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Research Article

Mechanism and Application of a New Guard Rail for Improving the Stability of Small Radius Curve Tracks with Continuous Welded Rails

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Abstract: This study studied an effect of a new guard rail on the stability of curve tracks with CWR and revealed a mechanism of the new guard rail for improving the stability of small radius curve tracks with CWR and also analyze the degree of the new guard rail for enlarging the pave range of small radius curve tracks with CWR. In order to achieve these, an improved load-deformation method for calculating the stability of tracks with Continuous Welded Rails (CWR) is suggested and verified. The results indicate that the improved load-deformation method not only has the same accuracy as the improved unified formula in specification, but also has the same clear and simple characteristics as the original load-deformation method. The mechanism of the new guard rail for improving the stability of small radius curve tracks with CWR is that the CWR stability can be greatly improved by increasing the stiffness of the track framework under conditions of maintaining the same cross-sectional area of the rails. The CWR with the new guard rail can allow the minimum laying radius from 300 m down to 230 m, i.e., the current specification limit can be relaxed 23.3%. If combined with the roadbed strengthening measures, the new guard rail can allow the minimum laying radius from 300 m down to 140 m, i.e., the current specification limit can be further relaxed 53.3%.

Keywords: Continuous welded rail track, new guard rail, railway track, small radius curve, stability

INTRODUCTION

Over the years, the rail joint, turnout and small-radius curved track have been the three major weak links of railway track. With the popularization and application of Continuous Welded Rail (CWR) and new heavy rail turnouts, rail joints and turnout have been strengthened and improved. However, the train derailment accidents on small-radius curved track happen from time to time. The disasters of small-radius curved track are so many that it would seriously threaten the safety and the insurance of production of the railway transport. The deficiencies include serious rail wear, poor track lateral stability, heavy workload of maintenance and repair and high operating costs. These problems become especially prominent under the new situation that there is an increasing demand to improve the speed of passenger and freight trains and develop the large axle load and transport capacity. For CWR construction of small-radius curved track, according to Maintenance and Repair Methods of CWR Paving (TB/T 2098-2007, 2008), the minimum radius of CWR allowed in China is 300 m, which limits the paving range of CWR. In some special sections, due to the limitation of topography, existing buildings, underground pipeline, etc., the small-radius curved track has to be built. Especially for the urban rail transport and factories and mines railways, the curved track with a radius less than 300 m accounts for a certain proportion. In order to build trans-section or all-section CWR, some departments have tried to pave CWR track in some small-radius curve section. It is found through on-site practice that if some special designs are introduced for small-radius curved track, it is possible to pave CWR as long as the track structure is strengthened. At present, there are some common strengthening measures, such as widening track bed and shoulder, adding anti-expansion baffle, using large adjustable volume fasteners and increasing the number of track gauge rod or rail brace (Lu, 2005). In order to fundamentally solve the long standing problems such as train derailment on the small-radius curved track, rail wear and damage and poor lateral stability, China Academy of Railway Sciences in collaboration with Ministry of Railways has developed a new guard rail device (Li and Fang, 1996; Li, 2000), which actually inverts the rail by 90° and is generally installed in the inside of the rail, as shown in Fig. 1. The new guard rail is completely different from the old one. In addition to the main functions of preventing the train derailment

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Fig. 1: Site photo of new guard rail

and delaying the rail wear, it can strengthen the structure of small-radius curved track, improving the stability of CWR and preventing the track buckling accidents. It can even lower the statutory limit of minimum radius for paving CWR on small-radius curved track. Therefore, the new technology of CWR can be applied to a even smaller curve radius of track. Currently, the research on new guard rail is confined primarily to the introduction of its device structure (Wang, 2008; Han and Jia, 2008; Xiong *et al.*, 2003; Tan and Tao, 2006). Theoretical research has not been reported, so the theoretical study lags far behind that of the application. How does the new guard rail improves the stability of CWR track with a small curve radius is studied in this study. The mechanism of anti-derailment and reducing wear with new guard rail will be reported in another study. These researches can provide a theoretical basis for formulation of industry standards for the new guard rail.

