In the laboratory, single sleeper push tests showed 101% increase in lateral resistance in the winged sleeper compared with the conventional sample. In the field test, the test track was divided into three parts, namely conventional sleeper part, winged sleeper part and mixed part (alternating between conventional and winged sleepers). The lateral resistance of each part was measured by LTPT. In the field test, 96% increase in lateral resistance was obtained. Winged sleeper panels and mixed sleeper panels showed 71% and 59% resistance increase, respectively, compared with the conventional panel. By using winged sleepers in ballasted tracks, lateral displacements decreased by increasing the shoulder and crib ballast’s volume through the passive pressure mechanism.

Keywords: railway track, STPT, LTPT, lateral resistance, winged sleeper

1. Introduction
Rail track forces are exerted in three directions, namely vertical, longitudinal and lateral. In each direction, the necessary resistance for resisting the forces should be supplied. Vertical forces are the design basis of rail tracks. It is also necessary to control the track stability in longitudinal and lateral directions. Increase in the lateral forces of CWR tracks leads to faster deterioration of their geometry and, consequently, increased maintenance and costs. Ballasted tracks’ lateral resistance is provided by rail, fastener and the interaction between sleeper and ballast, the latter of which played the main role [1,2].

Ballast resistance versus lateral load is composed of three parts: sleeper’s base friction, sleeper’s side friction and passive pressure at the end of the sleeper [3]. These parts are shown in Figure 1.
1.1. Methods for increasing lateral resistance

With understanding the resistance mechanism in each of the three mentioned parts under some alterations, lateral resistance can be increased. Le Pen [4] in his study on the ballast examined the relative contributions of the base, crib behavior and shoulder ballast to lateral resistance from a geotechnical perspective. Many different methods have been suggested and studied for decreasing tracks’ lateral displacements. Generally, methods for increasing the lateral resistance can be divided to three groups:

- Changing the material, shape and dimensions of track components
- Utilizing new technologies in the existing railway tracks
- Changing track geometry and maintenance plan

a) Changing the material, shape and dimensions of track components

The first group methods increase the lateral resistance by improving the interaction between sleeper and ballast. The concept of changing the sleeper shape including twin block sleeper [5] and frictional sleeper [6] has been studied and the lateral resistance increase of about 30 and 65 percent has been respectively represented. Adding vertical stiffeners to the bottom of steel sleepers and increasing the interaction between sleeper and its bottom ballast increases lateral resistance up to 140 percent by reinforcing the passive pressures’ mechanism at the sleeper’s bottom [7].

b) Utilizing new technologies in the existing railway tracks

Utilizing new technologies in the existing railway tracks for the goal of decreasing lateral displacements is the second solution for increasing the lateral resistance. Sabaghi [8] did STPTs and showed that the use of sleeper anchors resulted in 19% increase in the lateral resistance. Using polyurethane bonding method [9], Under Sleeper Pads (USP) [10], geosynthetics [11], and baby gabion [12] are other cases that affect the lateral resistance. The effect of geogrid on the lateral resistances was investigated by conducting STPT and LTPT. The STPTs in the lab and field confirmed more than 31% and 42% increase in single tie lateral resistance for ballast layers reinforced respectively with one and two geogrid layers, while these values were reached to 29% and 40% in the case of LTPT [13]. Substituting the rail track shoulder with baby gabions, which surround ballast particles and prevent their movement, increased the lateral resistance by about 40 percent. Also, the consumed ballast volume decreased by about 35 percent [12].

c) Changing track geometry and maintenance plan

Changing the track geometry and maintenance plan is the third group of solutions for improving the lateral behavior. Kabo [14] conducted 3D elastoplastic simulations of ballast deformation with a focus on lateral resistance. Ballast geometry, vertical and lateral loading and friction between the ballast and sleeper were being varied in a parametric study. Increasing shoulder width has a considerable effect on lateral resistance. The increase in shoulder width increases the resisting wedge’s volume and weight against the lateral displacement of the sleeper [1,15]. Track resistance decreases
after tamping operation and mechanical stabilization of the track will compensate for a part of the lost resistance [16].

The results of the studies on lateral resistance are presented in Table 1.

