Effects of ballast thickness and tie-tamper repair on settlement characteristics of railway ballasted tracks

Les effets de l'épaisseur de ballast et de la réparation de lien-bourreur sur le tassement des voies chemin de fer

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ABSTRACT: The effects of ballast thickness and tie-tamper repair on the settlement characteristics of ballasted tracks are investigated by conducting a series of cyclic loading tests on model grounds. A model sleeper at a one-fifth scale was used, and tie-tamper implementation was physically simulated in the model tests in which relationships between the number of loading cycles and sleeper settlement were obtained. In addition, maximum shear strain distributions generated in the model grounds were analyzed with particle image velocimetry. Results suggest that the 250 mm ballast thickness currently adopted as the standard design is ineffective for minimizing settlement that occurs when the nonlinearity of roadbed compressibility is relatively moderate. Moreover, characteristics of the initial settlement process are altered significantly after tie-tamper implementation, although the degree of gradual subsidence undergoes minimal change regardless of ballast thickness and roadbed type.

RÉSUMÉ : Les effets de l'épaisseur de ballast et de la réparation de lien-bourreur sur les caractéristiques de nivellement des voies lestées sont étudiés. Une série d'essais cycliques de chargement sur un modèle à une échelle d'un cinquième a été effectuée. L'exécution de lien-bourreur a été physiquement simulée dans les essais sur maquette. Les relations entre le nombre de cycles de chargement et le déplacement sont respectées. De plus, les distributions des contraintes de cisaillement maximales du modèle sont analysées par analyse d'image. Les résultats montrent que l'épaisseur de ballast de 250 mm adoptée actuellement comme standard est inefficace pour minimiser le tassement qui se produit pour une compressibilité de terre-plein non linéaire relativement modérée. De plus, le processus de tassement initial change considérablement après mise en oeuvre du lien-bourreur, malgré les effets minimes durant l'implantation.

KEYWORDS: Railway ballasted track, Maintenance, Residual settlement, Model test

1 INTRODUCTION

Railway ballasted tracks, which are composed of crushed stones, rails, and sleepers, usually undergo residual settlement due to railway traffic. In order to perform appropriate maintenance on these tracks, it is important to clarify such settlement characteristics. However, optimum relationships between ballast thickness and roadbed rigidity have not been well understood[1)], particularly with the 250 mm thick ballast currently used as the standard design. Ballasted tracks that show a substantial amount of settlement is often restored to the original positions by tie-tamper implementation. However, the manner in which this type of implementation alters the settlement characteristics of the ballasted tracks is poorly understood.

In this study, therefore, the effects of ballast thickness and tie-tamper repair on the settlement characteristics of ballasted tracks are investigated. A series of cyclic loading tests are conducted on a model sleeper at a one-fifth scale, as shown in Fig. 1. In the loading tests, tie-tamper repair was physically simulated by inserting a small tool into the ballasts. In addition, particle image velocimetry (PIV) analysis was performed to interpret deformation of the ballasts and roadbeds.

2 MODEL GROUNDS AND CYCLIC LOADING

Figure 1 shows the model test apparatus used in this research. Model grounds at a scale of one-fifth were constructed in a sand box with interior dimensions of 800 mm wide, 304 mm deep, and 300 mm high. A duralumin footing with a width of 48 mm was used to model the sleeper. Crushed stones approximately one-fifth the size of actual ballasts were selected to model the ballasts. The maximum particle diameter D_{max} was 19 mm, and the mean diameter D_{50} was 8.0 mm.

Cyclic loading tests were conducted on 12 model grounds under various conditions. Crushed stones with 20, 50, and 80 mm thicknesses were constructed on four types of roadbeds (Table 1). Crushed stones were compacted to achieve a dry density of 1.60 g/cm^3 in each test.

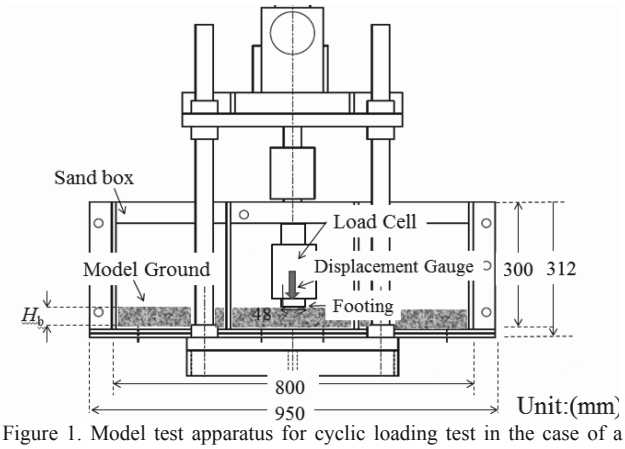

Figure 1. Model test apparatus for cyclic loading test in the case of a steel roadbed

As shown in Table 1, the roadbed in Case 1 was represented by the bottom steel plate of the sand box. The roadbed in Case 2 was constructed with Toyoura sand (D_r = 90%) with a thickness

H of 60 mm, mean diameter D_{50} of 0.21 mm, and uniform coefficient U_c of 1.70.

