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Dynamic analysis of vehicle-track response for subway with pumping house cancelled

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Abstract. Wastewater pump room is used to lead wastewater out of subway sections. The wastewater pump room is the side channel of subway sections which is often constructed by freezing method. Since the freezing method construction has a certain risk of failure which leads to soil foundation collapse easily, as an alternative, subway section drainage can be achieved by installing a drainage pump inside railway track concrete roadbed. Because the built-in pumping weakened the original integrity of roadbed structure, in this paper, by establishing a finite element analysis model of the vehicle-track-tunnel, 12 indexes including dynamic response of the track structure, stability and safety of running vehicle were calculated. Results show that, while vehicle passing through the section, the build-in pumping structure meet requirements of track structure dynamic responses, vehicle running safety and stability.

1. Introduction

The freezing method is often used in the construction of wastewater pumping stations for subway projects. In areas with complicated water and geological conditions, the freezing method often fails, which can easily lead to soil collapse, casualties and economic losses[1]. Install drainage pumps in the ballastless track structure is a possible solution if pumping house is cancelled. This paper analyzed the impact of the track structure, vehicle running safety and stability with railway track built-in water pump based on a subway project in Foshan China.

The design speed of the line is 100km/h. DTIII fasteners, long sleepers and C35 monolithic track bed are used for the railway track. The height of the track structure is 760mm. After the waste water pump room is cancelled, the ballastless track structure within 20m needs to be adjusted. In order to meet the requirements of the wastewater discharge and ensure that the pump does not start and stop frequently so as to fail, a ditch with a length of 20m, 800mm width and a depth of 1150mm (drain bottom to rail top) is cut out at the center of the track bed. Compared with the original monolithic track bed, the central ditch weakened the integrity of the track structure. When vehicles pass by, dynamic response of the track, running stability and safety of the train will be affected. Therefore, it is necessary to establish a finite element model, calculate relevant indexes under conditions of speeds of 90km/h, 100km/h, 110km/h and 120km/h, and compare with requirements pf standard to determine whether the design scheme meets specifications.

2. Finite Element Model

2.1. Building the model



This paper adopts the whole vehicle model of metro B type[2]. Same structure(Short sleeper embedded monolithic track bed) as the actual design are applied in the model. The track structure consist of 60kg/m U75V rail, DTIII type fasteners, and track bed plate. For the fastener, its static stiffness is 30kN/mm with dynamic and static ratio considered as 1.4. The fastener is simulated by a spring damping unit. As the actual design, railway roadbed is made of C35 reinforced concrete by using solid element for simulation[3]. The distance between fasteners is 595mm, same size as the central ditch is adopted for the track. Parameters used in the model are summarized in the table 1 and table 2.

radie 1. Woder building indexes of subway car type D[4].						
Parameter	Unit	Value				
Axle load	Ν	140000				
Wheelset mass	kg	1420				
Bogie mass	kg	2550				
Car mass	kg	21920				
Vertical stiffness of 1 st spring	N/m	1.7E6				
Longitudinal stiffness of 1 st spring	N/m	6.6E6				
Lateral stiffness of 1 st spring	N/m	10.4E6				
Vertical stiffness of 2 nd spring	N/m	2.75E6				
Lateral stiffness of 2 nd spring	N/m	3E5				
Vertical damping of 1 st spring	N·s/m	5E3				
Vertical damping of 2 nd spring	N·s/m	3E4				
Lateral damping of 2 nd spring	N·s/m	3E4				
Shaking inertia of wheelset	kg⋅m ²	985				
Shaking inertia of bogie	kg·m ²	1980				
Rolling inertia of bogie	kg·m ²	1050				
Nodding inertia of bogie	kg·m ²	1750				
Shaking inertia of car	kg·m ²	617310				
Rolling inertia of car	kg⋅m ²	14890				
Nodding inertia of car	kg·m ²	61730				
Distance of vehicle	m	19				
Axle distance	m	2.2				
Length of vehicle	m	12.6				
Half of lateral distance of 1 st spring	m	1.93				
Half of lateral distance of 2 nd spring	m	1.85				

Table 1	Model	building	indexes	of subway	car type R[4]
Table I.	. woaei	building	indexes	of subwav	car type BI41.

Table 2. Key parameters of track model.

