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Experimental analysis of ballast bed state in newly constructed railways after tamping and stabilizing operation

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ABSTRACT

Before the operation of newly constructed railways, tamping and stabilizing machines should be used to improve the quality of ballast beds. With the expansion of the railway network and increase of speeds and axle loads, higher quality and efficiency for tamping and stabilizing operation are required. However, previous studies did not involve the effects and parameters of three-sleeper tamping and stabilizing operation under complex working conditions. In the paper, the effect of a three-sleeper tamping and stabilizing machine on the ballast bed state has been studied by performing field experiments. The effect of important factors, including tamping modes, stabilizing frequency, and track lifting amount, are discussed in detail. The results show that the tamping operation on newly constructed railways causes a reduction of the lateral resistance by 56.5 % and a reduction of lateral resistance work by 64.9 %. After the stabilizing operation, the lateral resistance and lateral resistance work are increased by 168.6 % and 209.8 %, respectively. The tamping and stabilizing operation can significantly increase the support stiffness of ballast beds, which meets the requirements of train operation. Meanwhile, 2X tamping mode is more beneficial to improve ballast resistance. Besides, it is reasonable for a stabilizing frequency of 25 Hz to be used for newly constructed railways. The track lifting amount also has a large effect on the ballast bed quality, and it is recommended to keep the lift amount in the range of 20 mm ∼ 30 mm to achieve a better tamping quality.

1. Introduction

In recent years, rail transit infrastructure has been developed rapidly over the world. Due to the advantages of low cost and easy maintenance and repair [1–2], ballast tracks are the most used track structure for new lines, which have been widely adopted by railways in various counties, including heavy-haul railways and high-speed railways in special zones (long bridges, elevated stations, underground goaves, etc.) [3–5]. In general, tamping machines and stabilizing machines are used after the construction of railway lines to regulate track geometry so that the vertical and horizontal resistance of railways are high enough for train operation. Because there are various types of tamping machines and stabilizing machines with the large differences in structures and operation systems, it is usually difficult to reasonably choose operating parameters [6]. As a result, most of the tamping and stabilizing operations for newly constructed railways are only based on experience, which lacks theoretical understanding [7–8] and thus can considerably reduce the efficiency and quality of the tamping and stabilizing operations. Therefore, it is of great significance and economic value to research the effect of tamping and stabilizing operation on the quality of ballast in newly constructed railways.

At present, the research on the tamping and stabilizing operation has become increasingly popular. Many experimental and numerical studies have been conducted to investigate the mechanism of tamping and stabilizing operation and to optimize the operation parameters. In the aspect of experimental research, Kumara and Hayanoda [9] studied the settlement on railway track using a down-scaled test platform and found that the track settlement after the tamping operation is larger than that before tamping operation. Aingaran et al. [10] used triaxial tests to simulate the change of the stress direction in the ballast bed under sleepers caused by the tamping operation. The results show that the tamping operation changes the principal stress direction of ballast bed,

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which leads to the decrease of vertical stiffness and bearing capacity. Koc et al. [11] studied the correctness of measurement of the lateral resistance of ballast beds using the lift device of tamping vehicles. Mcdowell et al. [12] analyzed the influence of the number of tamping operations on the ballast settlement under cyclic loads using a ballast box model. Przybyłowicz et al. [13] studied the difference in the density and cumulative settlement of ballast beds under vertical and side directions using a down-scaled model. The results show that the settlement pace after vertical tamping is higher than that after side tamping. Liu et al. [14] conducted a track bed resistance test on a newly constructed railway and analyzed the correlation between the operation number of a two-sleeper tamping machine (DC-32 k) and the longitudinal and lateral resistance of ballast beds. The results show that the resistance of ballast beds decreases as the operation number increases. After the first tamping operation, the longitudinal and lateral resistance of the ballast bed decreased by 3.0 % and 4.3 % respectively, and the stiffness and damping increased by 21.5 % and 43.8 % respectively. Wang et al. [15] used a ballast box and small vibrator to simulate the stabilizing operation and analyzed the settlement, lateral resistance, and compactness of ballast beds at various frequencies. The results show that a high excitation frequency (36 Hz ~ 40 Hz) is detrimental to ballast stabilizing. Offenbacher [16] and Barbir [17] developed a measurement system of multi-sleeper tamping machines, and obtained the ballast energy and stiffness of ballast bed under sleeper in the tamping process through the analysis of measured data. Yan et al. [18] carried out field lateral resistance tests at different stabilizing frequencies, and analyzed the relationship between stabilizing operation frequency and lateral resistance of ballast bed. The results show that the working frequency of field stabilizing operation should not exceed 30 Hz.

The above experimental research mainly uses down-scaled models to analyze the effect of the tamping operation on the mechanical properties of ballast beds. However, the effect of the tamping operation, in reality, can be very different due to the interference of the boundary and size of models. Besides, the effect of the tamping operation is highly dependent on the type of machine. Although the stiffness and resistance tests of tamping and stabilizing operation bed were carried out in previous studies, the analyzed conditions were relatively simple, and tamping operation and stabilizing operation were considered separately. This leads to the influence of three-sleeper tamping and stabilizing operation on the state of ballast bed is still unknown.

In the aspect of numerical simulation, Shi et al. [7–8,24] developed a numerical model of a two-sleeper tamping machine (DCL-32) and ballast bed to analyze the effect of the tamping operation on the ballast density and crushing of ballast particles. Moreover, it is also pointed out that with the increase of the amount of track lifting, the stiffness and lateral resistance of the ballast bed after the tamping operation gradually decrease. Saussine et al. [19–20] conducted a model of a small tamping unit and ballast box to study the correlation between the frequency of tamping and ballast compactness. The results show that the optimal vibration frequency of tamping pick is 35 Hz [21–22]. Wang et al. [23] developed a dynamic model of a tamping system using EDEM software to analyze the dynamic response of ballast particles during the tamping process. The results show that vibration characteristics of ballast particles are largely related to particle shapes. Kaewunruen and Remennikov [25] utilized finite element software to analyze the influence of uneven stiffness of ballast bed on the stress characteristics of sleepers after tamping operation. The results show that the asymmetric ballast bed support state can increase the vibration characteristics of sleepers. Zhang et al. [26] established a simulation model of three-sleeper tamping operation considering the characteristics of ballast resistance, and analyzed the influence of tamping operation on the resistance and compactness of ballast bed. The results show that the three-sleeper tamping operation can reduce the lateral resistance of ballast bed by 50.50 %, the lateral resistance work by 50.04 %, and the compactness of ballast bed in the crib area is greatly reduced. Unfortunately, only special conditions were studied, which cannot fully reflect the effect of tamping operation. Li et al. [27] developed a stable machine-track panel model by using bond graph theory, and analyzed the working principle of the hydraulic system of the stable machine. The results show that increasing the hydraulic resistance value can improve the working efficiency of the stabilizing operation. However, it should be noted that the process does not consider the role of ballast bed.

Although the above-mentioned numerical simulation studies have analyzed the effect of tamping and stabilizing operations on the mechanical properties of ballast beds from a microscopic perspective, the validation has been rarely conducted. Thus, it is still necessary to investigate whether numerical studies' findings can explain macroscopic phenomena. Furthermore, Zakeri [28–30], Esmaeili [31] and Jing [32] analyzed the lateral resistance of different types of sleepers, proposed the enhancement method of the lateral resistance of the ballast bed, and explored the sensitivity of the parameters affecting the lateral resistance, including the thickness and width of the ballast shoulder, the friction coefficient between the ballast bed and the sleeper. These studies show that the ballast bed resistance plays an important role in evaluating the state of the railway lines, so it is necessary to focus on the evolution of ballast bed resistance when analyzing the influence of three-sleeper tamping and stabilizing operation on ballast bed state.

Due to the gap in existing studies, this paper intends to conduct a field experiment analysis on the effect of a three-sleeper tamping and stabilizing machine on the mechanical properties of ballast beds. The longitudinal and lateral resistance and support stiffness of ballast beds are first tested in the field. After that, the correlation between the resistance and stiffness of ballast beds and the tamping and stabilizing operation is analyzed. Besides, the tamping performance of 2X tamping mode and 1X tamping mode is compared. At last, the correlation between lifting amounts and lateral resistance of ballast bed is studied and the optimal tamping frequency is discussed. The paper can provide guidance and selection of operation mode and operation parameters for newly constructed railways as well as field verification for numerical studies.

2. Field tests

2.1. Test site

The tested line is located near Fengtai Station in Beijing, China, at $k11 + 500$ m. The field photo is shown in Fig. 1(a). The design standard of the railway is according to the Class-I of new railway lines in China, wherein the ballast gradation is shown in Fig. 2(a). The track is composed of CHN60N rail (60 kg/m), the Type-I fastener system, and the New Type-II concrete sleeper. The length, middle-section height and space of the sleeper are 2500 mm, 175 mm and 600 mm, respectively. The thickness of the ballast bed is 300 mm, the width of the ballast shoulder is 400 mm, and the top width of the ballast bed is 3300 mm, as shown in Fig. 2(b) and (c).