Reinforced roadbeds were introduced in Cases 3 and 4. A Toyoura sand roadbed (D_r = 90%, H = 60 mm) was overlain by an asphalt mixture layer in Case 3, and a Natom sand roadbed (D_r = 95%, H = 60 mm) was overlain by the same asphalt mixture layer in Case 4. The D_{50} of the Natom sand was 0.70 mm, and its U_c was 3.09. The 10 mm thick asphalt mixture was composed of straight asphalt 80–100 and sands.

Table 1. Model ground conditions

Case No.		Roadbed	Ballast thickness H_b (mm)
1	1-1	Steel (Bottom plate of a sand box)	20
	1-2		50
	1-3		80
2	2-1	Toyoura sand (D_r = 90%, H = 60 mm)	20
	2-2		50
	2-3		80
3	3-1	Toyoura sand (D_r = 90%, H = 60 mm) + Asphalt mixture (layer thickness = 10 mm)	20
	3-2		50
	3-3		80
4	4-1	Natom sand (D_r = 95%, H = 60 mm) + Asphalt mixture (layer thickness = 10 mm)	20
	4-2		50
	4-3		80

Cyclic loadings were applied to the model grounds with footing at a constant displacement rate of 0.05 mm/s. The amplitude of the cyclic stress applied in Case 1 was 110 kN/m^2; that applied in Cases 2, 3, and 4 was 80 kN/m^2. During the cyclic loadings, consecutive images of the model grounds were captured by a digital camera.

In each test, 100 cyclic loadings were first applied. Tie-tamper repair modeling was performed in the following manner. As shown in Fig. 2, the footing was reset to the initial position after 100 cyclic loadings were applied. A small spoon was next inserted into the model ground near lateral sides of the footing. After the spoon reached a fixed ground depth, it was tilted several times to permit the crushed stones to move laterally. This procedure was followed at several locations until the voids between the footing and the ground surface were completely filled by the crushed stones. Finally, additional crushed stones were introduced to the ground surface near the footing sides to produce a flat ground surface. After this tie-tamper modeling was implemented, 100 of cyclic loadings were applied again.

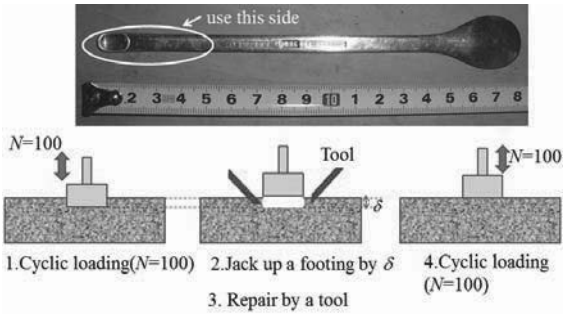

Figure 2. Tool and procedure used for simulating tie-tamper repair

3 RESIDUAL DEFORMATION CHARACTERISTICS

3.1 Effects of ballast thickness

The relationships between the number of cyclic loadings N and footing settlement δ were obtained before and after tie-tamper repair, as shown in Fig. 3. Each relationship obtained could be fitted by the following equation[2]):

$$\delta = C\left(1 - e^{-\alpha N}\right) + \beta N \quad (1)$$

where C and α are parameters representing the initial settlement process, and β represents the process of gradual subsidence.

