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Research Article

A New Design of Bridge-Subgrade Transition Sections Applied in Beijing-Shanghai High-Speed Railway

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This paper proposes a new design of bridge-subgrade transition sections in high-speed railways, in attempt to avoid typical defects observed in such sections. Field observations show that two types of defects tend to occur at bridge-subgrade transition sections of high-speed railways: ① the stiffness of the transition is usually too high so that tensile stress and even tensile cracks occur at the top surface of reserved trapezoid transition section and ② the compaction quality cannot be guaranteed within the first two meters from the abutment, which leads to excessive differential deformation within the transition section. For solving the above defects, a new design of the transition is proposed here: the section of the first 2 m from the abutment is filled with a graded gravel that is mixed with fly ash and cement to achieve specific stiffness and strength requirement, and the rest of the transition section is filled with roller-compacted concrete. For this new type of transition section, its dynamic performance is evaluated with on-site tests and numerical analysis. The results show that the bending angle of rail surface is almost constant along the route and the settlement of the rail surface along the route is in a linear distribution, which verifies the smoother transition from the rigid abutment to the flexible subgrade. Meanwhile, this new type of bridge-subgrade transition section has been successfully applied in the 680 km-long third bidding section of the Beijing-Shanghai high-speed railway, which provides valuable experiences for promoting and popularizing it in future construction of high-speed railways. In addition, the construction cost of the new type of bridge-subgrade transition section is verified by an economical efficiency analysis.

1. Introduction

One of the core requirements for high-speed railway is the route smoothness, which is also the precondition for train safety and passenger comfortability [1–3]. For both existing and new-built routes, transition sections between bridge and subgrade or between culvert and subgrade are always the key locations that affect the smoothness and evenness of the route. It is regulated in some specifications [4, 5] that a trapezoid structure should be adopted for the transition from rigid abutment (culvert) to flexible subgrade. However, field observation shows that such trapezoidal transitions are not immune of deflect that significantly affect the smoothness and evenness of high-speed railways.

This paper first summaries the typical defects observed at transition sections of high-speed railways in China and analyses the main causes of these defects. A new design of bridge-subgrade transition is then proposed. The performance of the new design is evaluated against field monitoring and numerical analysis of the Beijing-Shanghai high-speed railway.

2. Field Investigation

The bump at the end of the bridge is a known challenge for bridge-embankment construction [6, 7]. Field investigations of several high-speed railways in China (e.g., the Beijing-Tianjin high-speed railway) reveal that the current design and construction of bridge-subgrade transition sections are

Table 1: Compaction quality test results for graded gravel transition section.

Testing time	Coefficient of subgrade reaction K_{30} (MPa/m)	Dynamic modulus E_{vd} (MPa)	Static modulus E_{v2} (MPa)	Porosity n (%)
Filling standards	≥150	≥50	≥80	<28
Testing results for 4 h after finishing the filling of transition section	151	58	162	15~20
Testing results for 1 day after finishing the filling of transition section	431	170	446	—
Test results for 2 days after finishing the filling of transition section	*	174	449	—
(Testing results – filling standards[1])/ filling standards (%)	188	241	459	—
(Testing results – filling standards[1])/ filling standards (%)	*	248	461	—

Note: *when testing K_{30} of the transition section on the third day, the result cannot be tested because the strength of the graded gravel mixed with 5% cement is comparatively large, and when the hydraulic jack reaches its max top elevating force, the subsidence of loading board cannot reach 1.25 mm.

prone to defects such as surface cracks and large differential settlements. The stiffness of the transition is usually very high and increases with time, see Table 1. The difference of the stiffness between the transition section and subgrade section causes large differential settlement, a bump at the joint between transition and subgrade. The high stiffness can also cause tensile stress and even cracks at the top surface of the trapezoid transition section. In addition, the compaction quality within the first 2 meters from the bridge abutment cannot be guaranteed, as it is usually completed by adopting small-size rolling compaction instruments there. The poorly compacted cemented gravel further causes stiffness and strength differences within the transition section, leading to another bump at the joint with the abutment. Cyclic train loads will further increase the accumulated deformation of the subgrade, influencing the comfort level of train operation, worsening the condition of the route, decreasing the service life of the track structure and increasing the maintenance costs. Therefore, it is extremely important to improve the smooth transition from rigid abutment to flexible subgrade.

2.1. Analysis of the Current Design and Construction of Transition Sections. The current design of an abutment-subgrade transition is based on a trapezoidal structure constructed between the abutment and the subgrade. The trapezoidal structure is made of graded gravel mixed with 5% cement in mass. In accordance with the requirements of related standards [4, 5], the mean values of the compaction quality for the transition section are obtained for the third bidding section of the Beijing-Shanghai high-speed railway. The mean values are shown in Table 1.

