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Current situation and development trend of design methods for subgrade structure of high speed railways

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Abstract

Purpose – This method will become a new development trend in subgrade structure design for high speed railways.

Design/methodology/approach – This paper summarizes the structural types and design methods of subgrade bed for high speed railways in China, Japan, France, Germany, the United States and other countries based on the study and analysis of existing literature and combined with the research results and practices of high speed railway subgrade engineering at home and abroad.

Findings – It is found that in foreign countries, the layered reinforced structure is generally adopted for the subgrade bed of high speed railways, and the unified double-layer or multi-layer structure is adopted for the surface layer of subgrade bed, while the simple structure is adopted in China; in foreign countries, different inspection parameters are adopted to evaluate the compaction state of fillers according to their respective understanding and practice, while in China, compaction coefficient, subsoil coefficient and dynamic deformation modulus are adopted for such evaluation; in foreign countries, the subgrade top deformation control method, the subgrade bottom deformation control method, the subsurface fill strength control method are mainly adopted in subgrade bed structure design of high speed railways, while in China, dynamic deformation control of subgrade surface and dynamic strain control of subgrade bed bottom layer is adopted in the design. However, the cumulative deformation of subgrade caused by train cyclic vibration load is not considered in the existing design methods.

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Originality/value – This paper introduces a new subgrade structure design method based on whole-process dynamics analysis that meets subgrade functional requirements and is established on the basis of the existing research at home and abroad on prediction methods for cumulative deformation of subgrade soil.

Keywords High speed railway, Subgrade engineering, Subgrade bed structure, Design method, Existing research, Development trend

Paper type Research paper

1. Introduction

China has built the world's most developed high speed railway network. It is estimated that by 2030, the operating mileage of high speed railways in China will reach 45,000 km, and a national high speed railway network with "eight vertical and eight horizontal rail corridors" as the main channels will be completed (Lu, 2013; Wang, Yang, Zhou, & Gong, 2015). High speed railways are characterized by closely scheduled trips, high operation speed and demanding riding comfort, and require high track smoothness and stability of the whole line. Subgrade engineering is an essential part of the substructure of high speed railways. In order to ensure smooth, safe and comfortable operation of high speed railways, it is necessary to put forward higher standards and requirements for the design of subgrade structure (Hu & Li, 2010; Ye & Zhou, 2005; Ye, 2015).

Currently, the layered structure system reinforced by graded crushed stone is adopted for railway subgrade structure in China. The subgrade is formed by repeated vibration compaction during the filling process, and is subject to not only the static load transmitted by the track structure and auxiliary structure, but also the long-term cyclic dynamic load of trains in service (Wang, Yang, Zhou, & Gong, 2015; Ye & Zhou, 2005; Ye, 2015). Currently, in China, the equivalent dynamic load analysis method with the dynamic and static load effects in service considered is adopted for the design of high speed railway subgrade structure; the deformation modulus is determined according to the actual strain level of the soil mass, based on the laboratory test results, and considering the nonlinear properties of the soil mass; the dynamic stress and dynamic strain of the subgrade are calculated by Boussinesq formula on the assumption that the subgrade is an elastic half-space; the design criteria based on the dynamic deformation of subgrade surface and the dynamic strain control of bottom layer of subgrade bed are proposed combined with the measured data for the purpose of controlling the cumulative deformation of subgrade under the round-trip load (Zhang, Han, & Lü, 2005). The traditional design method simplifies the dynamic process in the construction and service stages of subgrade structure, and transforms the dynamic process into a quasi-static process through theoretical assumptions (Ye & Zhou, 2005; Zhang *et al.*, 2005), which can meet the engineering requirements, and the design refinement is not high on the whole. However, the *Code for Design of High Speed Railway* (TB 10621-2014) only gives unified general provisions for different types of subgrade bed structures with different speed levels of high speed railways (The Third Railway Survey and Design Institute Group Corporation & China Railway Siyuan Survey and Design Group Co., Ltd., 2014; Xiong, 2011; Zhang *et al.*, 2005; Zhang, Ma, & Cai, 2008). Therefore, establishing a new design method for subgrade structure based on whole-process dynamic analysis that meets the functional requirements of subgrade will help further improve and develop the current design theory of subgrade structure, optimize the subgrade bed structure, and enhance the subgrade design and construction level (Dong, Zhao, Cai, Zhang, & Ye, 2008; Wang *et al.*, 2015; Ye, 2015).

This paper, on the basis of systematical summarizing of the structural types, design methods and studies on the dynamic theory of subgrade bed structures of high speed railways in various countries, indicates the challenges in high speed railway subgrade design in China and analyzes the development trend of subgrade structure design of high speed railways.

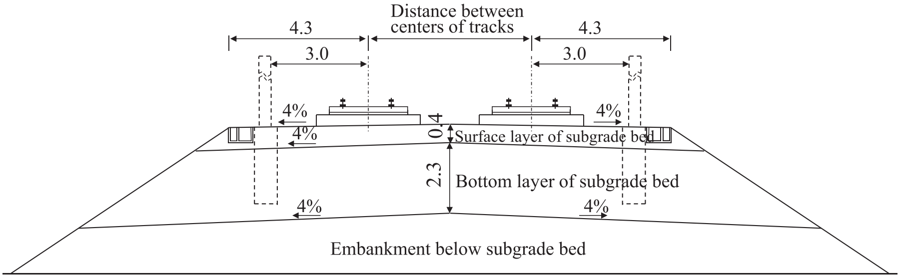
2. Structural types of subgrade bed of high speed railways

The condition of subgrade bed of high speed railways is mainly subject to its thickness, the filler and its compactness, the subgrade bed, waterproof and drainage structures and other factors, which directly affects the smooth operation and speed increase of trains. The subgrade bed structure should meet the requirements in terms of strength and deformation to ensure its long-term deformation stability under the action of multiple factors such as train load, rainwater, dry-wet cycle and freeze-thaw cycle (China Academy of Railway Sciences, 2011; Ye, 2004; Ye & Luo, 2007; Ye, Wang, Cheng, & Luo, 2007; Ye, Cheng, & Zhang, 2008; Ye *et al.*, 2015; Zhang, Zhu, & Dong, 2008).