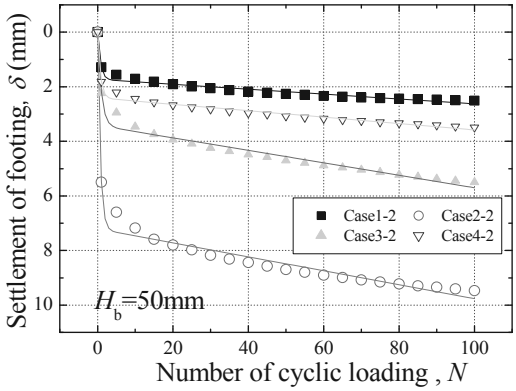

Figure 3. Relationships between number of cyclic loading cycles and footing settlement before tie-tamper implementation. Ballast thickness, H_b, = 50 mm

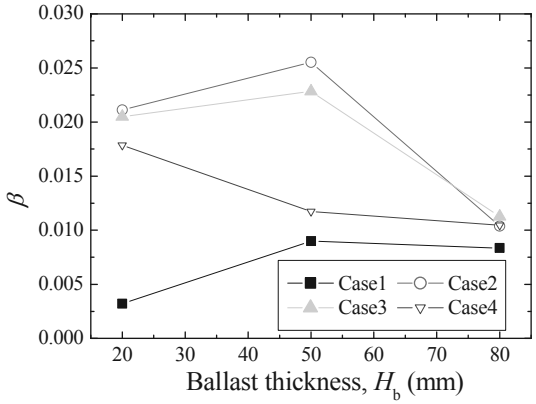

Figure 4. Relationships between gradual subsidence parameter β and ballast thickness H_b before tie-tamper implementation

Figure 4 shows the relationships between the gradual subsidence parameter β and ballast thickness H_b before tie-tamper implementation. It should be noted that 50 mm H_b was used to represent the 250 mm ballast thickness adopted for the standard design because the model size was at a scale of one-fifth. Interestingly, it is seen in the figure that β was highest when H_b = 50 mm in Cases 2 and 3. High β values indicate a substantial amount of gradual settlement; thus, these results suggest that the standard ballast thickness of 250 mm is ineffective for minimal settling.

The residual settlement characteristics were investigated in detail with PIV analysis. First, the displacement magnitude and direction of crushed stones and roadbeds induced by 100 cyclic loadings were estimated by analyzing consecutive digital images. The distributions of maximum shear strain γ_{max} generated in the crushed stones and roadbeds were next calculated. Figures 5 to 7 show the results obtained from Cases 1, 2, and 3. Results could not be obtained from Case 4 because the monotonic color of dark gray Natom sand resulted in ineffective pattern matching of PIV.

As shown in Fig. 5, a high value of γ_{max} was noted in Cases 1-1 and 1-2 until the ground depth reached the bottom steel plate. However, the concentration of γ_{max} could not be observed in Case 1-3 near the bottom steel plate. Similarly, the concentration of γ_{max} could not be observed in the roadbeds for Cases 2-3 and 3-3, as shown in Figs. 6 and 7. These results indicate that when H_b = 80 mm, γ_{max} can be sustained in

roadbeds, which can be explained by the limited distribution of stress applied by the footing with a width of 48 mm.

Except for the cases in which H_b = 80 mm, residual settling of the footing was attributed to total compression of crushed stones and roadbed materials. In general, stress concentration in roadbeds should be higher in the H_b = 20 mm cases than those in the H_b = 50 mm cases. Therefore, owing to the plastic deformation of roadbeds, the highest β value was observed in Case 4, in which H_b = 20 mm, as shown in Fig. 4.

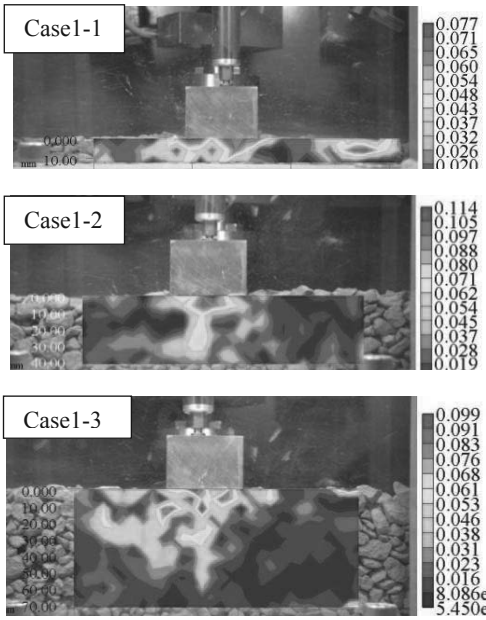

Figure 5. Distribution of maximum shear strain generated before tie-tamper implementation (Case 1)

