New Techniques of Ballastless Track Subgrade for High-Speed Railway

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Abstract: With the development of ballastless track in high-speed railway, higher requirements of subgrade have become increasingly urgent. Among these requirements, smoothness, durableness and least needs of maintenance are most important ones. Without enough useful references and standards, our research team made great efforts to apply a series of new techniques in ballastless track subgrade of high-speed railway, including many kinds of composite foundation, pile-board subgrade, pile- raft structure and transitional structures of subgrade and rigid structures such as bridge abutment. Research results have benefited our country's subgrade design of high-speed passenger dedicated line.

Key words: high-speed railway; ballastless track; composite foundation; pile-board subgrade; pile-raft structure; transitional structure control standards

China is moving into a high-speed railway time. 130 thousand kilometers of high-speed railway have been built by this year and three thousand more kilometers will be add into this number by 2020. In the coming decade, china will continue to build high-speed railway and passenger dedicated line, as well as to develop inter-city passenger transport and to speed up existing line. Our aim is to establish a transport network of connecting all major cities, in which high-speed railway and passenger dedicated line will play a part of backbone.

High-speed railway should be safe, reliable, and should have least need of maintenance. To achieve these purposes, we have raised the requirements of track structure's smoothness and stability. Under this condition, ballastless track has gradually embodied its superiority and gained increasingly wider applications in projects because in high speed case, durability of concrete in ballastless track is much better than that of gravel fillings used in ballast track.

Comparing with safety and usability, durability requirement plays a more dominant role in long-term consideration. Requirements of durability for ballastless track subgrade demand not only appropriate stiffness and right mode of stress propagation, but also low settlement. Thus the key issue of durability, how to strictly control settlement has become an urgent subject.

1. Basic Principles and Technical Requirements of Ballastless Track

Because of its superior stability, concrete bed is chosen to be used in ballastless track to transfer dynamic and static loads from vehicles. Elastic deformation cause by vehicles is provided by precisely defined material allocated under track and fastener. Ballastless track substructure's deformation after sleeper-laying is rigorously controlled in design. So it has good long-term stability in high speed condition, and seldom needs maintenance.

Subgrade structure of ballastless track needs to provide enough bearing capability and stiffness in order to guarantee the anti-fatigue safety of track bed and supporting layer. As one of the input parameter of roadbed mechanics, E_{v2}, the secondary deformation modulus of subgrade bed surface can explicitly express this requirement. Control of fillings' material, gradation and constructing quality can help improve this parameter.

Another requirement for subgrade is to guarantee the smoothness and stability of subgrade and its transitional sections with rigid structure, and to keep railway track continuously in designed elevation. It is not easily measured or quantitatively expressed in mechanics, but it's equally or even more important. This requirement can be seen from the harsh control of subgrade and foundation settlement, and it's directly influence the basic structure of subgrade and its treatment measures.

2. Structure and Feature of Ballastless Track Subgrade

Generally speaking, ballastless track subgrade is comprised of surface layer of subgrade bed, bottom layer of subgrade bed, subgrade main body and foundation. German railway gives special attention to a 3-meter area below rail top, which is the subgrade bed in our system, and calls it the security area. Subgrade bed suffers most from dynamic loads and natural forces, so it's filling material and compaction quality needs to meet higher standard. Theoretically, thickness of subgrade bed should be determined by designed loads, influence depth of frost heaving, stiffness of bottom layer of subgrade bed and bearing capability.

Compare with surface layer, bottom layer of subgrade bed is less affected by frost heaving. However, influence of traffic loads still can not to be neglected. Since surface layer of subgrade bed is relatively thin, mechanic parameters of bottom has a significant impact on whole subgrade rigidity under dynamic loads. Normally, designed thickness of bottom layer in China is 2 or 3 meters. Material of bottom layer fillings is controlled by restricting maximum particle diameter and percentage of fine particles. By doing this, the long-term stability, water stability, compactibility and uniformity of subgrade bed can be guaranteed fundamentally.

As for subgrade main body, the primary aim is to keep static stability since the influence of dynamic loads is relatively small. Correspondingly, design code has lower requirement for fillings' material and compaction factors in this area. For instance, C group material can be used in subgrade main body. Expect for some special conditions, in design of subgrade main body, the major concern is to ensure that subgrade settlement under dead loads can meet requirement of laying track. Many kinds of foundation treatment methods can be used based on mechanical properties of soil, height of subgrade, environment and geological conditions. Technology, economy and time limit should all be taken into consideration when choosing treatment method.

3. New Technology of Subgrade Design

The initial development and application of ballastless track subgrade in China is mostly through learning from external experiences. However, in a very short time, designers in China managed to grasp the key technologies of ballastless track subgrade. After establishment of design theory, a series of new techniques such as composite foundation, pile-board subgrade, pile- raft structure has been developed and some control standards are develop through research and practice.

