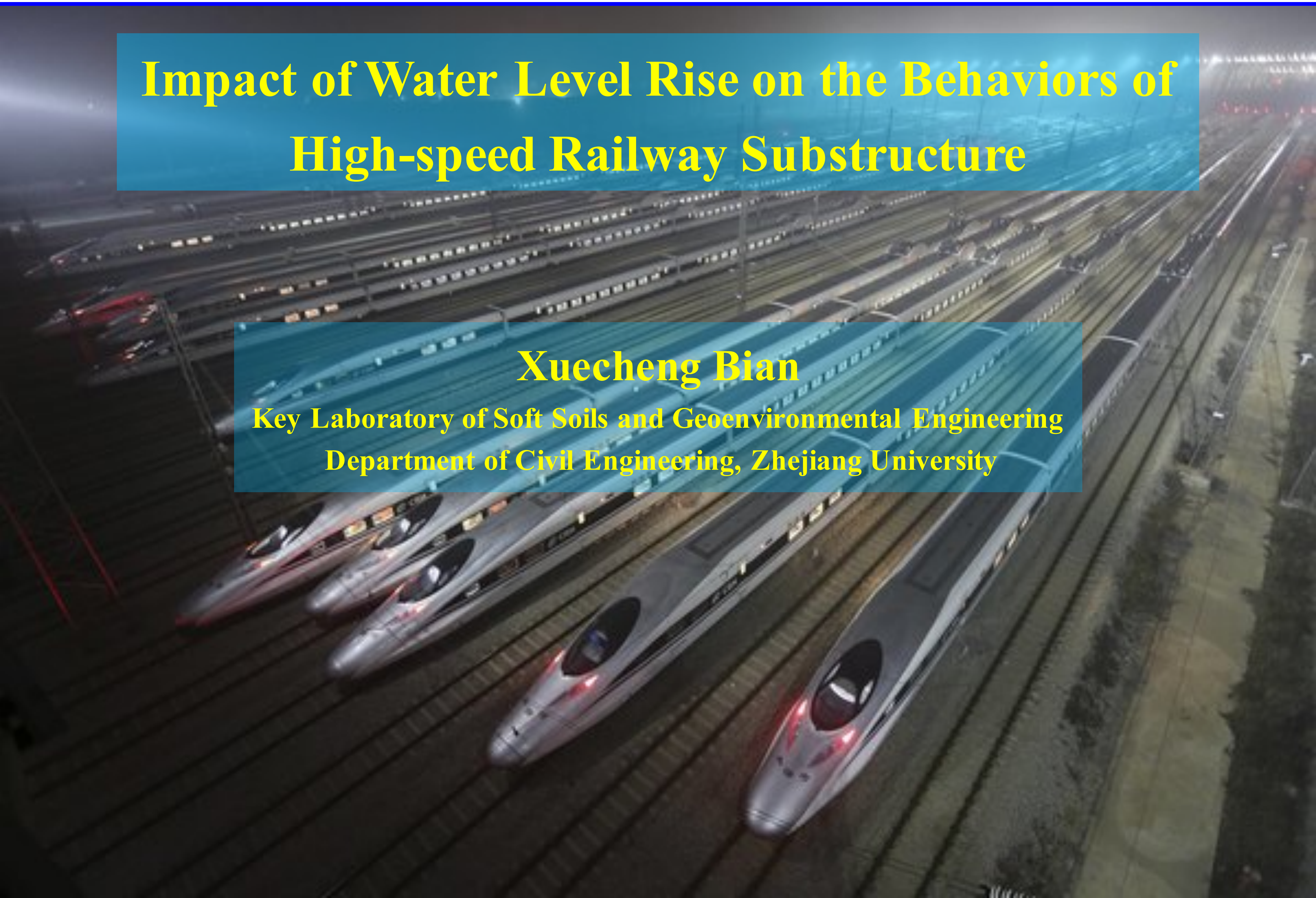
Edinburgh 2015

Impact of Water Level Rise on the Behaviors of High-speed Railway Substructure

Xuecheng Bian

Key Laboratory of Soft Soils and Geoenvironmental Engineering

Department of Civil Engineering, Zhejiang University



Outline

- Development of HSR in China
- Full-scale model test facility for high-speed railway
- Test results of track behaviors with water level changes
- Conclusions

Railway map of China

Colored lines showing CRH and other high speed rail services

Last update: 2015-04-26

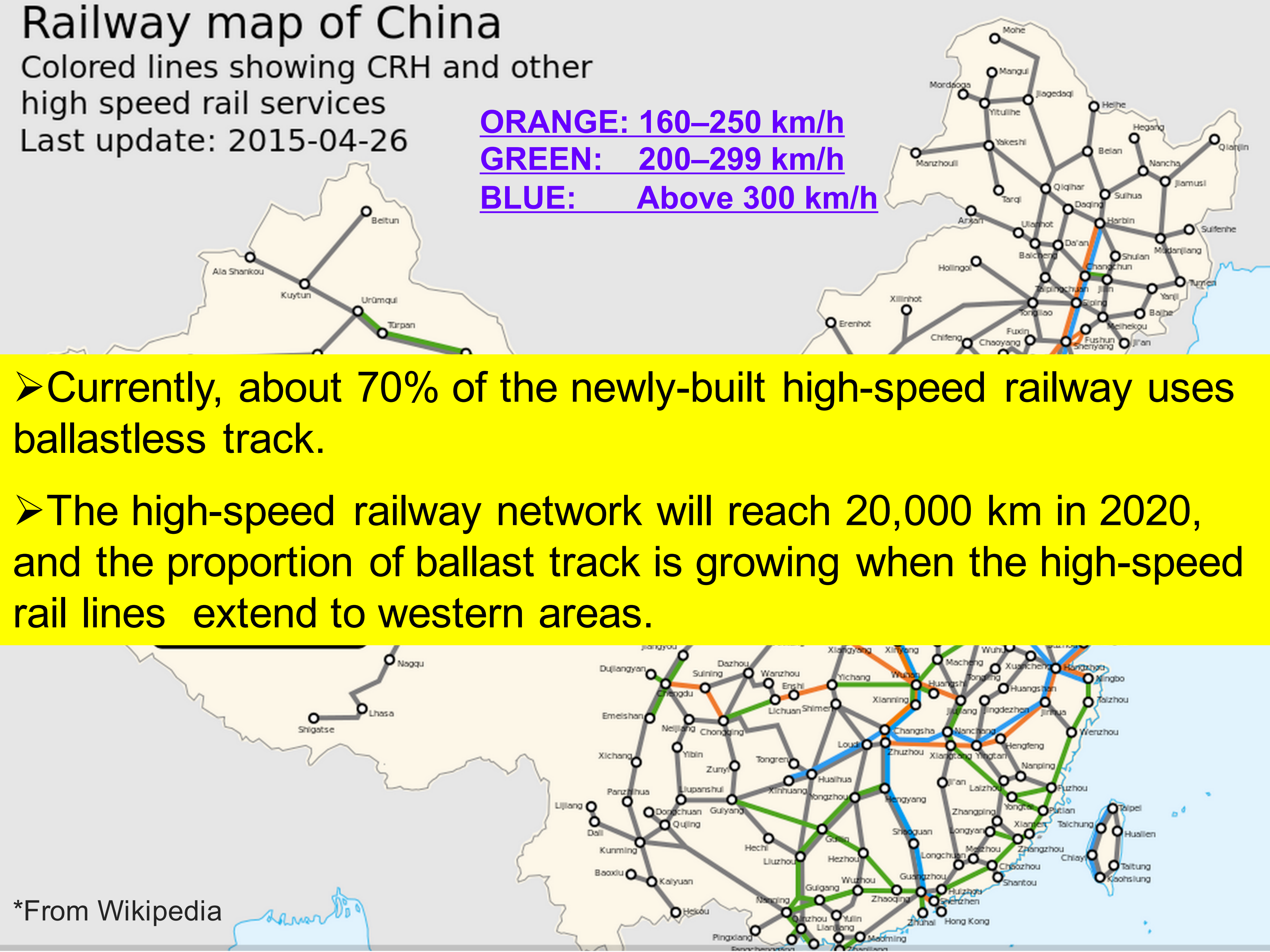
ORANGE: 160–250 km/h
GREEN: 200–300 km/h
BLUE: Above 300 km/h

*From Wikipedia

ORANGE: 160–250 km/h
GREEN: 200–299 km/h
BLUE: Above 300 km/h

- This HSR network is the most heavily used railway system in the world.
- Daily ridership has grown from ¼ Million in 2007 to 2.5 Million in 2014.
- Cumulative ridership had reached 2.9 Billion by October 2014.

*From Wikipedia



- Currently, about 70% of the newly-built high-speed railway uses ballastless track.
- The high-speed railway network will reach 20,000 km in 2020, and the proportion of ballast track is growing when the high-speed rail lines extend to western areas.

*From Wikipedia

Ballastless or ballast track?-A controversial issue

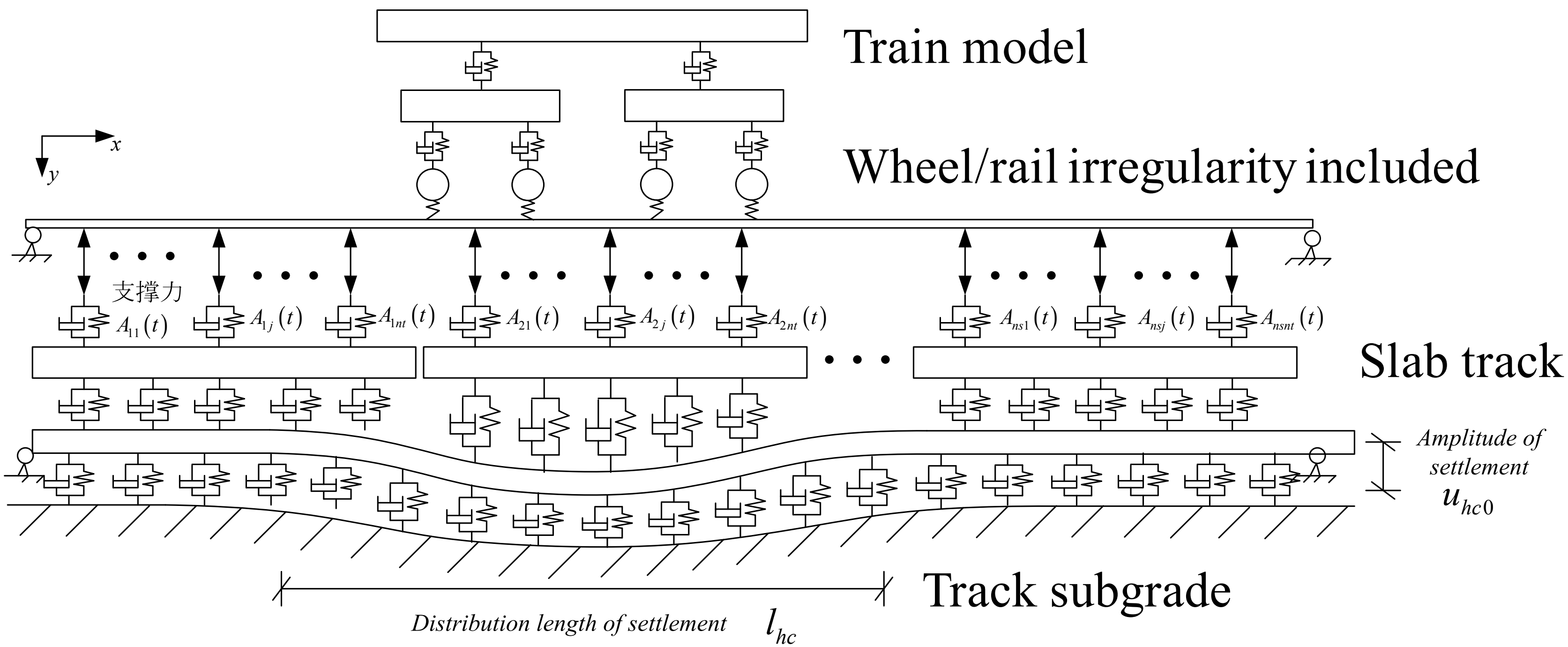
	Ballastless track	Ballast track
Track stability	Higher longitudinal and lateral stability.	Relatively low longitudinal and lateral stability.
Maintenance	Less maintenance for geometry	Frequent non-uniform track degradation and maintenance
Cost	Higher initial construction cost, but lower life cycle cost	Relatively low construction costs but higher life cycle cost
Riding quality	Excellent riding comfort even at speeds greater than 300 km/h	Good riding comfort at speeds 200-300 km/h
Life Expectation	Good Life expectation (about 70 years)	Life expectation is about 15 years
Ballast splash	No ballast particle splash	Ballasts fly up and cause serious damage to rails and wheels.