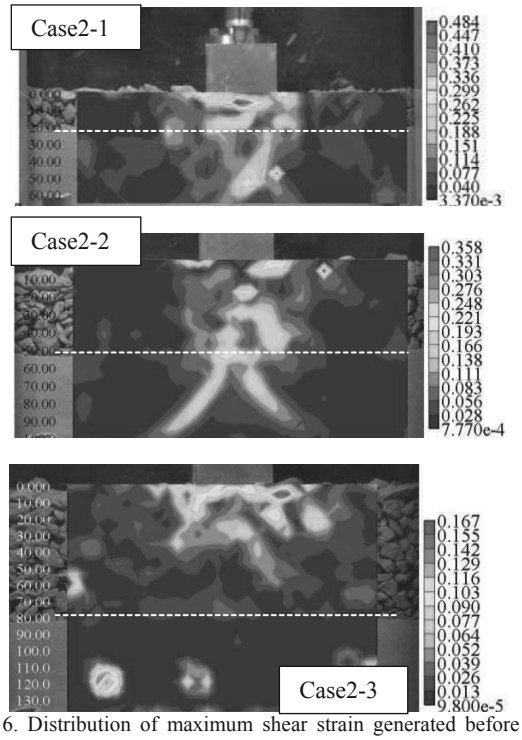

Figure 6. Distribution of maximum shear strain generated before tie-tamper implementation (Case 2)

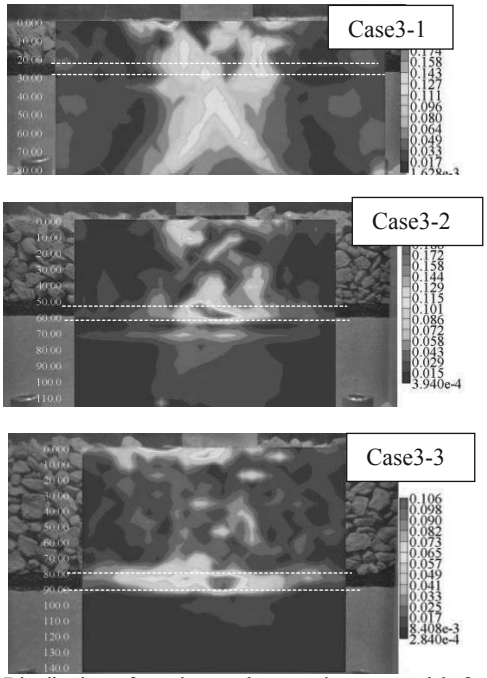

Figure 7. Distribution of maximum shear strain generated before tie-tamper implementation (Case 3)

Conversely, the compression of crushed stones was higher in the H_b = 50 mm cases than those in the H_b = 20 mm cases. If nonlinear compression of roadbeds is relatively moderate, the deformation modulus of the roadbeds changes slightly through the change in stress levels. In this situation, β can be higher in the H_b = 50 mm cases compared to that when H_b = 20 mm.

3.2 Effects of tie-tamper implementation

Figure 8 shows typical relationships between footing settlement and applied stress, represented by convex curves, in Case 1-1 when the 1st, 10th, and 100th cyclic loadings were applied before tie-tamper implementation. In this research, the curves were fitted by bilinear lines, and the slopes of the two lines were estimated as k_1 and k_2. Displacement u_2 was estimated by dividing the applied stress by k_2. The parameter u_2 decreased and tended to show a constant value in each case with an increase in the number of cyclic loadings (Fig. 9). Therefore, these constant values will be used in the following discussion.

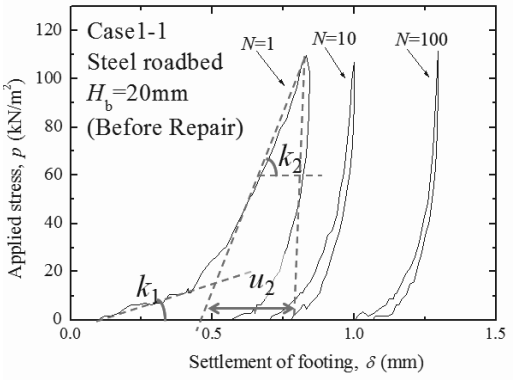

Figure 8. Relationships between footing settlement and applied stress in Case 1-1 before tie-tamper implementation

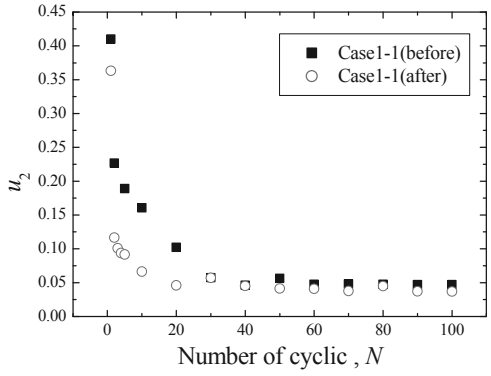

Figure 9. Relationships between displacement u_2 and number of cyclic loadings in Case 1-1 before and after tie-tamper implementation

Parameters u_2, C, α, and β in Eq. 1 were evaluated from 100 cyclic loadings conducted before and after tie-tamper implementation. The relationships between u_2 and the remaining three parameters before and after tie-tamper implementation are shown in Figs. 10, 11, and 12.