1.2. Winged sleeper

Winged sleeper is an example of the methods, in which with changing the sleeper’s geometry and adding some excrescences to the sides, sleepers’ lateral behavior is improved. The differences between the conventional and winged sleeper are shown in Figure 2. The increase in sleeper’s weight results in bigger bottom friction and increase in sleeper width and also increases the shoulder’s resisting ballast volume. Crib ballast’s volume also results in higher resistance. Winged sleeper has a proper performance against vertical loads. Considering the increased area under the loading, better stress contribution would be expected in the winged-type sleeper. Decreased vertical stresses and better stress contribution in the ballast area result in decreased subsidence and increased stability of the track geometry, which in turn results in less maintenance periods and, subsequently, less maintenance costs.

Winged sleeper was designed and built in Austrian Federal Railways (ÖBB) in 1972 [17]. Austria’s Federal Railroad provided a low radius curvature (including conventional and winged sections) for examining the performance of new sleepers and, with heating the rail, its lateral displacement was recorded. In this examination, for a 60 centigrade increase of rail temperature, 1.2 mm lateral displacement was recorded in the winged sleeper track. In the identical track, but with the conventional sleeper, the lateral displacement was 6.5 mm. Also, investigation of the winged sleeper resistant load in comparison with the conventional sleeper of Be14 in the ballast bed simulator under dynamic load showed an average 116% increase in winged sleeper lateral resistance [18]. A numerical model of a new sleeper with some prominence on the bottom was developed for examining the lateral displacements of the actual curves due to temperature changes. Comparing the results of the lateral displacement demonstrated that the new sleeper had 55 percent less lateral displacement than the timber sleeper and 53 percent less lateral displacement than the conventional concrete sleepers [19]. Also, in the studies regarding the lateral resistance of sleeper and ballast in a track test with one fifth scale, lateral resistance of winged sleepers compared was examined with the conventional sleepers. In a part of the study, STPT was performed on latter sleepers. 4mm/min displacements were performed and data from 0 to 10 mm were recorded. Results showed 40-90 percent increase in lateral resistant force for different types of winged sleepers compared with the simple ones (considering the geometry and different sizes of sleepers) [20].

1.3. Measuring methods of lateral resistance
Track’s resistance against lateral displacements has been measured using different methods [21]. The most conventional methods are single sleeper push test (so-called STPT) and track panel loading test (so-called LTPT). In the single sleeper method, a sleeper is put into the rail track. In this method, the test sleeper is disconnected from the rest of the track and a hydraulic jack applies the loading to one of the rails, the reaction of which subjects the sleeper. On the other hand, LVDT is installed on the other rail and records the lateral displacement of the sleeper. Schematic set-up of STPT is depicted in Figure 3.

In the LTPT method, load is implemented to a group of sleepers and rails in a panel shape and displace them laterally. According to the load-displacement behavior, the lateral resistance of track is estimated. LTPT is depicted schematically in Figure 4.

In this paper, lateral resistance of conventional sleepers (so-called B70) and winged sleepers (so-called B70w) was estimated thorough laboratory and field examinations. STPT was performed to examine the performance of a winged sleeper compared with its conventional type. LTPT was also performed to examine the lateral performance of the winged and conventional sleepers installed in a track panel.

2. Laboratory examination of winged sleeper’s lateral resistance

2.1. Preparing the test track

A full scale sample with 3 m length was built for performing STPT. Geometrical parameters of the track including shoulder width of 40 cm and ballast height under the sleeper of 30 cm were chosen in School of Railway Engineering (SRE) track laboratory. Sleepers’ interspace was 60 cm. Ballast layers with 10 cm thickness were poured and each layer was rolled 25 times with a 29 kg laboratory roller. The test’s sleeper was a B70, in which four wings were fixed on the sides. Sleeper’s dimensions are depicted in Figure 5. Wings increased the total weight of the sleeper from 280 kg to about 325 kg.

2.2. STPT results

STPT was performed as described in Section 1.3 to examine the resistant force versus lateral load. The device used was KS625N including hydraulic jack, LVDT, and processor. Figure 6 shows the installed equipment of the test. In the laboratory examination, a B70 sleeper’s resistance was measured through implementing a lateral load and recording the corresponding lateral displacements. Figure 7 shows the load-displacement diagram for B70 and B70w sleepers.
According to the diagram, the B70w winged sleeper with a 14.84kN resistant force, compared with the B70 sleeper with 7.38kN resistant force, showed a 101% increase in lateral resistance for 2 mm lateral displacement.