The DWL-48 tamping and stabilizing machine used in the test is consist of a tamping machine and a stabilizing machine, as shown in Fig. 1(b). The length, width, and height of the vehicle are 33990 mm, 3050 mm, and 4130 mm, respectively. Its weight is 129 t and the operational speed is 1 km/h. The maximum track lifting amount of the vehicle is 150 mm and the maximum track shifting amount is $\pm$ 150 mm. The pressure range of the external squeezing cylinder is 10 MPa. The pressure of the inner squeezing cylinder is 13 MPa. The pressure of the 3rd squeezing cylinder is 11.5 MPa. The height tamping tine is 70 mm and the thickness at the tip of tamping tine is 10 mm. The width of the half and full tamping tine are 100 mm and 140 mm, respectively. The vibration frequency of the tamping unit is 35 Hz. The vibration amplitude of tamping tines is 10 mm. The tamping time is 1.8 s and the tamping depth is 360 mm. The track lifting amount in the test was subject to on-site measurement data, which ranged from 11 mm to 47 mm, approximately. The vertical force of the stabilizing machine is 2×72 kN, the maximum vibration force is 235 kN, and the vibration

Fig. 1. Test site and tamping and stabilizing machines: (a) test site, (b) DWL-48 tamping and stabilizing machine.

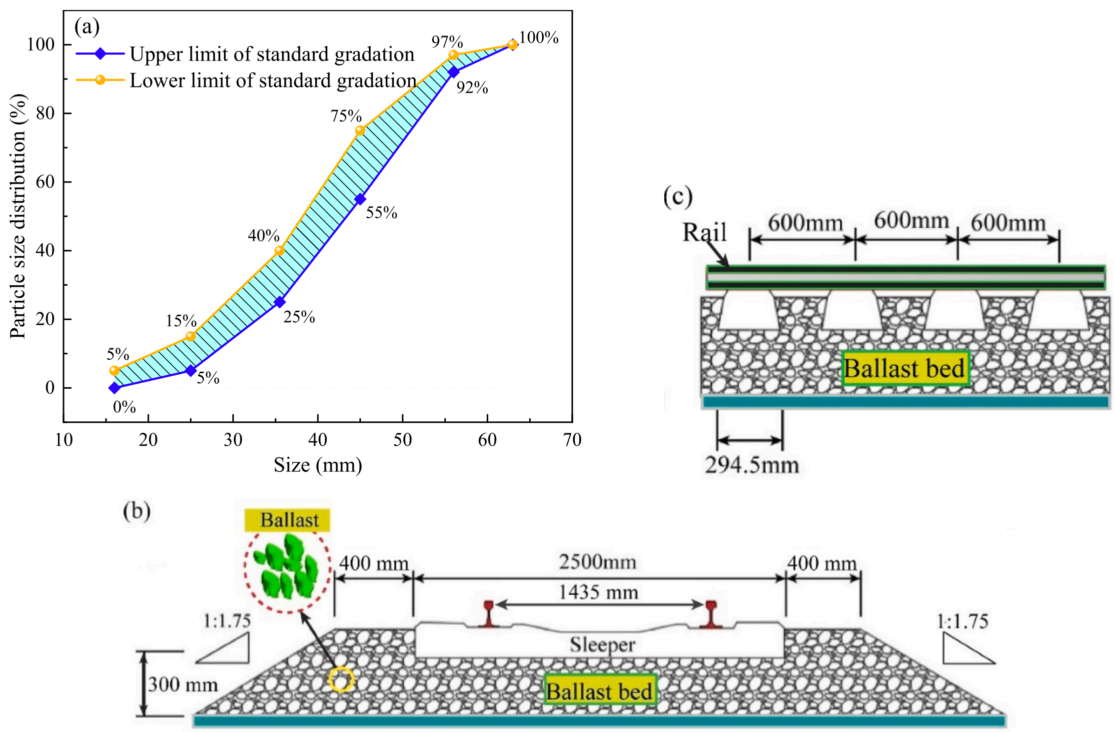

Fig. 2. Structure of tested track: (a) ballast gradation, (b) cross-section of track, (c) side view of track.

frequency is in the range of 0 Hz ~ 42 Hz. During the test, the vertical pressure of the single-side cylinder of the stabilizing machine was 5.5 MPa and the range of the vibration frequency was 20 Hz ~ 30 Hz.

The DWL-48 tamping and stabilizing machine can simultaneously carry out dynamic stability and ballast shoulder compaction after tamping operation, and quickly make the newly constructed railways meet the technical standards. This test aims to study the impact of tamping and stabilizing operation on the quality of ballast bed. Therefore, DWL-48 tamping and stabilizing machine only tamps and is unstable when passing through the test section. After the test of ballast bed resistance and support stiffness is completed, it can carry out stabilization operation separately, and test the ballast bed state.

2.2. *Test method*

2.2.1. *Resistance test*

The setup of ballast resistance tests are shown in Fig. 3(a) and 3(b). The tests were conducted on every other 3 sleepers to avoid mutual interference between lateral resistance tests and longitudinal resistance tests. The tests followeded the method of longitudinal and lateral resistance in References [33–35] and three independent repeated tests were carried out at each sleeper to achieve reliable measurement data. The previous studies [36–37] shows that the resistance of ballast bed increases gradually with the increase of sleeper displacement. However, when the sleeper displacement reaches 2 mm, the resistance increases slowly and gradually becomes stable. To reasonably obtain the resistance characteristics of the ballast bed, according to the Reference [40], this paper analyzes the experimental results by taking the resistance that needs to be overcome when the longitudinal or lateral displacement of a

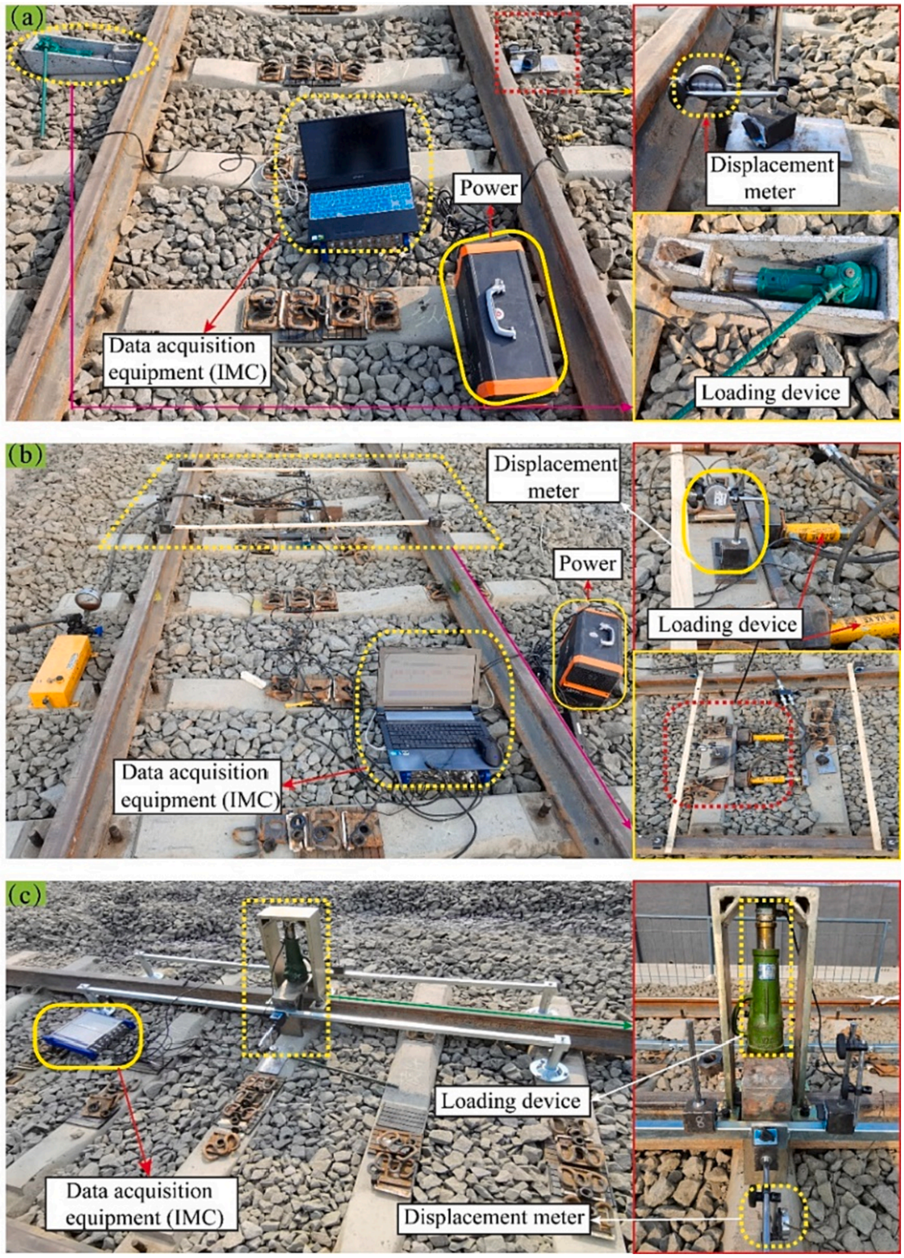

Fig. 3. Test equipment installation: (a) lateral resistance, (b) longitudinal resistance, (c) support stiffness.

single sleeper is 2 mm as the evaluation quantity of the longitudinal or lateral resistance of the ballast bed.

2.2.2. Support stiffness test

When testing the support stiffness of ballast beds, the fasteners and pads of the tested sleeper were first removed. After that, the high-precision displacement meters were installed on both sides of a rail and a loading device was installed above the rail as shown in Fig. 3(c).

During the test, the loading device applied a load on the test sleeper, which was measured by a pressure sensor. At the same time, the vertical displacement of the test sleeper was collected by displacement meters. After that, the support stiffness of the ballast bed, at the initial state, after tamping, and after stabilizing, can be calculated using Eq. (1).

$$k_1 = \frac{p_1 - p_0}{x_1 - x_{01}} \tag{1}$$

Where k_1 is the support stiffness of the ballast bed; p_1 is the load of 35 kN; p_0 is the load of 7.5 kN; x_1 is the average vertical displacement of the sleeper corresponding to 35 kN; x_{01} is the average vertical displacement of the sleeper corresponding to 7.5 kN.