It can be seen from Table 1 that the elastic moduli within the first 4 hours after compaction can satisfy the requirements of the specifications. However, the modulus values at 1 day, 2 days, and 3 days after compaction are significantly higher than the specifications. The time-dependent stiffness is the nature of the cement-mixed material. The strength and stiffness of the material within the first 4 hours mainly come from the graded gravel, as the cement is still coagulating and has little load-bearing capacity. The material at this stage has a lower strength and a higher plasticity. As the material ages, the cement paste hardens and the strength of the material comes from the cement-gravel block, which has a higher strength and a lower plasticity.

The "obvious" solution to the above problem seems to reduce the cement content in the gravel via one of the two methods: reducing the dosage of cement in the gravel or lowering the cement content in the cement-water paste. However, reducing the cement dosage will significantly affect the evenness of the graded gravel. Hence, only the second method is viable. The goal of the second method is to reduce the cement content in the same dosage and replace it with another material that has the same binding power but does not age in its stiffness.

2.2. New Design of Bridge-Subgrade Transition. In line with the abovementioned problems and thoughts, learning from the experiences in hydraulic works and dam-building projects, we proposed a new type of bridge-subgrade transition for high-speed railways. The goal is to reduce the two bumps at the end of the bridge. This new transition section is composed of the roller-compacted concrete and the improved graded gravel. The improved graded gravel is made of a mixture of graded gravel, cement, and fly ash. Paste of cement and fly ash is poured into a graded gravel manually, and the mixture is then vibrated using the concrete vibrator, producing a concrete-like material. The roller-compacted concrete has the same material composition as the improved graded gravel but prepared by grinding the improved graded gravel with the help of the roller compaction technology. The improved graded gravel is used for the first 2 meters from the abutment, while the roller-compacted concrete is used in the trapezoidal transition section.

A key component of the roller-compacted concrete and the improved graded gravel is the cement to fly ash ratio. A large number of field tests have been carried out in a test section of the east station of Qufu which belongs to the third bidding section of the Beijing-Shanghai high-speed railway. In this test section, different fly ash-cement ratios were used to produce the roller-compacted concrete, while the overall

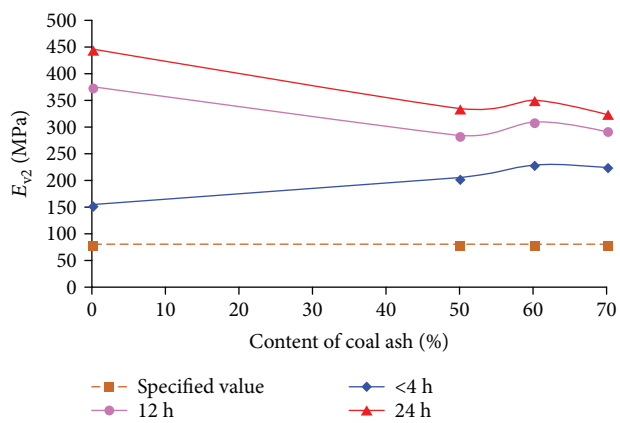


Figure 1: Relation diagram between static deformation modulus E_{v2} and the content of coal ash.

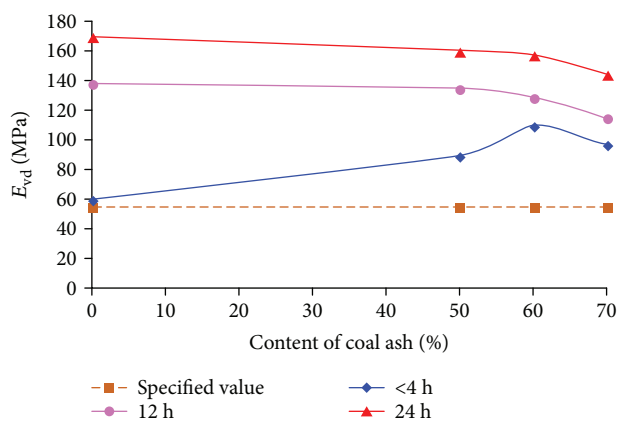


Figure 2: Relation diagram between dynamic deformation modulus E_{vd} and the content of coal ash.

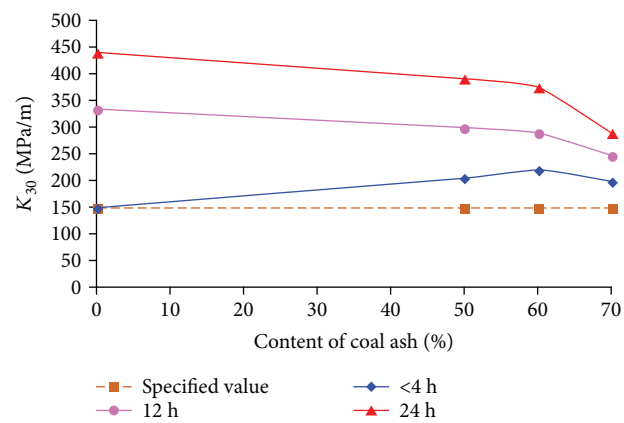


Figure 3: Relation diagram between the coefficients of subgrade reaction K_{30} and the content of coal ash.