IMPROVED LOAD-DEFORMATION METHOD

CWR stability theory research has received much attention from domestic and foreign railway experts and monographs and literature of various schools are flourishing (Lu, 2005; Chen, 2005; Grissom and Kerr, 2006; Lim *et al.*, 2003; Kish and Samavedam, 2001; Kerr, 1980). At present, the calculation method of CWR track stability is the improved unified formula for calculating CWR stability (improved unified formula) proposed by Chen (2005) from Central South University, which was included in the norms and standards issued by the Ministry of Railways (TB10082-2005, 2005). At the same time, researcher Lu (2005) from the Academy of Railway Sciences of China proposed unequal wavelength model, made Table of Allowed Temperature for Paving CWR, which was included in the ministerial standards. Zhang *et al.* (2007) proposed a load-deformation method for solving the CWR track stability. The main research idea is to consider CWR track as the engineering press bar with initial bending in the elastic-plastic uniform medium. The rail temperature force formula was derived by using the load-deformation relationship considering the balance of the internal and external torque. The multivariate extreme value theory was applied to derive the most unfavorable track bending wavelength and the formula for CWR track stability would be established. This method is based on more clarified physical concepts and easy calculation and is worthy of popularization. The formula derived in this method is as follows:

$$P = \frac{4EI\frac{\pi^2 f}{l^2} + M_q + M_n}{f + f_o + f_R} \tag{1}$$

The denotations of the symbols in the formula can be referred to literature (Zhang *et al.*, 2007). However, there are still defects in the derivation process. It has been made clear in reference (Chen, 2005) that the deformation work done by the track to resist bending is composed of two parts; the first part is the work M_f done by resisting the inner torques of bending deformation caused by temperature and pressure; the second part is the work done to resist the inner torque of elastic bending M_{oe} on the track angle of rotation. When M_f does the work, the original M_{oe} continues to do work. The CWR track is considered to be placed on engineering press bar in the elastic-plastic uniform medium and the inner torque of cross-section at the midpoint of press bar should be $M_{Inner} = M_f + M_{oe}$. However, Zhang *et al.* (2007) did not consider the term M_{oe}. In this study, in accordance with the ideas of the literature (Zhang *et al.*, 2007), by considering the item of M_{oe}, the calculation formula is derived once again as follows:

$$P = \frac{4EI\frac{\pi^2 (f + f_{oe})}{l^2} + M_q + M_n}{f + f_o + f_R} \tag{2}$$

where, f_{oe} represents the track initial elastic bending deformation; other symbols are the same as in the formula (1).

According to the structural stability theory, formula (2) represents the equilibrium state of the CWR track under rail temperature force *P*. Given the track bending wavelength l, since *E*, *I*, M_q, M_n, f_{oe}, f_o and f_R are all known, the curved surface in equilibrium state *P* depends on the bending deformation f, which is unknown. By derivation of f, the value f corresponding to the instability limit load is found. When different values of l are input, determine the minimum value of *P*. At this time, the value l is the most unfavorable deformation wavelength; and the corresponding value of *P* is the critical load, denoted as P_k; the corresponding critical temperature rise is denoted as Δt_k. According to Chen (2005) bending deformation of CWR track f = 0.2 cm is taken. The corresponding temperature force is divided by the safety factor to obtain the allowable temperature force, denoted as P_u. And the corresponding allowable temperature rise is denoted as Δt_u.

Table 1: The comparison between three methods (f_{oe} = 3 mm)

	Method 1		Method 2		Method 3	
R/m	P_u/N	Δt_u/°C	P_u/N	Δt_u/°C	P_u/N	Δt_u/°C
200	806077	21.00	998397	26.01	996862	25.97
250	883069	23.00	1135731	29.59	1134537	29.56
300	940129	24.49	1244210	32.41	1243382	32.39
350	983907	25.63	1331297	34.68	1330825	34.67
400	1018459	26.53	1402385	36.54	1402238	36.53

Table 2: The comparison between three methods (f_{oe} = 4 mm)