Parameter	Unit	Value			
Rail elastic modulus	Ра	2.06×m ¹¹			
Rail Poisson's ratio	-	0.3			
Rail density	kg/m ³	7830			
Track (C35) elastic modulus	Pa	3.15×10 ¹⁰			
Track (C35) Poisson's ratio	-	0.2			
Track (C35) density	kg/m ³	2500			
Fastener vertical stiffness	MN/m	30			
Fastener vertical damping	kN·s/m	37.5			
Fastener lateral stiffness	kN·s/m	30			

The length of the model can neither be too short nor too long. If the length is too short, reflection effects of dynamic wave at the model boundary will appear which may affect calculation accuracy. If the length is too long, it may occupy too much time and computer resources. The length of the model of this project is about 119m.

2.2. Checking the model

This report selects measured data of Shenzhen Metro Line 11 as comparison to verify the correctness of the model.

Shenzhen Metro Line 11 has a design speed of 120km/h. Type A vehicles with axle load of 16t is used. The on-site testing period is from October 9, 2016 to November 25, 2016. Test data of the left line of Chegongmiao-Hongshuwan section which is located in a straight section is adopted. The passing speed is 110km/h. The Type of rail is 60kg/m rail and the fastener is DT-III type. The type of the test section is shield tunnel. Comparison between test and calculated data are shown in table 3.

Table 3. Comparison between calculated and tested value.					
Parameter	Unit	Calculated Value	Test Value		
Vertical rail-wheel force	kN	102.23	81.46~117.04		
Lateral rail-wheel force	kN	6.77	5.42~8.29		
Derailment ratio	-	0.068	0.06~0.10		
wheel load reduction rate	-	0.056	0.05~0.14		
Vertical displacement of rail	mm	1.08	0.7~1.44		

It can be seen from table 3 that results calculated by the finite element model are within the range of test results, which proves that the vehicle-track coupling model established in this report can be used in the subsequent track structure dynamics analysis.

2.3. Selecting of Calculation indexes

The dynamic indexes are divided into three categories: dynamic indexes of the track structure (dynamic displacement, acceleration, dynamic stress), vehicle running stability indexes (vertical acceleration of the vehicle body, lateral acceleration of the vehicle body), driving safety indexes(Vertical force of wheel and rail, lateral force of wheel and rail, derailment ratio and wheel load reduction rate).

2.3.1 Railway track dynamic indexes

- For the vertical displacement of the rail and the horizontal displacement of the rail, "Technical Specifications for Urban Rail Transit Acceptance" (DB11/T 1714-2020) could be used as reference. It specifies the rail vertical and lateral displacement are 1.5mm. (when the speed is greater than 100km/h, the lateral displacement limit of the rail is taken to be 1.0mm).
- 2) Rail Vertical and lateral acceleration limits are both taken to be 2000m/s². If this value is exceeded, the rails are considered having excessive vibration.
- 3) Rail dynamic bending stress is the bending stress value generated by the rail under dynamic load of the train. The value should not exceed the allowable stress value of the rail. Since 60kg/, U75V rail is modelled, its allowable stress is 363MPa. The section of the built-in pump is underground which leads to relatively constant temperature. Applying the worst case, the rail temperature change range is 20°C, then rail allowable stress is 313MPa after deducting the temperature stress. Therefore, the upper limit of dynamic bending stress of the rail in this report should not exceed 313MPa.

4) The track bed is made of C35 concrete cast-in-place. According to the "Code for Design of Concrete Structures (2015 Edition)" (GB 50010-2010), design value of the tensile strength of C35 concrete is 1.57MPa. Therefore, the longitudinal stress and lateral stress limits of the roadbed in this report are taken as 1.57MPa.

2.3.2 Vehicle running stability indexes

According to "Technical Specifications for Safety Evaluation of Urban Rail Transit before Initial Operation Part 1: Metro and Light Rail", the vertical acceleration limit of the car body is taken as 1.0m/s^2 , and the lateral acceleration limit is taken as 0.6m/s^2 .

2.3.3 Vehicle running safety indexes

- 1) This project adopts subway B-type car, the axle weight is 14t. Therefore, the maximum lateral force of the wheel and axle is 55.74kN.
- 2) The derailment ratio and the wheel load reduction rate are important indexes for evaluating the safety of train operation. The derailment ratio is defined as the ratio of the lateral force divided by the vertical force of the wheel at a certain moment. The wheel load reduction rate is defined as the ratio of load reduction for wheels on reduction side to the average wheel weight of the wheel set.
- 3) The derailment ratio should be less than 0.8 and the wheel load reduction rate should be less than 0.6[5][6].