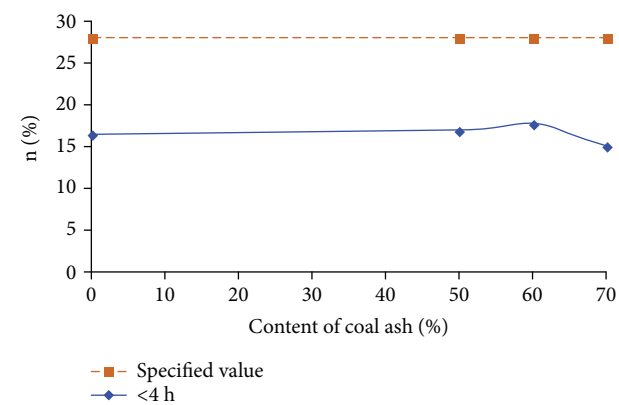


Figure 4: Relation diagram between porosity n and the content of coal ash.

cement-fly ash to gravel mass ratio is kept at 5 : 95 in percentage. The variation of various elastic moduli and the porosity with the fly ash content are shown in Figures 1–4.

The results in Figures 1–4 show that (1) the stiffness parameters of the material do not significantly increase with time at higher fly ash contents (Figures 1–3); (2) the stiffness parameters within the first 4 hours after finishing roller compaction increase with increasing fly ash content (Figures 1–3); (3) the stiffness parameters for 12 h and 24 h after finishing roller compaction actually decrease somewhat with increasing fly ash content (Figures 1–3); (4) a fly ash content of 60% seems to lead to optimal stiffness values for the material; and (5) the porosity of the material does not change significantly with time or with fly ash content. These results indicate that the roller-compacted concrete is not as stiff as the graded gravel mixed with 5% cement which was previously used for abutment-subgrade transition sections and more importantly that the material stiffness does not increase significantly with time. Such behavior is very desirable for avoiding differential settlement at transition sections. A possible reason for such behavior is the difference between Portland cement and fly ash. Fly ash generally has a faster coagulation process, but a lower strength and a lower coagulation ability than Portland cement. The stiffness and strength of the material within the first 4 h after finishing the roller compaction are mainly controlled by the graded gravel bonded by the fly ash, while the Portland cement is still coagulating. However, at 12 h and 24 h after finishing the roller compaction, the Portland cement is in the hardening stage, and the strength and stiffness of the material are mainly controlled by the gravel coagulated by the cement. The stiffness indices are therefore smaller with decreasing cement content (or increasing fly ash content). Based on the above results, a mixture of 60% fly ash to 40% cement is chosen for construction of transition sections and for the analyses below.

3. Numerical Analysis

In order to compare the dynamic responses of the new bridge-subgrade transition design against the transition section built with graded gravel mixed with 5% of cement, a numerical model for the dynamic vehicle-track interaction was established and used to calculate the rail-wheel load; a numerical model for the dynamic track-subgrade interaction was established and used to work out the dynamic responses

of subgrade. Both models were coupled by wheel-track interaction and built based on the software ADAMS.

3.1. Dynamic Model of Vehicle-Track-Subgrade Coupled System. Based on the reversed trapezoid transition used in Beijing-Shanghai high-speed railway (Figures 5(a)–5(d)), this paper considers the interaction of different structural layers in the subgrade system further and established the vertical dynamic model of vehicle-track-subgrade coupled system. This model included a vehicle-track and track-subgrade coupled dynamic interaction which was coupled with the wheel-track interaction. The model was established and simplified as shown in Figure 5(c), where the car body was assumed as a rigid body and the rail was assumed as a Euler beam with continuous point supports [8], and track plate was simplified as a free beam of a finite length based on elastic foundation. The rail, track slab, supporting layer, and frictional slab were supported on continuous point springs and dampers. Cement asphalt mortar between frictional slab and subgrade was simplified as continuously distributed viscous elastic unit consisting of linear springs and dampers (K_{CA}, C_{CA}) [9]. The bedding surface layer, bedding bottom layer, and subgrade were discretized into rigid blocks [10]. The continuous point springs, dampers, and stress pieces (K_i, C_i, and σ_{maxi}) were distributed among structural layers, where parameters changed gradually along bridge- (culvert) subgrade transition, which were used to simulate the interactions. Other physical parameters involved are described in [11–16].