3. Field examination of winged sleeper’s lateral resistance

3.1. Preparing the test track in the field

The track used in this study was one of the currently active tracks in Karaj Railroad Station. This track had concrete sleepers and UIC60 rails. The ballast height under the sleeper was about 30 cm and was measured after the track had been reconstructed. The ballast was loose and had low density. That's because new ballast is used when installing winged sleepers, which is ordinarily low in density. The use of new ballast results in critical conditions so that the resistance of the track with the new ballast will be lower. A part of the track with the length of 18 m was selected and divided into three sections with 6 m length including 10 sleepers. The first section was equipped with the conventional concrete sleeper, B70. The second section was an alternate mixture of B70 and B70w sleepers. The third section was equipped with B70w sleepers. In all of the laboratory and field tests, the center-to-center sleeper spacing was set to 60 cm. For implementing the panel with a specific number of sleepers, the additional sleepers were separated from the rest of the panel. The length of the panel in all the states containing 5, 7 and 9 sleepers was 3, 4.2 and 5.4 m, respectively. Figure 8 shows the three aforementioned sections.

The winged sleeper used in field tests had minor differences from the sleepers used in the laboratory considering manufacturing reasons. This sleeper was built in the RSTC Company. These sleepers’ wings were reinforced to prevent from probable detachment from the body. Winged sleeper, B70w, is schematically depicted in Figure 9.

According to the prior planning, two STPTs and nine LTPTs were done in order to examine the effect of winged sleepers on the lateral stability of the railroad. Results of these tests were examined. In each of the three sections, LTPT was performed on the panels containing five, seven and nine sleepers. In the TPLT, force was exerted to the rail via a hydraulic jack, the panel’s lateral displacements were recorded at 3 different points and the average amount was considered as the panel’s lateral displacement.

3.2. STPT field results

Lateral resistant forces were measured using STPT in field, and load-displacement diagram for B70 and B70w sleepers is shown in Figure 10.
The measured resistant force for 2 mm lateral displacement was 12.92 kN for winged sleeper and 6.59 kN for conventional sleeper. This diagram shows that lateral resistant force in B70w was 1.96 times bigger than that of the conventional B70 sleeper. An increase of 96% in lateral resistance was observed in this test. Increased lateral resistant force of the winged type compared with the conventional type of the sleeper obtained in the laboratory study was 101%. Figure 11 shows the load-displacement diagram for B70 and B70w sleepers.

### 3.3. LTPT field results

As mentioned earlier, nine discrete panels were tested on three differently prepared sections. Test results of conventional, wing and mixed panels can be found in Figures 12, 13 and 14, respectively.

For comparing the lateral performance of each of the studied cases, the lateral resistant force corresponding to 2 mm lateral displacement was extracted for all the cases. Lateral resistant forces corresponding to 2 mm lateral displacement can be seen in Table 2.

According to Table 2, the increased resistance of the panels equipped with winged sleepers and also mixed sleepers, compared with conventional sleepers, was obtained and drawn in Figure 15. In this diagram, the increase of lateral resistant force of winged sleeper compared with conventional sleeper, which was obtained from STPT, is also presented in terms of percent.

### 4. Discussions on results
4.1. Comparing results with previous studies:
Comparing the results of STPT in this study with previous studies has proven a significant effect of winged sleeper on improving the lateral stability of the railway, so that in this study, the increase of 96% and 101%, in the study of Austria’s Federal Railroad [18] the increase of 116%, and in the study of Koike et al. [20], the increase of 40-90% was observed. The results were different due to differences in the dimensions of sleepers and wings, differences in the type of tests, and differences in geometry and quality of the test track (including sleeper distance, shoulder size, etc).

4.2. Comparing STPT laboratory and field results:
This study showed 96% increase in lateral resistance in winged sleepers compared with the conventional sleepers. Reviewing the laboratory test results, which showed 101% increase in lateral resistance of winged sleepers compared with the conventional sleepers, demonstrated a good agreement between these test results. Both laboratory and field tests were full-scale and these results confirmed the satisfactory lateral performance of winged sleepers. The lateral resistance values and the percentage change of the STPTs are presented in Table 3.