2.1 China

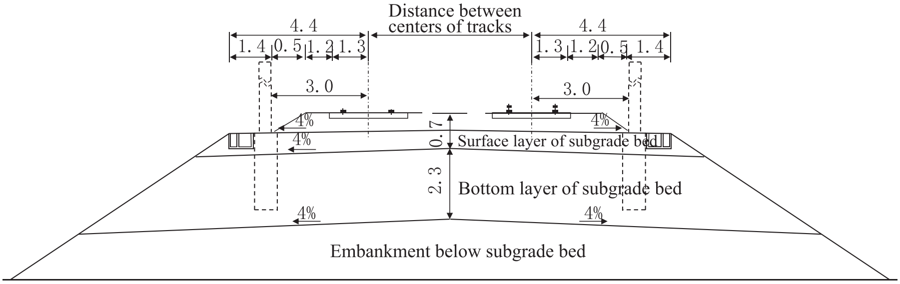
China adopts a layered subgrade bed structure that consists of a surface layer and a bottom layer of subgrade bed for high speed railways (China Academy of Railway Sciences, 2011; The Third Railway Survey and Design Institute Group Corporation & China Railway Siyuan Survey and Design Group Co., Ltd., 2014; Wang *et al.*, 2015; Zhang, Ma, *et al.*, 2008; Zhang, Zhu, *et al.*, 2008). For ballastless tracks, the surface layer of subgrade bed is 0.4 m thick, and the bottom layer of subgrade bed is 2.3 m thick; for ballasted tracks, the surface layer of subgrade bed is 0.7 m thick, and the bottom layer of subgrade bed is 2.3 m thick, as shown in Figure 1.

The surface layer of subgrade bed is filled with graded crushed stone with a particle size less than 60 mm, and the bottom layer of subgrade bed is filled with Group A and Group B fillers or chemically improved soil of gravelly and sandy soil with a particle size less than



Ballastless track

(a)



Ballasted track

(b)

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Figure 1. Schematic diagram of standard cross-section of subgrade of high speed railways in China (Unit: m)

60 mm. The compaction coefficient K, subsoil coefficient K_{30} and dynamic deformation modulus E_{vd} are used as the compaction control indexes for subgrade bed of graded crushed stone, gravel and sandy soil, and the compaction coefficient and 7 d unconfined compressive strength of saturated soil are used as the compaction control indexes for subgrade bed of chemically improved soil. See Table 1 for the compaction standards for fillers of the surface layer and the bottom layer of subgrade bed.

2.2 Japan

In the design of subgrade for high speed railways in Japan, it is treated as a structural system, which is divided into the surface layer of subgrade bed, upper fill and lower fill from top to bottom. The surface layer of subgrade bed includes 3 types: asphalt surface layer, concrete surface layer and crushed stone surface layer. Among them, the asphalt and concrete surface layer types can be used for ballastless tracks, the asphalt surface layer can be used for important ballasted tracks and the crushed stone surface layer can be used for general ballasted tracks.

2.2.1 Surface layer of subgrade bed.

(1) Asphalt surface layer of subgrade bed

The asphalt surface layer of subgrade bed is composed of an upper asphalt mixture layer and a lower graded crushed stone layer. The basic constructions of the asphalt mixture layer in the asphalt surface layer of subgrade bed for ballastless tracks and for ballasted tracks are same but are designed in different ways due to different track structures which the subgrade bed supports.

In design of the asphalt mixture layer in the asphalt surface layer of subgrade bed for ballastless tracks, the fatigue failure of the asphalt mixture layer and the residual deformation of the subgrade bed are calculated to determine the optimized thickness of the asphalt mixture layer. The schematic diagram of the cross-section of the asphalt surface layer of subgrade bed for ballastless tracks is shown in Figure 2, the longitudinal section structure is shown in Figure 3, and the section size is shown in Table 2. The compaction coefficient K of

Table 1.
Compaction standards for fillers of surface layer and bottom layer of subgrade bed

		Compaction standard			
Position	Filler	Compaction coefficient, K	Subsoil coefficient, K_{30}/(MPa·m^{-1})	7 d unconfined compressive strength of saturated soil/kPa	Dynamic deformation modulus, E_{vd}/MPa
Surface layer	Graded crushed stone	≥0.97	≥190		≥55
Bottom layer	Group A and Group B coarse gravel soil and crushed stone	≥0.95	≥150		≥40
	Group A and B sandy soil (except silty sand) and fine gravel soil	≥0.95	≥130		≥40
	Chemically modified soil	≥0.95		≥350 (550)	

Note(s): The bracketed value is the strength required for chemically improved soil considering the freeze-thaw cycle in severe cold areas. Refer to the *Code for Design on Subgrade of Railway* (TB 10001-2016)
Source(s): Authors' own work

the asphalt mixture layer is ≥ 0.95 (core sampling), and the compaction coefficient K of the graded crushed stone layer is ≥ 0.95 (replaced with sandy soil).

In design of the asphalt mixture layer in the asphalt surface layer of subgrade bed for ballasted tracks, the surface displacement of the asphalt surface layer of subgrade bed is calculated, and the thickness of the graded crushed stone layer is optimized with the consideration of subgrade bed conditions and train loads. The schematic diagrams of the cross-section of the asphalt surface layer of subgrade bed for ballasted tracks, the longitudinal section structure and the section size are shown in Figure 4, Figure 5 and Table 3, respectively. Graded crushed stone, graded iron and steel slag (MS), hydraulic graded iron and steel slag (HMS) and other crushed stone materials are used for the lower part of the asphalt surface layer of subgrade bed for ballasted tracks.

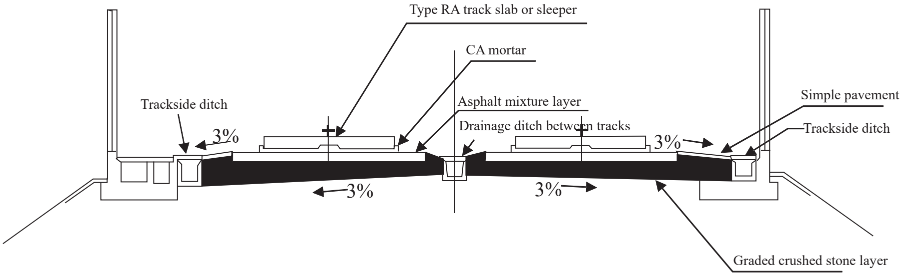

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Figure 2.
Schematic cross section of asphalt surface layer of subgrade bed for ballastless tracks in Japan

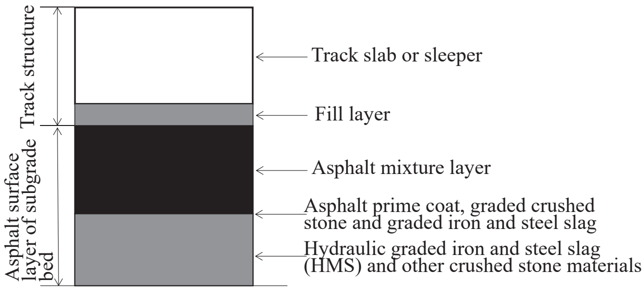

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Figure 3.
Longitudinal section structure of asphalt surface layer of subgrade bed for ballastless tracks in Japan

