

文章编号: 1005-0523(2024)06-0011-08



## 双块式无砟轨道路基不均匀沉降静力 损伤影响及评级

陈利<sup>1</sup>, 余翠英<sup>2</sup>, 龚凯<sup>2</sup>, 宋晓东<sup>3</sup>, 万水<sup>3</sup>, 丁德云<sup>4</sup>, 郭庆祥<sup>2</sup>

(1. 中铁二局集团有限公司, 四川成都 610031; 2. 华东交通大学轨道交通基础设施性能监测与保障国家重点实验室, 江西南昌 330013; 3. 东南大学交通学院, 江苏南京 211189; 4. 北京九州一轨环境科技股份有限公司, 北京 100071)

**摘要:**【目的】为补充双块式无砟轨道沉降维修标准, 研究双块式无砟轨道路基不均匀沉降损伤问题。【方法】建立含路基不均匀沉降的双块式无砟轨道三维有限元模型, 分析路基沉降作用下轨道结构各部件的空间受力和变形影响规律; 在此基础上, 提出一种双块式无砟轨道路基不均匀沉降静力损伤等级划分及评价方法。【结果】结果表明: 沉降波长 20 m, 幅值对轨道结构应力变形及层间离缝影响较大; 沉降幅值 10, 15, 20 mm 及以上, 损伤评级依次为 II 级, III 级和 IV 级。沉降幅值 10 mm, 波长越小, 轨道结构层间越易产生脱空现象; 沉降波长 12 m 及以上对轨道结构应力影响较大, 道床板纵向拉应力最大值均超过限值 3.50 MPa; 建议 20 m 以下波段沉降损伤评级 III 级, 20 m 及以上波段沉降, 损伤评级均为 II 级。【结论】研究成果便于高铁智慧运维“科学修和精确修”, 建议沉降损伤等级与线路轨道静态几何容许偏差管理值关联, 保持维修等级与损伤等级一致, 沉降综合维修控制在 15 mm 以内。

**关键词:** 双块式无砟轨道; 路基不均匀沉降; 受力变形; 损伤影响; 损伤评级; 智慧运维

中图分类号: U213.2

文献标志码: A

本文引用格式: 陈利, 余翠英, 龚凯, 等. 双块式无砟轨道路基不均匀沉降静力损伤影响及评级[J]. 华东交通大学学报, 2024, 41(6): 11-18.

## Damage Rating and Influence of Double-Block Ballastless Track Under Uneven Subgrade Settlement

Chen Li<sup>1</sup>, Yu Cuiying<sup>2</sup>, Gong Kai<sup>2</sup>, Song Xiaodong<sup>3</sup>, Wan Shui<sup>3</sup>, Ding Deyun<sup>4</sup>, Guo Qingxiang<sup>2</sup>

(1. China Railway ERJU Group Co., Ltd., Chengdu 610031, China; 2. State Key Laboratory of Performance Monitoring and Protecting of Rail Transit Infrastructure, East China Jiaotong University, Nanchang 330013, China; 3. School of Transportation, Southeast University, Nanjing 211189, China; 4. Beijing Jiuzhouyigui Environmental Technology Co., Ltd., Beijing 100071, China)

**Abstract:** 【Objective】 In order to provide a little basis for improving the settlement maintenance standard of double block ballastless track, the uneven settlement damage problem of double block ballastless track subgrade is studied. 【Method】 A three-dimensional finite element model of double-block ballastless track with uneven settlement of roadbed is established, it aims to analyse the spatial stress and the deformation law of each component of the track structure under the action of roadbed settlement. On this basis, a static damage classification and evaluation method for differential settlement of double block ballastless track subgrade is proposed. 【Result】 The results

收稿日期: 2024-05-21

基金项目: 国家自然科学基金项目(52068028); 华东交通大学博士启动资金项目(452); 江西省自然科学基金项目(20212BAB204015, 20224BAB204065); 华东交通大学大学生创新创业训练项目(S202310404033)

show that when the settlement wavelength is 20 m, the amplitude has a great influence on the stress-deformation and inter-layer seam of the track structure. The settlement amplitude is 10, 15, 20 mm and above, and the damage rating is II, III and IV respectively. When the settlement amplitude is 10 mm, the smaller the wavelength is, the easier the void phenomenon is to occur among the layers of the track structure. The settlement wavelengths of 12~16 m have a great influence on the damage of track structure, and the maximum longitudinal tensile stresses of track slab exceed the limit value 3.50 MPa. So, it is recommended that the settlement damage rating of wave band below 20 m is the grade III, and that of wave band above 20 m is grade II. **【Conclusion】** In order to facilitate the “scientific repair and accurate repair” of high-speed rail intelligent operation and maintenance, it is suggested that the settlement damage level should be associated with the static geometric allowable deviation management value of the line track, the maintenance level should be consistent with the damage level, and the comprehensive maintenance of settlement should be controlled within 15 mm.