The resistant force of the sleeper end can be calculated by calculation of friction changes in the sleeper bottom and the sleeper sides, to calculate the effect of the wings on the lateral resistance. The following assumptions have been made to estimate the resistant force of the bottom and the sides, similar to calculations done by le pen [4,22] and according to the test track conditions:

\[ \gamma = 15 \text{kN/m}^2, \quad \phi = 45 \text{deg}, \quad \delta = 24 \text{deg}, \quad A_{\text{side-B70w}} = 0.92 \text{m}^2, \quad A_{\text{side-B70}} = 1.04 \text{m}^2 \]

Where \( \gamma \) is the density of ballast, \( \phi \) is the internal friction angle of the ballast, \( \delta \) is the frictional resistance angle at interfaces (e.g. ballast to sleeper), \( A_{\text{side}} \) is the contact area of the sleeper and the ballast.

The friction force of the winged and conventional sleeper of 2.87 and 2.47 kN, respectively were calculated. Also, according to following calculations, resistant force of sides of the winged and conventional sleepers fixed at 1.24 and 1.4 kN, respectively:

\[ k = (1 + \sin \phi) / (1 – \sin \phi) = 2, \quad (1) \]
\[ \sigma_v = \gamma h / 2 = 1.5 \text{kN/m}^3, \quad (2) \]
\[ \sigma_h = k \sigma_v = 3 \text{kN/m}^3, \quad (3) \]
\[ F_h = \sigma_h \times A_{\text{side}}, \quad (4) \]
\[ \rightarrow F_{h-B70w} = 2.76 \text{kN}, \quad F_{h-B70} = 3.12 \text{kN}, \]
\[ R_{\text{side}} = F_h \times \tan \delta, \quad (5) \]
\[ \rightarrow R_{\text{side-B70w}} = 1.24 \text{kN}, \quad \text{and} \quad R_{\text{side-B70}} = 1.40 \text{kN} \]

The values are in the same range as the previous studies [23]. After estimating the resistance of the bottom and the sides of the sleepers, the end resistance in both of the sleepers is obtained as follows:

\[ R_{\text{end}} = R_{\text{total}} – R_{\text{bottom}} – R_{\text{side}} \quad (6) \]
\[ \rightarrow R_{\text{end-B70w}} = 8.73 \text{kN}, \quad \text{and} \quad R_{\text{end-B70}} = 2.70 \text{kN} \]
As mentioned, increasing the lateral resistance is achievable by reinforcing the friction of sleepers’ bottom and sides and passive pressure mechanism. In this study, the friction of sleepers’ bottom and sides has changed slightly and the increase in lateral resistance is due to passive pressure mechanism of ballast. The increase in the sleeper width increases the resisting wedge’s volume and weight against the lateral displacement of the sleeper. Estimates show that due to the increase in the volume of shoulder failure wedge, the shoulder resistance in the winged sleeper is about 3.2 times greater than conventional one.

4.3. Comparing the winged sleeper’s STPT and LTPT results:

In the panel test case, in the panels with five, seven and nine sleepers, 72, 73 and 69 percent increase in winged track’s resistant force was seen, respectively. Comparing the results of STPT with LTPT, there was about 25% difference in the increased lateral force between these two test results. For understanding this subject, the common load area in ballast should be mentioned. When a sleeper is loaded, it uses the entire shoulder failure wedge’s capacity which is created at the end of the sleeper. When multiple sleepers are loaded, a part of ballast endures two lateral sleepers’ lateral loads, which leads to decreased resistance of each frame sleeper compared with a single sleeper. On the other hand, with increasing the sleeper width, the common loading area will be greater, which results in more reduction of each sleeper resistance in the panel. This fact is shown in Figure 16.

According to Figure 16 and considering more percentage of lost resistance in winged sleeper, the difference in the results obtained from single sleeper test and panel displacement test seems rational. This fact also applies to crib ballasts, in which almost all the crib ballast is also loaded by the adjacent sleeper.

4.4. Comparing the results of winged and mixed panels:

According to Figure 15, mixed panels formed by five, seven and nine sleepers had 61, 59 and 57 percent increase, respectively, in lateral resistant force compared with the conventional sleepers. Comparing winged panels (with the average increase of 71%) and mixed panels (with the average increase of 59%) showed 12% difference in lateral resistance increase rate. Crib ballast’s capacity played an important role in providing mixed panel’s lateral resistance. Comparing the ballast failure wedge created in mixed track, with that of winged track, showed that a big part of ballast’s capacity was used. There was also less lost resistance in this case. In fact, when all the sleepers were substituted with winged sleepers, the common loading area was increased which resulted in relatively low increase in fully winged tracks compared with mixed tracks. In Figure 17, the resistant ballast is shown for both cases.