Figure 5 shows the following: M_c, mass of car body (kg); J_c, nodding inertia of car body (kg·m^2); C_{S2}, damping coefficient of secondary suspension damper (N·S/m); $Z_C(t)$, displacement of car body (m); M_t, secondary suspension mass (kg); $\beta_{t1}(t)$, angular displacement of the left bogie (rad); $\beta_{t2}(t)$, angular displacement of the right bogie (rad); $Z_{t1}(t)$, displacement of bogie (m); C_{S1}, damping coefficient of primary suspension damper (N·S/m); K_{S1}, primary suspension stiffness coefficient (N·S/m); Z_{Wi}, displacement of wheel (m); $Z_{0i}(t)$, irregularity displacement of rail (m); $P_i(t)$, wheel-rail force (kN); m_r, mass of rail (kg); EI, inertial moment of rail (N·m^2); $Z_r(x, t)$, displacement of rail (m); K_{P1}, stiffness coefficient of cushion under the rail (N/m); C_{P1}, damping coefficient of damper of cushion under the rail (N·S/m); M_{CA}, mass of slab (kg); K_{CA}, stiffness coefficient of slab (N/m); K_{b1}, stiffness coefficient of track slab (N/m); C_{CA}, damping coefficient of damper of slab (N·S/m); C_{b1}, damping coefficient of damper of track slab (N·S/m); K_{c1}, stiffness coefficient of supporting layer (N/m); C_{c1}, damping coefficient of damper of supporting layer (N·S/m); K_{d1}, stiffness coefficient of frictional slab (N/m); C_{d1}, damping coefficient of damper of frictional slab (N·S/m); m_b, mass of track slab(kg); m_c, mass of supporting layer (kg); and m_d, mass of frictional slab (kg).

3.2. Track-Subgrade Dynamic Model. The operating point which is in the third bidding section of the Beijing-Shanghai high-speed railway was taken as the research object. This operating point adopts the reversed trapezoid transition for realizing the transition from a rigid abutment to a flexible subgrade. In this transition, the bedding surface layer is 0.7 m thick, the bedding bottom layer is 2.3 m thick, the subgrade is 6 m thick, and the track plate size is 6450 mm × 2550 mm × 200 mm in (length × wide × height). The hydraulic material is 300 mm thick, and the top surface and the bottom surface of hydraulic material supporting layer are 2950 mm wide and 3250 mm wide, respectively. The frictional slab is 9 m wide and 0.4 m thick. The design thickness of the adjustment layer is cement-emulsified asphalt mortar. The bottom boundary of the transition is 3 m long and its slope gradient is 1 : 2.7. At the same time, the slope gradient on two sides of the transition is 1 : 1.5. The filling material of the bedding surface layer is graded gravel. The filling materials of the bedding bottom layer and the subgrade are both sandy stratum mixed with 28% broken stones. The filling material of the reversed trapezoid is the graded gravel mixed with 5% of cement. The material type of the foundation is weathered granite. A specific geometric model is shown in Figure 6. Based on the above geometric model, we established a numerical model of bridge-subgrade transition by using software MIDST/GTS and ADAMS/Rail, as shown in Figure 7.

3.3. Determination of Computational Parameters

3.3.1. Material Parameters. Since the boundary reflection has large influence on the dynamic response of the bridge-subgrade section, this paper intended to reduce this influence by adding a viscoelastic boundary.

The material parameters were obtained by field tests and the lab tests and were shown in Table 2. According to the typical behavior of the materials involved, permanent deformation in the abutment, track slab, supporting layer, and friction slab can be neglected. Therefore, a linear elastic constitutive model was used for simulating the mechanical behavior of the abutment, track slab, supporting layer, and friction slab. The Mohr-Column (M-C) model was used for the graded gravel mixed with 5% of cement, the roller-compacted concrete, the improved gravel, the subgrade, the bedding surface layer, and the bedding bottom layer. The material parameters used in the following analysis can be found in Table 2 and Figures 8–11.

3.3.2. Train Load. This paper selected the related parameters of high-speed passenger train used in the Beijing-Shanghai high-speed railway to establish the vehicle-track-subgrade coupled dynamic model with a speed of 350 km/h by using the simulation software ADAMS, where a wheel load of 250,000 cycles was imposed to consider the role of repeated load of high-speed train. The monitoring points were set at about 72 m away from the start position to eliminate the effect of high-speed train launching and braking on the dynamic response observation. In order to improve the simulation results, this paper chose the site-adjusted results of smoothness of the track in the third bidding section of the Beijing-Shanghai railway to consider the track irregularity. Because the ADAMS/Rail contains only two material models (i.e., flexible body and rigid body) that cannot simulate the constitutive behavior of soils,