	Method 1		Method 2		Method 3	
R/m	P_u/N	Δt_u/°C	P_u/N	Δt_u/°C	P_u/N	Δt_u/°C
200	706455	18.40	946442	24.66	944939	24.62
250	761702	19.84	1064570	27.73	1063319	27.70
300	801717	20.89	1155990	30.11	1154999	30.09
350	831935	21.67	1228288	32.00	1227544	31.98
400	855519	22.29	1286644	33.52	1286121	33.51

Table 3: The comparison between three methods (f_{oe} = 5 mm)

	Method 1		Method 2		Method 3	
R/m	P_u/N	Δt_u/°C	P_u/N	Δt_u/°C	P_u/N	Δt_u/°C
200	626753	16.33	902616	23.52	901137	23.48
250	668098	17.41	1006357	26.22	1005071	26.18
300	697589	18.17	1085435	28.28	1084342	28.25
350	719628	18.75	1147299	29.89	1146385	29.87
400	736704	19.19	1196834	31.18	1196077	31.16

Table 4: The comparison between three methods (f_{oe} = 6 mm)

	Method 1		Method 2		Method 3	
R/m	P_u/N	Δt_u/°C	P_u/N	Δt_u/°C	P_u/N	Δt_u/°C
200	562232	14.65	864995	22.54	863539	22.50
250	594239	15.48	957559	24.95	956252	24.91
300	616824	16.07	1027294	26.76	1026137	26.73
350	635876	16.51	1081401	28.17	1080378	28.15
400	646504	16.84	1124462	29.29	1123558	29.27

By comparing formula (2) and (1), it appears that formula (2) has an additional $\frac{4EI\,(\pi^2 f_{oe}/l^2)}{f+f_o+f_R}$ which is absent in formula (1). The following examples specify the extent of the impact of this item.

Examples: For comparison purposes, the allowable temperature force P_u and allowable temperature rise Δt_u are calculated respectively according to the parameters in the example in reference (Zhang *et al*., 2007). Known: 60 kg/m rail, type II sleeper, the number of sleepers per kilometer is 1760. Calculate the parameters of the fastener resistance moment $H = 2.2\times10^4$ and $\mu = 2$. In normal operation of the rail, unit lateral resistance of roadbed is $q = 13.9 - 1299\,y + 1291\,y^{3/4}$. Considering the role of the train axle load, the track skeleton between two bogies will float under negative bending moment. So the roadbed resistance decreases by 35%. Load-deformation method (Method 1), improved load-deformation method (Method 2) and improved unified formula (3) are respectively used to calculate the allowable temperature force P_u and corresponding allowable temperature rise Δt_u when curve radius R = 200, 250, 300, 350, 400 m, respectively; and f_{oe} = 3, 4, 5, 6 mm, respectively. The results are shown in Fig. 2 and 3 and Table 1 to 4.

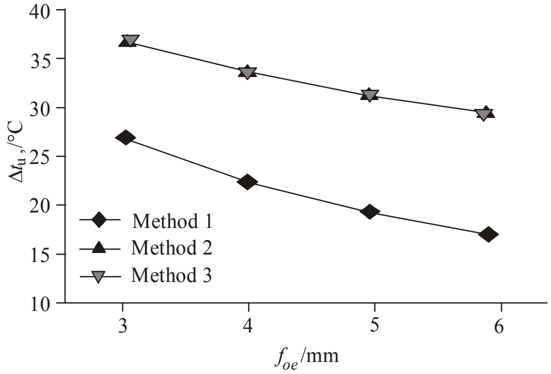

Fig. 2: The comparison between three methods (R = 400 m)

Table 1 to 4 and Fig. 2 and 3 shows that there is a considerable gap between the results calculated by Method 1 and 3. For example, for the curved track with radius R = 400 m, when the initial elastic bending deformation f_{oe} = 3 mm, the allowable temperature rise calculated by Method 1, 2 and 3 was 26.53, 36.54 and 36.53°C, respectively; for Method 1 and 3, the relative error is 27.37% and that for Method 2 and 3 is only 0.02%; and for the same curve radius, with the increase of f_{oe}, the relative error between Method 1 and the method 3 shows an increasing trend, (Fig. 2); while between Method 2 and 3, the relative error is less than