Railway deterioration

- Trackbed and subsoil deformations are the main sources of track settlement under train traffic loads.
- Uneven track settlement will intensify the dynamic impact between train and track, and significantly accelerate the deterioration of the track structure and the track roadbed, increasing maintenance cost, risk of train derailment and foundation failure.
- High-speed train places high demand on the track alignment(of both vertical and lateral directions).

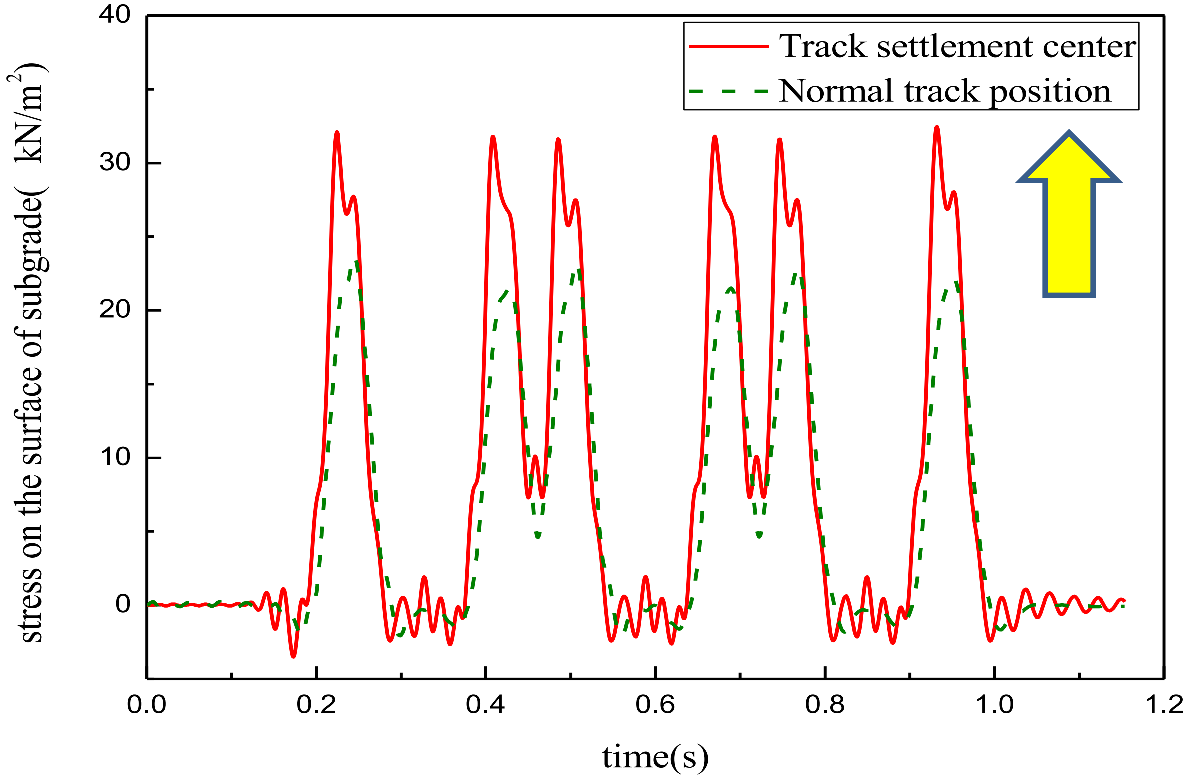
Effect of subgrade settlement on track responses

- Train-track-subgrade dynamic interaction model
  - Train speed: 350km/h
  - Subgrade settlement: 30mm/20m



Effect of subgrade settlement on track responses

- Train-track-subgrade dynamic interaction model
  - Train speed: 350km/h
  - Subgrade settlement: 30mm/20m



Dynamic loading on subgrade increases by 45%

- Chinese high-speed railway design code limits subgrade settlement: 15mm/20m

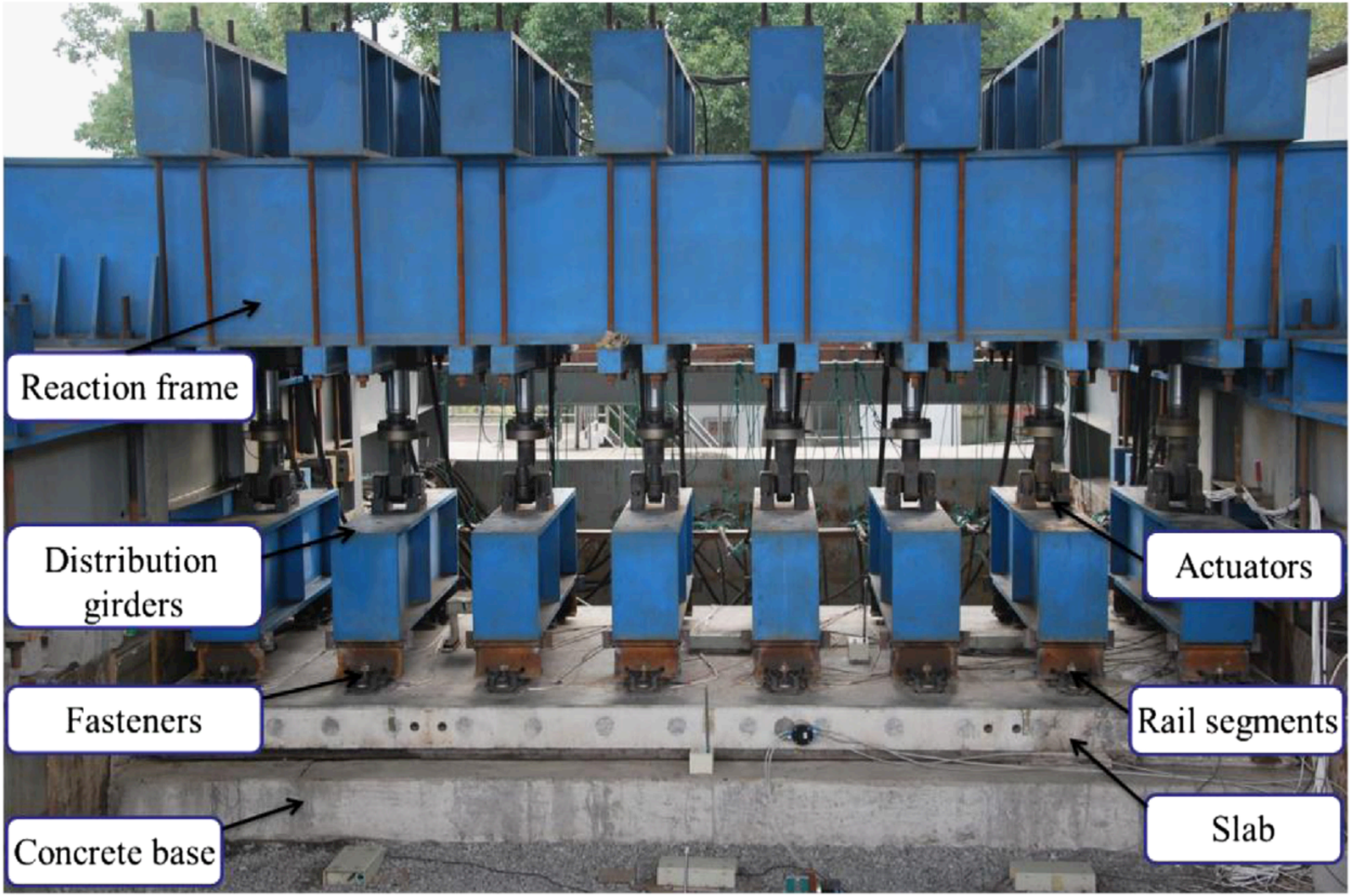
Railway deterioration

- Railway track is a complex soil-structure interaction system. The track substructure consists of **several soil layers with different soil materials and compact conditions**.
- At the same time, high-speed railways are subjected to several kinds of weather-induced loads in addition to regular traffic loadings.
- Extreme rainfall, storms and floods are typical climate impacts on transportation infrastructure.
- The purpose of this study is to investigate the **impact of water level rise** on the **dynamic performance** and **permanent deformation** of track substructure under train moving loading based on full-scale model tests.