To further analyze the effect of tamping and stabilizing operation on the elasticity of ballast beds, the rebound displacements of the ballast bed in the unloading stage were collected. The rebound stiffness of the ballast bed is calculated by Eq. (2).

$$k_2 = \frac{p_1 - p_0}{x_2 - x_{02}} \tag{2}$$

Where k_2 is the support stiffness of the ballast bed; x_2 is the average vertical displacement of the sleeper under corresponding to 35 kN in the unloading stage; x_{02} is the average vertical displacement of the sleeper corresponding to 7.5 kN in the unloading stage.

2.3. Test cases

During the test, each tamping operation and stabilizing operation are separated by 1 day and the three tamping and stabilizing operations are conducted on the tested track. The first tamping operation used the 2X mode (the tamping unit inserts twice). The second tamping operation used the 1X mode (the tamping unit inserts once). The third tamping operation used the 2X mode again. To study the effect of the stabilizing frequency on the quality of ballast beds, the vibration frequency of the first stabilizing operation was set to 30 Hz, the second time 25 Hz, and the third time to 20 Hz. The detailed parameter of the tamping and stabilizing machine under various cases are shown in Table 1.

3. Results and discuss

3.1. Ballast bed quality during tamping and stabilizing operation

3.1.1. Ballast bed resistance characteristics

The ballast resistance is crucial to counter the expansion and contraction of rails and to prevent rail bulging after the operation of newly constructed railways, which is used as the main indicator to assess tamping operation [11]. The lateral resistance R_s of ballast beds is mainly composed of the resistance R_b at the bottom of sleepers, the resistance R_e at the ends of sleepers, and the resistance R_c at the sides of sleepers. The longitudinal resistance R_{sL} is mainly composed of the resistance R_{bL} at the bottom of sleepers, the resistance R_{eL} at the ends of sleepers, and the resistance R_{cL} at the sides of sleepers, as shown in Fig. 4.

To study the effect of a tamping and stabilizing operation on the lateral and longitudinal resistance of ballast beds, resistance and resistance work of ballast beds at various displacements in the initial state, after tamping, and after stabilizing are drawn as shown in Fig. 5 and Fig. 7. Besides, the logistic regression analysis is conducted according to Eq. (3) [38–39] and the fitting using polynomial nonlinear function is conducted according to Eq. (4). Furthermore, the change in the longitudinal and lateral resistance of ballast beds before and after the tamping and stabilizing operation is also calculated.

$$R_s(R_sL) = b - \frac{b-a}{(1+(\frac{d}{d_o})^p)} \quad (3$$

$$w_s(w_{sL}) = w_o + c_1 d + c_2 d^2 \quad (4$$

Where d is the lateral or longitudinal displacement of the sleeper; a, b, d_0, c_1, c_2 and p are fitting parameters, which should be reasonably selected according to the characteristics of the resistance of ballast beds; w_o is the constant in the lateral or longitudinal resistance work, which depends on the initial contact state between the sleeper and ballast.

Table 1
Test cases.

Tamping/ stabilizing operation	Research target			
	Reference case	Tamping method	Track lift amount	Stabilizing frequency
Tamping method	2X mode	1X mode, 2X mode	2X mode	1X mode, 2X mode
Track lift amount (mm)	39	34 (Lateral resistance)36 (Longitudinal resistance)	18, 23, 34, 41, 47	36
Insertion under sleeper bottom (mm)	10 ~ 15	10 ~ 15	10 ~ 15	10 ~ 15
Squeezing time (s)	0.8	0.8	0.8	0.8
External squeezing cylinder pressure (MPa)	10	10	10	10
vertical pressure (MPa)	5.5	5.5	5.5	5.5
Stabilizing frequency (Hz)	30	–	–	20, 25, 30

As seen from Fig. 5, with the gradual increase of sleeper lateral displacement, the variation and trend of ballast bed lateral resistance and resistance work before and after tamping are relatively similar, and they are positively correlated with sleeper displacement. Also, the slopes of the curves of lateral resistance and lateral resistance work after tamping are both smaller than that in the initial state and after stabilizing, which is reasonable since ballast beds are disturbed by the tamping operation.

As seen from Fig. 5, the lateral resistance of the ballast bed is 8.86 kN in the initial state and reduces to 3.85 kN after tamping operation, and later increases to 10.34 kN after stabilizing operation. The tamping operation causes a reduction of the lateral resistance by 56.5 %, while stabilizing operation leads to an increase of 168.6 %. Thus, if the stabilizing operation is conducted immediately after the tamping operation, the lateral resistance of the ballast bed can be increased by 16.7 %. The above results are consistent with some conclusions of literature [14,26], which indicate that tamping operation can reduce the lateral resistance of the ballast bed. A similar trend can be found in the changes of the lateral resistance work. The lateral resistance work of the ballast bed is 13.38 J in the initial state, 4.69 J after the tamping operation, and 14.53 J after the stabilizing operation. The resistance of the ballast bed to the lateral deformation is reduced by 64.9 % after tamping and increased by 209.8 % after stabilizing. Compared to the initial state, the lateral resistance work is increased by 8.6 % after stabilizing.

The changes show that the tamping operation disturbs the lateral stability of ballast beds and reduces the capability of resistance to lateral deformation, while stabilizing operation can improve the quality of ballast beds. The reason is that the ballast particles at the sides of the sleeper are pushed to the bottom of the sleeper by tamping tines during the tamping operation. The ballast particles at the sides of the sleeper are reduced and, consequently, the ballast density at the sides of the sleeper reduces, which leads to a decline in the lateral resistance of the ballast bed, as shown in Fig. 6(a), (b) and (c). When the tamping operation is over, the sleeper falls freely under gravity and contacts ballast particles again. At that moment, the contact area between the sleeper and the ballast decreases due to the gap in the middle of the sleeper, as shown in Fig. 6(c). Later, due to the vertical pressure and lateral vibration in the stabilizing operation, the contact area between the sleeper and ballast bed gradually increases and the interaction between ballast particles amplifies, leading to restraint at the bottom, ends and sides of the sleeper increase and consequently improved the lateral resistance and lateral resistance work of ballast, as shown in Fig. 6(d).

It can be seen from Fig. 7 that the longitudinal resistance and longitudinal resistance work of the ballast bed continue to increase as the longitudinal displacement of the sleeper grows, which is similar to the trend of the lateral resistance of the ballast bed. The longitudinal resistance is 9.18 kN in the initial state, 8.35 kN after the tamping operation, and 14.87 kN after the stabilizing operation, which is reduced by 9.0 % by tamping operation, and increased by 78.1 % by stabilizing. Compared to the initial state, the longitudinal resistance is increased by 62.0 %. Besides, the longitudinal resistance work is 13.48 J, reduces to 11.74 J (by 12.9 %) after tamping operation, and increased to 20.16 J (by 71.7 %). Compared to the initial state, the longitudinal resistance work is increased by 49.5 %. It shows that during the tamping and stabilizing operation of the newly constructed railway, the tamping operation will weaken the longitudinal resistance and longitudinal resistance to deformation of the ballast bed, while the stabilizing operation will greatly improve them.

3.1.2. Ballast bed stiffness characteristics

The support stiffness of ballast beds is an important indicator for evaluating the bearing capacity and elasticity of ballast beds of a new line [14]. According to Eqs. (1) and (2), the support stiffness and the rebound stiffness of the ballast bed in the initial state, after the tamping, and after stabilizing are obtained. The load and displacement curves of the sleeper are drawn in Fig. 8, wherein the dissipation energy (U_d),

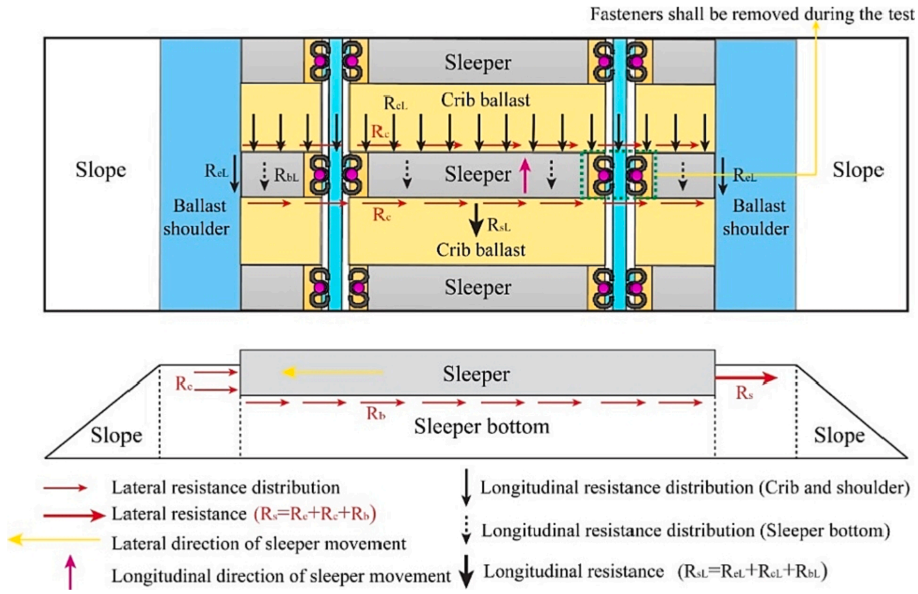

Fig. 4. Composition of longitudinal and lateral resistance of ballast beds.