Figure 10 shows that α were in the range 0.9–1.5 before tie-tamper implementation regardless of roadbed type and ballast thickness. Here, α represents the duration periods of the initial settlement process (Eq. 1). The figure also shows that α decreased more after tie-tamper implementation than that before. This tendency can be clearly observed when u_2 is higher, which indicates that the duration periods of the initial settlement process increased after tie-tamper implementation.

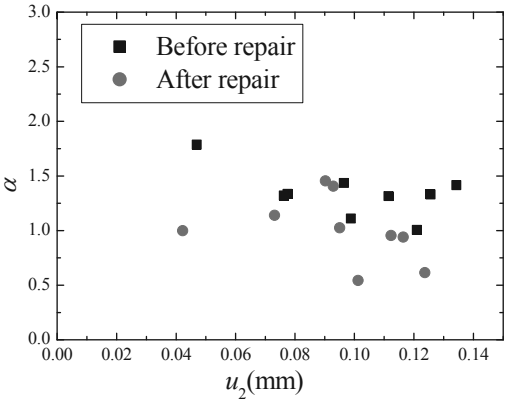

Figure 10. Relationships between displacement u_2 and duration periods of the initial settlement process α

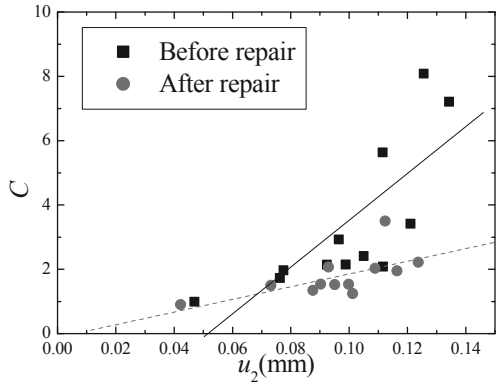

Figure 11. Relationships between displacement u_2 and amount of initial settlement C

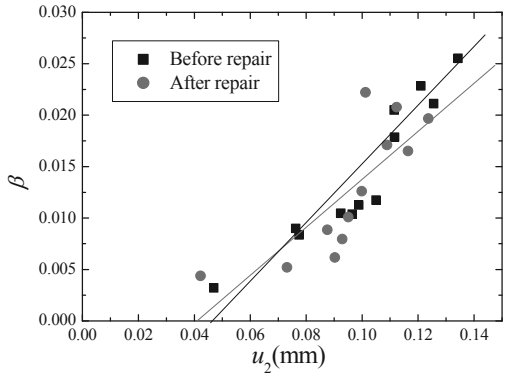

Figure 12. Relationships between displacement u_2 and degree of gradual settlement β

Parameters C and β proportionally increased with an increase in u_2, as shown in Figs. 11 and 12. Here, C represents the amount of initial settlement, and β represents the degree of the gradual settlement. Figure 11 shows a higher decrease in C after tie-tamper implementation than that before. The same tendency was also clearly observed at higher u_2 because roadbeds became denser as a result of cyclic loadings; therefore, the amounts of initial settlement decreased after tie-tamper implementation. Conversely, Fig. 12 shows that β was nearly the same after tie-tamper implementation as that before. These results suggest that although the characteristics of the initial settlement process are significantly altered after tie-tamper repair, the degree of gradual subsidence is minimal regardless of ballast thickness and roadbed type.

4 CONCLUSION

The effects of ballast thickness and tie-tamper repair on the settlement characteristics of ballasted tracks were investigated by conducting a series of cyclic loading tests on model grounds. The following conclusions were derived from this research:

(1) The standard 250 mm ballast thickness is ineffective for minimizing settlement, particularly when the nonlinearity of roadbed compressibility is relatively moderate.

(2) The characteristics of the initial settlement process are altered considerably after tie-tamper implementation; however, the degree of gradual subsidence is minimal regardless of ballast thickness and roadbed type.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

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