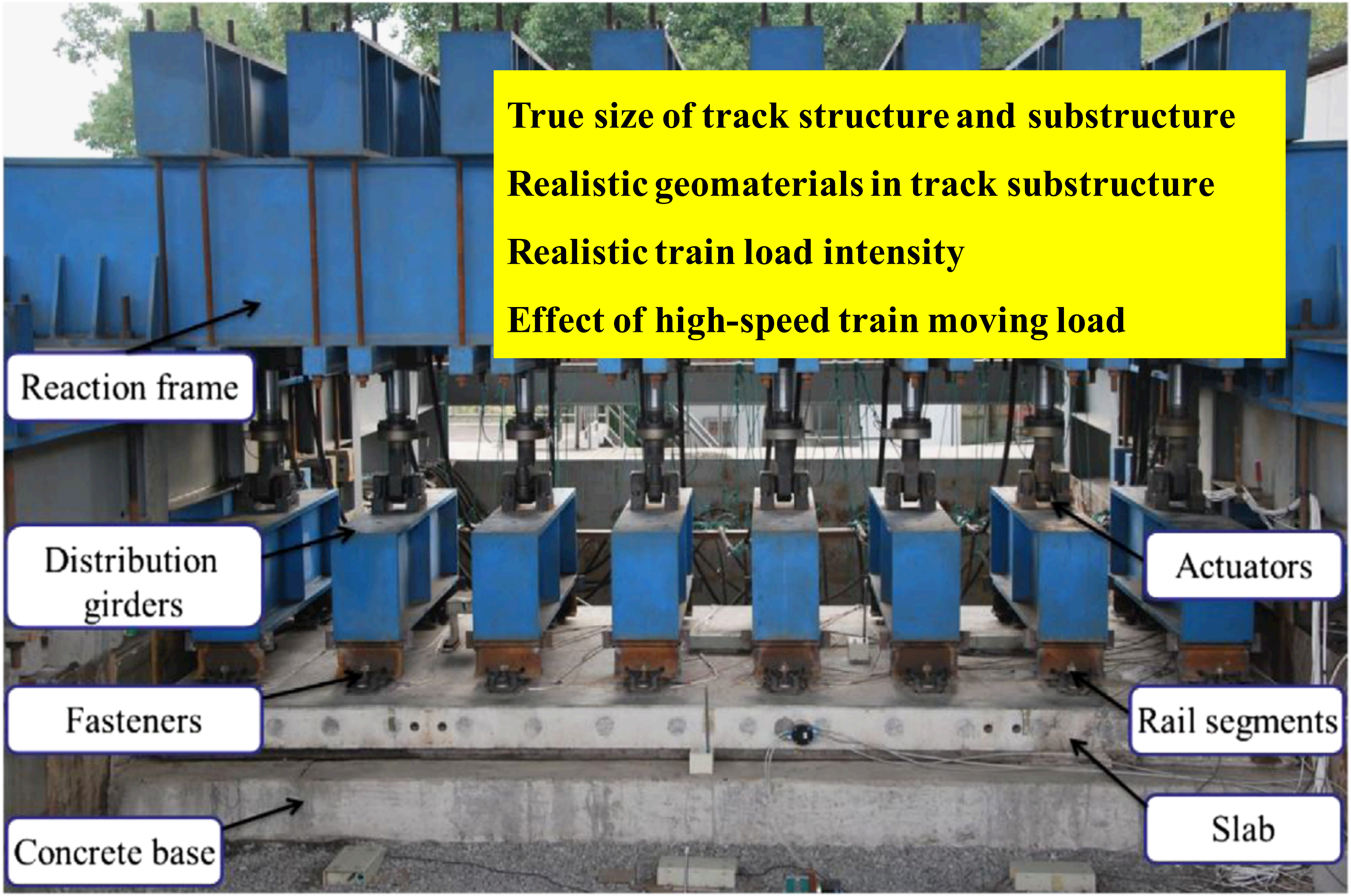
Outline

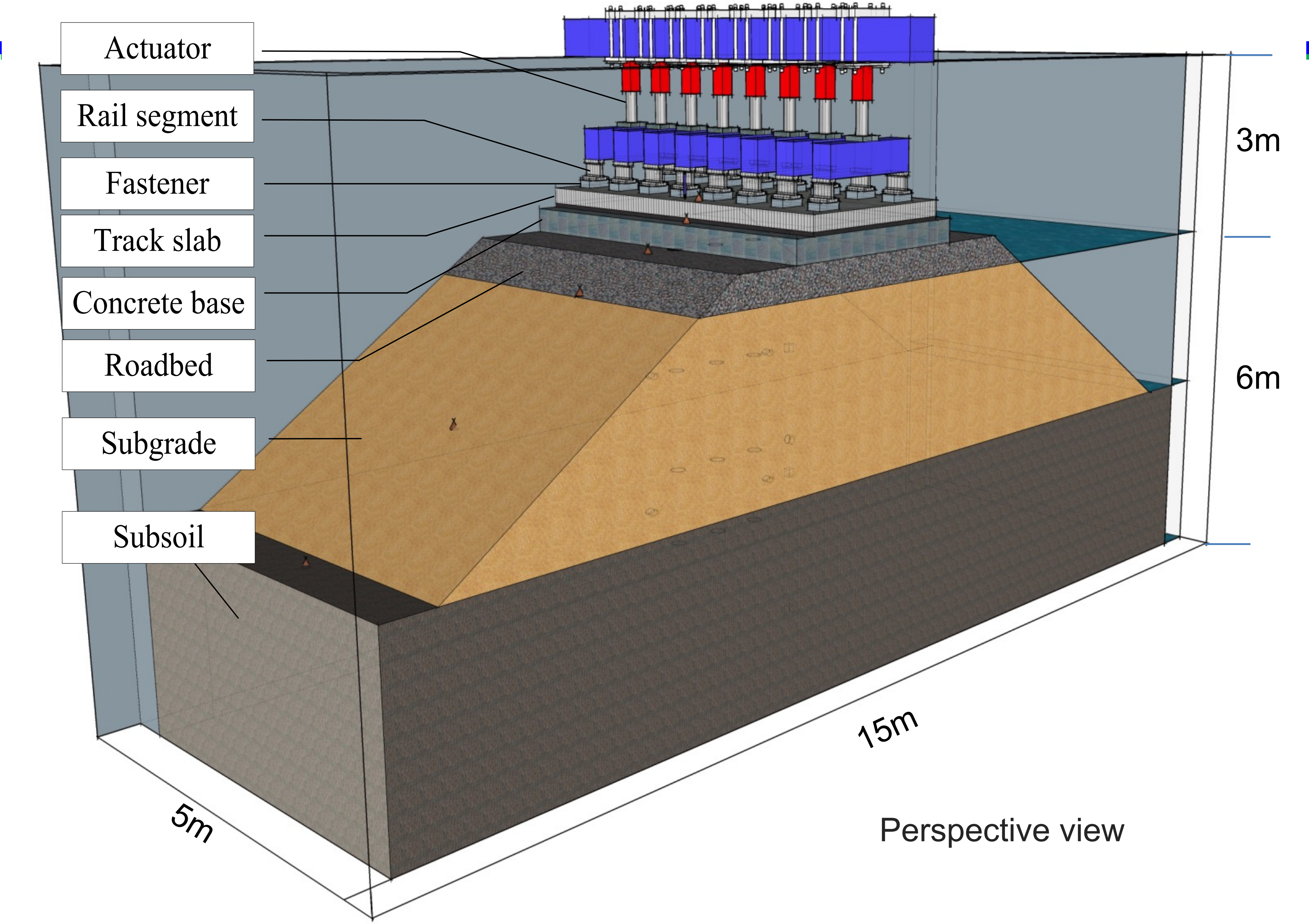
- Development of HSR in China
- Full-scale model test facility for high-speed railway
- Test results of track behaviors with water level changes
- Conclusions

Full-scale model tests for high-speed railway

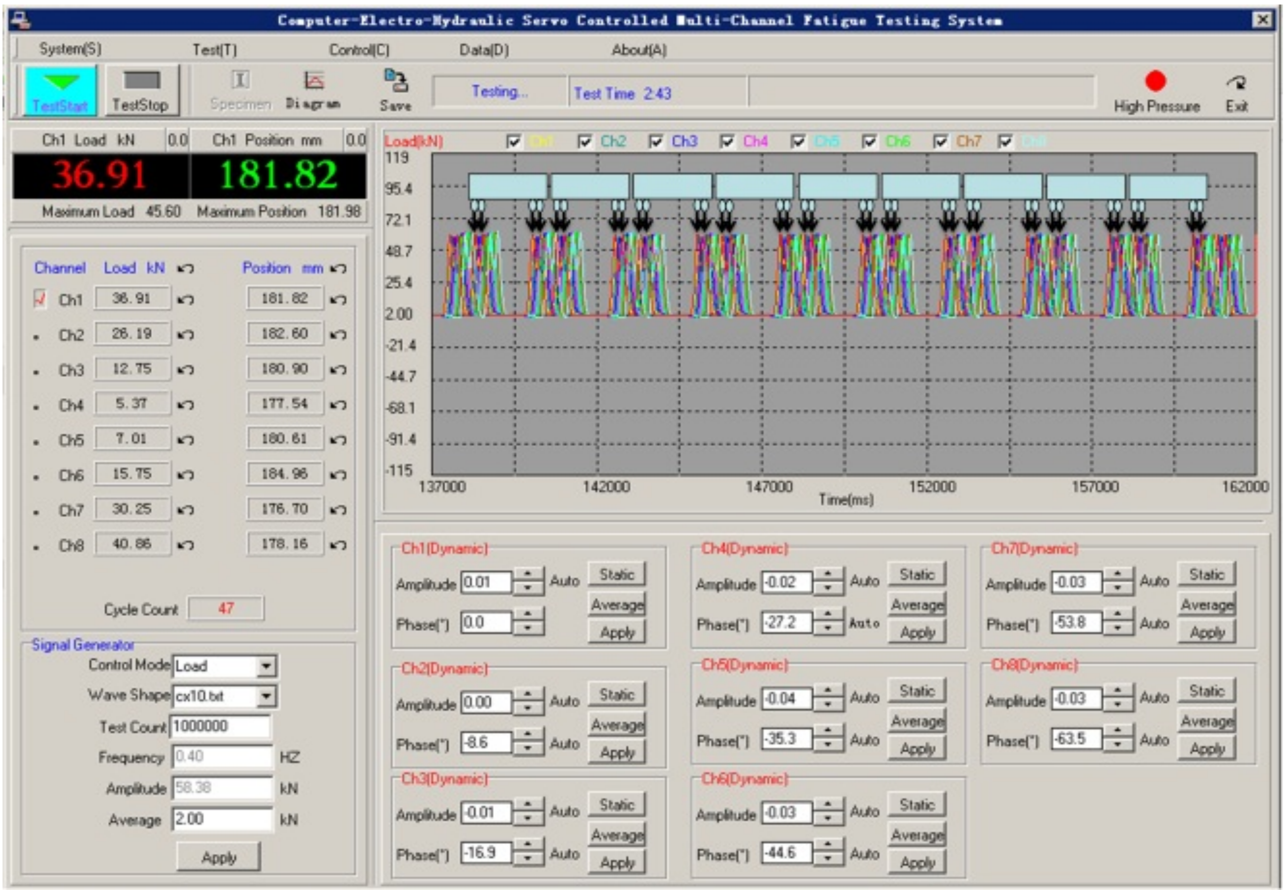


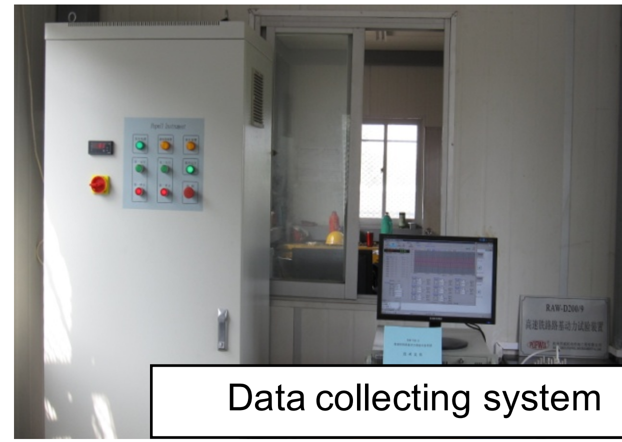
Full-scale model tests for high-speed railway




Actuator
Rail segment
Fastener
Track slab
Concrete base
Roadbed
Subgrade
Subsoil
3m
6m
15m
5m
Perspective view

Full scale model test facility for HSR at Zhejiang University



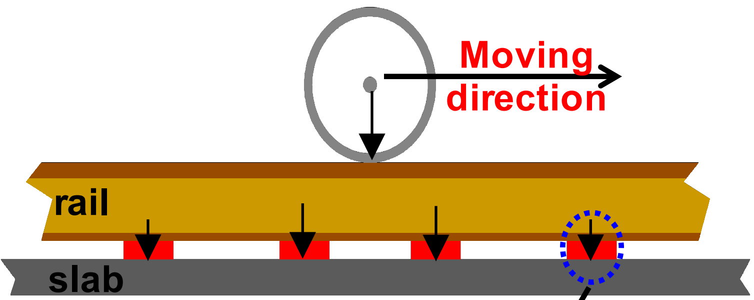


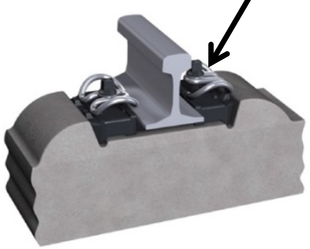
Data collecting system

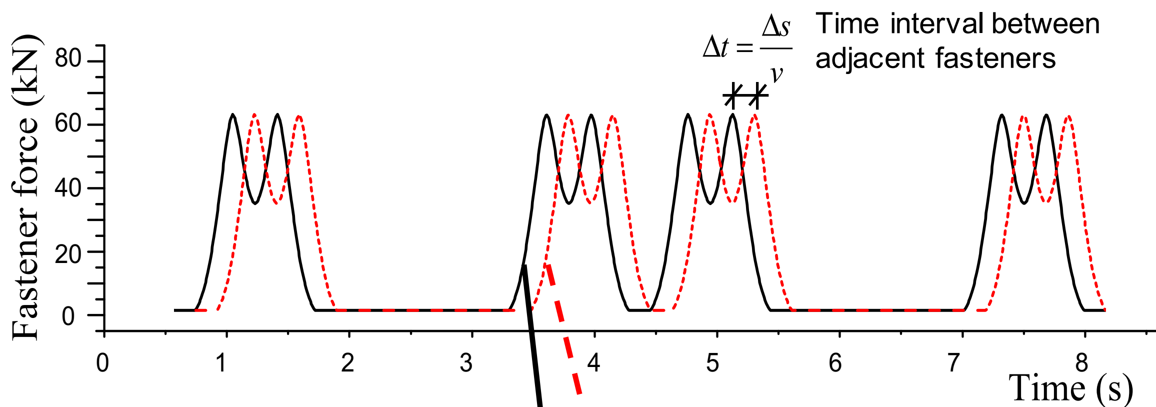
Power supply system

Dynamic loading on fasteners due to train moving

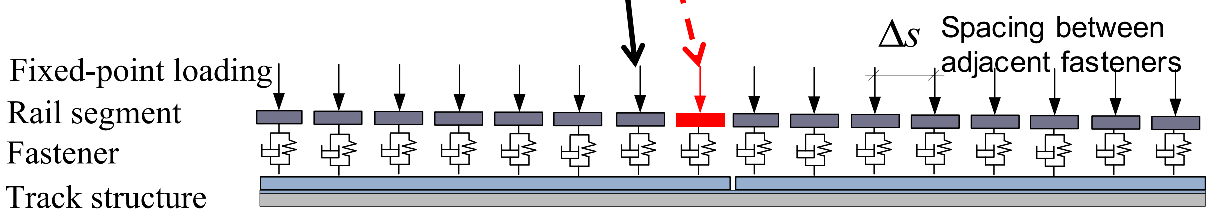
- **The principle of simulating moving trains is to apply equivalent vertical loading at individual fastener.**