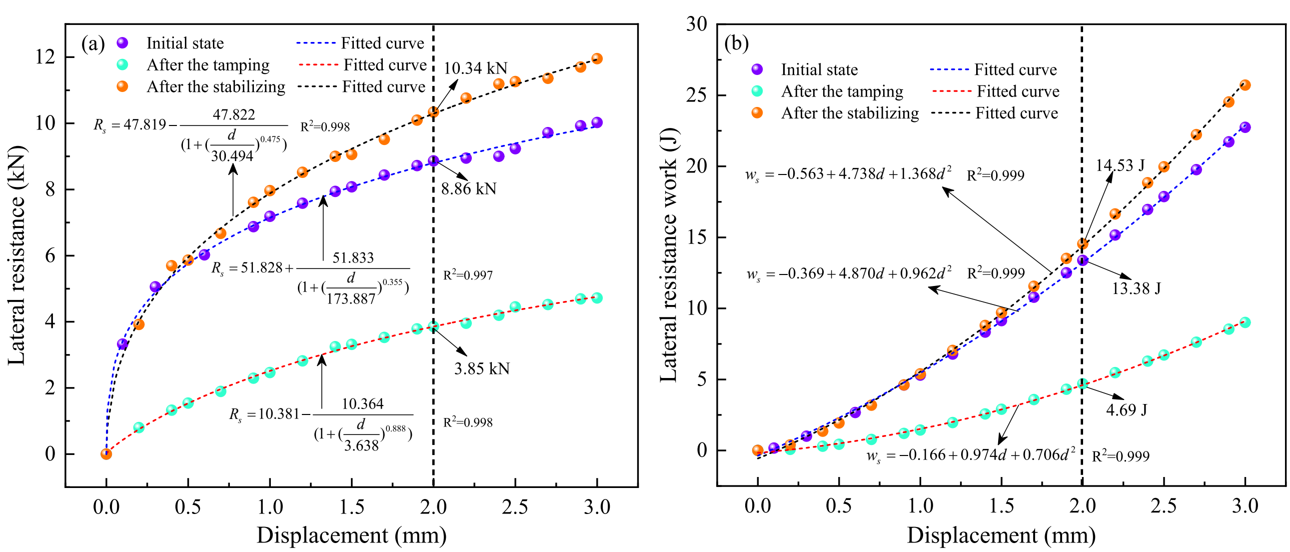

Fig. 5. Results of lateral resistance test: (a) lateral resistance, (b) lateral resistance work.

elastic strain energy of the ballast bed (U_s), and the total energy (U_t) are calculated. It should be noted that the dissipation energy U_d is the area of the closed region ABC obtained by numerical integration, the elastic strain energy U_s is the area of the closed region BCD, and the total energy U_t is the area of the closed region ABD.

It can be seen from Fig. 8(a) that the support stiffness of the ballast bed is 4.9 kN/mm in the initial state, 53.9 kN/mm after tamping, and 82.9 kN/mm after stabilizing, which are 10 times and 15.9 times higher than in the initial state, respectively. This is in good agreement with the research results of References [10,14], which indicates that the first tamping operation for the new railway can increase the stiffness of ballast bed. Furthermore, the rebound stiffness of the ballast bed is 16.1 kN/mm in the initial state, 190.9 kN/mm after tamping operation, and 156.6 kN/mm after stabilizing operation, which are 10.8 times and 8.7 times higher than in the initial state, respectively. It shows that the support stiffness of track beds in newly constructed railways can be significantly improved by the the first tamping and stabilizing operation. However, the amplitude of the increase in the stabilizing operation is larger. The reason is that the newly built ballast bed is loose, the bite between ballasts is not tight, and the compactness is low. Although tamping operation can increase the stiffness of the ballast bed, it can only improve the compactness of some areas due to the limited tamping operation region. The dynamic stability is a large area operation process under the action of the vertical pressure and horizontal excitation force of the entire track panel, which has a stronger role in improving the support stiffness of the ballast bed. In addition, The changes of rebound stiffness are similar to that of the support stiffness in the initial state and after tamping, while the growth of rebound stiffness is lower than that of support stiffness after stabilizing. Further comparison shows that the ratio of rebound stiffness to support stiffness of ballast bed in initial state is 3.28, 3.54 after tamping operation and 1.9 after stabilizing operation, which indicates that stabilizing operation can improve the elasticity of ballast bed.

From Fig. 8(b)~(d), the dissipation energy of the ballast bed in the initial state accounts for 74.7 %, while the elastic strain energy accounts for 25.3 %. After the tamping operation, the dissipation energy accounts for 80.8 %, while the elastic strain energy accounts for 19.2 %. After the stabilizing operation, the proportion of dissipation energy becomes 57.9

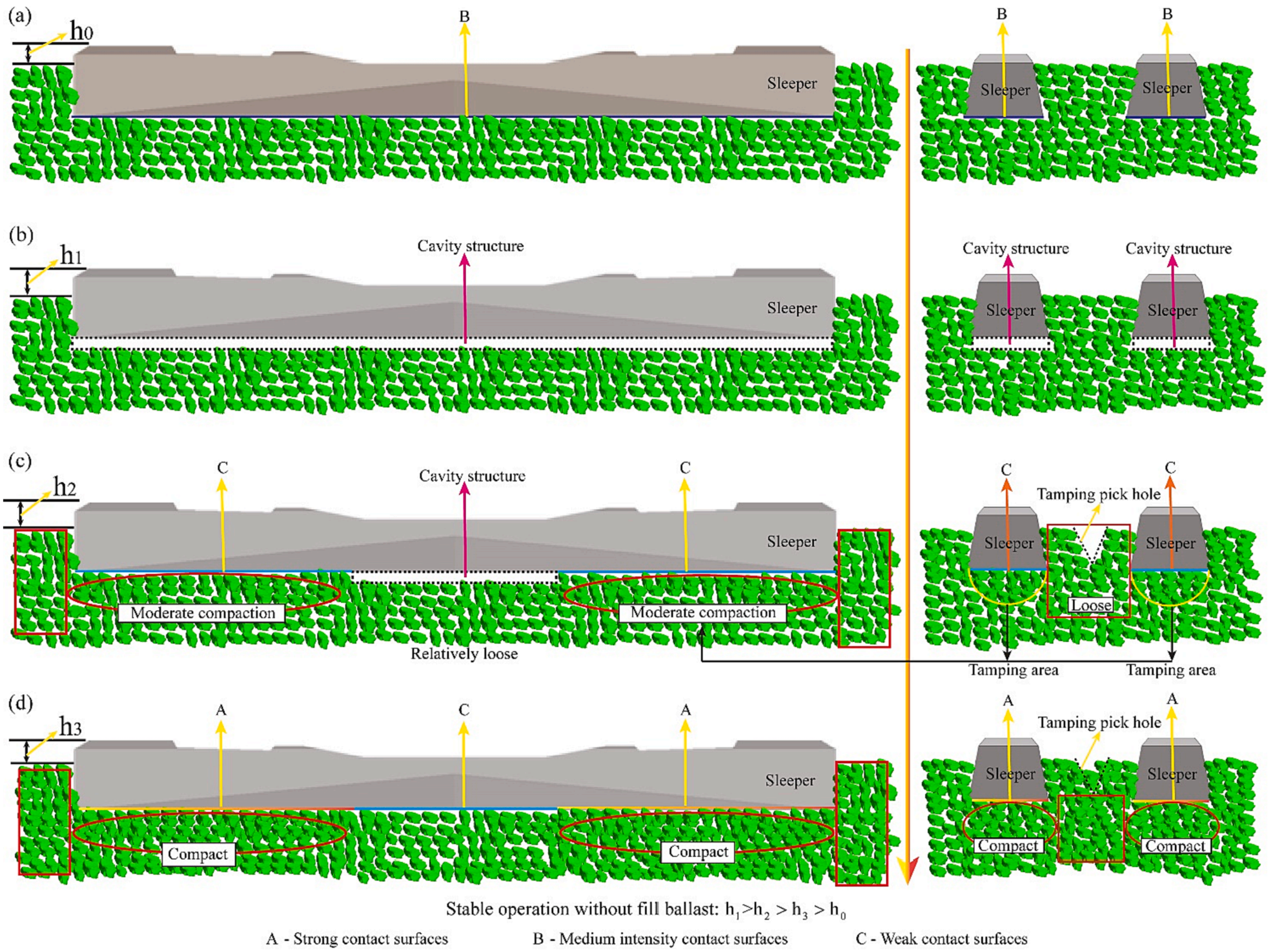

Fig. 6. Diagram of ballast compactness change during tamping operation: (a) initial state, (b) state after lifting, (c) state after tamping, (d) state after stabilizing.