Surface structural layer of subgrade bed	Track category	Width of surface layer of subgrade bed/m	Standard thickness of surface layer of subgrade bed/m Type RA ballastless track	 Sleeper-embedded track
Asphalt mixture layer	Standard gauge	3.20	0.15	0.20
Graded crushed stone layer	Standard gauge		0.15	0.15

Source(s): Authors' own work

Table 2.
Section size of asphalt surface layer of subgrade bed for ballastless tracks in Japan

(2) Concrete surface layer of subgrade bed

The concrete surface layer of subgrade bed is composed of a reinforced concrete slab and graded crushed stone. The schematic diagram of cross-section of the concrete surface layer of subgrade bed for ballastless tracks, the longitudinal section structure and the section size are shown in Figure 6, Figure 7 and Table 4, respectively. The function of the reinforced concrete slab is to transmit track load to the part underneath and suppress deformation with its large flexural rigidity, to ensure the smoothness of the surface layer of subgrade bed. The function of graded crushed stone is to support the reinforced concrete slabs and distribute and transmit load to the subgrade bed.

(3) Crushed stone surface layer of subgrade bed

The crushed stone surface layer of subgrade bed is constructed with a single material with excellent mechanical properties, and the structure is shown in Figure 8. In order to avoid mud pumping of the surface layer of subgrade bed, the thickness of the surface layer of subgrade bed should be 0.3 m.

K_{30} and K are adopted to control the compaction quality of the crushed stone surface structure of subgrade bed, and it should be ensured that $K_{30} \geq 110\ \mathrm{MPa \cdot m^{-1}}$ or $K \geq 0.95$.

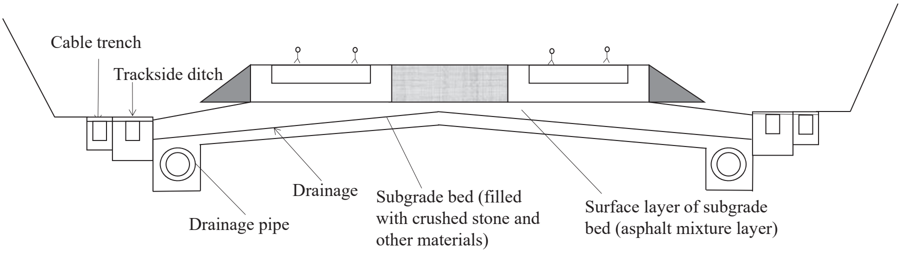

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Figure 4.
Schematic cross section of asphalt surface layer of subgrade bed for ballasted tracks in Japan

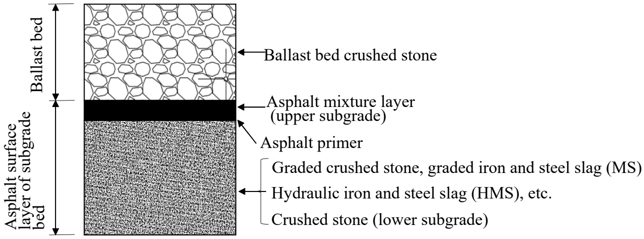

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Figure 5.
Longitudinal section structure of asphalt surface layer of subgrade bed for ballasted tracks in Japan

Table 3.
Section size of asphalt surface layer of subgrade bed for ballasted tracks in Japan

Subsoil coefficient/($\mathrm{MPa \cdot m^{-1}}$)	Coarse-grained asphalt mixture/mm
$K_{30} \geq 110$	50
$70 \leq K_{30} < 110$	50
$K_{30} \geq 110$	50
$70 \leq K_{30} < 110$	50

Source(s): Authors' own work

2.2.2 Upper fill. The part of the embankment with a depth of 3 m below the formation level is collectively referred to as the upper fill, for which the subgrade compaction state is mainly controlled by K_{30}, and it should be ensured that $K_{30} \geq 110$ MPa·m^{-1}.

2.2.3 Lower fill. When the fines content F_c of the lower fill is lower than 20%, and K is used to control the compaction state, it is necessary to ensure that $K \geq 0.9$. When the fines content F_c of the lower fill is greater than 20%, the percentage of air voids n_a can be used to control the compaction state. When $20\% \leq F_c \leq 50\%$, it is required that $n_a \leq 15\%$; when $F_c > 50\%$, it is required that $n_a \leq 10\%$.

2.3 France

In France, subgrade is divided into good, medium and poor quality levels according to the filler conditions of the surface layer of subgrade and the filler quality of subgrade for high speed railways. One layer of adjusted cushion (equivalent to the surface layer of subgrade bed

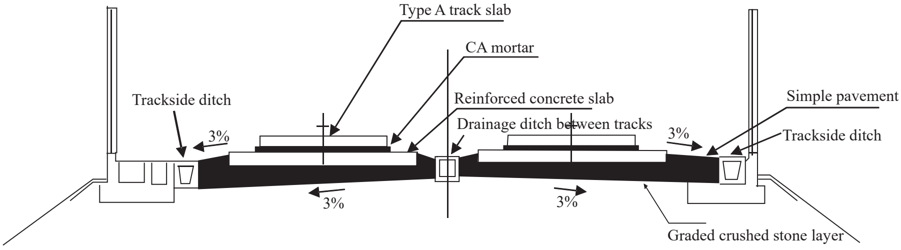

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Figure 6. Schematic cross-section of concrete surface layer of subgrade bed for ballastless tracks in Japan

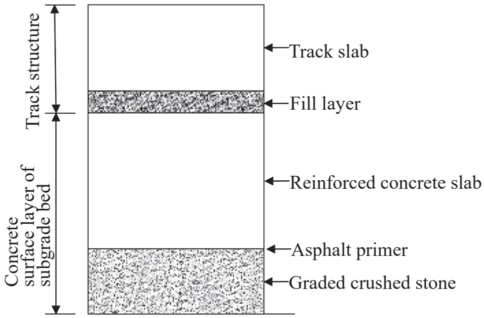

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Figure 7. Longitudinal section structure of concrete surface layer of subgrade bed for ballastless tracks in Japan

Surface structural layer of subgrade bed	Track category	Load-bearing width of surface layer of subgrade bed/m	Standard thickness/m
Concrete slab	Standard gauge	3.20	0.30
Graded crushed stone layer	Standard gauge		0.15

Source(s): Authors' own work

Table 4. Section size of concrete surface layer of subgrade bed for ballastless tracks in Japan

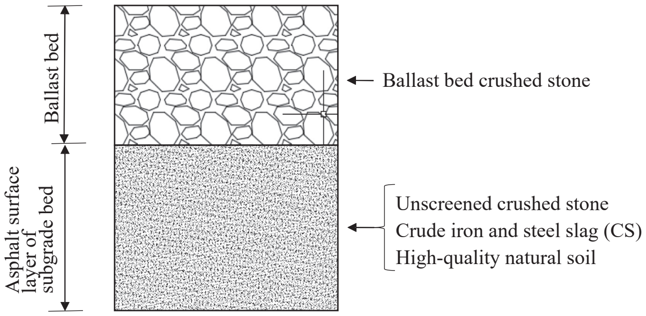

Figure 8.
Structure of crushed stone surface layer of subgrade bed in Japan

Source(s): Authors' own work

for high speed railways in China) is set between the ballast layer and the subgrade, and a transversely inclined subgrade surface layer is arranged at the subgrade top. The section is shown in Figure 9.