Fastener force obtained from theoretical model

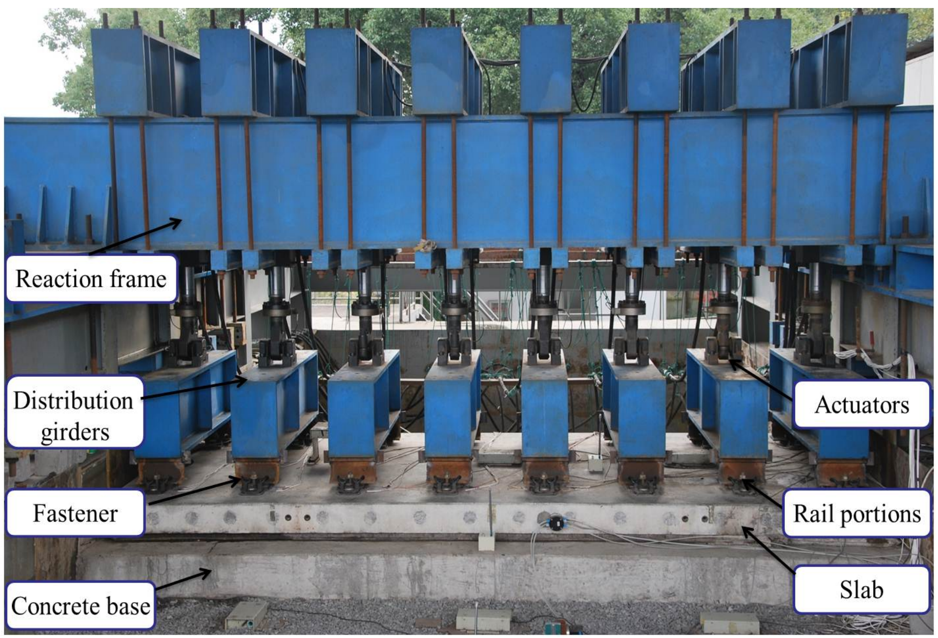


Rail segment with fastener

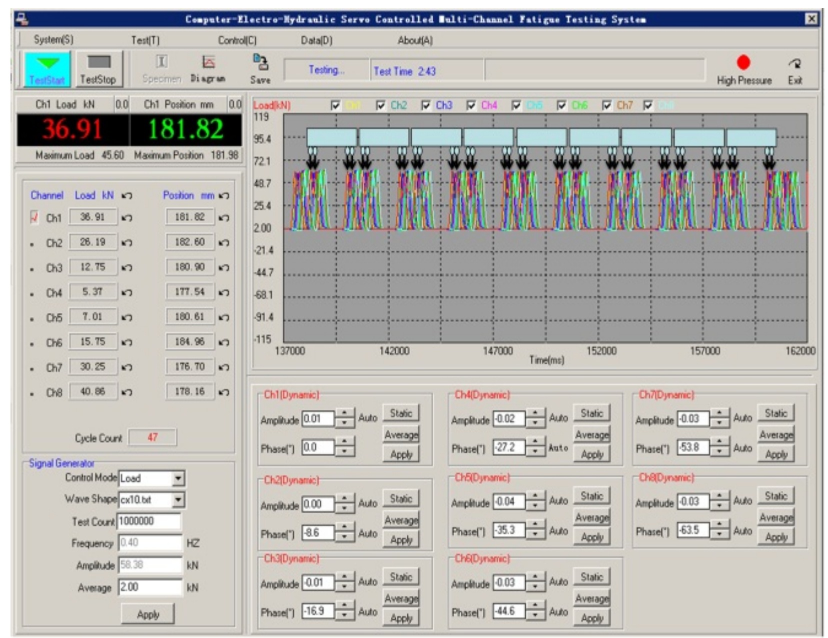
Fixed-point loading at rail segment with fasteners

Dynamic tests with train moving loads

- Eight actuators are used in the current test for a portion of high-speed railway(5m long).
- The proposed train-track-subgrade interaction solving algorithm has been implemented and integrated into the controlling software of the testing system. The highest train speed achieved in the tests is up to 360km/h.



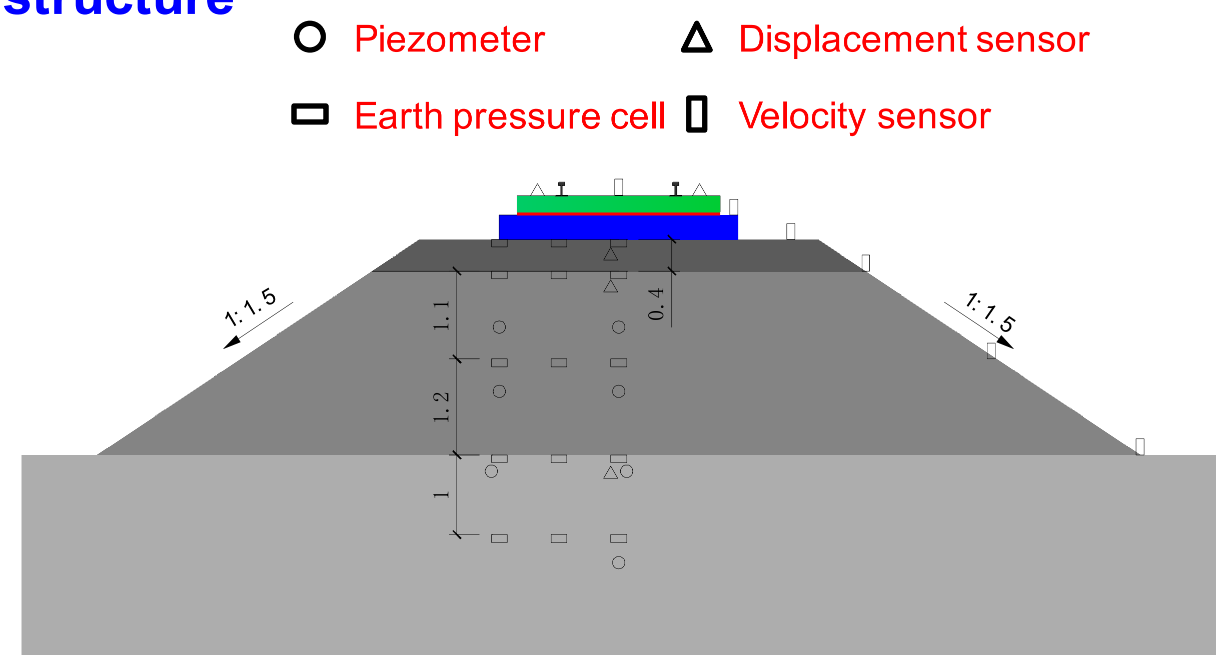
Sequential loading device

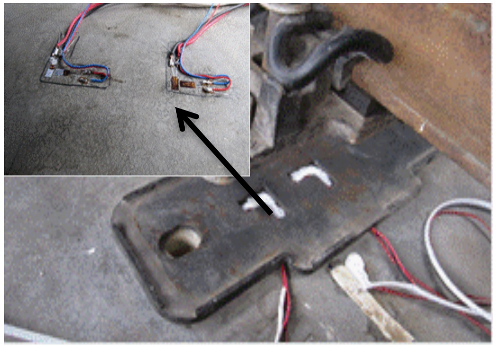


Controlling software

Instrumentation

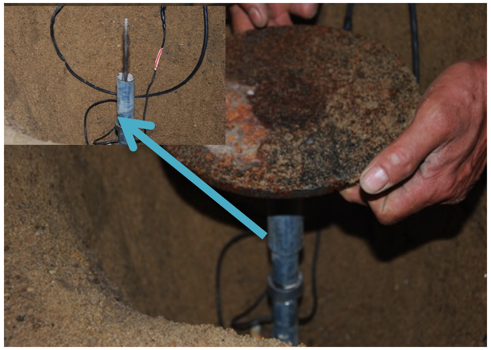
- Strain gauges on track structure
- Accelerometers
- Velocity sensors
- Displacement sensors
- Earth pressure cells
- Settlement plates
- IS settlement sensors
- Piezometers
- Temperature sensors





Strain gauge

Earth pressure cell

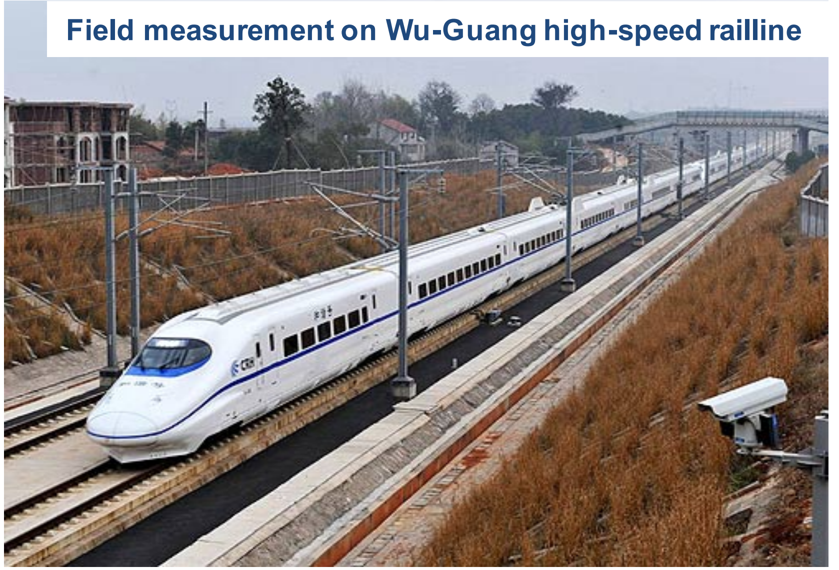


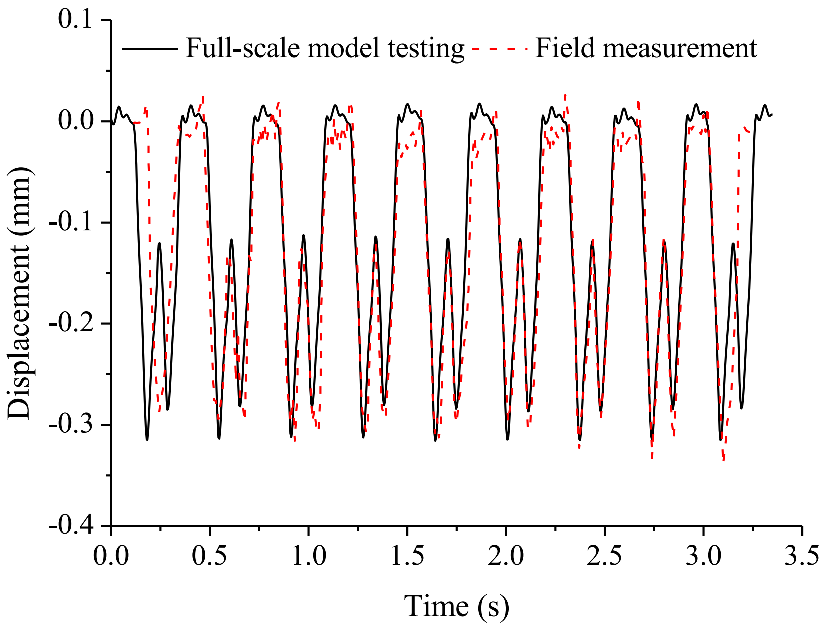
Settlement plate

IS settlement sensor

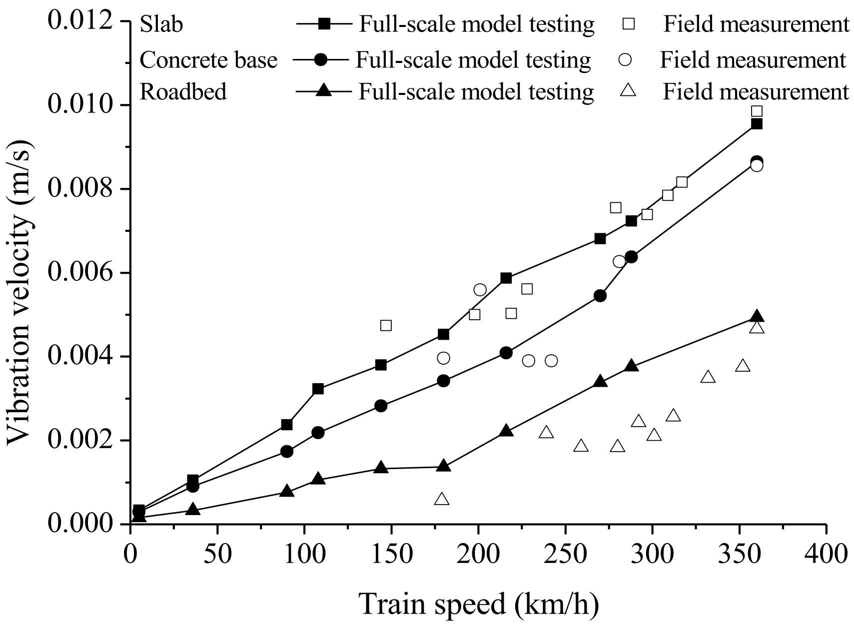
Comparison with in-situ tests

- Comparisons with the field measurements have fully validated the reliability of the testing apparatus and test scheme.