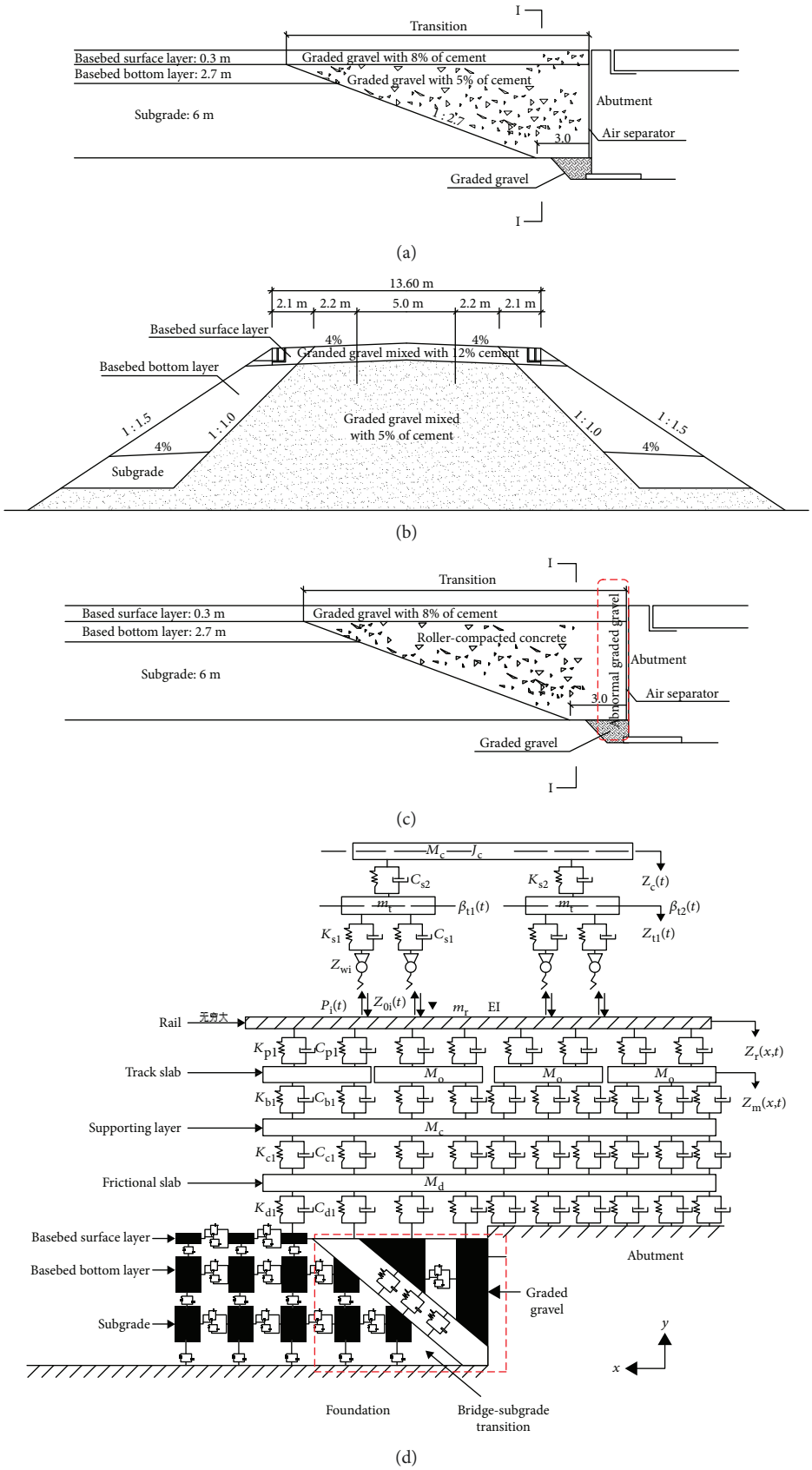


Figure 5: (a) Design diagram of bridge- (culvert) subgrade transition section. (b) I-I cross-section diagram. (c) Design diagram of the new type of bridge- (culvert) subgrade transition section. (d) Vertical dynamic analysis model of vehicle-track-subgrade coupled system.

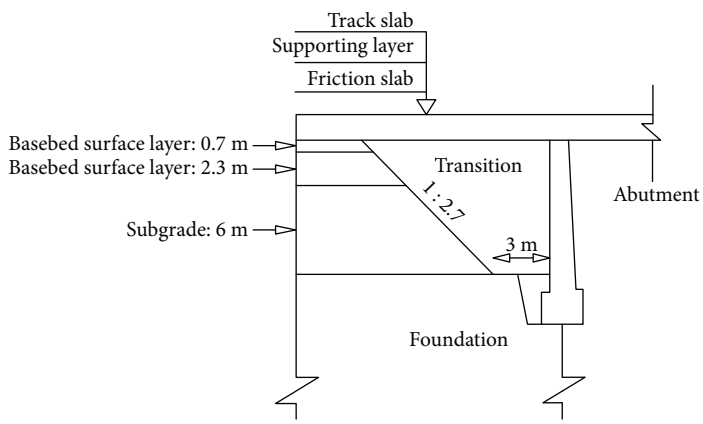


Figure 6: Geometric model of transition section.

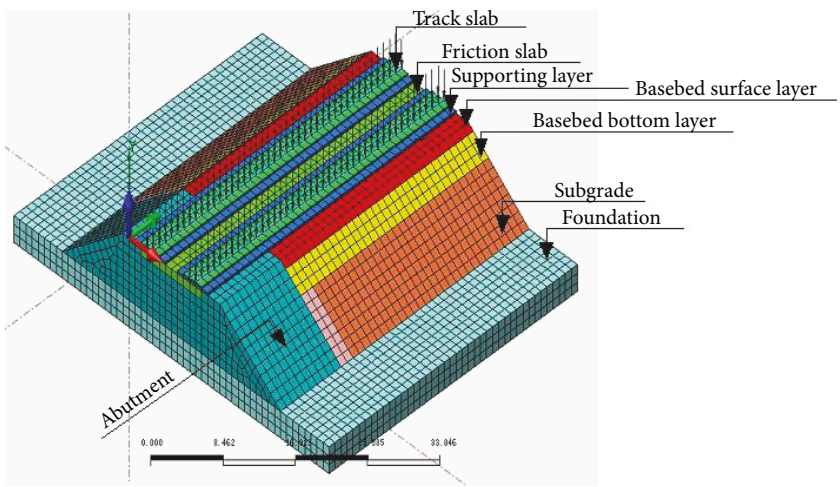


Figure 7: Numerical model of transition section.