The top surface of the cushion is sloped at 3%–5% (Association Française de Normalisation, 2009), and the cushion is composed of the following 3 parts.

(1) Ballast cushion: It is composed of pure gravel (particle size ≥30 mm), with $K \geq 1.0$, and it is required under any circumstance, and its thickness is subject to the change of sleeper and subgrade types and transportation conditions.

(2) Subbase: It is composed of graded pure gravel, with $K \geq 1.0$, and a minimum thickness of 15 cm, and it is optional when the soil conditions are good.

(3) Anti-fouling layer: It is sometimes used together with a layer of pure sand cushion, or an additional layer of synthetic felt cushion is laid on the surface layer of subgrade to serve as the anti-fouling layer. If the surface layer of subgrade contains solid particles that can abrade or damage the felt cushion, the felt cushion needs to be arranged between the sand layers.

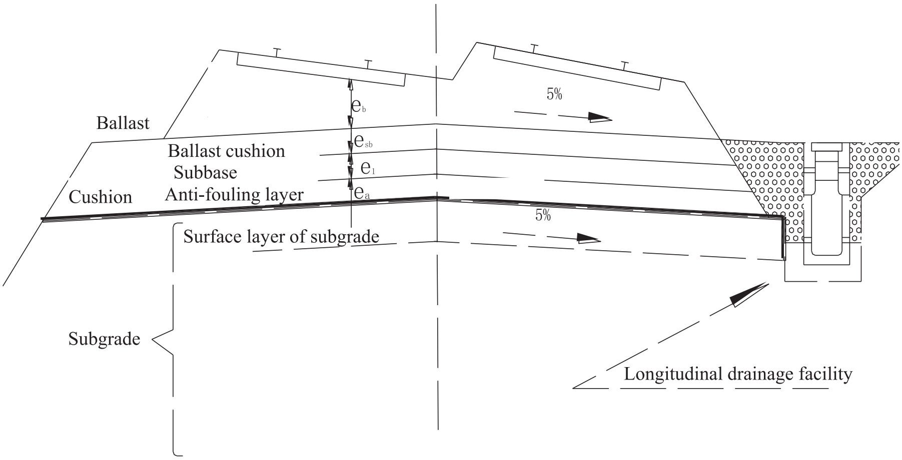

Figure 9.
Structure of subgrade bed for high speed railways in France

Source(s): Authors' own work

In embankments, the surface layer of subgrade is constructed with the same soil mass or soil materials with good properties as those used for the filled embankments, and is compacted with $K \geq 0.95$. The surface layer of subgrade can also be finished with mortar according to the actual situation of the works. In cuttings, the surface layer of subgrade is compacted with $K \geq 0.95$ and a thickness of at least 30 cm. Meanwhile, it is specified that the cushion can be constructed only when the deformation modulus E_{v2} of the surface layer of subgrade is ≥ 50 MPa. See Table 5 for the specific compaction standard for each part.

2.4 Germany

The subgrade structure for high speed railways in Germany is composed of a protective layer, a frostproof layer and a soil subgrade layer from top to bottom. The protective layer and the frostproof layer of subgrade serve the same purposes as that of the surface layer of subgrade bed for high speed railways in China, and their total thickness is determined according to the deformation modulus value required by the subgrade protective layer. The soil subgrade layer serves the same purposes as that of the bottom layer of subgrade bed and embankment for high speed railways in China. According to the characteristics of each stressed layer and the engineering properties of the fillers, several comprehensive indexes such as deformation modulus E_{v2}, dynamic deformation modulus E_{vd}, compaction coefficient K and percentage of air voids n_a are used to control the compaction state of subgrade and assess the corresponding compaction quality (Translated by Zhao & Zhuang, 1995). Typical section and compaction standards of subgrade in Germany are shown in Figures 10 and 11, respectively. In the figures, KG1 and KG2 are granular mixture 1 and 2, respectively; GW is well-graded gravel; GI is gap-graded gravel; GE is poorly graded gravel; SE is poorly graded

Structural layer of subgrade	Thickness/cm	K	E_{v2}/MPa
Ballast cushion	To be determined according to transportation conditions and sleeper type	≥1.00	
Subbase	Generally ≥15 according to actual needs	≥0.95	
Surface layer of subgrade		≥0.95	≥50

Source(s): Authors' own work

Table 5. Subgrade compaction standards in France

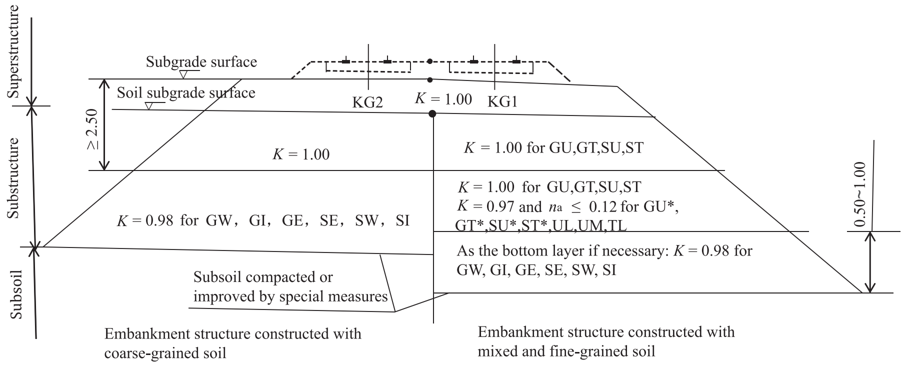

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Figure 10. Typical section and compaction standards of subgrade of ballasted tracks for high speed railways in Germany (Unit: m)