Recorded track responses



Recorded vibrations vs. train speeds

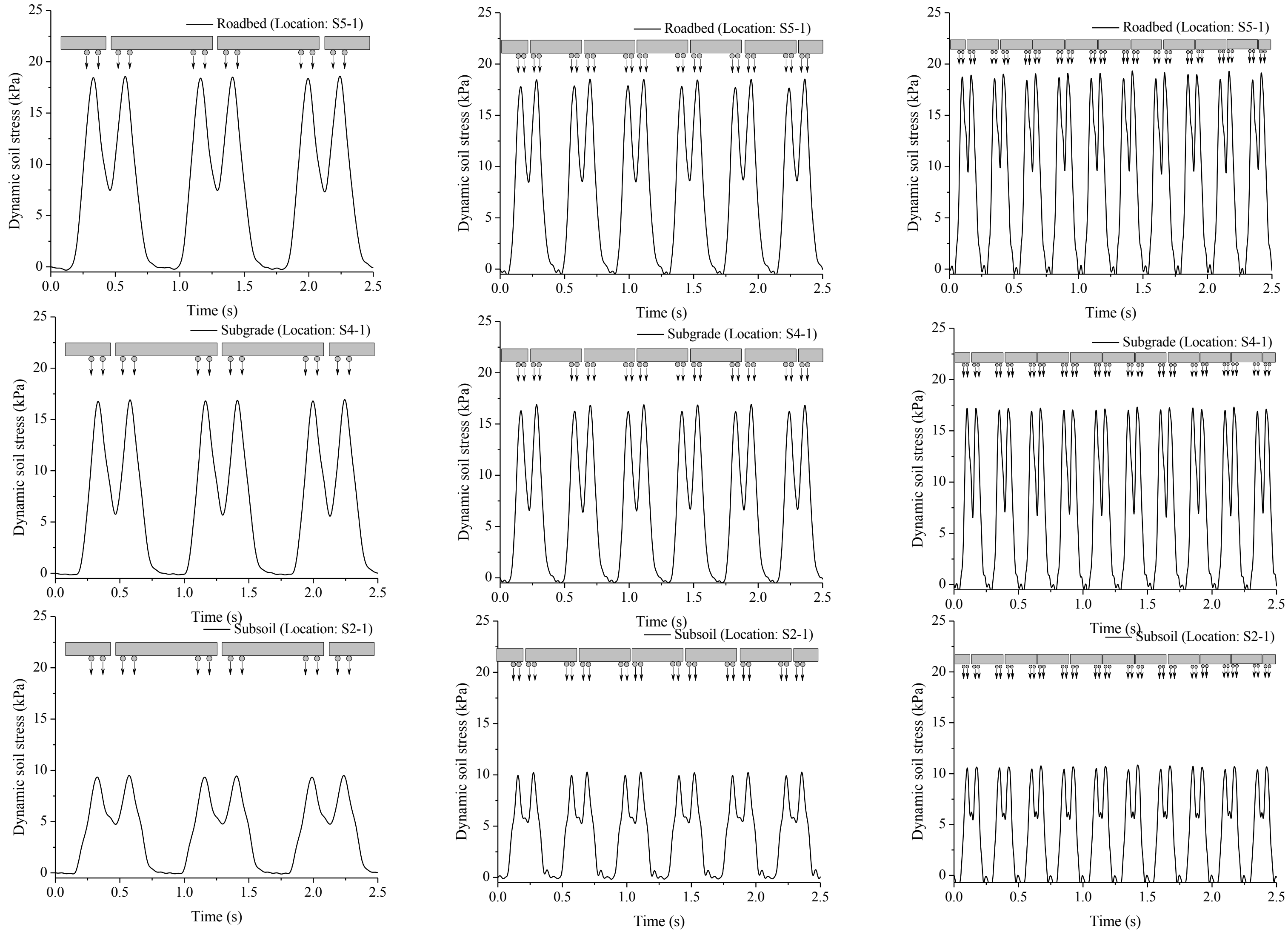
Dependency of dynamic stresses on train speed

❑ Dynamic soil stress at roadbed, subgrade and subsoil

Roadbed surface

Subgrade

Subsoil



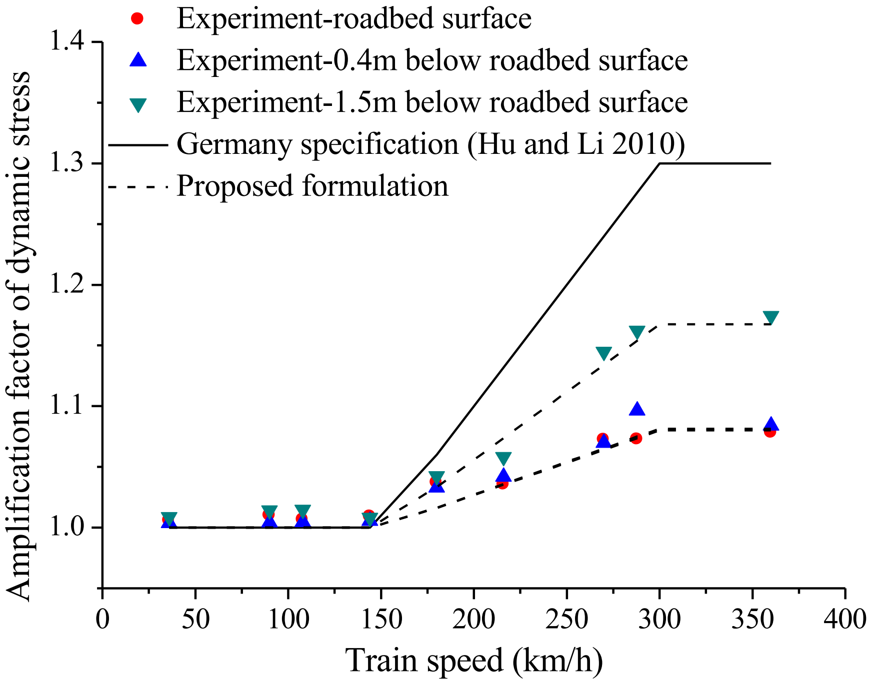
V=108 km/h **V=216 km/h** **V=360 km/h**

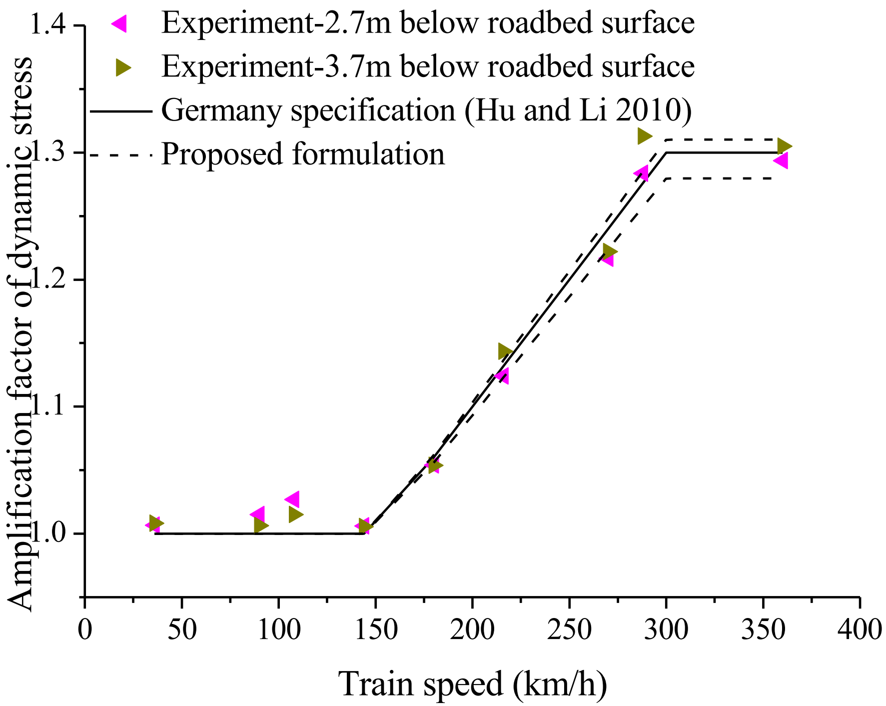
Dynamic stresses with train speed and depth

Amplification factor of dynamic stress

$$\phi_d = 1.0 \qquad 0 \le v \le 150 km/h$$
$$= 1.0 + (v_e - 150)/150 \times (\phi_{d\max} - 1) \qquad 150 < v \le 300 km/h$$
$$= \phi_{d\max} \qquad v > 300 km/h$$