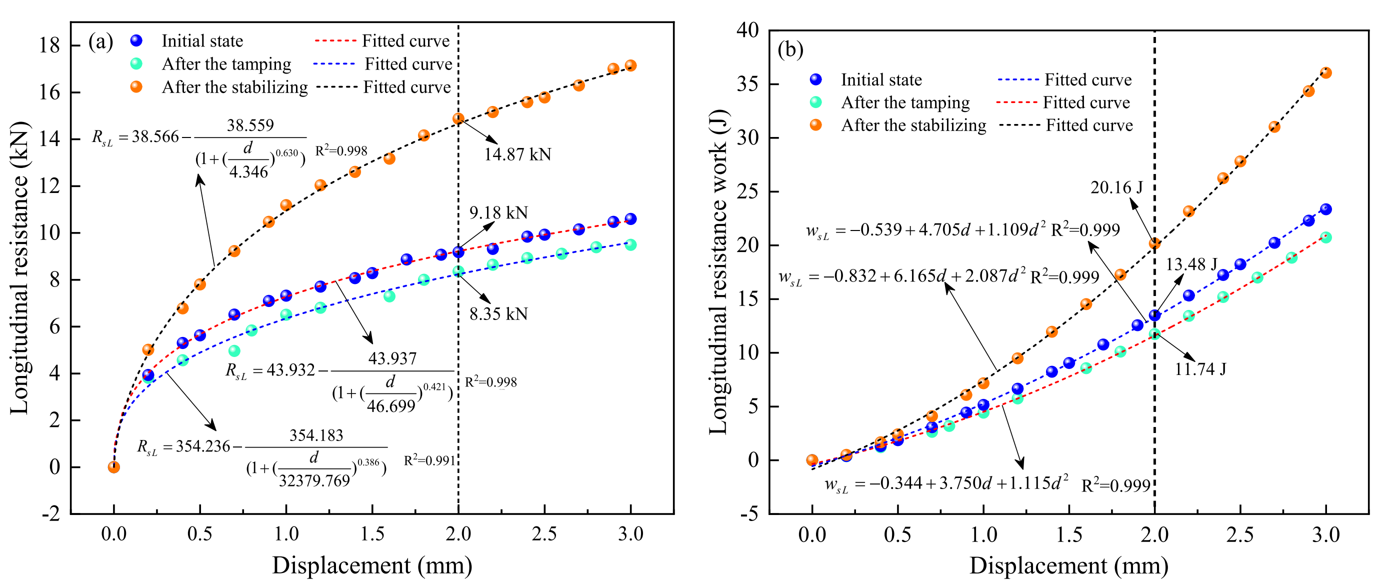

Fig. 7. Results of longitudinal resistance test: (a) longitudinal resistance, (b) longitudinal resistance work.

%, while the proportion of elastic strain energy is 42.1 %. This indicates that the tamping operation on newly constructed railways enhances the capacity of energy dissipation of ballast beds, while the stabilizing operation enhances the elasticity of ballast beds.

3.2. Effect of tamping modes

The tamping modes may have different effects on ballast beds. At present, 2X mode and 1X mode are commonly used in the tamping

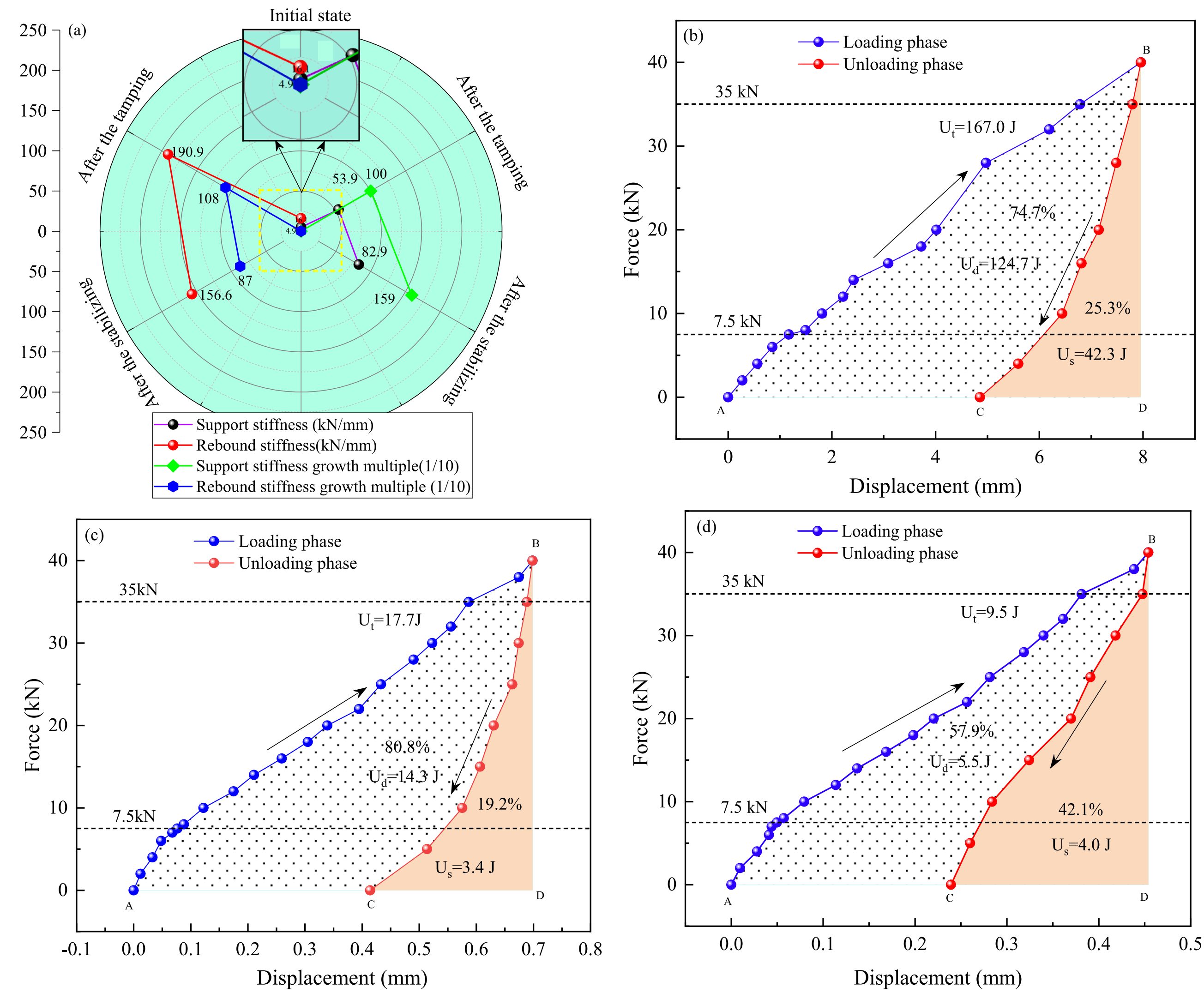

Fig. 8. Changes in support stiffness and energy of ballast bed: (a) change of support stiffness, (b) initial state, (c) state after tamping, (d) state after stabilizing.

operation on site. The relationship between ballast bed resistance, resistance work and sleeper displacement are calculated, as shown in Figs. 9 and 10.

From Fig. 9, the lateral resistance of the ballast bed in the case of 1X tamping mode is reduced by 74.6 % and the lateral resistance work is reduced by 10.45 J, by 69.3 %. On the contrary, the lateral resistance of the ballast bed in the case of 2X tamping mode is reduced by 17.4 % and the lateral resistance work is reduced by 16.9 %, the reduction of which are both smaller than that in the 1X tamping mode. When the sleeper displacement is less than 0.35 mm, the lateral resistance under the 2X tamping mode is larger than that in the initial state, which shows the 2X tamping mode is more conducive to maintaining the lateral resistance of ballast beds. The reason is that the tamping tines hold the ballast under sleepers for a longer time in the 2X tamping mode. As a result, the ballast particles between sleepers are filled into the space under the sleeper bottom. Due to the same reason, the ballast density under sleepers is increased, constraining effect of ballast beds at the sleeper bottom is enhanced, leading to a smaller reduction of ballast resistance and ballast resistance work.

From Fig. 10, the longitudinal resistance of the ballast bed under the 1X tamping mode is reduced by 30.9 % and the longitudinal resistance work is reduced by 30.6 % (6.16 J). However, the longitudinal resistance and longitudinal resistance work of the ballast bed under the 2X tamping mode is reduced by 36.1 % and 37.1 %, respectively, which are larger than that under the 1X tamping mode. Therefore, it can be seen that the 1X tamping mode is more effective than the 2X tamping mode for the longitudinal resistance. According to reference [40], the longitudinal resistance of ballast beds after tamping should be larger than 10 kN/mm. Because the longitudinal resistance is high in the initial state, the longitudinal resistance after tamping is 10.7 kN/mm and thus still meets the requirement. Further comparison between Fig. 9 and Fig. 10 shows that the difference between the attenuation rate of lateral resistance under 2X tamping mode and 1X tamping mode is 57.2 %, while the difference between the attenuation rate of longitudinal resistance is 5.2 %. and the difference is nearly 10 times. This shows that different tamping modes have greater influence on lateral resistance. Therefore, it is suggested that lateral resistance should be considered as the main factor in the evaluation of the tamping quality of newly constructed railways.

In summary, tamping modes have a larger impact on the lateral resistance of ballast beds and the 2X tamping mode is more favourable to maintain the lateral resistance of ballast beds. It is suggested that the 2X tamping mode should be adopted in the tamping operation of newly constructed railways and ballast should be supplemented in time.