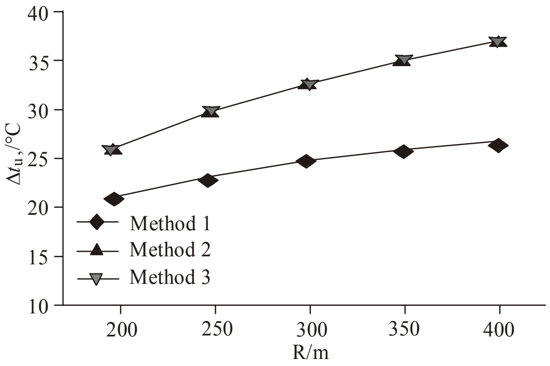

Fig. 3: The comparison between three methods (f_{oe} = 3 mm)

0.1%, see Table 1 to 4. For the same f_{oe}, as the curve radius increases, the relative error between Method 1 and 3 shows an increasing trend, (Fig. 3); whereas between Method 2 and 3, the relative error is less than 0.2%, as shown in Table 1. Thus, the influence of the initial elastic bending deformation of the track cannot be ignored. The improved load-deformation method not only has the same precision as the improved unified formula, but also maintains the physical concept of the original load-deformation method, with easier calculation.

STABILITY-INCREASING MECHANISM AND APPLICATION OF NEW GUARD RAIL

Influence law of new guard rail on CWR track stability: Improved load-deformation method is used to calculate the stability of CWR track with a small curve radius after the use of new guard rail device. In specific calculation, the new guard rail can be seen as increasing the lateral bending stiffness of the track. Set the original lateral bending stiffness of the track as *EI*. The lateral bending stiffness of the track after installing of new guard rail is $EI + EI_h$.

The specific calculation parameters are as follows: 60 kg/m rail, guard rail 43 kg/m rail, elastic modulus of the rail $E = 2.1\times10^{-5}$ MPa, parameter of fastener resistance moment $H = 2.2\times10^{4}$ and $\mu = 2$, unit lateral resistance of roadbed $q = 22.0 - 38.0\ y^{1.5} + 110.0\ y^{1/3}$, initial bending deformation of the track $f_o = 1$ M% l, the initial elastic bending deformation is 58.33% of the total elastic bending deformation. Note that the moment of inertia *I* of two main rails with respect to the vertical neutral axis is 1048 cm^4. As the guard rail is to invert the rail by 90°, the moment of inertia I_h of guard rail with respect to the horizontal neutral axis is 1489 cm^4. Thus, the sum of moment of inertia of the three rails becomes $I + I_h = 1048 + 1489 = 2537\ cm^4$.

Stability of CWR with curve radius *R* = 200, 250, 300 and 400 m with and without the guard rail is calculated, respectively. The calculated results are shown in Table 5 and Fig. 4.

Seen from Table 5 and Fig. 4, for the same curve radius, the allowable temperature rise with guard rail is higher than that without guard rail; and as the curve radius increases, the increase amplitude is also increasing. For track with curve radius *R* = 300 m that allows the paving of CWR, before installing new guard rail, the allowable temperature rise is 28.76°C; after installation of the new guard rail, the allowable temperature rise is 34.88°C, higher by 21.3%. For track with a smaller curve radius *R* = 200 m, before installing new guard rail, the allowable temperature rise is 22.94°C; after installation, the allowable temperature rise is 26.04°C, higher by 13.5%. Therefore, the new guard rail will greatly contribute to the stability of CWR track with small curve radius. Moreover, we can get the inspiration that the use of new guard rail will expand the application of CWR paving on small radius curved track.