Table 2: Physical and mechanical characteristic parameters of the materials.

Position	Material type	Constitutive model	Deformation modulus E_{v2} (MPa)	Poisson ratio υ	Internal friction angle ψ (°)	Cohesion C (kPa)	Density ρ (g/cm^3)
Bedding surface layer	Graded gravel	M-C	120	0.33	27	70	1.95
Bedding bottom layer	Sand stratum mixed with 28% of broken stones	M-C	80	0.35	20	55	1.90
Subgrade		M-C	36.5	0.3	10	30	2.1
Improved Sections	Graded gravel (+5% of cement)	M-C	449	0.21	/	/	2.4
	Roller-compacted concrete	M-C	307.1	0.26	/	/	2.3
	Abnormal graded gravel	M-C	652.3	0.19	/	/	2.45
Track/friction slab	Concrete	Linear elastic	$2.0E+04$	0.15	/	/	2.5
Supporting layer	Concrete	Linear elastic	$2.0E+04$	0.15	/	/	2.5
Abutment	Concrete	Linear elastic	$2.0E+04$	0.15	/	/	2.5

Figure 8: Plate loading test (K_{30}).

Figure 9: Ring sampler test (density).

Figure 10: Dynamic sounding test (E_{vd}).

Figure 11: Static deformation modulus test (E_{v2}).

nonlinear springs and dampers are set uniformly between the rigid subgrade and the track along the line to consider the interactions between the track and the subgrade. The simulation model is shown in Figure 12 and calculation results are shown in Figure 13.

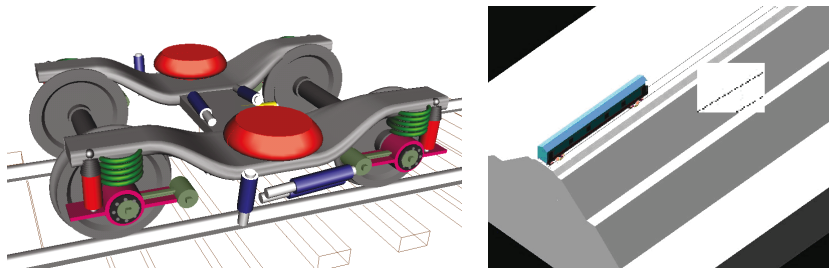
3.4. Computational Results. The rail-surface bending angles in this paper are all the tangential intersection angle at a certain point on the rail surface, rather than the secant line intersection angle.

The dynamic responses of the new type of bridge-subgrade transition and the original bridge-subgrade transition built with graded gravel mixed with 5% of cement under the high-speed train load were studied here, and the computational results are shown in Figures 14–15.

Figure 14 shows that, in the transition section, the maximum settlement of the new type of transition is slightly larger than that of the original transition built with the graded gravel mixed with 5% of cement (latter), and in the subgrade, the maximum settlements of the two designs are consistent with each other. However, at the bridge-transition joint section (0–6 m from the bridge) and the transition-subgrade joint section (27–3 m from the bridge), the settlement difference of the new design is much smaller than that of the original design, which was considered the reason of the tensile stress occurring at the top surface of the inverted trapezoid transition. Figure 15 shows that, in the transition section, the maximum bending angle of the new design is much smaller than that of the original design, and the bending angle of the new design is more constant along the route. In the subgrade, the bending angles of both tend to be consistent and are close to zero. At the bridge-transition joint section and the transition-subgrade joint section, the sudden change of bending angle of the original design is about four times as that of the new design, and it is this sudden change of bending angles that greatly affects the smoothness of the track.

The possible reason for the apparent improvement of the transition is as follows. First, the roller-compacted concrete used in the new design has a lower stiffness itself on a condition that the requirements of rolling quality strengthen the plasticity itself, increase the settlement, then decrease the settlement difference of the transition-subgrade section and the sudden increment of bending angles at this section, and lower the danger of the cracking occurring at the upper boundary of the reversed trapezoid transition, which reflects the superiority of the roller-compacted concrete fully. At the same time, the high-intensity abnormal graded gravel is used in the abutment contact area for the former, which can effectively resist the additive impact force of the train load and thereby reduces the settlement volume and makes the vertical settlement on the rail surface distributed in linear shape along the vertical direction. This has preferably realized the stable transition from rigid abutment to flexible subgrade, showing the advantage of abnormal concrete to full.

Based on the above analysis, it can be known that the roller-compacted concrete can solve the problem of excessive stiffness on the transition section with efficiency, reducing the danger of cracking on the upper boundary of the transition section. Meanwhile, the abnormal graded gravel can guarantee the compaction quality while conducting compaction with small-size machinery within 2 m from the



(a) (b)

Figure 12: (a) Rail-bogie model (axis view). (b) Vehicle-track-subgrade coupling system model (axis view).