3.3. *Effect of stabilizing frequency*

The operating frequency of the stabilizing unit affects the quality of ballast beds. To study the effect of different stabilizing frequencies on

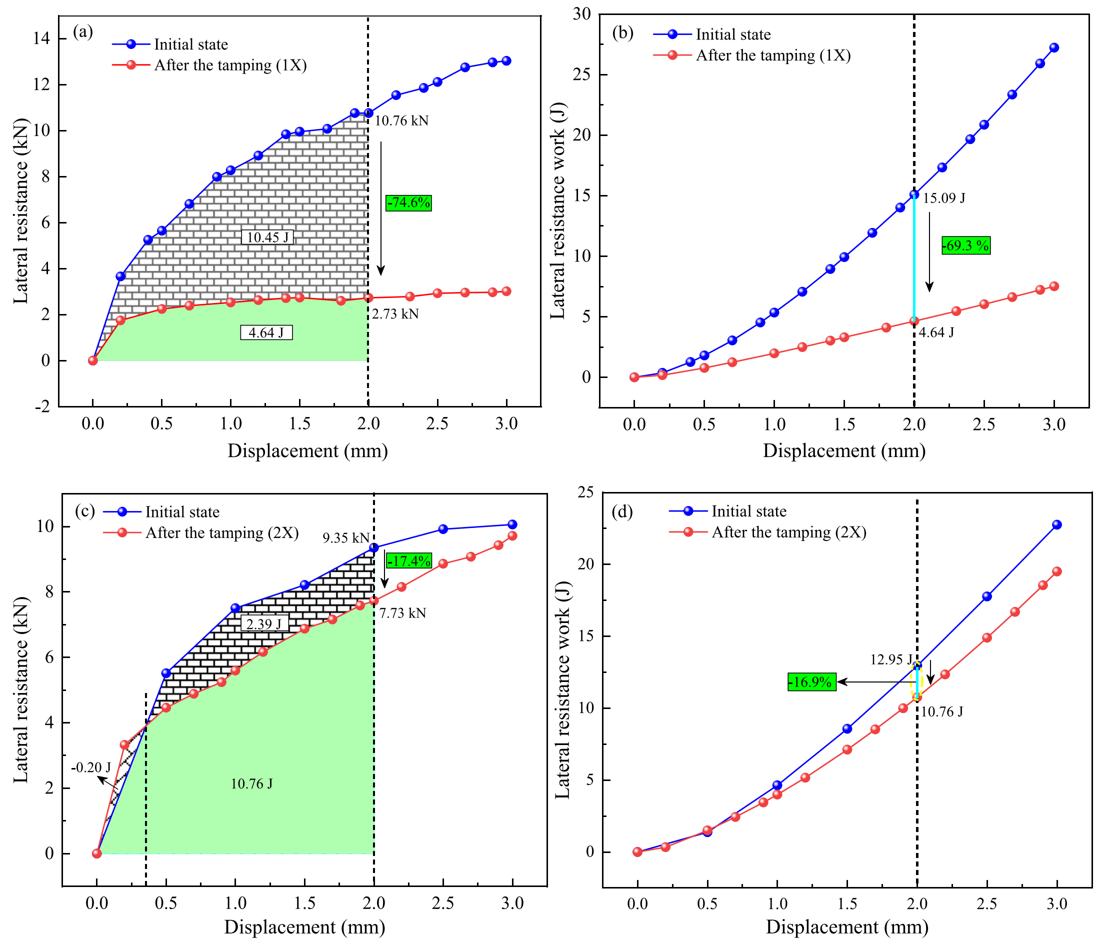

Fig. 9. Effect of tamping modes: (a) ballast lateral resistance in 1X tamping mode, (b) ballast lateral resistance work in 1X tamping mode, (c) ballast lateral resistance in 2X tamping mode, (d) ballast lateral resistance work in 2X tamping mode.

the longitudinal and lateral resistance of ballast beds, the relationship between the longitudinal and lateral resistance, resistance work and sleeper displacement of ballast beds under three different stabilizing frequencies (20 Hz, 25 Hz, 30 Hz) are analyzed, as shown in Fig. 11.

From Fig. 11(a) and (c), with the stabilizing frequency grows, the changes in the lateral and longitudinal resistance of the ballast bed first increases and then decreases. When the stabilizing frequency is 20 Hz, the increase of the lateral and longitudinal resistance are 4.32 kN and 5.22 kN, respectively. When the stabilizing frequency is 25 Hz, the increase of the lateral and longitudinal resistance are 7.25 kN and 9.61kN, respectively. When the stabilizing frequency is 30 Hz, the increase of the lateral and longitudinal resistance are 6.49 kN and 5.69 kN, respectively. It can be found that the increase of lateral and longitudinal resistance is the highest when the stabilizing frequency is 25 Hz.

As seen from Fig. 11(b) and (d), the increase of lateral resistance work becomes larger as the stabilizing frequency grows, while the increase of longitudinal resistance work first becomes larger and then smaller. The inflection point again appears at 25 Hz, wherein the increase reaches 14.65 J. This shows that a high stabilizing frequency is beneficial to improve the lateral and longitudinal deformation resistance of ballast beds, but the improvement of lateral resistance work is limited when the stabilizing frequency exceeds 25 Hz.

To further analyze the effect of stabilizing frequency on the growth rate of the ballast resistance and resistance work, a bar graph of the growth rate of the ballast resistance work is calculated as shown in Fig. 12.

From Fig. 12(a), the growth rate of lateral resistance and lateral resistance work of ballast beds first increases then decreases as the stabilizing frequency grows. The largest growth rate appears at 25 Hz, the lateral resistance increased by 2.2 times, and the growth rate of lateral resistance work is consistent with the finding in Fig. 11 (b). As seen from Fig. 12(b), the growth rate of longitudinal resistance and resistance work also shows the pattern of first increasing then decreasing. The growth of longitudinal resistance and resistance work are largest at 25 Hz, which are 93.57 % and 104.6 %, respectively. The reason is that newly constructed railways have not been compacted by train loads. In this case, ballast beds are loose and the bite effect between ballast particles is weak, resulting in that a lower stabilizing frequency can achieve a better effect than a higher stabilizing frequency. Therefore, it is suggested that a stabilizing frequency of 25 Hz should be used during stabilizing operations for newly constructed railways.

3.4. Effect of track lifting amount

The track lifting amount is an important parameter of the tamping operation. Different track lifting amounts causes changes in the gap between the sleeper bottom and ballast, which affects ballast particle moving from sleeper space to sleeper bottom and consequently may affect tamping quality. According to Sections 3.1.1 and 3.2, it is known that the longitudinal resistance of ballast beds is larger than the lateral resistance after the tamping. And the tamping operation has a larger effect on the lateral resistance of ballast beds. Based on this, the variation curve of the lateral resistance of the ballast bed with the lateral displacement of the sleeper under the condition of stabilizing first and then tamping is drawn for different track lifting amounts (18 mm, 23 mm, 34 mm, 41 mm, and 47 mm), as shown in Fig. 13.

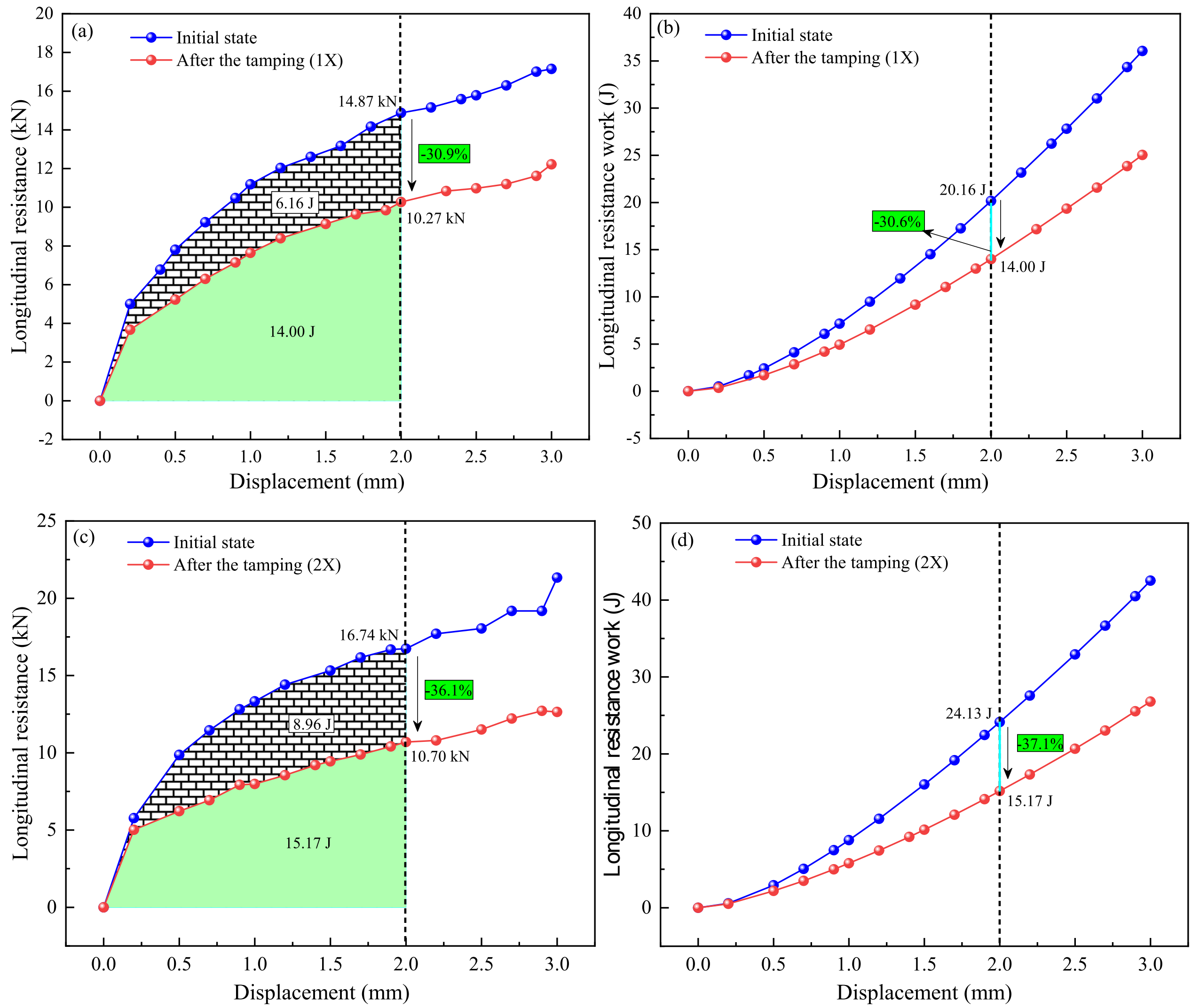

Fig. 10. Effect of tamping modes: (a) ballast longitudinal resistance in 1X tamping mode, (b) ballast longitudinal resistance work in 1X tamping mode, (c) ballast longitudinal resistance in 2X tamping mode, (d) ballast longitudinal resistance work in 2X tamping mode.