Mechanism analysis: It is shown in reference (Chen, 2005) the favorable factors affecting the stability of CWR track are stiffness, lateral resistance of roadbed; and unfavorable factors are initial bending deformation of track and temperature force. Under the initial bending deformation at the same temperature force, the greater the stiffness of the track frame, the greater the capacity of CWR track to resist lateral deformation and the higher the stability is; similarly, the greater the lateral resistance of roadbed, the greater the ability of CWR track to resist lateral deformation and the higher the stability is. Therefore, in order to ensure the stability of CWR track, we should give full play to the favorable factors and minimize the impact of unfavorable factors. For CWR track with a small curve radius and equipped with new guard rail device, the stiffness of the entire track can be increased without changing the cross-sectional area of the rail. The installation of new guard rail takes advantage of major favorable factors to improve the stability of CWR track. This is the stability-increasing mechanism of

Table 5: Effect of with guard rail and without guard rail on track stability of CWR

	Without guard rail		With guard rail		
R/m	P_u/N	Δt_u/°C	P_u/N	Δt_u/°C	Relative value of Δt_u/%
200	880858	22.94	999556	26.04	13.5
250	1005237	26.18	1182198	30.79	17.6
300	1104078	28.76	1338729	34.88	21.3
400	1249079	32.54	1587993	42.30	30.0

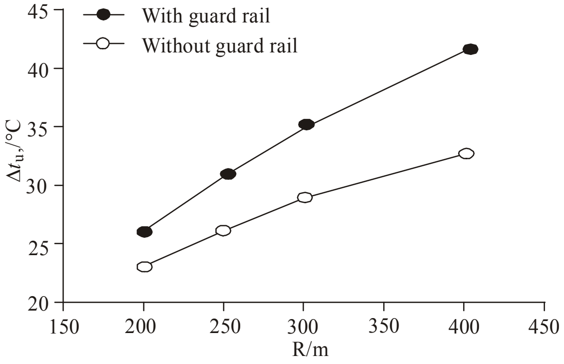

Fig. 4: Effect of with guard rail and without guard rail on the stability of CWR

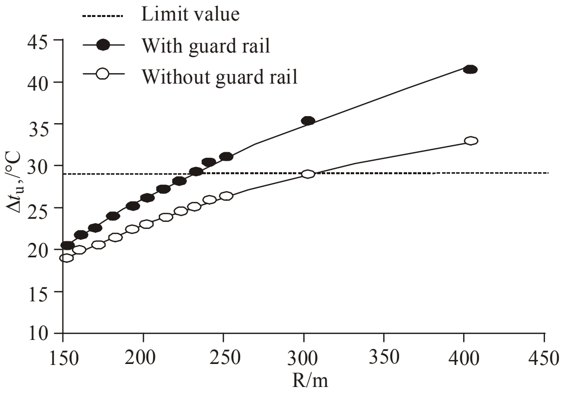

Fig. 5: Effect of new guard rail on pave range of small radius CWR

the new guard rail for CWR track with a small curve radius. In fact, for 60 kg/m type rail, after installing 43 kg/m, the cross-sectional area of the two rails is not changed and the stiffness of the entire track increases by 142.1%, so as to dramatically improve the stability of the CWR track.

Applications: The new guard rail for improving the stability of CWR track with a small curve radius has a significant effect, which inspires us to apply the guard rail to expand the range of CWR paving. According to the minimum curve radius of 300 m that is allowed for CWR paving[1], we calculate the stability of CWR track with R<300 m after the installation of guard rail. In general, with the decreasing of curve radius, the stability of CWR track will reduce. However, the installation of new guard rail will increase its stability. In accordance with the codes for CWR paving and maintenance and repair and using the principle of allowable temperature rise which is the same as with R = 300 m, the allowable minimum curve radius of CWR paving is determined. The specific steps are shown as follows:

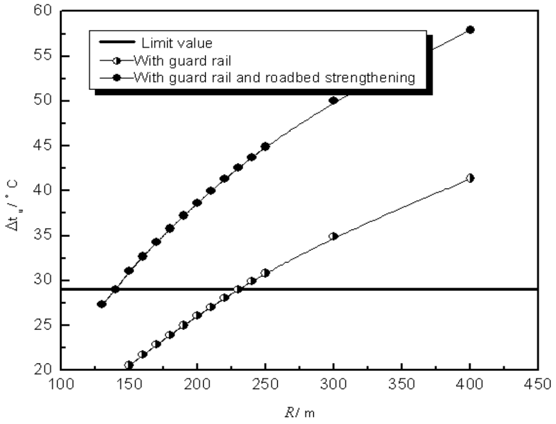

Fig. 6: Effect of new guard rail and roadbed strengthening measure on pave range of small radius CWR