3. Data analysis

3.1. Calculation date summary

Calculation results are shown as table 4.

Parameter	Unit -	Speed(km/h)				т [.] , 1
		90	100	110	120	Limit value
Rail vertical displacement	mm	0.91	0.95	0.96	0.98	1.50
Rail lateral displacement	mm	0.20	0.20	0.20	0.21	1.50 (1.00)
Rail vertical acceleration	m/s^2	610.21	636.62	677.90	708.57	2000.00
Rail lateral acceleration	m/s^2	98.98	102.48	107.82	113.21	2000.00
Rail bending stress	MPa	37.96	38.15	38.24	38.90	213.00
Fastener lifting force	kN	6.88	6.96	7.01	7.16	20.00
Track transverse stress	MPa	0.30	0.30	0.31	0.32	1.57
Track longitudinal stress	MPa	0.05	0.06	0.06	0.06	1.57
Vertical acceleration of car	m/s^2	0.49	0.53	0.55	0.56	1.00
Lateral acceleration of car	m/s^2	0.19	0.22	0.23	0.24	0.60
Axial lateral force	kN	6.39	6.56	6.67	6.88	55.74
Derailment ratio	-	0.21	0.22	0.22	0.24	0.80
wheel load reduction rate	-	0.37	0.39	0.40	0.40	0.60

Note: value in () apply to speed of 120km/h.

3.2. Data analysis

As data shown in table 4, following laws could be drawn:

- Rail displacement: As the speed changes from 90km/h to 120km/h, the vertical displacement of the rail changes from 0.91mm to 0.98mm which is proportional to the speed. The vertical displacement of the rail at each speed meets the 1.5mm limit value. Meanwhile, the lateral displacement of rail changes from 0.20mm to 0.21mm which has little change. Both displacement indexes are less than limit values.
- 2) Rail acceleration: As the speed changes from 90km/h to 120km/h, the vertical acceleration of the rail increases from 610.21m/s² to 708.57 m/s² which is proportional to the speed. The lateral acceleration of the rail changes from 98.98 m/s² to 113.21 mm/s² with relatively small changes. In general, the vertical and lateral acceleration of the rail are less than limit value which is 2000m/s².
- 3) Rail dynamic bending stress and fastener lifting force: As the speed changes from 90km/h to 120km/h, the rail dynamic bending stress changes from 37.96Mpa to 38.90Mpa which is proportional to speed and less than 213Mpa. The lifting force of the fastener changes from 6.88kN to 7.16kN with the change of the speed which is basically proportional to the speed and meets with the standard lifting force of DTIII type fastener which is 20kN.
- 4) Roadbed stress: As the speed changes from 90km/h to 120km/h, the lateral stress of the roadbed changes from 0.30MPa to 0.32MPa which is proportional to the speed. The longitudinal stress of the track bed changes from 0.05MPa to 0.06MPa which is proportional to the speed. Both longitudinal and lateral stresses are less than the C35 concrete tensile limit of 1.57MPa.
- 5) Car body acceleration: As the speed changes from 90km/h to 120km/h, the vertical acceleration of the car body changes from 0.49m/s² to 0.56m/s². The lateral acceleration changes from 0.19 m/s² to 0.24 m/s². Both acceleration indexes are proportional to the speed. The vertical acceleration of the car body meets the limit of 1.0 m/s², and the lateral acceleration meets the limit of 0.6 m/s².
- 6) Axle lateral force: As the speed changes from 90km/h to 120km/h, the axle lateral force changes from 6.39kN to 6.88kN. The axle lateral force is proportional to the speed, and meet the 55.74kN limit.
- 7) Derailment ratio and wheel load reduction rate: As the speed changes from 90km/h to 120km/h, the derailment ratio increases from 0.21 to 0.24, which is proportional to the speed and meets the specification requirement (0.8). The wheel load reduction rate changes from 0.37 to 0.40 and the values meet the specification requirement (0.6).

4. Conclusion

With the speed of the model changes from 90km/h to 120km/h, track dynamics indexes, vehicle running stability and safety indexes are calculated and analyzed in this paper. Results show that all these indexes are basically related to the speed with a linear proportional relationship. With a scenario of 120km/h as design speed, all checking data meet the limit value (see Table 6) which means the design scheme meets the engineering needs.

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