3.1 CFG Composite Subgrade

Cement Fly-ash Gravel Piles (CFG Piles) consist of gravels, stone chips, sand, fly-ash and cement. Their stiffness lies between gravel piles and plain concrete piles. They can be produced to strength-variable piles by different equipments. By using CFG piles to reinforce subgrade, bearing capability and stiffness of subgrade can be improved remarkably. As a new type of pile-supported subgrade, this structure is especially suitable for subgrade of clayey soil, silt, sand and pain soil and has been widely used in engineering practice. It can smooth the stiffness transition from subgrade to rigid structures, so that the vehicle's running stability can be guaranteed; it can make sure large differential settlement of new built and existing line will not occur, so that the new line can be put into use in time; Also, it have a lot of other advantages such as short construction period, little lateral deformation and settlement.

In CFG Composite Subgrade, a bedding cushion is laid on the bottom layer of subgrade to adjust the displacement of piles and soil, so as to make full use of their load-bearing capacity. This cushion is an essential part of CFG piles subgrade, as same as piles and soil. Pile's modulus of elasticity is much larger soil's, so deformation of soil between piles under loads effect is much larger than that of piles. As a result, piles will protrude to the direction of cushion during which granular soils will keep filling the interspaces. Since subgrade is keeping connection with soil between piles through this cushion, capability of soil can be fully used. Also, the ratio of load beard by piles and soil can adjust by the cushion.

3.2 Pile-board Subgrade

Pile-board Subgrade is comprised of pile, soil, support beam and loading plate. As a bearing structure system, pile-board subgrade has great bearing capability, stability, smoothness and duration. By combining characteristics of ballastless track and pile foundation, it can overcome the shortcoming of normal subgrade structures. For example, high subgrade tends to have larger settlement and low subgrade normally have poor dynamic stability. Pile-board subgrade is normally embedding in foundation rather than spanning across spaces, and that is why it is named a subgrade not a bridge.

There are three types of pile-board subgrade, including independent column type, supporting beam type and composite type. In independent column pile-board subgrade, piles are directly connected to loading plate; while in supporting beam pile-board subgrade, piles are laterally connected with supporting beam and then supporting the loading plate together with beam. Composite pile-board subgrade is a composite type of independent column pile-board subgrade and supporting beam pile-board subgrade, with independent column used in mid-span and support beam used in side-span. Loading plate of pile-board subgrade direct supports both dead loads of superstructure and repeatedly traffic loads. Its stress condition is very complex especially in double-track railways. The foremost function of supporting beam is to enhance the horizontal connection of structure, so structure's stiffness and resistance of settlement can be largely improved.