4.5. Effects of sleepers’ numbers on track’s panel resistance
Effect of sleepers’ numbers on lateral resistance was also examined in this paper. For better comparison, each sleeper’s lateral resistance, for different tested panels, is recorded in Table 4.

The resistance measured for each sleeper in Table 4 was obtained by dividing the total resistant force by the number of sleepers. In reality, resistant force in side sleepers is greater than other sleepers. Also, in mixed panels, depending on the sleeper’s type and location in the panel, the resistant force will be different. However, this examination was aimed to make these cases comparable. Also, the number attributed to resistant force in STPT in mixed track was the average number of conventional and winged sleepers.

Figure 18 shows the amount of decrease in each sleeper’s resistant force according to panel’s number of sleepers. This diagram was obtained by dividing the resistant force attributed to each sleeper in panel by the resistant force of a single sleeper. In this diagram, \( N_s \) is the number of panel’s sleepers, \( R_{STPT} \) is the resistant force in STPT and \( R_{ESP} \) is the resistant force of each sleeper in the panel.

Figure 18 determines that using the mixed layout, less decrease in lateral resistant force will be seen. This issue marks the optimized usage of crib ballast and shoulder’s capacity in mixed layout, compared with conventional and winged layouts.

**Conclusion:**

Increased load and speed of rolling stock, necessity for tracks’ continuity, existence of sharp curves (the curves with the radius of less than 400 m [24]) and longitudinal loads due to thermal changes have increased the importance of rail track’s lateral stability. Increasing the rail track’s stability is possible by reinforcing the lateral resistance mechanisms. Improvement of passive pressure mechanism of ballast and friction of sleepers’ bottom and sides are possible by changing the material, shape and dimensions of track components. Moreover, it is also applicable using technologies which stabilize the ballast layer. This study introduced the winged sleeper as a special type of sleeper and examined its lateral resistance by laboratory and field tests. Using winged sleeper in tracks decreased the lateral displacements by increasing the volume of shoulder and crib ballast, which led to two mechanisms of passive pressure and friction. In this study, laboratory and field tests performed on the conventional and winged sleeper (STPT) showed 101 and 96 percent increase of lateral resistance in B70w compared with B70 sleepers. Also, LTPT field tests showed an average lateral resistance increase of 71 and 59 percent for fully winged and mixed sleepers (alternating between winged and conventional), respectively. In this work, the ballast capacity was better used in the mixed layout. According to the lateral resistant force of the panels with winged and mixed sleepers, it was found that crib ballast’s capacity was very important in providing the lateral resistance.
of mixed panel. A large part of crib ballast capacity was observed by comparing the passive wedge formed in the mixed track with the one formed in the full-winged one. Moreover, the lost resistance of the shoulder and crib ballast caused by the simultaneous loading zone effects of adjacent sleepers in mixed panels was less than that of winged panels. Consequently, taking into account the economic aspects, despite the higher resistance of the winged panel and due to its slight difference with the mixed panel, selecting a mixed panel can be a more economical option to provide lateral resistance.

**List of notation**

| Abbreviation | Description |
|--------------|-------------|
| STPT         | Single sleeper (tie) push test |
| TPLT         | Track panel loading test |
| B70w         | Winged type of B70 sleeper |
| DTS          | Dynamic track stabilizer |
| CWR          | Continuous welded rails |
| SRE          | School of Railway Engineering |
| \( R_{STPT} \) | Lateral resistant force in STPT |
| \( R_{ESP} \) | Lateral resistant force of each sleeper in panel loading test |

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Figure 1. Lateral resistance component caused by the interaction of sleeper and ballast

Figure 2. Conventional and winged sleepers

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Figure 4. Schematic set-up of TPLT

Figure 5. Sleeper dimensions in the laboratory study

Figure 6. The installed equipment of the laboratory examination

Figure 7. Lateral resistant force of B70 and B70w sleepers in the laboratory STPT

Figure 8. Conventional, mixed and winged sections on the test track

Figure 9. Sleeper dimensions in the field study

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Figure 11. STPT field results for B70 and B70w sleepers

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Table 2. Lateral resistant force in 2 mm lateral displacement (kN)