**Key words:** double block ballastless track; uneven subgrade settlement; stress-deformation; damage effects; damage rating; smart operation and maintenance

**Citation format:** CHEN L, YU C Y, GONG K, et al. Damage rating and influence of double-block ballastless track under uneven subgrade settlement[J]. Journal of East China Jiaotong University, 2024, 41(6): 11-18.

**【研究意义】**据统计,截至2023年底,我国铁路营业里程突破15.9万km,其中高铁运营里程达到4.5万km。随着高速铁路网的加密和建设规模的扩大,新建线与既有线上跨、交叉、并行等工后沉降现象屡见不鲜<sup>[1]</sup>,长距离跨越多雨软土、湿陷性黄土、高寒冻土,大风沙漠和活动断裂带等特殊地质区域的路基日益增多<sup>[2]</sup>,可能引发既有线路基板结-翻浆冒泥-变形和路基冻胀-融化-变形的周期性循环<sup>[3-4]</sup>。在列车长期动荷载作用下,线路容易出现路基不均匀沉降和层间离缝及轨道几何形位劣化等一系列问题,从而影响高速列车动力响应,乘车舒适性甚至走行安全性<sup>[5-7]</sup>。

**【研究进展】**在路基沉降方面,我国科研人员对板式无砟轨道动力性能及其车轨振动响应做了较多研究。任娟娟和肖威<sup>[8-11]</sup>基于有限元法和多体动力学,建立了考虑路基沉降的列车-轨道耦合系统模型,提出了板式无砟轨道的路基沉降控制限值<sup>[8-11]</sup>。向俊等<sup>[4, 12]</sup>基于塑性损伤本构关系,从路基冻融循环-沉降变形角度演化了CRTS I型和CRTS II型板的轨道不平顺和离缝损伤的映射过程。肖源杰等<sup>[13]</sup>提出一种新的迭代方法,将路基沉降作为位移边界条件,研究沉降和列车荷载共同作用下的轨道结构跟随性变形。冯玉林等<sup>[14]</sup>引入非线性接触

函数,研究路基不均匀沉降对板式无砟轨道动力性能的影响。唐进锋等<sup>[15]</sup>针对CRTS III型板路基沉降,研究不同行车速度、路基不均匀沉降幅值和波长对系统动力响应的影响。吴斌等<sup>[16]</sup>针对土质路基上双块式无砟轨道结构沉降变形问题,建立了考虑混凝土开裂的双块式无砟轨道沉降模型,研究轨道结构空间力学特性。郭宇等<sup>[17]</sup>等采用弹性地基叠合梁模型,研究沉降波长、幅值与轨面几何变形特征及其映射关系。张乾等<sup>[18]</sup>考虑混凝土非线性损伤特性,研究沉降区损伤演化过程、层间离缝行为与轨面不平顺传递规律。

**【创新特色】**本文从高铁智慧运维管理“科学修和精确修”的角度,关联沉降损伤和线路轨道静态几何容许偏差管理值,科学评估路基不均匀沉降变形条件下无砟轨道结构损伤对自身结构性能的影响;在此基础上,提出一种双块式无砟轨道路基不均匀沉降静力损伤等级划分及评价方法,旨在快速简便开展路基沉降维修等级评估。

**【关键问题】**建立沉降变形→层间离缝→轨面不平顺路径,关联沉降变形→轨道静态几何容许偏差管理值→离缝损伤等级,提出沉降变形损伤等级划分,确定沉降变形分级维修决策,为高铁双块式无砟轨道沉降智慧运维提供依据,补充无砟轨道结

构维修规则沉降损伤等级及维修等级。

## 1 含沉降变形的双块式无砟轨道有限元模型

### 1.1 有限元模型建立

图1为双块式无砟轨道结构-路基有限元模型,由钢轨、弹性扣件、道床板和支承层组成。模型计算考虑5块板,长度32.5 m(5×6.5 m)。钢轨采用标准60 kg/m钢轨,采用空间点支承梁单元进行模拟,弹性模量取值为210 GPa,道床板和支承层等部件均以实际尺寸按实体单元建模<sup>[4]</sup>,见表1。钢轨与道床板间采用连接器单元模拟弹性扣件,其间距以实际取值。

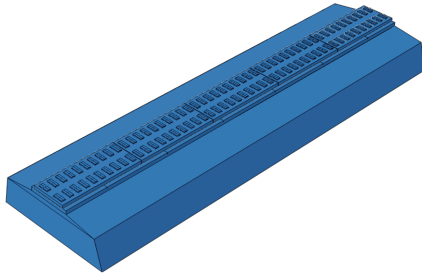


图1 双块式无砟轨道-路基有限元模型

Fig.1 Finite element model of double block ballastless track-subgrade

表1 材料参数

Tab.1 Material parameters

| Name             | Parameter type               | Value  |
|------------------|------------------------------|--------|
| Roadbed          | Elastic modulus/MPa          | 32 500 |
|                  | Density/(kg/m <sup>3</sup> ) | 2 500  |
|                  | Thickness/m                  | 2.80   |
|                  | Width/m                      | 0.24   |
| Fasteners        | Vertical stiffness/(kN/mm)   | 30     |
|                  | Elastic modulus/MPa          | 25 500 |
| Supporting layer | Density/(kg/m <sup>3</sup> ) | 2 500  |
|                  | Thickness/m                  | 0.30   |