$$\phi_{d\max} = 1.33 - \frac{0.25}{1 + 0.14 z^{3.4}}$$





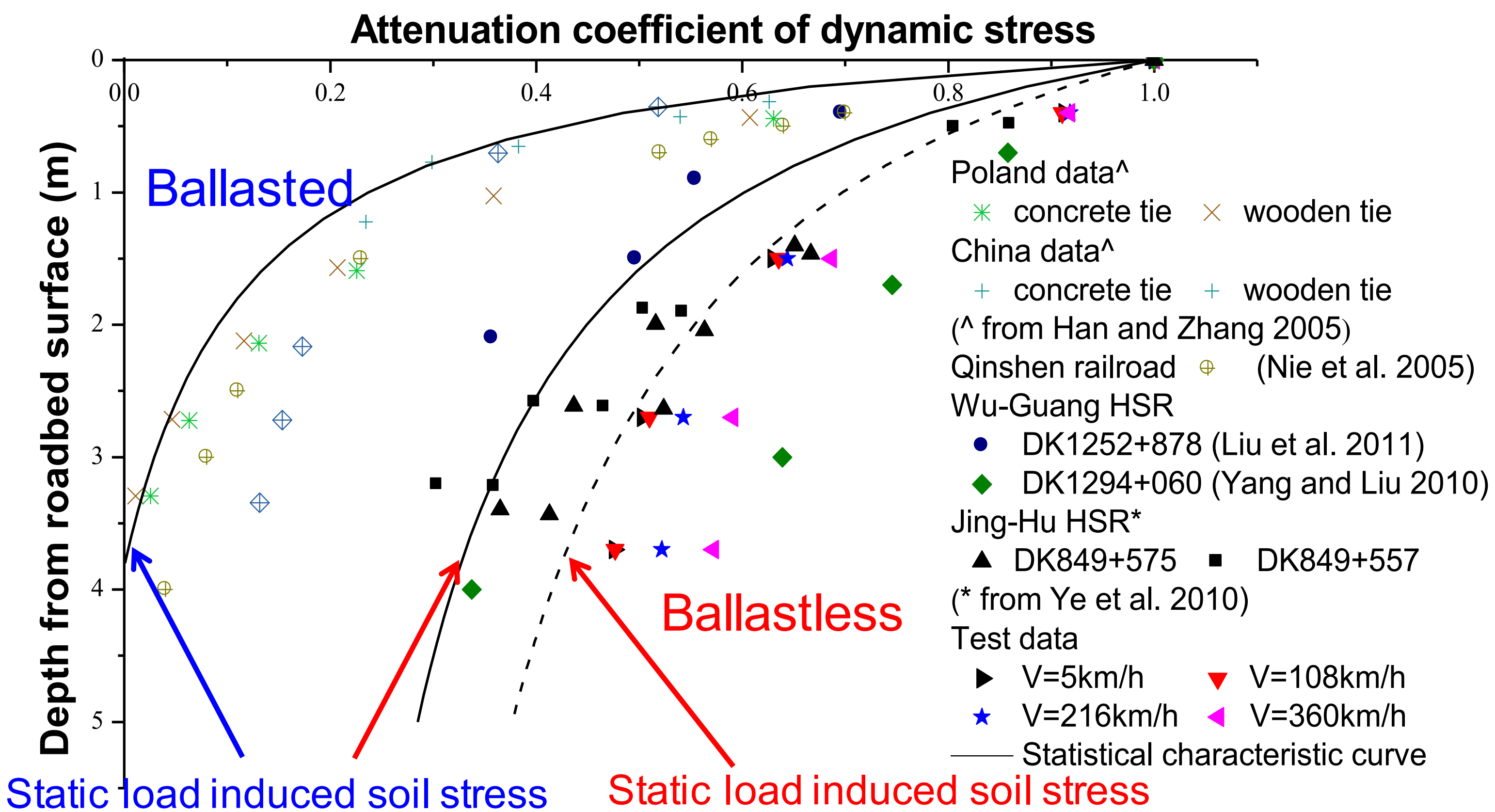
Roadbed and Subgrade **Subsoil**

Dynamic stresses with train speed and depth

❑ Attenuation coefficient of dynamic soil stress

$$\eta = 1 - \frac{z}{a + b \cdot z}$$

For ballasted railway, a=0.42,b=0.89;
For ballastless railway of field test, a=1.39,b=1.12;
For ballastless railway of model test, a=2.66,b=1.11.

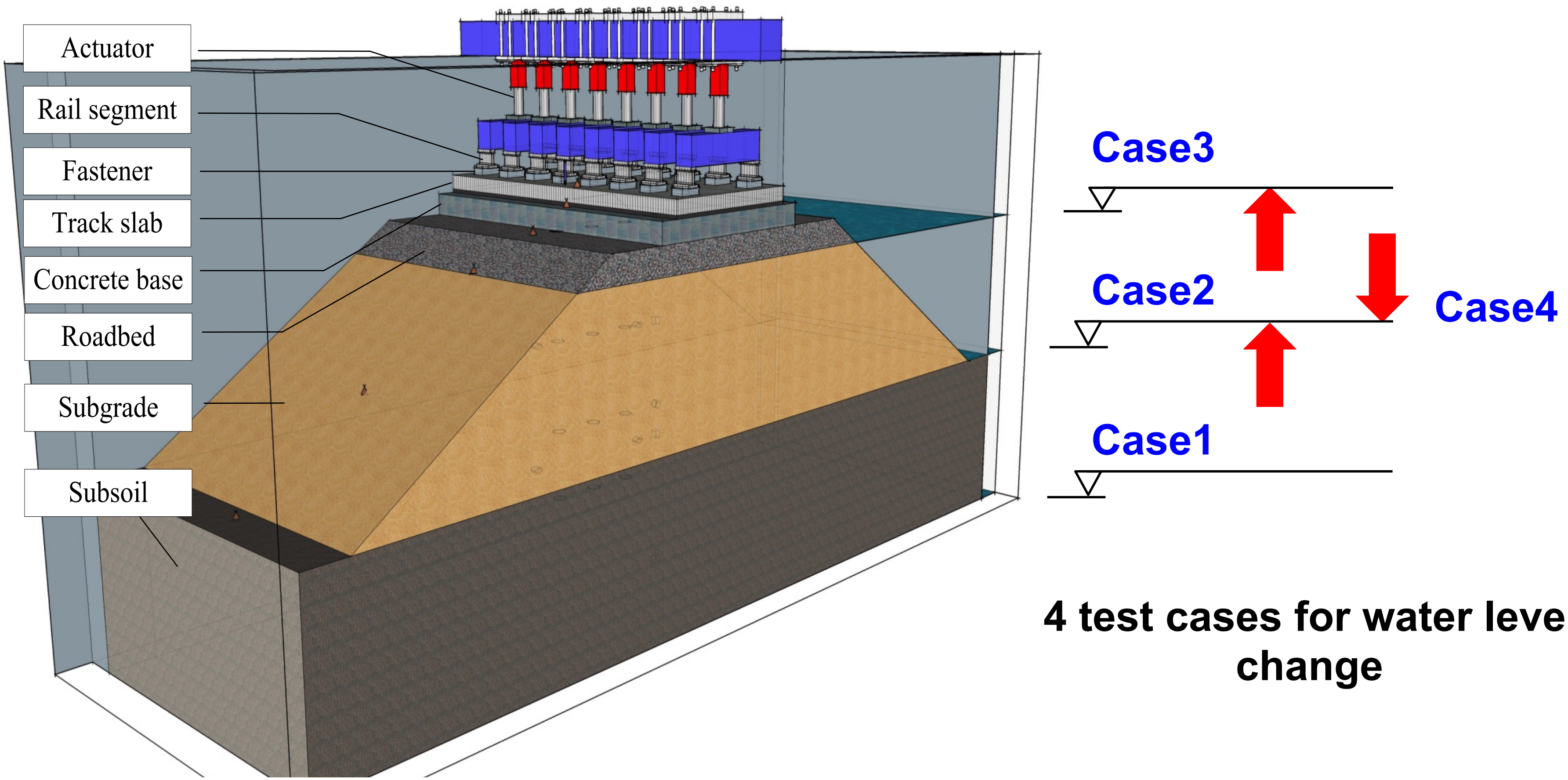


Outline

- Development of HSR in China
- Full-scale model test facility for high-speed railway
- Test results of track behaviors with water level changes
- Conclusions

Influence of water level rising

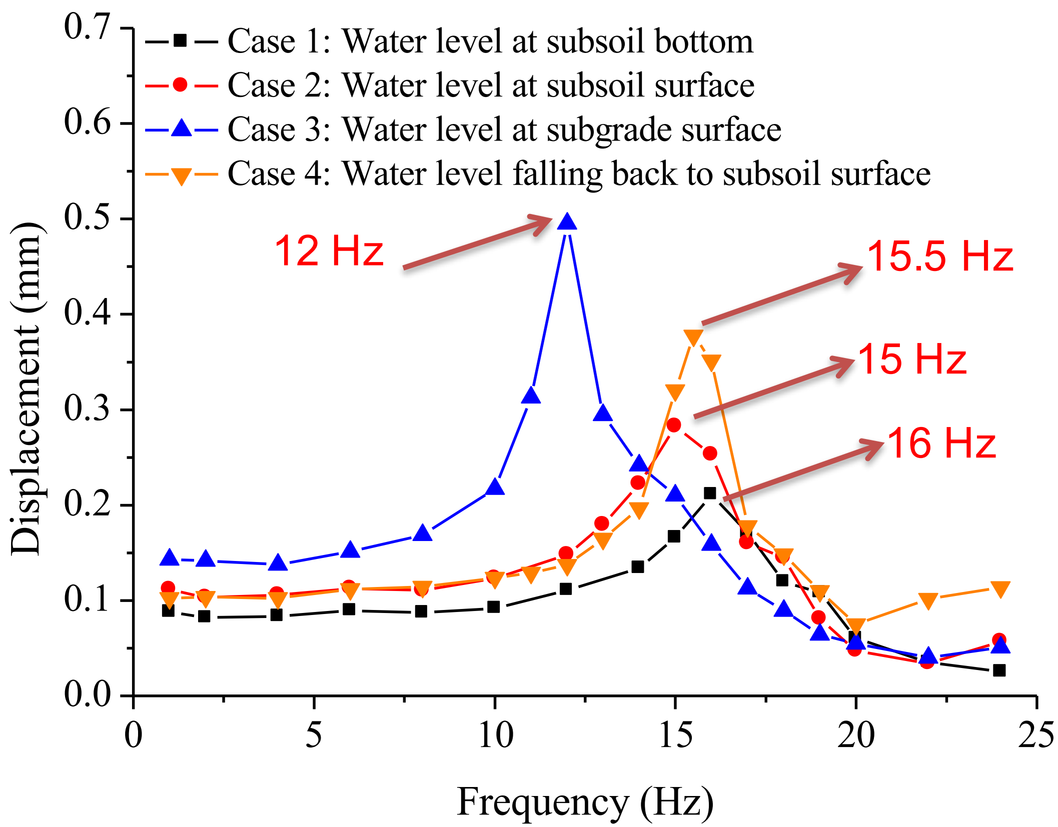
- Water level rises are mostly due to rainfall or underground water lifting
- In the test, water levels rose gradually from the subsoil bottom to the subgrade surface, and then fell back to the subsoil surface.



4 test cases for water level change

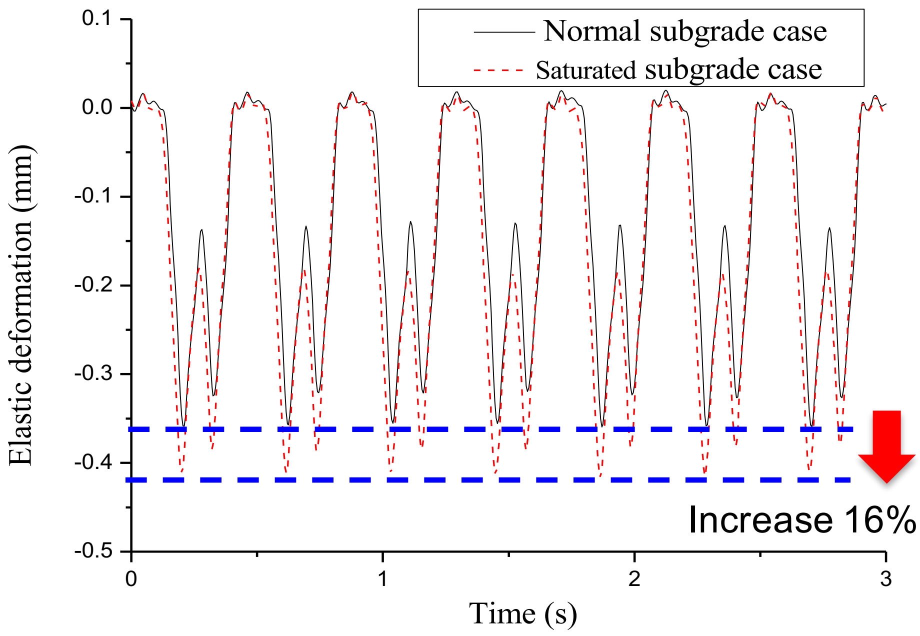
Influence of water level rising

- Resonant frequency of the track-substructure system
  - Sinusoidal loads of 100kN with frequency range of 1-24 Hz were applied to the track structure using single actuator.
- Water level rising results in decrease in the track system's stiffness, and consequently decrease in the resonant frequency