It can be seen from Fig. 13 (a) that with the increase of track lifting amount, the reduction amplitude of lateral resistance of track bed gradually increases, while the reduction of the lateral resistance work shows a trend of increasing–decreasing-increasing. It is worth noting that the variation of the lateral resistance reduction amplitude of the ballast bed with the track lifting amount is similar to the research results of Reference [7]. When the track lifting amounts are 18 mm, 23 mm, 34 mm, 41 mm, and 47 mm, the reduction amplitude of lateral resistance are 2.03 kN, 3.04 kN, 4.08 kN, 4.29 kN and 5.90 kN, respectively; while the reductions of lateral resistance work are 0.14 J, 3.80 J, 8.05 J, 5.85 J and 9.01 J, respectively. It can be found that a large track lifting amount leads to a high reduction in the lateral resistance and resistance work of the ballast bed. The reason is that the higher the sleeper is lifted, the contact area and contact number between the ballast and the sleeper decrease after the tamping operation, resulting in a large reduction in the lateral resistance of the ballast bed. To further analyze the effect of the track lifting amount on the resistance to lateral deformation, the reduction amplitude and rate of lateral resistance and resistance work under different track lifting amounts are calculated, as shown in Fig. 14.

It can be seen from Fig. 14(a) and 14(b) that as the track lifting amount grows, the slope of the surface that is composed of the reduction of the lateral resistance and the resistance work gradually decreases and later tends to be stable. As seen from Fig. 14(c), as the track lifting amount grows, the reduction rate of the lateral resistance shows a linear trend, with R^2 of 0.983 and the largest reductions of 65.6 %. On the contrary, the reduction rate of the lateral resistance work shows a trend of increasing–decreasing-increasing, with the largest reductions of 68.8 %. This shows that the track lifting amount has a large impact on the tamping quality. Therefore, the tamping parameters should be adjusted with different lift amounts, e.g., the squeezing time and squeezing pressure. Besides, when the track lifting amount is in the range of 23 mm ~ 34 mm, the reduction of lateral resistance is lower and the slope of the reduction rate of lateral resistance work also becomes smaller. Therefore, it is suggested to keep the lift amount in the range of 20 mm ~ 30 mm during the tamping operation. For the section that requires a large lift amount, the principle of a step-by-step lift should be used, wherein the lift amount each time should not exceed 30 mm. In addition, the ballast should be supplemented in time after the tamping operation to achieve a better tamping quality.

4. Conclusions

The longitudinal, lateral resistance and support stiffness tests of ballast beds have been conducted to study the effect of tamping and stabilizing operation on the quality of ballast in newly constructed railways in Fengtai Station in Beijing, China. The mechanical behaviour of ballast bed after tamping and stabilizing operation is studied. And the effect of the tamping modes, stabilizing frequency and track lifting

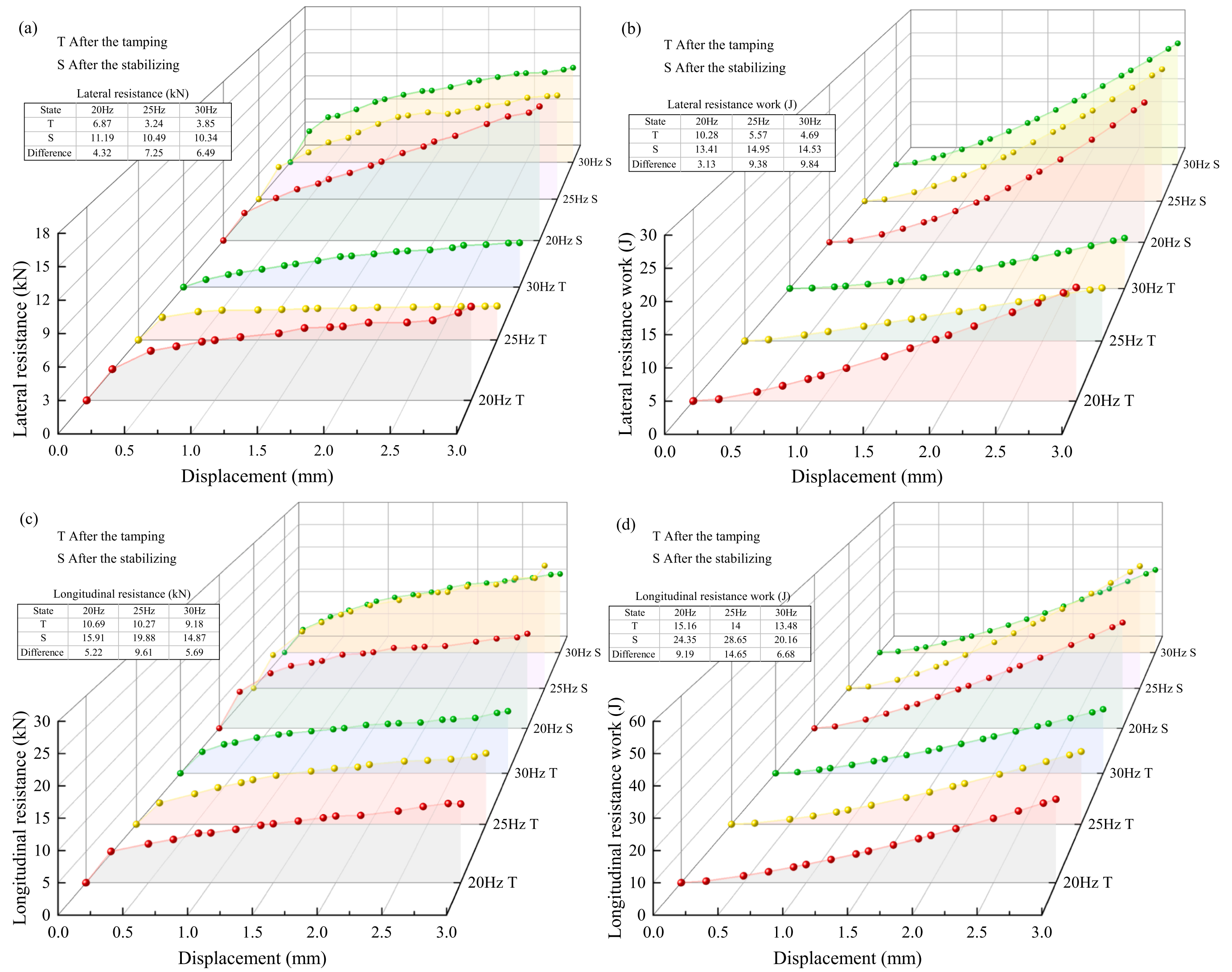

Fig. 11. Effect of stabilizing frequency: (a) ballast lateral resistance, (b) ballast lateral resistance work, (c) ballast longitudinal resistance, (d) ballast longitudinal resistance work.

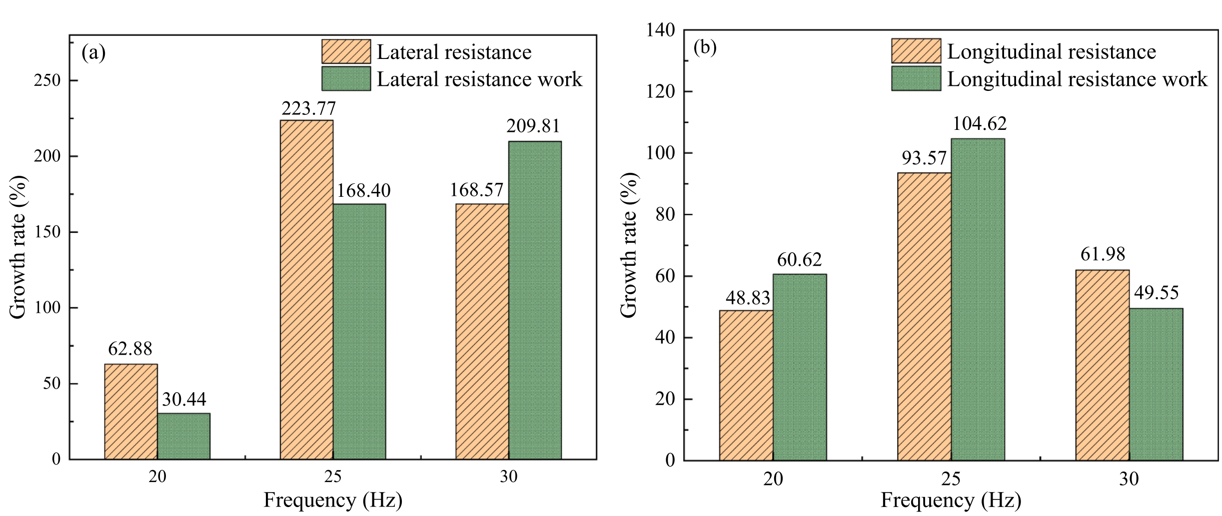

Fig. 12. Growth rate of ballast bed resistance and resistance work under different stable frequencies: (a) lateral, (b) longitudinal.