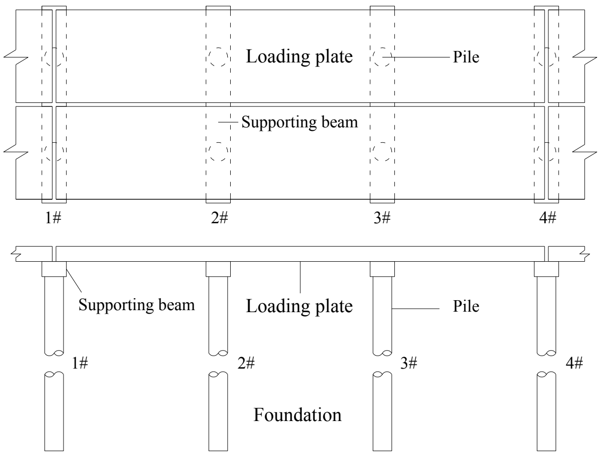

Fig.1. Pile-board Subgrade of Supporting Beam Type

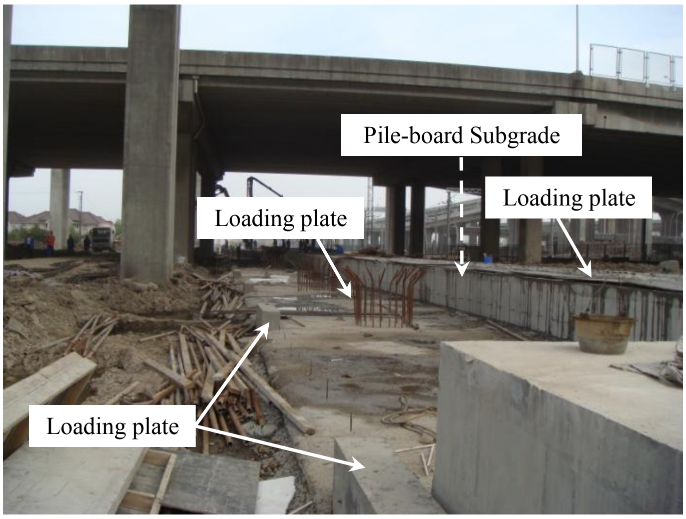

Fig.2. In-situ Pile-board Subgrade Structure

Pile-board subgrade is suitable for fast improvement of soft foundation and is more convenient for excavation section comparing with bridge. Also, it has good lateral stiffness because of the lateral support force of soil. In pile-board subgrade, piles can strictly control settlement by piercing through soft soil layer, and subgrade soil can provide vertical support to loading plate, so the capability of structure can be enhanced. Another advantage of pile-board subgrade is that it does not need any special equipment and its construction is very convenient. Because of all these factors, pile-board structure has been widely used in China as well as in many other countries, including Turku-Toijala railway in the southwest swampy areas of Finland, South section of HSL-S railway from Netherlands to Belgium, Zhengzhou-Xi'an Passenger Dedicated Line, Wuhan-Guangzhou Passenger Dedicated Line, Beijing-Shanghai Passenger Dedicated Line in China.

3.3 Pile- raft Structure

Pile-raft Structure of high-speed railway subgrade is comprised of raft and piles, as is shown in the followed sketch. Its design concept is to use joint bearing capability of piles and raft. Bearing behavior of pile-raft structure is not easy to be fully grasped since it is one node of the complex superstructure-raft-soil cooperation system. For a very long time, people only considered the supporting effect of piles in design to keep the structure safe, ignoring the contribution of soils and raft; And thickness of raft is determined by punching shear capacity, which makes the design of pile-raft structure rather conservative. Deep investigations of pile-raft structure's bearing mechanism can definitely help understanding the structure and optimizing the design.

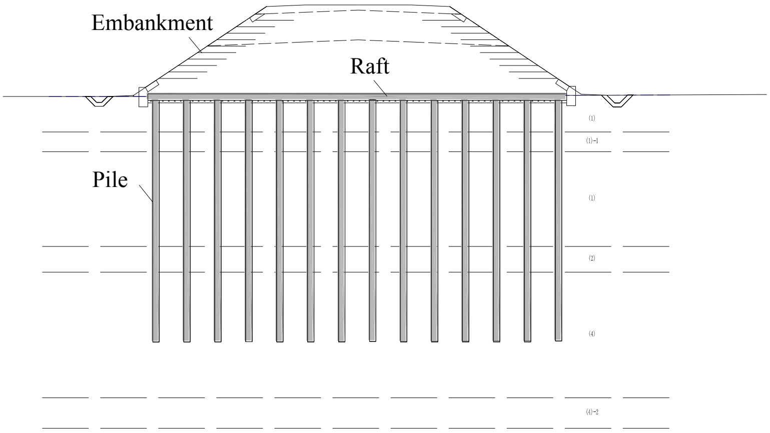

Fig.3. Sketch of pile-raft structure

Fig.4. In-situ Pile-raft Structure

Design of pile-raft subgrade can consult that of flat slabs, but the difference is obvious. Flat slab in constructional engineering is a plate-column structure, but pile-raft subgrade in high-speed railway engineering is a board-pile structure. Piles in foundation soils are bound from side directions and the raft is closely contact with ground soil, which makes the pile-soil and raft-soil interaction can not be ignored. Considering the effect of long-term repeated loads, supporting effect of soil can be regarded as safety reservation in actual design, because the connection of soil and raft may break after long-term dynamic loads.

3.4 Transitional Structure of Subgrade and Rigid Structures

Transitional Structure is that sets between the subgrade and rigid structures in order to smooth the variation of rigidity and differential settlement of the two different substructures under railway track. Since it is set between structures with very different materials and mechanical behaviors, transitional structure is extremely vulnerable to differential settlement or partial failure. In order to ensure that transitional structure will not be damaged by vibration caused by traffic or seismic loading, strict design requirements of transitional structure must be established.

Firstly, stiffness of transitional structure should smoothly transform from subgrade to the rigid structure in right order. Also, abrupt change of stiffness is not allowed in vertical direction from foundation to track. Only in this way can a smooth running condition be provided for vehicles. High-speed railway design standard of China formulates that after construction, subgrade settlement should not exceed 15 mm, differential settlement between subgrade and bridge should not exceed 5 mm, and bending angle of rail top caused by differential settlement should not exceed 1/1000. Through dynamic analysis of transitional structure by setting assessment index of dynamic performance as target function, more specific control standards for rail top bending angle can be classified by speed grade as: $\theta \leq 5.5‰$ when $V=160$km/h, $\theta \leq 3.0‰$ when $V=250$km/h and $\theta \leq 1.5‰$ when $V=350$ km/h. This result is in good agreement which that of Japanese research.

4 Conclusion

Appropriate treatment can conclusively guarantee the stability and safety of railway subgrade after operation. When choosing countermeasure of weak subgrade, geological condition, meteorological condition, hydrologic condition as well as features of subgrade itself should all be taken into consideration, so the most scientifically reasonable and economic method will be found.

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