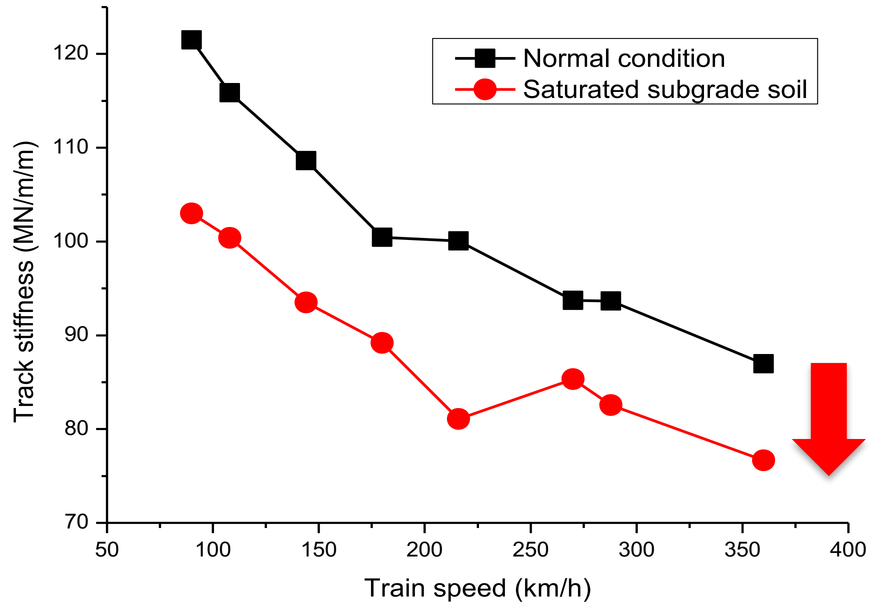


Influence of water level rising

- **When water level reaches the subsoil surface, the track vibration intensity increases by 16%, and track stiffness decrease correspondingly.**



- **Increase in track vibration intensity**

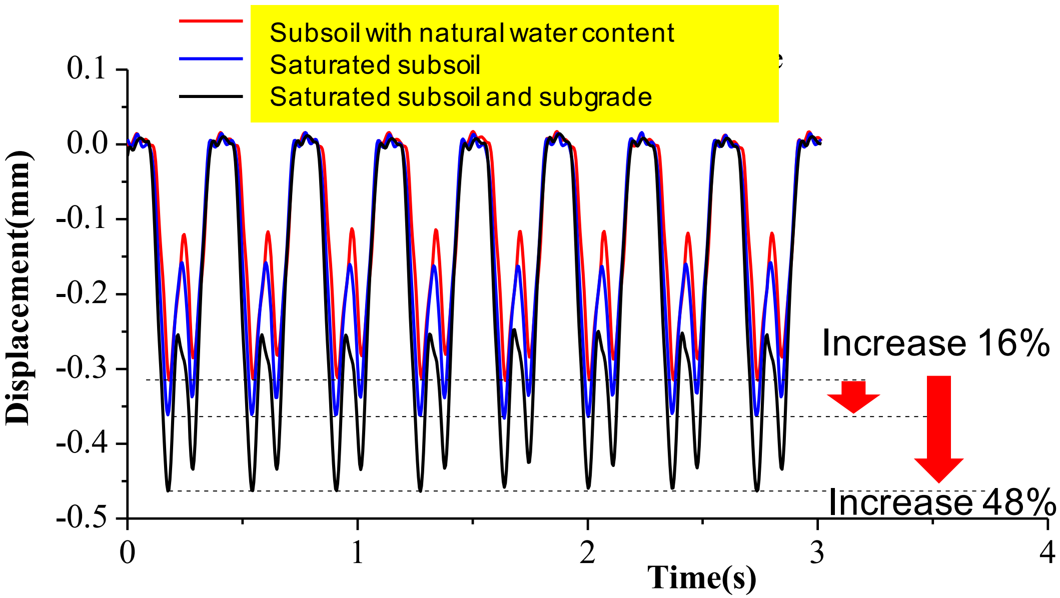


- **Degradation of track stiffness**

Influence of water level rising

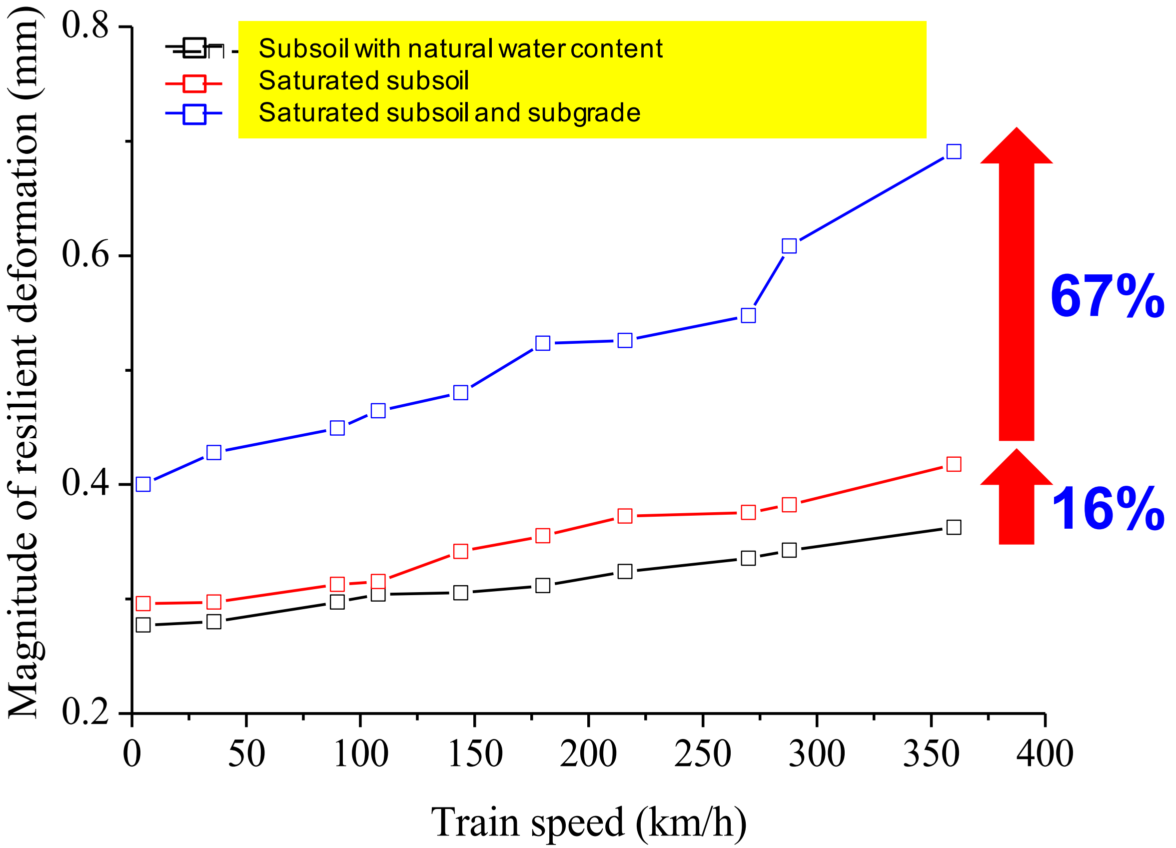
❑ When water level reaches the subgrade surface

- The elastic deformations of track in this case are much larger(48%) than those in the normal and saturated subsoil case(16%).



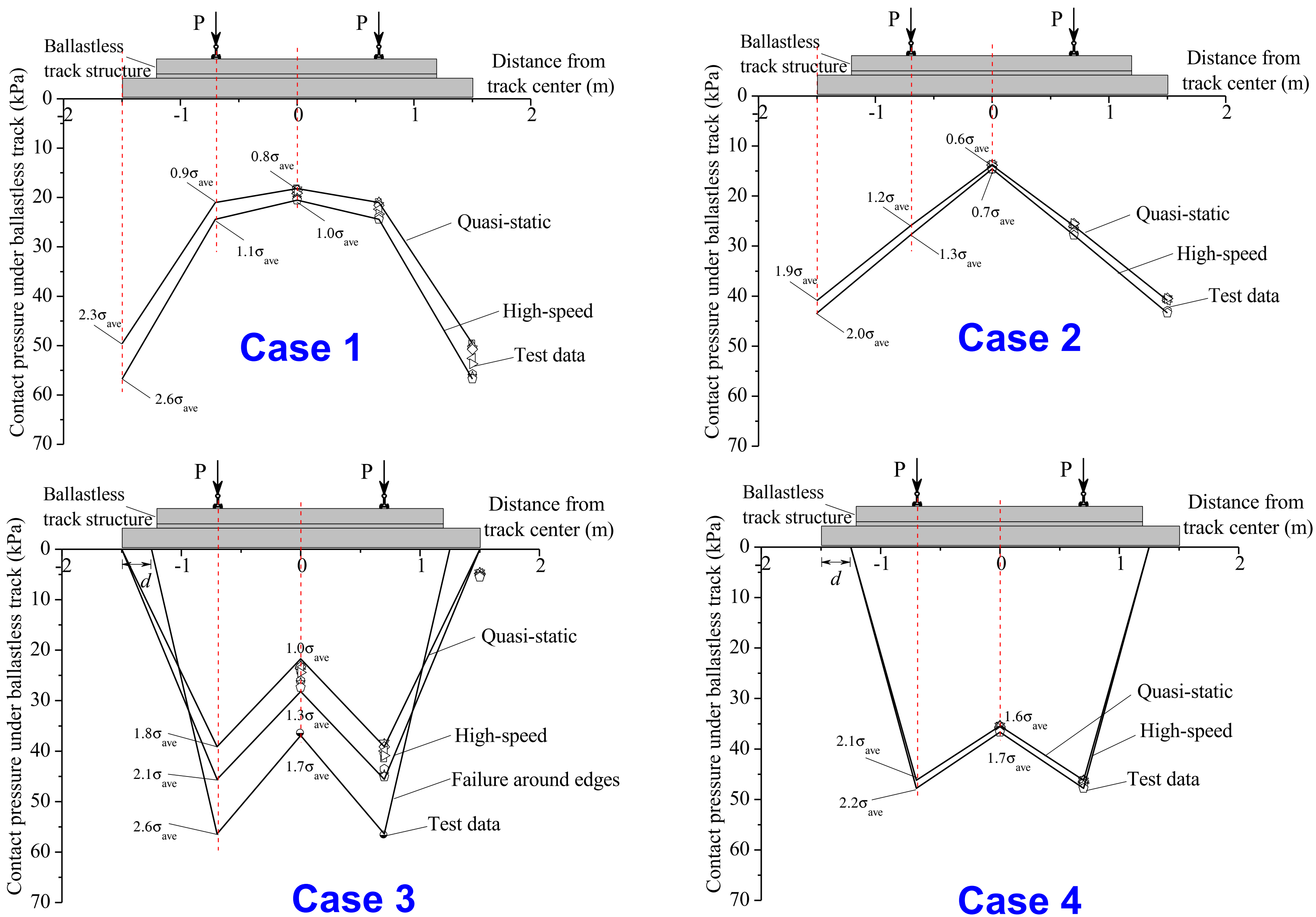
Influence of water level rising

- Track's dynamic response amplitudes grow with the rise of water level, and this effect is intensified by the train's increasing speed.