1. In accordance with the codes for CWR paving and maintenance and repair, we can know that the allowable temperature rise corresponding to CHN60 rail on CWR track with R = 300 m is 29°C.
2. With R = 400 m as the starting point of calculation, R is reduced by a small margin each time and calculate the allowable temperature rise Δt_u before the installation of the new guard rail.
3. With R = 400 m as the starting point of calculation, reduce R by a small margin each time and calculate the allowable temperature rise $\Delta\acute{t}_u$ after the installation of the new guard rail.
4. If $\Delta\acute{t}_u \neq 29$°C, repeat step 3, until $\Delta\acute{t}_u = 29$°C. At this time, the corresponding curve radius is the minimum allowable curve radius $\acute{R}$ after expanding the range of paving CWR on small radius curve. At this time, although the curve radius is reduced from R = 300 m to the current $\acute{R}$ (<300 m), the allowable temperature rise remains the same at that with R = 300 m, both being 29°C. In specific calculation, the same calculation parameters as in above section are used.

Figure 5 is the curve showing how allowable temperature rise changes with curve radius after the installation of the new guard rail. The thick solid line indicates the standard value of allowable temperature rise (i.e., 29°C) before the installation of guard rail at R = 300 m. F The curve radius $\acute{R}$ corresponding to the intersection of relational curve after the installation of the new guard rail with the thick solid line is the new minimum curve radius. It can be known from Fig. 5 that $\acute{R}$ = 230 m. This means that after the installation of the new guard rail the minimum curve radius allowed in CWR paving has decreased from 300 to 230 m, lower by 23.3% compared with the limit value.

According to the above-mentioned mechanism analysis, the combination of the new guard rail and roadbed strengthening measures will further lower the minimum curve radius allowed for CWR paving. Take the measures of roadbed widening and increasing the height of shoulder of the roadbed for example. According to Lu (2005), the unit lateral resistance of the roadbed before strengthening $q = 22.0 - 38.0\ y^{1.5} + 110.0\ y^{1/3}$; the unit lateral resistance of the roadbed after strengthening $q = 8.5 - 343.35\ y^{1.4} + 470.88\ y^{1/15}$, with the rest of the parameters being the as same as in above section. The calculation results are shown in Fig. 6. In Fig. 6, after the combined application of new guard rail and roadbed strengthening measures, the minimum curve radius allowed for CWR paving is decreased from 300 to 140 m, lower by 53.3% compared with the existing limit value.

CONCLUSION

- The deficiencies in the load-deformation method to calculate the CWR track stability in literature (Zhang *et al*., 2007) are addressed. An improved load-deformation method has been proposed and verified. The results show that the improved load-deformation method not only has the same precision as the improved unified formula in the existing standard specification, but also retains the characteristics of clear physical concepts and convenient computation in the original load-deformation method.
- The initial intention of the invention of the new guard rail is to prevent the train derailment on a small-radius curved track and to reduce rail wear. This study supposes that the new guard rail can also strengthen the track structure and studies the stability-increasing mechanism of new guard rail for CWR track with a small curve radius. The installation of the new guard rail can greatly increase the stability of CWR track by increasing the stiffness of the track frame, without changing the cross-sectional area of the rail.
- New guard rail decrease the minimum curve radius allowed for CWR paving from 300 to 230 m, lower by 23.3% compared with the limit value. When combined with the roadbed strengthening measures, the new guard rail would further allow the minimum curve radius to decrease from 300 to 140 m, lower by 53.3% compared with the limit value. Therefore, the joint use of the new guard rail and roadbed strengthening measures is recommended to promote the CWR construction of small-radius curved track.

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