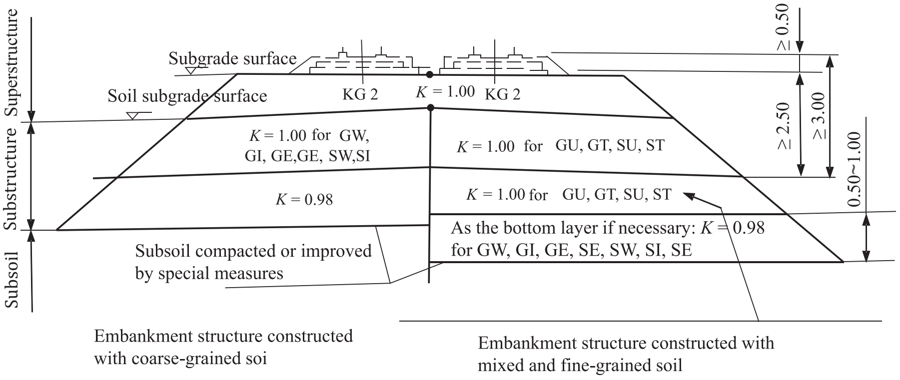

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Figure 11.
Typical section and compaction standards of subgrade of ballastless tracks for high speed railways in Germany (Unit: m)

sand; SW is well-graded sand; SI is gap-graded sand; GU is silty gravel; GT is clayey gravel; SU is silty sand; ST is clayey sand; GU*, GT*, SU* and ST* are silty gravel, clayey gravel, silty sand and clayey sand with a particle size less than 0.06 mm and particle content of 15%–40%, respectively; UL is weak plastic silt; UM is medium plastic silt; TL is weak plastic clay. See Table 6 for specific compaction standards.

2.5 Similarities and differences among countries

In conclusion, in order to meet the needs for service, the layered reinforced structure system is generally adopted for the surface layer of subgrade bed for high speed railways in the countries, such as the surface structure of subgrade bed composed of a protective layer and a frostproof layer for ballasted tracks, and the surface structure of subgrade bed composed of a hydraulic layer and a frostproof layer for ballastless tracks in Germany; the surface structure of subgrade bed composed of ballast cushion, subbase and an anti-fouling layer in France; the surface layer of subgrade bed composed of asphalt, concrete and crushed stone in Japan. In order to ensure a clear load transmission path and simple construction, a simple structural system is adopted for the surface layer of subgrade bed in China.

In terms of fillers, China uses graded crushed stone for the surface layer of subgrade bed, with the grain size gradation and impermeability of graded crushed stone being basically the same as those adopted by France and Germany.

Table 6.
Compaction standards of subgrade in Germany

	Subgrade surface			Protective layer					
					Specified thickness for areas with different degrees of frost heave/cm				
Superstructure	E_{v2}/MPa	E_{vd}/MPa	Granular mixture	K	I	II	III	E_{v2}/MPa	E_{vd}/MPa
Ballasted tracks	120	50	KG1 or KG2	1.00	70	70	70	80	40/35
Ballastless tracks	120	50	KG2	1.00	40	40	40	60	35/30

Source(s): Authors' own work

In terms of compaction quality control of subgrade, China uses the compaction coefficient, subsoil coefficient and dynamic deformation modulus as the indexes to assess the compaction quality of subgrade constructed with graded crushed stone, gravel and sandy soil. And Japan uses the subsoil coefficient and compaction coefficient as the indexes, and France and Germany use the compaction coefficient and deformation modulus as the indexes. All the countries use the compaction factor. See Table 7 for details.

3. Design method of HSR subgrade bed structure

3.1 China

The subgrade bed of high speed railways is generally of a structure gradually reinforced from bottom to top in China. The thickness design of the surface layer of subgrade bed is the core of the design of the subgrade bed structure, and is crucial in controlling the deformation of the subgrade bed and protecting the lower fill. China Academy of Railway Sciences (Railway Engineering Research Institute, 2005; Railway Engineering Research Institute, 2006; Zhang, Ma, *et al.*, 2008; Zhang, Zhu, *et al.*, 2008) has carried out a large number of field and laboratory tests, systematic analysis of the distribution pattern of high speed railway subgrade load, and studies on the basic rules of dynamic stress and dynamic deformation of subgrade bed. In order to avoid cumulative deformation and cumulative pore pressure effect of subgrade under the cyclic load of trains, the dual-control criterion of dynamic deformation of subgrade surface and dynamic strain of bottom layer of subgrade bed are determined and the design method of subgrade bed structure based on strain control is developed.

3.1.1 Determination of critical value of dynamic strain. In the calculation of dynamic stress and dynamic deformation of high speed railway subgrade, the selection of train axle load and track structure parameters are basically the same, while the selection of filler modulus that has a great impact on results is very different. The shear modulus ratio G/G_{max} (the ratio of the actual shear modulus to the maximum shear modulus) obtained from the test versus strain γ is shown in Figure 12. It can be seen from Figure 12 that the filler modulus shows a nonlinear attenuation trend with the increase of strain. Considering the proportional conversion between deformation modulus and shear modulus, the calculation parameters of deformation modulus should be determined based on compaction test indexes and nonlinear characteristics of fillers. In order to avoid cumulative deformation of subgrade bed, the strain of subgrade bed should be controlled within a certain range. The critical shear modulus ratio corresponding to the critical strain without causing the volume effect is about 0.65,

Compaction parameter	China	Japan	Germany	France	UK	UIC	Italy
Compaction coefficient, K	√	√	√	√	√	√	√
Subsoil coefficient, K_{30}	√	√					
Relative density, D_r	√						
Porosity, n	√						
California bearing ratio, CBR		√					
Percentage of air voids, n_a		√	√				
Deformation modulus, E_{v2}	√		√	√		√	
Dynamic deformation modulus, E_{vd}	√		√	√			
Blow counts of lightweight dynamic cone penetration test, N_{10}					√		
Indexes used together	K_{30}, K or K_{30}, n	K_{30}, K or K_{30}, n_a	K, E_{v2} or K, n_a	K, E_{v2}	K, N_{10}	K, E_{v2}	K, E_v

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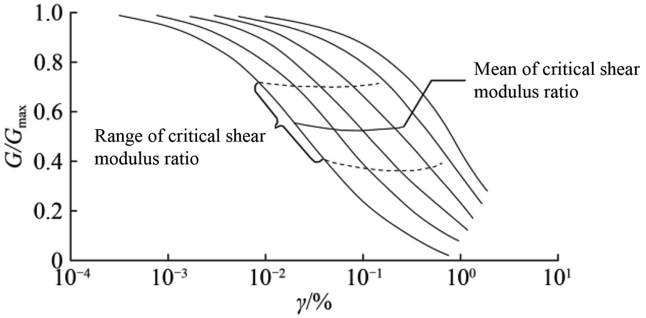
Table 7. Compaction parameters used by countries

Figure 12.
Shear modulus ratio vs strain



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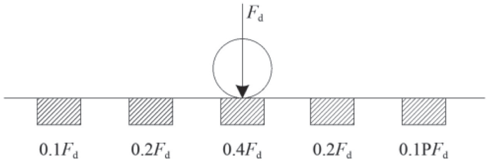
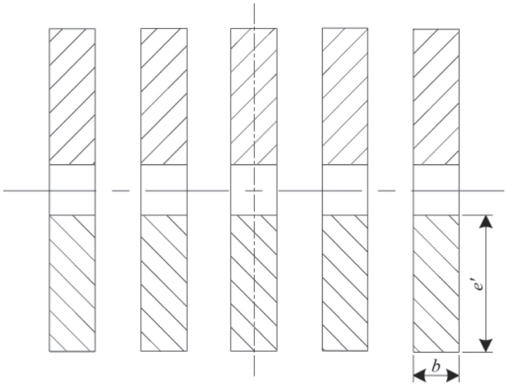
which is generally between the two horizontal dotted lines that are close to each other in the figure, so the deformation modulus should be 0.65 times the maximum modulus.