### 1.2 边界条件设置及沉降模拟

模型边界条件设置如下:轨道上部结构竖向可自由变形,固定纵、横向2个自由度,路基底面采用全约束处理。路基沉降通过在基床表层加强制位移来实现,假设路基沉降横向分布均匀,以纵向不均匀沉降为主,见式(1)余弦型曲线,图2为CRTS I型双块式无砟轨道有限元沉降变形。

$$Z(y) = \frac{A}{2} \left( 1 - \cos \left( \frac{2\pi(y-y_0)}{L} \right) \right) \quad (1)$$



图2 CRTS I型双块式无砟轨道有限元沉降变形

Fig.2 Settlement deformation of CRTS I double block ballastless track by finite element

式中:A为不均匀沉降幅值,mm;y为不均匀沉降位置坐标,m;y<sub>0</sub>为不均匀沉降中点位置坐标,m;L为不均匀沉降波长,m。

### 1.3 模型验证及损伤评估方法

为验证该模型的正确性,考虑温度荷载和温度梯度作用,选取钢轨和道床板的竖向位移与现场实测数据进行比较,可知模型计算值与实测数据在数量级上是相同的,总体差异较小,模型可行,见表2。

表2 竖向位移比较

Tab.2 Comparison of vertical displacement mm

| Vertical displacement | Calculated values | Measured values |
|-----------------------|-------------------|-----------------|
| Rail                  | 0.98              | 0.78~1.22       |
| Bed                   | 0.26              | 0.13~0.35       |

图3为双块式无砟轨道沉降损伤分级流程图,通过现场调研沉降范围,建立含沉降的双块式无砟轨道模型,开展静力特性分析,研究路基沉降与轨道结构受力变形,探讨沉降损伤分级评估,为高铁智慧运维路基健康状态评估、行车安全预警和沉降阈值确定以及分级维修决策等提供参考。

## 2 计算工况及说明

模型以轨道结构自重作用充分沉降完成为初始条件,计算结果忽略结构自重影响。通过改变沉降幅值和沉降波长,提取双块式无砟轨道结构的最大竖向位移和空间应力最大值,分析不均匀沉降对轨道结构各部件的受力和变形规律及轨道结构层间位移映射关系的影响。工况类型1:沉降幅值一定,不同沉降波长引起的轨道结构受力变形;工况类型2:沉降波长一定,不同沉降幅值引起的轨道结构受力变形,详情见表3。

## 3 计算结果分析

### 3.1 沉降波长对轨道结构受力和变形影响分析

由图4可知,沉降幅值10 mm不变,随着沉降范

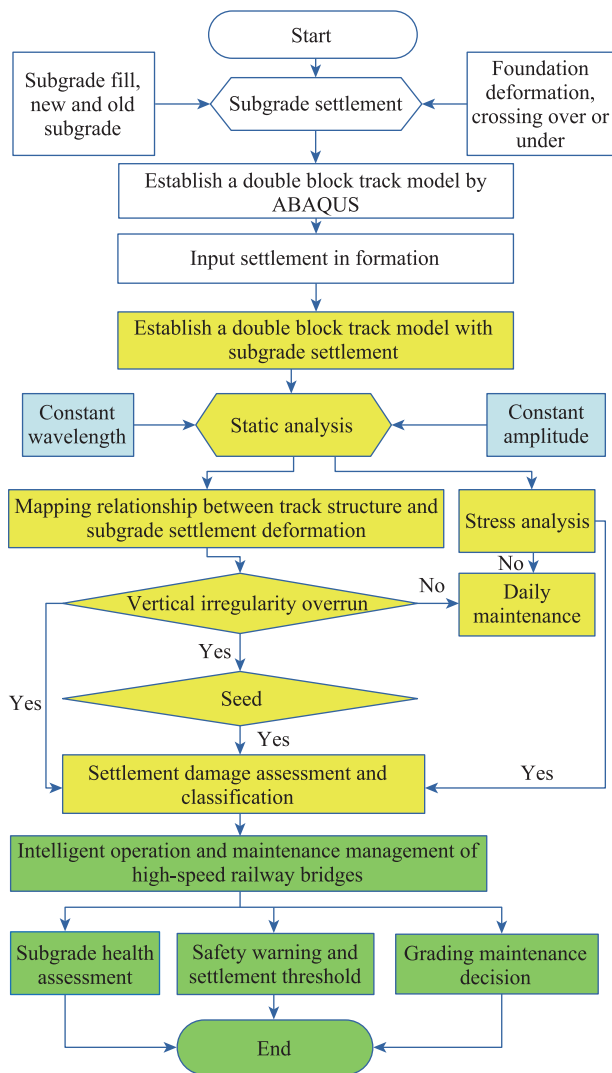


图3 双块式无砟轨道沉降损伤分级评估流程  
Fig. 3 Grading assessment of settlement damage of double block ballastless track