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Table 3. STPT laboratory and field results

Figure 16. Common loading area in conventional and winged sleepers

Figure 17. Lateral loading of shoulder and crib ballast in winged and mixed panels

Table 4. Average lateral resistant force of every sleeper in different tests (kN)

Figure 18. Amount of decrease in each sleeper’s resistant force according to panel’s number of sleepers

Figure 1
## Experimental Investigation on Effect of Winged Sleeper on Lateral Resistance of Ballasted Track

| Category                                                        | Studied item                              | Difference (%) | Reference                  |
|-----------------------------------------------------------------|-------------------------------------------|----------------|----------------------------|
| Changing the material, shape and dimensions of track components | twin block sleeper                       | 30             | Profillidis [5]            |
|                                                                | frictional sleeper                        | 65             | Zakeri et al. [6]          |
|                                                                | steel sleepers with vertical stiffeners  | 140            | Zakeri and Talebi [7]      |
| Utilizing new technologies in the existing railway tracks      | sleeper anchors                           | 19             | Sabaghi [8]                |
|                                                                | polyurethane bonding method               | 100 ~ 184      | Jing et al. [9]            |
|                                                                | under sleeper pads                        | 20             | Pucillo et al. [10]        |
|                                                                | baby gabion                               | 40             | Darkhosh [12]              |
|                                                                | geogrid                                   | 29 ~ 42        | Esmaeili et al. [13]       |
| Changing track geometry and maintenance plan                   | increasing ballast shoulder               | 15 ~ 20        | Kabo [14]                  |
|                                                                | increasing ballast shoulder               | 16 ~ 22        | Zakeri et al. [15]         |
|                                                                | tamping operation                         | -43            | Sussmann et al. [16]       |
|                                                                | mechanical stabilization                  | 31             | Sussmann et al. [16]       |

Table 1

Figure 2

Figure 3
Experimental Investigation on Effect of Winged Sleeper on Lateral Resistance of Ballasted Track

Figure 4

Figure 5

Figure 6

Figure 7
Experimental Investigation on Effect of Winged Sleeper on Lateral Resistance of Ballasted Track

Figure 8

![Conventional Track, Mixed Track, Winged Track comparison diagram]

Figure 9

![Figure 9 image showing wing section and sleeper end dimensions]

Figure 10

![Figure 10 image showing experimental setup with hydraulic jack and load cell, LVDTs installed on rail]

Figure 11

![Figure 11 graph showing lateral resistance force vs. displacement for B70 and B70w]
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Figure 1

Figure 12

Figure 13

Figure 14
## Table 2

| Track Type | 1 Sleeper (STPT) | 5 Sleepers (TPLT) | 7 Sleepers (TPLT) | 9 Sleepers (TPLT) |
|------------|-----------------|------------------|------------------|------------------|
| Conventional | 6.59            | 17.19            | 22.40            | 26.40            |
| Mixed      | -               | 27.65            | 35.63            | 40.82            |
| Winged     | 12.92           | 29.57            | 38.76            | 44.11            |

## Table 3

| Environment | Conventional | Winged | Difference (%) |
|-------------|--------------|--------|----------------|
| Laboratory  | 7.38         | 14.84  | 101            |
| Field       | 6.59         | 12.92  | 96             |

## Figure 15

![Graph showing increase in resistance for different track types](image)

## Figure 16

![Diagram comparing conventional and winged track types](image)
Experimental Investigation on Effect of Winged Sleeper on Lateral Resistance of Ballasted Track

Figure 17

| track type ▼ test type ▶ | 1 sleeper (STPT) | 5 sleepers (TPLT) | 7 sleepers (TPLT) | 9 sleepers (TPLT) |
|--------------------------|------------------|-------------------|-------------------|-------------------|
| Conventional             | 6.59             | 3.44              | 3.20              | 2.89              |
| Mixed                    | 9.75             | 5.53              | 5.09              | 4.54              |
| Winged                   | 12.92            | 5.91              | 5.54              | 4.90              |

Table 4

Figure 18

Biographies

Jabbar-Ali Zakeri received his PhD degree in Road and Railway Engineering from Beijing Jiaotong University, China, in 2000. Dr Zakeri is currently Professor at the School of Railway Engineering, Iran University of Science and Technology. His research interests include dynamic analysis of train-track interaction, railway track dynamics, track maintenance and construction.

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