3.1.2 Determination of initial dynamic load of ballast bed. When calculating the dynamic load of subgrade of ballasted tracks, the dynamic wheel load is proportionally distributed to the sleeper. The dynamic load on the top surface of the ballast bed is calculated by Formula (1) (Ye *et al.*, 2015), and the effective supporting area of the sleeper is converted into the load distribution area, as shown in Figure 13. Where b is the average width of the sleeper; e' is the average effective supporting length of the sleeper; F_d is the dynamic axle load.

Figure 13.
Distribution of train load on top surface of ballast bed



Longitudinal section
(a)



Horizontal section
(b)

Source(s): Authors' own work

$$F_\mathrm{d} = F_\mathrm{s}(1 + av) \tag{1}$$

where F_s is the static axle load (in kN); α is the speed influence coefficient, which should be 0.003 for high speed railways; v is the design speed (in km·h^{-1}).

When calculating the dynamic load of subgrade of ballastless tracks, the distribution of dynamic load on subgrade is simplified, and the two axle loads of one bogie are considered as a concentrated force, which is multiplied by the corresponding dynamic coefficient to obtain the design dynamic load of trains.

3.1.3 Determination of modulus. In the absence of measured test data, the modulus for the calculation of the surface layer of subgrade bed and ballast bed should be 180 MPa for the graded crushed stone surface layer of subgrade bed and 300 MPa for the ballast bed. The modulus for the calculation of the bottom layer of subgrade bed should be selected considering the nonlinear influence of strain level on the modulus. During the K_{30} test, the average strain level of subgrade filler is about 0.18%. On the assumption that the subgrade is an elastic half-space, when Poisson's ratio $\mu = 0.21$, deformation modulus $E = 0.23K_{30}$ is obtained. The deformation modulus E_max of the filler can be calculated according to Figure 9. Since the design puts weight on ensuring safety, the calculated modulus of the bottom layer of subgrade bed is equal to the modulus corresponding to the critical strain, i.e. $E = 0.65E_\mathrm{max}$.

3.1.4 Dynamic stress and dynamic deformation of subgrade. After the dynamic load and the modulus of filler of the top surface of subgrade are determined, considering the subgrade as an elastic homogeneous half-space, the dynamic stress and dynamic deformation of subgrade are calculated by analytical solutions of the Boussinesq equation.

3.1.5 Thickness of surface layer of subgrade bed. Taking different thickness values of the surface layer of subgrade bed, the dynamic stress and dynamic deformation of subgrade bed are calculated by the Boussinesq equation, and the thickness of the surface layer of subgrade bed is determined according to the criterion that the calculation results obtained with the thickness should be less than the critical limits of dynamic deformation of subgrade surface and dynamic strain of bottom layer of subgrade bed.

The above design method for subgrade structure of high speed railways has been incorporated into the *Code for Design of High Speed Railway* (TB 10621-2014).

3.2 Japan

The deformation control method for the top surface of subgrade is adopted by Japan for the reinforced subgrade bed structure of high speed railways. Based on the favorable engineering experience of highway asphalt pavement, the bending angle θ is used to control the structural deformation of the surface layer of subgrade bed, which should be limited to prevent the structure from bending and cracking, as shown in Figures 14 and 15.

Based on the finite element method, the checking calculation for the performance of different types of subgrade bed reinforced structure is conducted: (1) the surface layer of concrete subgrade bed is subject to checking calculation for safety against rupture, safety

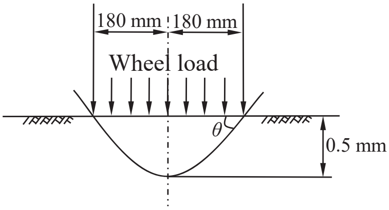


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Figure 14. Control standard for bending angle of highway pavement

against fatigue failure and usability; (2) the asphalt surface layer of subgrade bed is subject to checking calculation for the service life subject to the fatigue failure of the asphalt mixture layer and the displacement of the asphalt surface layer of subgrade bed respectively. The allowable number of loading cycles corresponding to the fatigue failure of the asphalt mixture layer is calculated with the strain on the bottom of the asphalt mixture layer, and Japan uses the finite element method to calculate the strain on the asphalt mixture layer. If the checking calculation results cannot meet the requirements for the expected service life, the thickness of the asphalt mixture layer should be increased. Measures such as increasing the sleeper size, reducing the elasticity of track pads, reinforcing the subgrade bed or using a high-quality asphalt mixture can also be considered.

3.3 Germany

In Germany, the thickness of the surface layer of subgrade bed for high speed railways is determined according to the required deformation modulus for top surface of subgrade (Association Française de Normalisation, 2009). The thickness of the protective layer of subgrade for high speed railways should be designed to ensure that the whole bearing system has sufficient bearing capacity and is frostproof. The protective layer should be subject to calculations for bearing capacity design and frostproof design respectively. The maximum thickness of the protective layer is determined by the two design calculations.

For ballastless tracks, the protective layer is divided into hydraulic and non-hydraulic types according to different structural types, and the thickness is designed by calculation respectively. For ballasted tracks, the thickness of the protective layer as the bearing layer is related to the deformation modulus E_{EPL} of the subgrade soil or the original ground surface, the deformation modulus E_0 of the filler for the protective layer, and the deformation modulus E_{PL} of the subgrade surface of the protective layer. According to the calculation chart for the thickness of the protective layer of subgrade in the DB Guide DS 836 “Specification for Earthworks” (Figure 16), the thickness of the protective layer as the bearing layer is determined based on the bearing capacity of the subgrade soil and the required bearing capacity for the subgrade. The deformation modulus E_{PL} of the subgrade surface of the protective layer is determined according to E_{v2}. And the thickness of the protective layer as the frostproof layer is calculated according to the total atmospheric temperature drop and the annual average temperature.