表3 计算工况类型

Tab.3 Type of calculation condition

| Conditions | Settlement of amplitude/mm | Settlement of wavelength/m |
|------------|----------------------------|----------------------------|
| 1          | 10                         | 4, 8, 12, 16, 20, 24       |
| 2          | 5, 10, 15, 20, 25          | 20                         |

围的扩大会使支承层与基床表层的位移差值减小,当波长大于24 m时,轨道结构各部件位移与沉降变形趋向一致,钢轨位移9.67 mm。

如图5,离缝最大值主要出现在沉降中心位置,当波长4 m时,基床顶面与支承层底面完全脱空,离缝值高达9.86 mm。波长大于20 m时,层间离缝值小于1 mm,当波长24 m时,支承层与路基之间离缝值不超过0.40 mm;反之,沉降波长越小,跟随性变

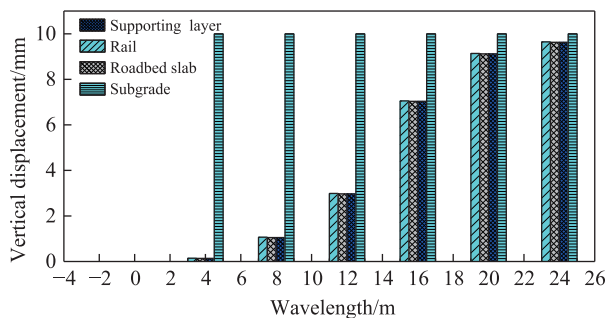


图4 不同沉降波长下轨道结构各部件最大竖向位移  
Fig. 4 The maximum vertical displacement of each component of the track structure under different settlement wavelengths

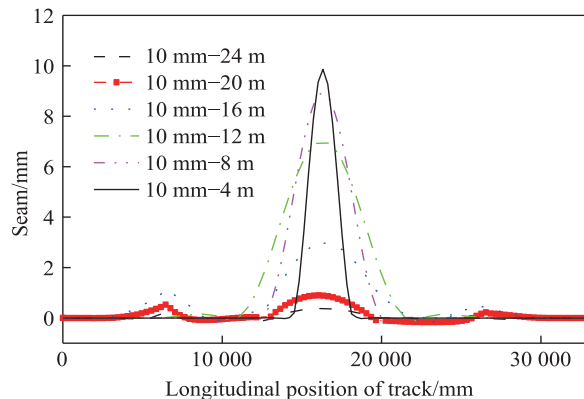


图5 支承层与路基表层间离缝值(A=10 mm)

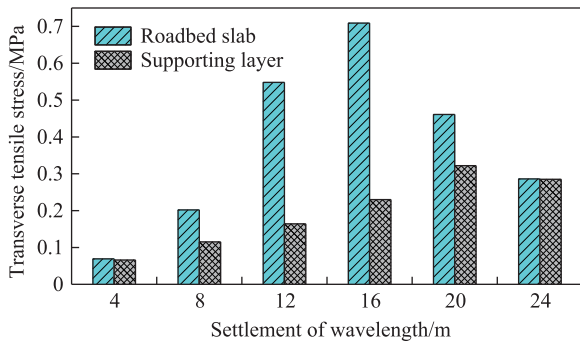
Fig. 5 The seam value between the supporting layer and the top layer of the subgrade (A=10 mm)

形越小,脱空现象越严重。

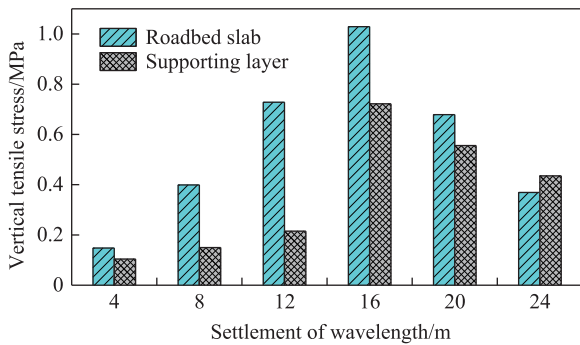
图6计算结果可知,波幅不变,沉降波长对轨道结构各部件的纵向拉应力最大,应力整体变化呈现先升后降趋势,沉降变形对道床板应力影响最大。当沉降波长介于12~20 m时,道床板纵向拉应力达到3.50 MPa及以上,超过C40混凝土拉应力限值2.39 MPa;波长介于16~20 m时,支承层的纵向拉应力最大值均超过C20混凝土拉应力限值1.54 MPa。尤其当沉降波长为16 m时,道床板和支承层的纵向拉应力均超过限值,长期运营时可能引起双块式无砟轨道结构局部开裂。