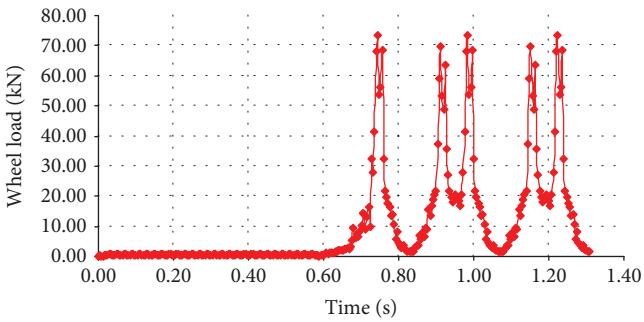


Figure 13: Wheel load versus time curve.

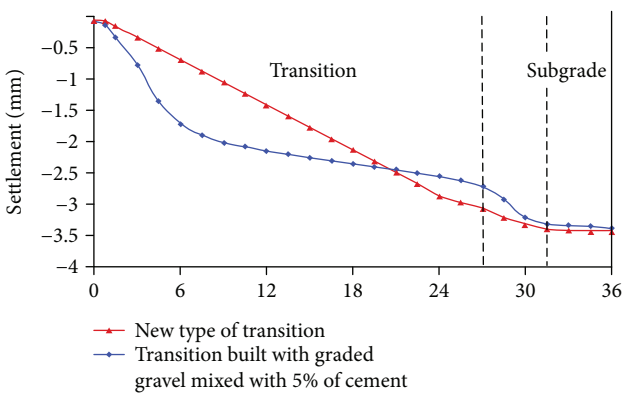


Figure 14: Diagrams for longitudinal distribution of the volume of vertical settlement on rail surface.

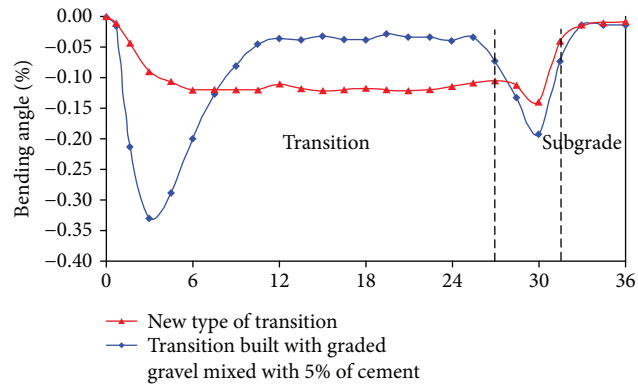


Figure 15: Diagrams for longitudinal distribution of rail-surface bending angle. Note: the place between two dotted lines is defined as the transition-subgrade section in this paper.

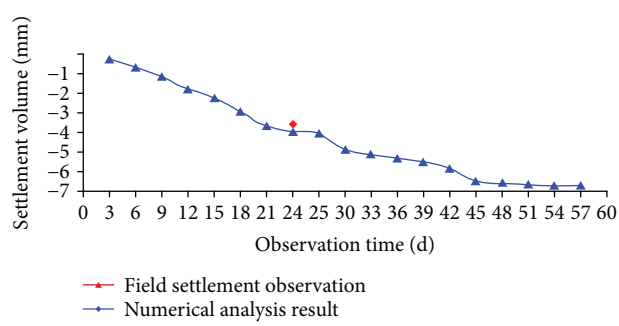


Figure 16: Data of settlement observation.

abutment. So, the new type of bridge- (culvert) subgrade transition preferably realizes stable transition from rigid abutment to flexible subgrade.

4. Field Settlement Observation

To verify the feasibility of the new type of bridge- (culvert) subgrade transition section further, the third bidding section of Beijing-Shanghai high-speed railway chose the prototype of the numerical analysis model of bridge- (culvert) subgrade transition section (DK533 + 440.5 operating point) and constructed the new type of transition section which was composed of the abnormal graded gravel and the roller-compacted concrete by using the same construction machines. The settlement observation instruments were buried at the top of the bedding surface layer, which was also away from the abutment about 25 m, so as to make regular observation. The detailed observation result is shown in Figure 16.

It can be known from Figure 16 that, for twenty-four days after construction, the site measured settlement volume is 4.06 mm, which is consistent with the numerical analysis result. The settlement volume at the top of the bedding surface layer has been mostly stabilized forty-eight days later, and the maximum settlement volume after construction is smaller than 15 mm, which can meet with the requirements of specifications. Hence, the new type of bridge- (culvert) subgrade transition section is feasible.

Figure 17: Material abandoning.

Figure 18: Leveling.

Figure 19: Smoothing.

5. Site Application

The new type of bridge- (culvert) subgrade transition section has been successfully adopted in the third bidding section of Beijing-Shanghai high-speed railway; the construction process contains eight steps, which are material abandoning, leveling, smoothing, roller compaction, grouting, vibrating, maintenance, and detection, successively. Details are shown in Figures 17–24.