According to the required deformation modulus for subgrade, the thickness of the protective layer of subgrade bed is determined by a method similar to the thickness design method for highway subgrade. The test load for determining the deformation modulus for the subgrade surface of highways is similar to the service load. Therefore, conformity with the

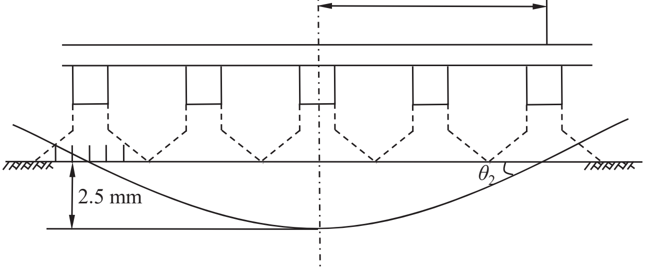
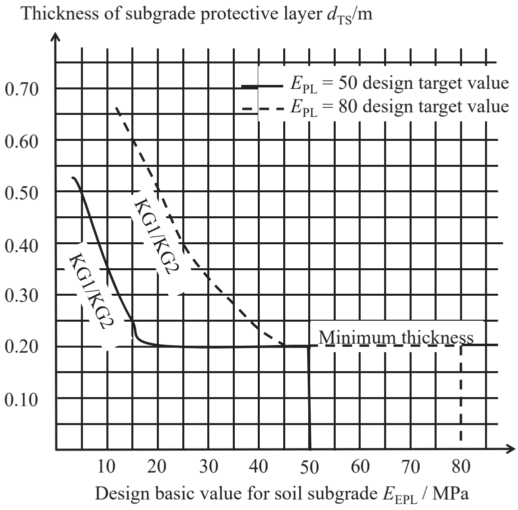


Figure 15.
Control standard for bending angle of high speed railway surface

Source(s): Authors’ own work



Source(s): Authors' own work

Figure 16. Design calculation chart for protective layer thickness (Unit: MPa)

requirement for the test load indicates the bearing capacity for the service load. However, due to the large difference between the test load for the deformation modulus and the service load in the action range in high speed railways, subgrade tested with the required deformation modulus of the surface may have different service performance in use, which also results in the lack of necessary basis for determining the deformation modulus limits of the surface layer of railway subgrade of different grades.

3.4 United States and South Africa

In the United States and South Africa, the thicknesses of ballast bed and cushion for high speed railways are determined by controlling the strength of fill under the surface layer of subgrade bed. In order to protect the lower fill, the stress on the lower fill is required to be less than the allowable stress (AREMA-American railway engineering and maintenance of way association, 2007). The allowable stress can be determined in many methods, including static strength calculation and dynamic strength calculation. There are many ways to determine strength. This method is applicable for destructive problems of subgrade bed such as subgrade bed defects of heavy haul railways, but it is difficult to implement when there are strict requirements for high speed railway deformation. In case of requirements for minor deformation, the definition and determination method of strength are challenges.

3.5 Similarities and differences among countries

In conclusion, the current design methods for subgrade bed structure of high speed railways in various countries include the control method of deformation of the subgrade top surface, the control method of deformation modulus of the subgrade bottom surface, the control method of lower fill strength under subgrade bed surface, etc. China adopts the dynamic deformation of subgrade surface and the dynamic strain of bottom layer of subgrade bed as the control indexes for design. Such design method, without taking the cyclic vibrating load into consideration, and on the assumption that the subgrade is an elastic half-space, simplifies the dynamic process of construction and service stages of the subgrade structure to transform the dynamic process into a static process. The design made by this method is based on too many assumptions and is not sufficiently refined, and the cumulative effect of cyclic train load on subgrade deformation cannot be calculated.

4. Current research on cumulative deformation prediction methods for subgrade of HSR

Ballastless tracks are mainly adopted for high speed railways in China, which require strict control of subgrade settlement with a clear limit of 15 mm for post-construction settlement of subgrade. High speed railways are characterized by fast operating speeds, closely scheduled trips and high traffic volumes, and are inevitably subject to cumulative settlement and deformation of subgrade under long-term train operation load, which will affect the operation of high speed railways. At present, the design method for high speed railway subgrade does not directly consider the cumulative deformation of subgrade caused by cyclic dynamic load of trains. In this field, studies have been carried out at home and abroad (Chen & Bian, 2018; Dong, Cai, Ye, Zhang, & Zhao, 2010; Liu, 2013). However, a relatively complete calculation method of cumulative deformation of subgrade under train load for ballastless tracks of high speed railways has not yet been developed.

4.1 Cumulative deformation of subgrade soil under cyclic load

Cai and Cao (1996) carried out the triaxial cyclic loading test on clay, obtained the relation curve between cumulative plastic strain and loading cycles, and divided the cumulative strain curve into the developing type and the attenuated type by the “concave-convex” of the curve in semi-logarithmic coordinates, and the two types of curves respectively show a failure trend and a stability trend. Based on the triaxial test results, Wang, Xie, and Ba (2010) divided the cumulative plastic deformation curve into the stable type, the attenuated type and the failure type, and took the cumulative plastic strain not exceeding 4% as the basis for the acceptable deformation of the pavement structure. Werkmeister, Dawson, and Wellner (2001) divided the cumulative plastic strain curve of subgrade at different stress levels into stages of plastic stability, plastic creep and incremental failure. Minassian (2003) divided the cumulative deformation process of subgrade into three states, namely, the steady state, the critical state and the unstable state according to the cumulative plastic strain. Hoff divided the cumulative plastic deformation process into the elastic state, the plastic state and the failure state according to the average cumulative strain rate. It can be seen that the cumulative plastic deformation of coarse-grained soil forms in different states under different stress levels with the increase of loading cycles.

At present, it is difficult to quantify the cumulative plastic deformation. However, it is still feasible to carry out structural design under the premise that there is no cumulative plastic deformation of subgrade and that the requirements for engineering use are met. Due to the strict requirement for deformation of foundation under high speed railway tracks, it is still necessary to conduct in-depth and systematic research on scientific and reasonable classification, judgment and control of cumulative plastic deformation states of subgrade bed structure under round-trip cyclic load.

4.2 Calculation model of cumulative plastic deformation of subgrade caused by train operation

Estimation of cumulative plastic deformation is one of the important tasks in the study of subgrade soil deformation characteristics under cyclic load. In the development of railways, various calculation models for cyclic cumulative settlement of subgrade have been proposed, which can be roughly divided into empirical models and elastic-plastic mechanics theoretical models. Some of these models have been applied in practical engineering (Chen & Bian, 2018).