### 3.2 沉降幅值对轨道结构受力和变形影响分析

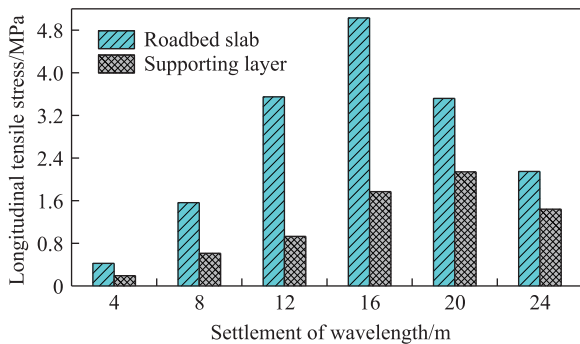
图7为波长20 m,波幅5~25 mm引起的轨道结构各部件最大竖向位移值。波幅5 mm时,钢轨、道床板、支承层和路基竖向位移非常接近,依次为4.81, 4.79 mm和4.79 mm;随着波幅增加,结构竖向位移随之增加,与路基变形差值越来越大,当沉降



(a) Maximum transverse tensile stress



(b) Maximum vertical tensile stress



(c) Maximum longitudinal tensile stress

图6 不同沉降波长下轨道空间拉应力(A=10 mm)

Fig. 6 Spatial tensile stress of each component of track structure under different settlement wavelength

波幅 25 mm 时,钢轨、道床板和支承层竖向位移依次为 20.12, 19.95 mm 和 19.95 mm。

图8为波长 20 m,波幅 5~25 mm 引起的层间离缝值。可见,离缝值随沉降幅值增加而逐渐增大直至脱空,且离缝最大值靠近沉降中心处;其次体现在第一块板末尾和第五块板端位置。此外,位于沉降起终位置处的上拱比较明显,上拱值随沉降幅值增加而增大;当波幅 15 mm 时,离缝值为 1.40 mm; 20 mm 及以上,离缝发展为完全脱空,最大离缝值达到 5.65 mm。

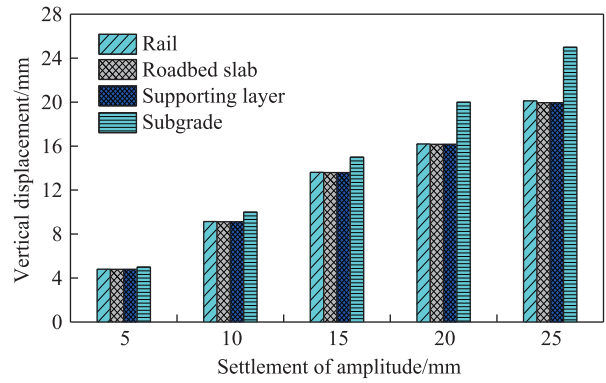


图7 不同沉降幅值轨道结构竖向位移最大值(L=20 m)

Fig. 7 Maximum vertical displacement of track structure with different settlement amplitude (L=20 m)

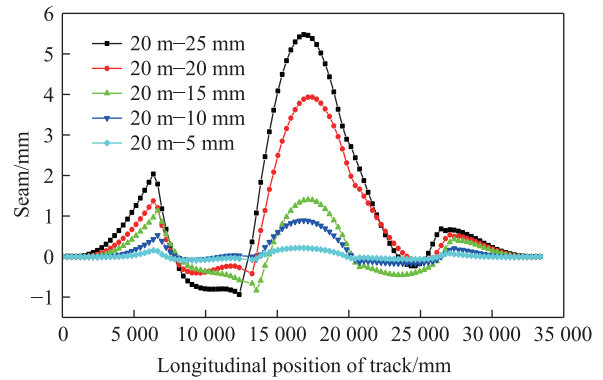


图8 支承层与路基表层间离缝值(L=20 m)

Fig. 8 The seam values between the supporting layer and the top layer of the subgrade (L=20 m)

由图9可知,道床板和支承层的最大空间拉应力受路基沉降幅值影响显著,依次为纵向、竖向和横向应力,其中,沉降幅值对道床板纵向拉应力值影响最大,随沉降幅值的增加整体呈上升趋势。当波幅 10 mm 及以上时,道床板和支承层结构拉应力均超过限值。可见,沉降幅值增加会导致层间离缝和支承层假缝开裂的风险,可能影响轨道结构耐久性和服役期。

### 3.3 路基不均匀沉降损伤评定及维修建议

综合各工况计算结果和维修便利性,选择以轨道高低不平顺为主的评定指标,综合考虑离缝损伤程度,提出一种双块式无砟轨道路基不均匀沉降的损伤等级划分,见表4和表5。在表5中,轨面下沉最大值为沉降中心处轨面竖向位移幅值,层间离缝\*为支承层与路基脱空,应力\*为结构拉应力超过相应混凝土标号的规范限值,C60抗拉强度 2.85 MPa,