6. Economical Efficient Analysis

In order to verify the superiority of the new type of the bridge- (culvert) subgrade transition section, this thesis

Figure 20: Roller compaction.

Figure 21: Grouting.

Figure 22: Vibrating.

Figure 23: Maintenance.

Figure 24: Detection.

has made some contrastive analysis between the unit prices of unit dosage of materials used for graded gravel method before and after improvement. The analysis was based on the unit prices of mobilization materials listed in the procurement contract for the third bidding section of Beijing-Shanghai high-speed railway. Please refer to Table 3.

It can be learnt from Table 3 that the cost of unit dosage for graded gravel before improvement is 12.31 yuan higher than that for abnormal graded gravel after improvement. If the III type coal ash or substandard ash is taken, the cost can be further reduced. Within 2 m of this structure, abnormal graded gravel can be taken for construction. As for producing paste, circulating slurry machine or mixing station is used for intensive mixing and stirring. It is only needed to add a Φ150 mm vibrating stick to replace the small-size roller compaction equipment. In this way, the lease expenses for machinery can be reduced.

The total length for bridge and tunnel of Beijing-Shanghai high-speed railway is 1077.1 km, accounting for 81.7% of the total length of the whole route. There are large numbers of projects on bridge- (culvert) subgrade transition sections. The adoption of the new type of high-speed railway bridge- (culvert) subgrade transition section can not only solve the problems such as excessive stiffness and guarantee compaction quality by compacting with small-size instruments within 2 m from the abutment so as to realize stable transition from rigid abutment (culvert) to flexible foundation but can also reduce the construction cost, which can help saving the construction cost. Consequently, this also can bring immense economic benefit to the country and society and even push forward the construction of high-speed railway in the whole world.

7. Conclusion

The following conclusions can be drawn from the above analysis:

(1) Successful introduction of the design concept and guiding ideology of roller-compacted concrete and abnormal concrete into the field of high-speed railway construction will promote the development of high-speed railway career of China and even of the whole world in certain extent.

(2) Under the repeated train load, for the bridge- (culvert) subgrade transition section built with the graded gravel mixed with 5% of cement (former) and the new type of bridge- (culvert) subgrade transition section composed of abnormal graded gravel and the roller-compacted concrete (latter), in the transition section, the maximum settlement of the track surface of the former is smaller than that of the latter, but the settlement of the latter is in linear distribution along the route; the maximum bending angle of the track surface of the former is bigger than that of the latter. The distribution of the bending angle of the track surface of the former is very even, and the maximum value occurs at the location away from the abutment about 5 m, but that of the latter is almost constant along the route. In the subgrade section, the settlement and the bending angle of the track surface of the former are consistent with those of the latter. In the transition-subgrade section, the settlement difference of the former is larger than that of the latter, and the sudden increment of the bending angle of the track surface of the former is bigger than that of the latter. So, the new type of bridge- (culvert) subgrade can realize the smooth transition from the rigid abutment to the flexible subgrade.

(3) Comprehensive analysis was done to the new type of bridge- (culvert) subgrade transition section from four aspects, which are numerical analysis, settlement observation, field application, and construction cost. And the results show that this new type of bridge- (culvert) subgrade transition section has prominent advantages, obvious effects, positive functions, and satisfying quality. First, by adopting coal ash to replace some of the cement, construction cost is reduced and the total cost of the project can be saved, which makes immense contribution to the nation and the society. Next, the particle size of coal ash and cement is different, so mixing the coal ash can improve the graded composition of the graded gravel, which can improve the compaction quality. At the same time, the problem of excessive stiffness of the transition section can be also solved, reducing the danger of the cracking on the upper boundary of the transition section. Finally, through using the abnormal graded gravel to replace small-size vibrating compaction equipment within 2 m from the abutment, the compaction quality can be enhanced, with the work efficiency being improved and construction cost reduced. And the problem of compaction quality being not guaranteed by using small-size machinery for compacting within 2 m from the abutment can also be solved.

(4) The successful applications of the new type of bridge- (culvert) subgrade transition section in the construction of the third bidding section of Beijing-Shanghai high-speed railways have proved the feasibility and

Table 3: Correlation Table for Unit Prices of Graded Gravel Transformed before and after improvement.

Type	Volume of materials used in each cubic meter (kg/m^3)				Unit price (yuan/m^3)
	Cement	Coal ash	Tail sand	Graded gravel	
Unit price for mobilization (yuan/ton)	285	87	26	50	/
Abnormal mortar	400	400	/	/	138.2
Graded gravel (+5% cement)	120	/	1062	1062	111.66
Improved graded gravel	48	72	1062	1062	99.35

Note: the abnormal mortar can be only used within 2 m from the structure (the large-size machines cannot make roller compaction, so small volumes of filling materials will be used).

superiority of these construction technologies fully and provide valuable experiences for the application and dissemination of these technologies into the construction of future high-speed railways.

Conflicts of Interest

The authors of this manuscript do not have any conflicts of interest regarding the publication of this article.

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