4.2.1 Empirical models. In the early stage, the dynamic triaxial test results are often used to establish the empirical subgrade cumulative settlement model (Chen & Bian, 2018; Dong *et al.*, 2010) with stress level and number of load cycles as variables, such as exponential, logarithmic and power function models, and the exponential model proposed by Monismith, Ogawa, and Freeme (1975) is the most widely applied. These models are characterized by a single form, few parameters and convenient application. It should be mentioned that if good test results are available, the cumulative deformation development trend of subgrade can be predicted accurately with these models. However, due to the large difference in cumulative plastic deformation of subgrade at different stress levels, one specific model is not enough to accurately describe the trend.

Subsequently, Li and Selig (1996) introduced the soil strength parameters and stress conditions, and established the calculation formula of subgrade soil settlement under traffic load. And based on the model established by Li and Selig (1996), Chai and Miura (2002) established an exponential empirical formula considering the initial static deviatoric stress. Chen, Huang, and Chen (2008) modified the empirical formula of Li and Selig based on the triaxial test results and considering the effect of consolidation pressure, vibration cycles and dynamic and static eccentric stress, and accordingly, established a strain prediction model that can well describe the deformation law of soil samples before failure. However, the strain calculated with this model tends to increase infinitely with the increase of the number of cycles, which does not agree with the tendency towards a stable value of soil mass due to vibration density and deformation when the cyclic load ratio is lower than a certain critical dynamic stress. Wichtmann, Rondon, Niemunis, Triantafyllidis, and Lizcano (2010) corrected the HCA model of cumulative deformation of sandy soil established by Niemunis *et al.* based on the dynamic triaxial test results and proposed a cumulative deformation model applicable for non-cohesive soil mass that can describe the cumulative deformation law of subgrade with complex boundaries. Bian, Jiang, and Chen (2010) established a calculation formula for the cumulative plastic strain increment of soil mass under different number of load cycles based on the dynamic triaxial test results of subgrade soil.

4.2.2 Elastic-plastic models. Abdelkrim, Bonnet, and Patrick (2003), Chazallon, Hornych, and Mouhoubi (2006) and Karg, Francois, Haegeman, and Degrande (2010) established elastic-plastic constitutive models based on the stability theory, which are used to accurately predict the cumulative deformation of soil mass under cyclic load. By these methods that have the advantage of wide application scope, accurate cumulative plastic deformation under different complex stress states can be obtained. However, it generally requires tests to verify and provide calculation parameters, and requires a huge amount of computation, and the prediction deviation is large if the calculation parameters are not accurate enough. Wang and Yu (2014) obtained the lower bound solution of the stability limit value based on the ideal elastic-plastic theory. Zhang (2006) introduced reasonable hardening law and shear-dilation formula, and proposed a cyclic constitutive model of cumulative plastic deformation of non-cohesive soil mass. Degrande *et al.* (2006) modified the yield function and plastic strain expression of the mechanism of sliding friction and volume compaction deformation, and established a cyclic cumulative deformation model of granular soil under small load.

In brief, it is urgent to develop a subgrade cumulative deformation calculation model with higher accuracy and calculation efficiency for high speed railway subgrade. Although the empirical models can be used in practical engineering, they are generally difficult to meet the calculation accuracy requirement (Chen & Bian, 2018; Dong *et al.*, 2010). It is a development trend to establish the cumulative elastic-plastic model of subgrade for the whole process based on the elastic-plastic dynamic constitutive model of coarse-grained fillers (Bian *et al.*, 2010; Huang, Yang, Lai, & Yue, 2012). How to include the accumulation of plastic strain and hardening characteristics, grain breakage law and energy dissipation characteristics in this kind of model are the technical difficulties that need to be taken seriously.

5. Conclusions and development trend

This paper systematically summarizes and analyzes the structural types and design methods of subgrade bed for high speed railways in China, Japan, France, Germany, the United States and other countries, points out some problems existing in these design methods and obtains the following basic understanding and conclusions.

(1) The layered reinforced structure is generally adopted for subgrade bed of high speed railways in various countries. In order to meet the high requirements for use, the unified double-layer or multi-layer structure is often adopted for the surface layer of subgrade bed. A simple structural system is adopted for the surface layer of subgrade bed, and graded crushed stone is used for the filler in China, which allow easy construction and a clear load transmission path. There are a variety of inspection parameters for compaction quality control. The control indexes adopted by various countries are related to their respective understanding and habits, and their common purpose is to effectively control the compaction quality. The compaction coefficient is used by all the countries as a compaction quality control index for high speed railways. China adopts the compaction coefficient, subsoil coefficient and dynamic deformation modulus to assess the compaction state of graded crushed stone, gravel and sandstone fillers of high speed railway subgrade.

(2) The design methods for subgrade bed structure of high speed railways in various countries mainly include the control method of deformation of the subgrade top surface, the control method of deformation modulus of the subgrade bottom surface, and the control method of lower fill strength under subgrade bed surface, etc. China adopts the dynamic deformation of subgrade surface and the dynamic strain of bottom layer of subgrade bed as the control indexes for design. For these design methods, the subgrade is assumed to be an elastic half-space, and the dynamic process is transformed into a static process, without considering the cyclic vibration load of trains. In general, the design method is too rough and insufficiently refined, and unable to calculate the cumulative deformation of subgrade caused by cyclic train load.

(3) The cumulative plastic deformation of coarse-grained soil forms in different states under different stress levels with the increase of loading cycles. A lot of studies have been carried out at home and abroad on the cumulative plastic deformation of filler under dynamic load, and empirical models and elastic-plastic theoretical models are constructed. However, there is no relatively complete calculation method and design theory of cumulative deformation of subgrade for high speed railways yet.

The following development trend in the design of subgrade for high speed railways can be found according to the analysis of the current design of subgrade structure for high speed railways.

(1) Optimization and improvement of subgrade bed structure. For example, in view of the defects such as frost heaving and mud pumping caused by cracking and water seepage of the sealing layer of subgrade for high speed railways currently faced, a new asphalt graded crushed stone subgrade structure enclosed on full section is proposed, that is, an asphalt graded crushed stone layer is set on the subgrade bed top as a waterproof and reinforcing layer for water isolation, improvement of subgrade bed load bearing, shock absorption and noise reduction.

(2) Development of a whole-process cumulative plastic strain calculation method for subgrade based on the elastic-plastic constitutive model of coarse-grained fillers, which is necessary to improve the calculation accuracy of cumulative deformation of subgrade, and is also a development trend of subgrade design.

(3) Establishment of a theoretical analysis model of high speed train-track-subgrade and development of a whole-process dynamics design method for subgrade structure of high speed railways with the excitation of construction and operation load taken into consideration. This will be the theoretical basis for the transition of subgrade structure design from semi-theoretical and semi-empirical design to refined design, the necessary premise for optimization of subgrade bed structure for high speed railways and a development trend of subgrade design.

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