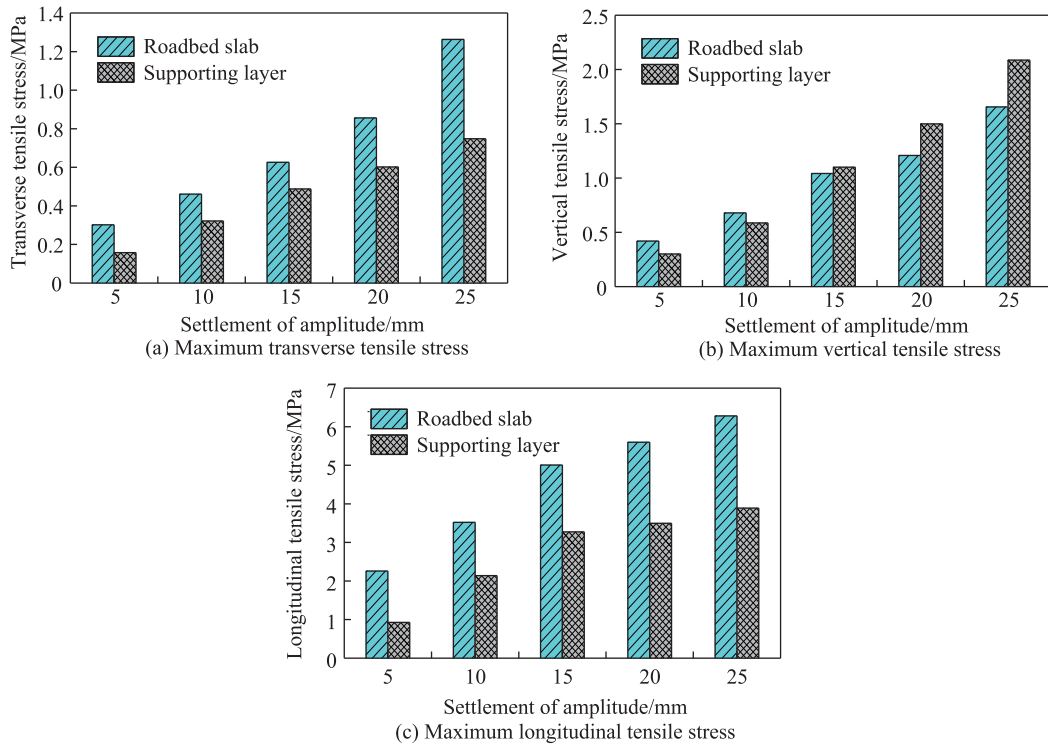


图9 不同沉降幅值下轨道结构空间拉应力(L=20m)

Fig. 9 The spatial tensile stress of track structure under different settlement amplitude (L=20 m)

表4 250(不含)~350 km/h线路轨道静态几何容许偏差管理值

Tab.4 Track static geometric allowable deviation management value at the 250 ( excluding )~350 km/h

| Track irregularity /mm | Damage grade        |                              |                   |                               | Track irregularity /mm | Damage grade        |                              |                   |                               |
|------------------------|---------------------|------------------------------|-------------------|-------------------------------|------------------------|---------------------|------------------------------|-------------------|-------------------------------|
|                        | Daily maintenance I | Comprehensive maintenance II | Urgent repair III | Speed-limiting at 200 km/h IV |                        | Daily maintenance I | Comprehensive maintenance II | Urgent repair III | Speed-limiting at 200 km/h IV |
| 7                      | I                   |                              |                   |                               | 12                     |                     |                              | III               |                               |
| 9                      |                     | II                           |                   |                               | 15                     |                     |                              |                   | IV                            |

表5 双块式无砟轨道路基不均匀沉降伤损等级及维修等级(建议)

Tab.5 Damage grade and maintenance level on subgrade uneven-settlement of double-block ballastless track (Suggested)

| Subgrade settlement |              | Damage assessment index       |                     |                        |                                  | Damage grade | Maintenance level |
|---------------------|--------------|-------------------------------|---------------------|------------------------|----------------------------------|--------------|-------------------|
| Wavelength/m        | Amplitude/mm | Rail vertical displacement/mm | Inter-layer seam/mm | Bed tensile stress/MPa | Support-layer tensile stress/MPa |              |                   |
| 20                  | 5            | 4.81                          | 0.22                | 2.26                   | 0.91                             | I            | I                 |
|                     | 10           | 9.14*                         | 0.88                | 3.52*                  | 2.14*                            | II           | II                |
|                     | 15           | 13.62*                        | 1.40                | 5.01*                  | 3.27*                            | III          | III               |
|                     | 20           | 16.19*                        | 3.93*               | 5.60*                  | 3.50*                            | IV           | IV                |
|                     | 25           | 20.12*                        | 5.65*               | 6.28*                  | 3.89*                            | IV           | IV                |
| 4                   | 10           | 0.14                          | 9.86*               | 0.42                   | 0.19                             | III          | III               |
| 8                   |              | 1.07                          | 8.95*               | 1.56                   | 0.61                             | III          | III               |
| 12                  |              | 2.99                          | 7.03*               | 3.55*                  | 0.93                             | III          | III               |
| 16                  |              | 7.05                          | 2.97*               | 5.03*                  | 1.77*                            | III          | III               |
| 20                  |              | 9.14*                         | 0.88                | 3.52*                  | 2.14*                            | II           | II                |
| 24                  |              | 9.67*                         | 0.37                | 2.15                   | 1.44                             | II           | II                |