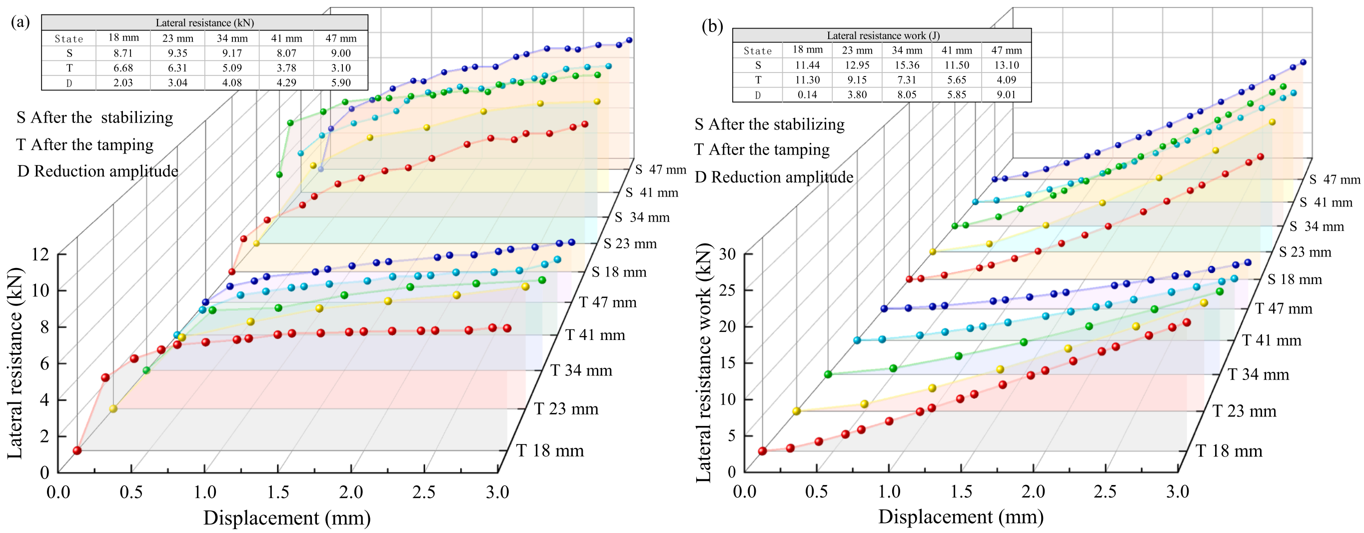

Fig. 13. Effect of track lifting amount: (a) the lateral resistance ballast bed, (b) the lateral resistance work ballast bed.

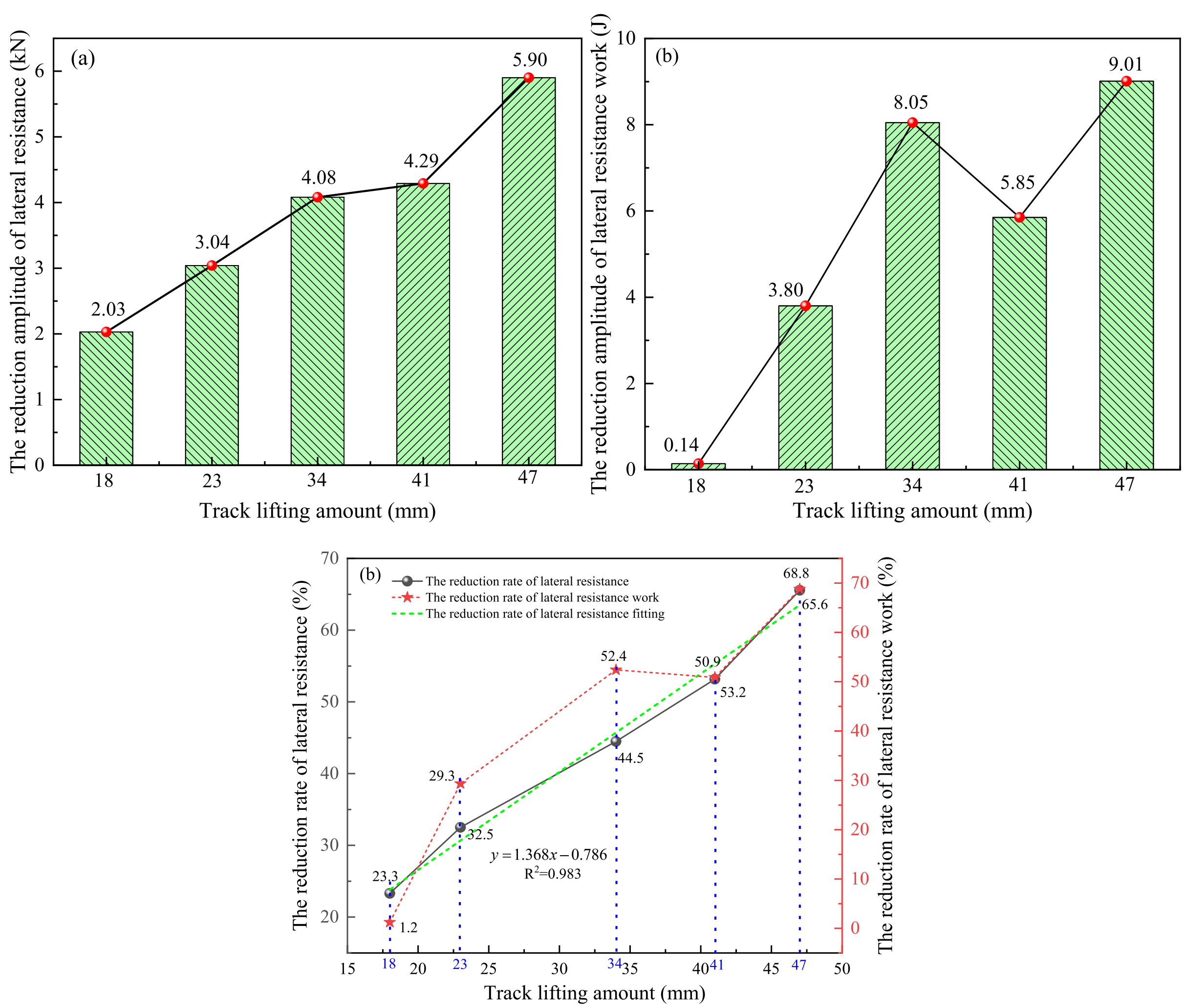

Fig. 14. Changes of lateral resistance and resistance work of ballast bed under different lifting amounts: (a) The reduction amplitude of lateral resistance, (b) the reduction amplitude of lateral resistance work, (c) reduction rate.

amount are discussed. The following conclusions are drawn.

(1) The tamping operation on newly constructed railways causes a reduction of the lateral resistance by 56.5 % and a reduction of lateral resistance work by 64.9 %. After the stabilizing operation,

the lateral resistance and lateral resistance work increase considerably. A similar trend can be found also in longitudinal resistance and longitudinal resistance work. Therefore, timely stabilizing operation plays an important role in restoring the quality state of ballast beds. Besides, because the tamping operation has a larger effect on the lateral resistance of ballast beds, it is suggested to use the lateral resistance as an indicator to assess the quality of tamping operation for newly constructed railways.

(2) The support stiffness of ballast beds is 4.9 kN/mm in the initial state, which becomes 53.9 kN/mm after the tamping operation and 82.9 kN/mm after the stabilizing operation, increased by 10 times and 15.9 times, respectively. The support stiffness after the stabilizing operation meets the requirements of newly constructed railways. It shows both the tamping and stabilizing operation improve the bearing capacity of ballast beds.

(3) The 1X tamping mode reduces the lateral resistance of ballast beds by 74.6 % and the lateral resistance work by 69.3 %, while the 2X tamping mode only reduces them by 17.4 % and by 16.9 %, respectively. From the perspective of lateral stability of ballast bed, it is recommended to adopt 2X tamping mode for tamping operation of the newly constructed railways, and conduct ballast replenishment operation in time.

(4) As the stabilizing frequency grows, the growth rate of the longitudinal and lateral resistance of ballast beds increases first and then decreases. The maximum growth rate appears at 25 Hz, wherein the lateral resistance is increased by 223.8 % and the longitudinal resistance work is increased by 104.6 %. Therefore, it is suggested that a frequency of 25 Hz should be utilized during stabilizing operations for newly constructed railways.

(5) As the track lifting amount grows, the reduction amplitude of the lateral resistance of the ballast bed gradually becomes larger, while the reduction amplitude of the lateral resistance work shows a trend of increasing–decreasing-increasing. Therefore, it is suggested to adjust the tamping parameters according to the track lifting amount during the tamping operation. The track lifting amount is recommended to keep in the range of 20 mm ~ 30 mm. Furthermore, for the section that requires a large track lifting amount, the principle of a step-by-step lift should be used, wherein the lift amount each time should not exceed 30 mm.

CRediT authorship contribution statement

Hong Xiao: Funding acquisition, Project administration. **Zhihai Zhang:** Conceptualization, Methodology, Formal analysis, Supervision. **Yajie Zhu:** Validation, Software, Formal analysis. **Tiancheng Gan:** Software, Data curation. **Haoyu Wang:** Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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