C20抗拉强度1.54 MPa。需要说明的是大范围脱空建议损伤等级在Ⅲ级;若是多项超限,比如轨道不平顺和离缝超限,按单项损伤等级提1级评定,如下。

1) 波长20 m,沉降幅值10 mm及以上,轨面竖向位移均大于9 mm;沉降幅值20 mm及以上,层间完全脱空。10~15 mm,损伤Ⅱ级;15~20 mm,损伤Ⅲ级,20 mm及以上,损伤Ⅳ级。10 mm及以上道床板和支承层应力均超限3.50 MPa,长期运营存在开裂风险,建议路基日常保养沉降幅值控制在10 mm以内。

2) 沉降幅值10 mm,沉降波长16 m及以下,层间出现大范围脱空,建议损伤等级Ⅲ级;沉降波长20 m及以上,轨道结构道床板和支承层应力超限,轨面不平顺趋近沉降幅值10 mm,层间离缝逐渐变小,建议损伤等级为Ⅱ级,建议监控完全脱空的区域。

#### 4 结论

1) 沉降幅值10 mm时,波长16 m及以下时,离缝值大于规范限值1.5 mm,出现完全脱空现象,损伤评级Ⅲ级;当沉降波长16 m及以上时,道床板和支承层纵向拉应力均超过限值,长期运营易引起轨道结构开裂,损伤评级Ⅱ级。

2) 沉降波长20 m时,随沉降幅值增加,轨道结构各部件的竖向位移和空间应力不断增大,支承层与基床表层离缝持续扩大直至脱空,20 mm及以上,轨道不平顺,离缝及应力均超限,损伤评级Ⅳ级;沉降幅值10 mm及以上时,道床板和支承层纵向拉应力将超限,轨道结构存在开裂风险,影响耐久性。

3) 提出一种双块式无砟轨道路基不均匀沉降静力损伤评价方法及等级划分,为科学修和精确修提供决策依据。考虑高铁智慧运维,建议维修等级与损伤等级一致,并控制双块式无砟轨道结构脱空范围。当路基沉降波长20 m时,日常保养幅值控制在10 mm以内,综合维修控制在15 mm以内。

#### 参考文献:

- [1] 赵国堂, 赵如锋, 刘俊飞. 高速铁路路基工后沉降变形源、变形传递与轨道不平顺控制方法[J]. 铁道学报, 2020, 42(12): 127-134.  
ZHAO G T, ZHAO R F, LIU J F. Deformation source, deformation transmission of post-construction settlement and control methods of track irregularity for high-speed railway subgrade[J]. Journal of the China Railway Society, 2020, 42 (12): 127-134.
- [2] 翟婉明, 赵春发, 夏禾, 等. 高速铁路基础结构动态性能演变及服役安全的基础科学问题[J]. 中国科学: 技术科学, 2014, 44(7): 645-660.  
ZHAI W M, ZHAO C F, XIA H, et al. Basic scientific issues on dynamic performance evolution of the high-speed railway infrastructure and its service safety[J]. Scientia Sinica (Technologica), 2014, 44(7): 645-660.
- [3] 杨国涛, 高亮, 刘秀波, 等. 基于动力分析的CRTSⅢ板式无砟轨道路基冻胀控制标准研究[J]. 铁道学报, 2017, 39(10): 110-117.  
YANG G T, GAO L, LIU X B, et al. Research on division standard of subgrade frost heaving for CRTSⅢ slab track based on dynamic analysis[J]. Journal of the China Railway Society, 2017, 39(10): 110-117.
- [4] 向俊, 林士财, 余翠英, 等. 路基不均匀沉降下无砟轨道受力与变形传递规律及其影响[J]. 交通运输工程学报, 2019, 19(2): 69-81.  
XIANG J, LIN S C, YU C Y, et al. Transfer rules and effect of stress and deformation of ballastless track under uneven subgrade settlement[J]. Journal of Traffic and Transportation Engineering, 2019, 19(2): 69-81.
- [5] 张乾, 蔡小培, 钟阳龙, 等. 无砟轨道路基不均匀沉降区高速列车动力特性[J]. 西南交通大学学报, 2023, 58(1): 133-140.  
ZHANG Q, CAI X P, ZHONG Y L, et al. Dynamic characteristics of high-speed trains in differential subgrade settlement zone of ballastless track[J]. Journal of Southwest Jiaotong University, 2023, 58(1): 133-140.
- [6] ZHANG N, ZHOU S, XIA H, et al. Evaluation of vehicle-track-bridge interacted system for the continuous CRTS-II non-ballast track slab[J]. Science China (Technological Sciences), 2014, 57(10): 1895-1901.
- [7] 宋欢平, 边学成, 蒋建群, 等. 高速铁路路基沉降与列车运行速度关联性的研究[J]. 振动与冲击, 2012, 31(10): 134-140.  
SONG H P, BIAN X C, JIANG J Q, et al. Correlation between subgrade settlement of high-speed railroad and train operation speed[J]. Journal of Vibration and Shock, 2012, 31(10): 134-140.
- [8] REN J J, YANG R S, WANG P, et al. Influence of contact loss underneath concrete under layer on dynamic performance of prefabricated concrete slab track[J]. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 2017, 231(3): 345-358.
- [9] 肖威, 郭宇, 高建敏, 等. 高速铁路路基不均匀沉降对

- CRTS III 板式轨道受力变形的影响[J]. 铁道科学与工程学报, 2015, 12(4): 724-730.
- XIAO W, GUO Y, GAO J M, et al. Effect of uneven subgrade settlement on the CRTS III slab track stress and deformation of high-speed railway[J]. Journal of Railway Science and Engineering, 2015, 12 (4): 724-730.
- [10] JIANG H G, LI X L, XIN G F, et al. Geometry mapping and additional stresses of ballastless track structure caused by subgrade differential settlement under self-weight loads in high-speed railways[J]. Transportation Geotechnics, 2019, 18: 103-110.
- [11] 崔旭浩, 杨怀志, 杜博文, 等. 路基不均匀沉降对CRTS II型板式无砟轨道损伤和变形影响分析[J]. 铁道学报, 2021, 43(10): 91-97.
- Cui X H, Yang H Z, Du B W, et al. Analysis of effects of differential subgrade settlement on damage and deformation of CRTS II slab track[J]. Journal of the China Railway Society, 2021, 43(10): 91-97.
- [12] 向俊, 林士财, 余翠英, 等. 路基冻胀-融化-沉降循环作用下板式无砟轨道受力与变形分析[J]. 中南大学学报(自然科学版), 2019, 50(8): 2043-2052.
- XIANG J, LIN S C, YU C Y, et al. Analysis of stress and deformation of slab ballastless track under effect of subgrade frost heaving-melting-settlement cycle[J]. Journal of Central South University (Science and Technology), 2019, 50(8): 2043-2052.
- [13] 肖源杰, 周思嘉, 畅振兴, 等. 路基不均匀沉降下列车-有砟轨道-路基三维耦合系统动力响应分析[J]. 中南大学学报(自然科学版), 2023, 54(12): 4763-4776.
- XIAO Y J, ZHOU S J, CHANG Z X, et al. Analysis of influence of differential subgrade settlement on dynamic responses of the three-dimensional train-ballasted track-subgrade coupled system[J]. Journal of Central South University (Science and Technology), 2023, 54(12): 4763-4776
- [14] 冯玉林, 侯宇, 何彬彬, 等. 余弦型路基沉降对纵连板式无砟轨道变形与层间接触性状的影响[J]. 华东交通大学学报, 2023, 40(2): 9-15.
- FENG Y L, HOU Y, He B B, et al. Influence of cosine subgrade settlement on deformation and interlayer interface state of longitudinally connected ballastless track[J]. Journal of East China Jiaotong University, 2023, 40 (2): 9-15.
- [15] 唐进锋, 刘文峰, 王浩, 等. 路基不均匀沉降对车辆-CRTS III型轨道系统动力特性影响[J]. 铁道科学与工程学报, 2018, 15(10): 2455-2462.
- TANG J F, LIU W F, WANG H, et al. Influence of subgrade uneven settlement on the dynamic characteristic of vehicle-CRTS III slab track system[J]. Journal of Railway Science and Engineering, 2018, 15(10): 2455-2462.
- [16] 吴斌, 张勇, 徐庆元, 等. 路基上双块式无砟轨道道床板空间力学特性研究[J]. 铁道科学与工程学报, 2010, 7(6): 24-29.
- WU B, ZHANG Y, XU Q Y, et al. Study on spatial mechanical characteristic of track concrete layer of twin-block ballastless track on subgrade[J]. Journal of Railway Science and Engineering, 2010, 7(6): 24-29.
- [17] 郭宇, 高建敏, 孙宇, 等. 路基沉降与双块式无砟轨道轨面几何变形的映射关系[J]. 铁道学报, 2016, 38(9): 92-100.
- GUO Y, GAO J M, SUN Y, et al. Mapping relationship between subgrade settlement and rail deflection of the double-block ballastless track[J]. Journal of the China Railway Society, 2016, 38 (9): 92-100.
- [18] 张乾, 蔡小培, 钟阳龙, 等. 路基沉降区双块式无砟轨道损伤行为与轨面不平顺分析[J]. 中南大学学报(自然科学版), 2022, 53(7): 2573-2581.
- ZHANG Q, CAI X P, ZHONG Y L, et al. Analysis of damage and rail irregularity of double-block ballastless track in subgrade settlement area[J]. Journal of Central South University (Science and Technology), 2022, 53(7): 2573-2581.



第一作者: 陈利(1980—),男,工程师,研究方向为高速铁路道路与桥梁建造和施工工艺。E-mail:476735520@qq.com。



通信作者:余翠英(1976—),女,副教授,博士,硕士生导师,研究方向为高速列车安全控制,无砟轨道结构振动及损伤机理。E-mail:yucuiying1023@163.com。

(责任编辑:李根)