Contact pressure below track structure

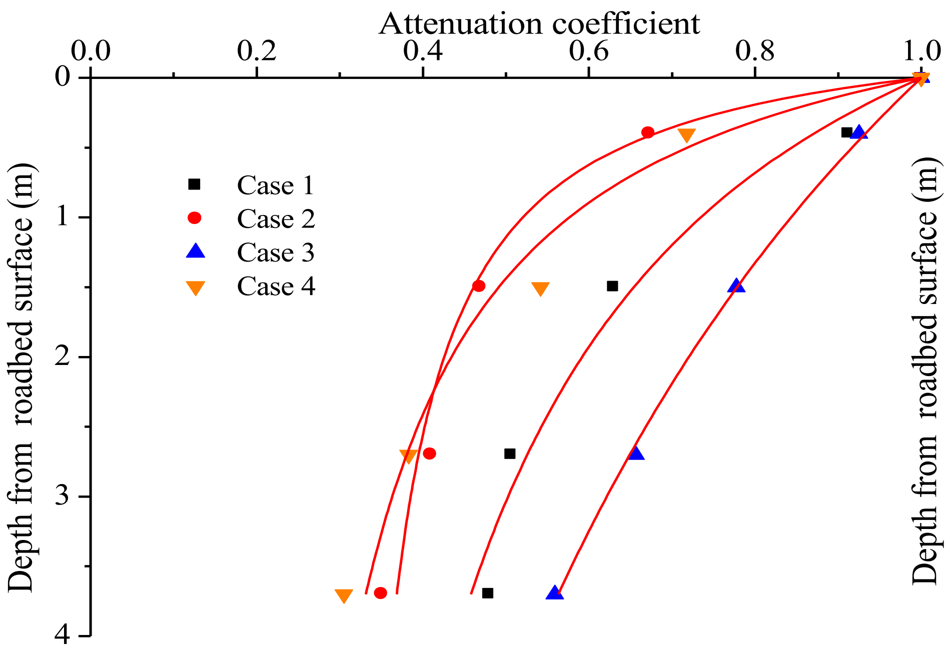
Contact pressure between concrete base and roadbed surface



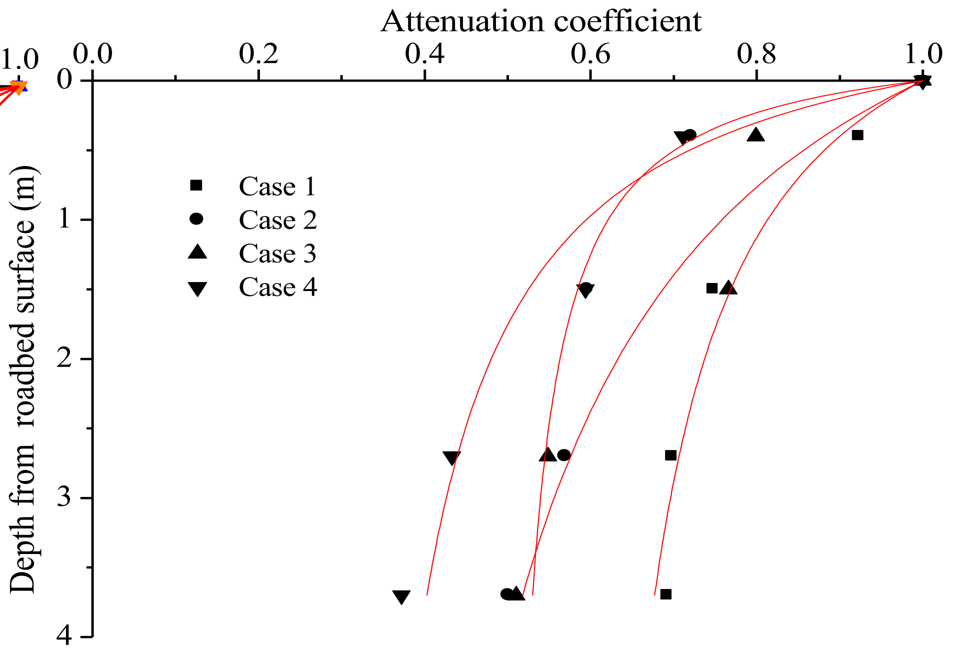
Dynamic stresses with train speed and depth

❑ Attenuation coefficient of dynamic soil stress

$$\eta = 1 - \frac{z}{a + b \cdot z}$$



V= 5km/h

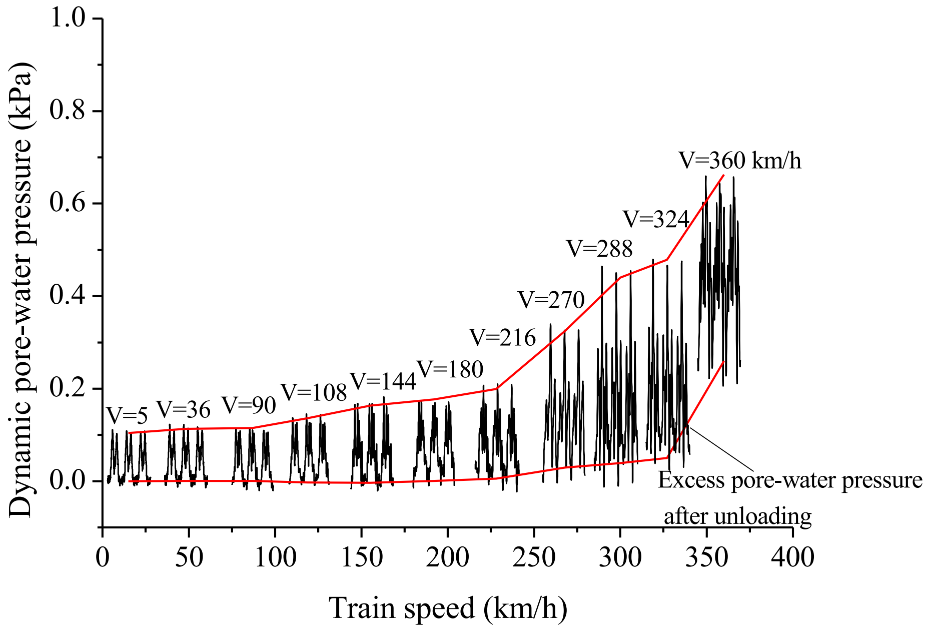


V= 360km/h

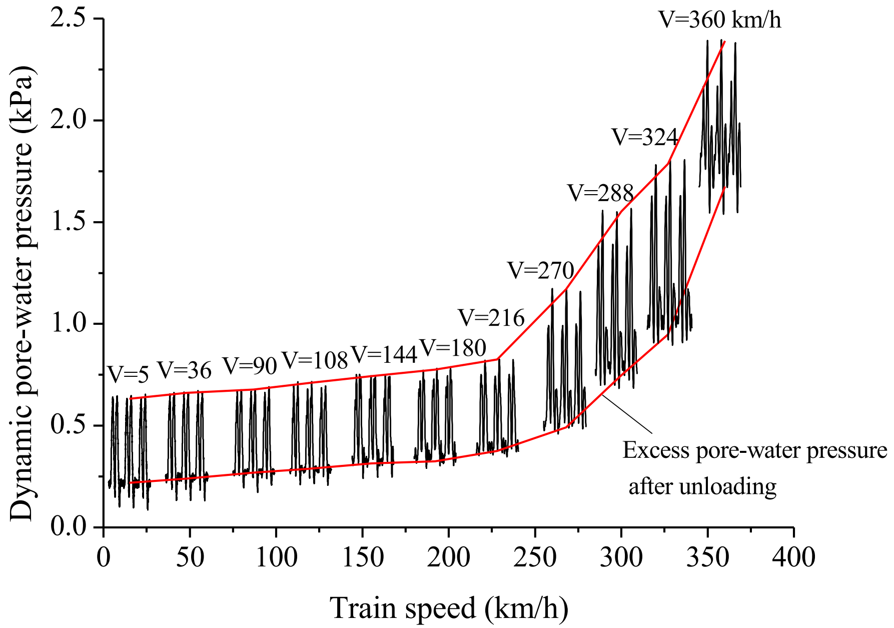
- **Water level rising reduces the modulus of soil layers, leading to the change in the soil stress attenuation.**
- **Dynamic soil stresses attenuate more slowly at higher train speeds.**

Pore water pressure

Pore water pressure recorded in test case 3



In subgrade of coarse sand

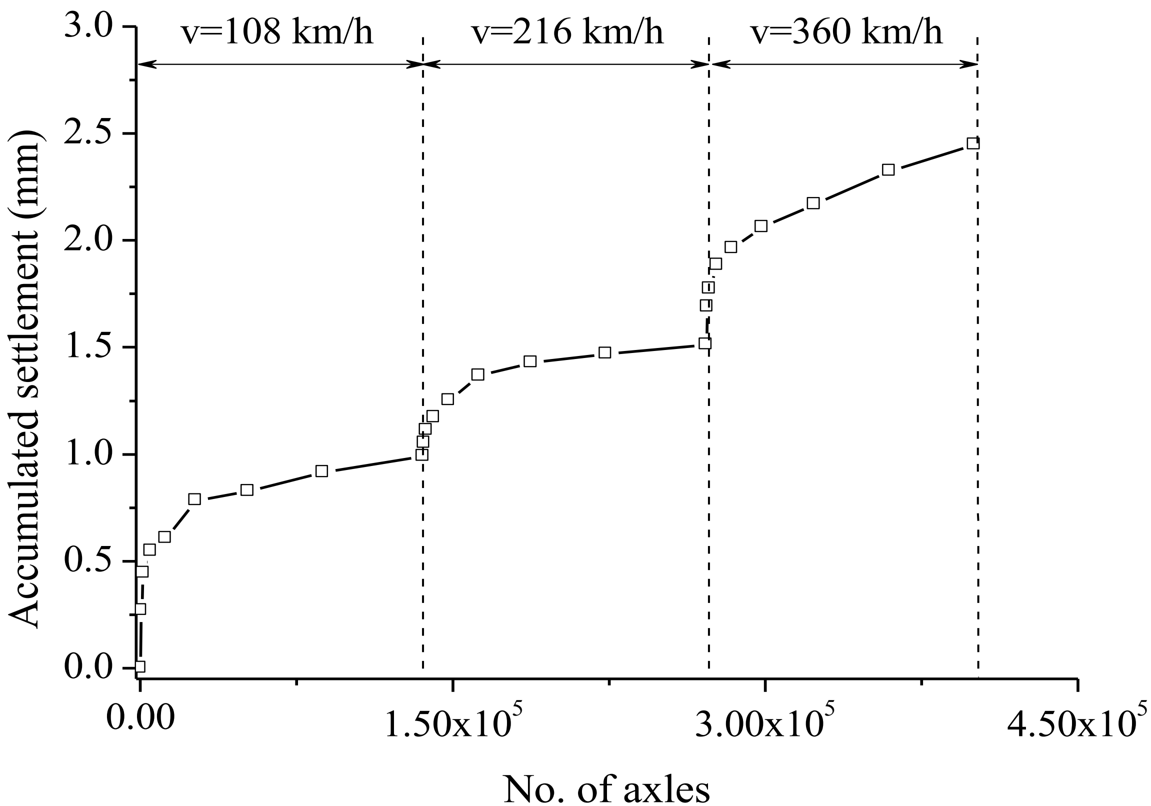


In subsoil of silty soil

- Pore water pressure in the subgrade is about 0.1-0.4 kPa, and does not accumulate significantly.
- Pore water pressure in the subsoil is about 0.4-0.8 kPa, and accumulates significantly at higher train speeds.

Accumulated settlement

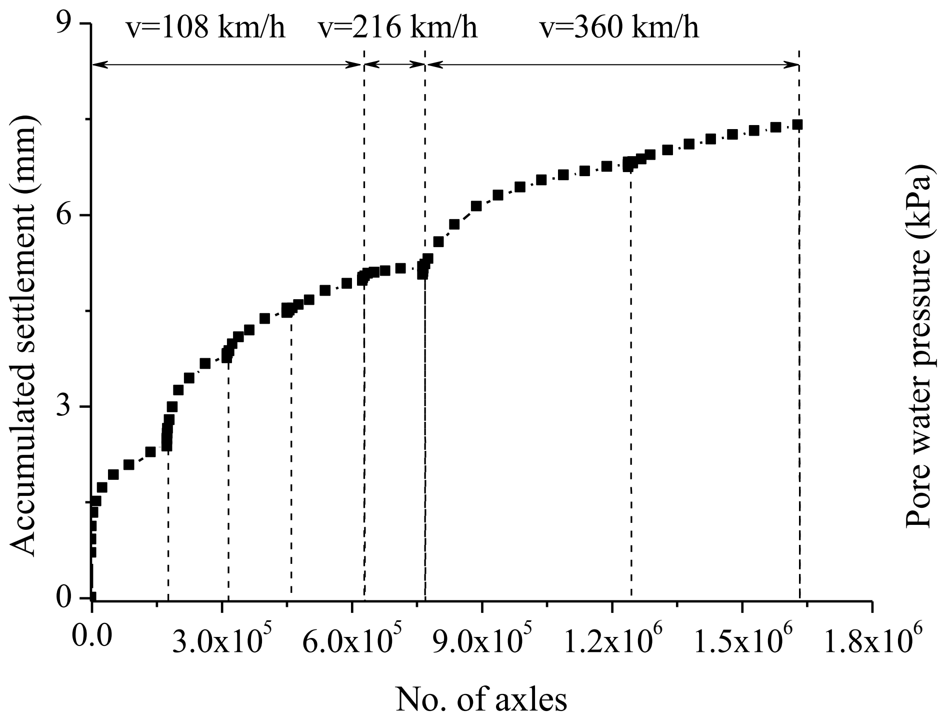
❑ Case 1: water level at the subsoil bottom.



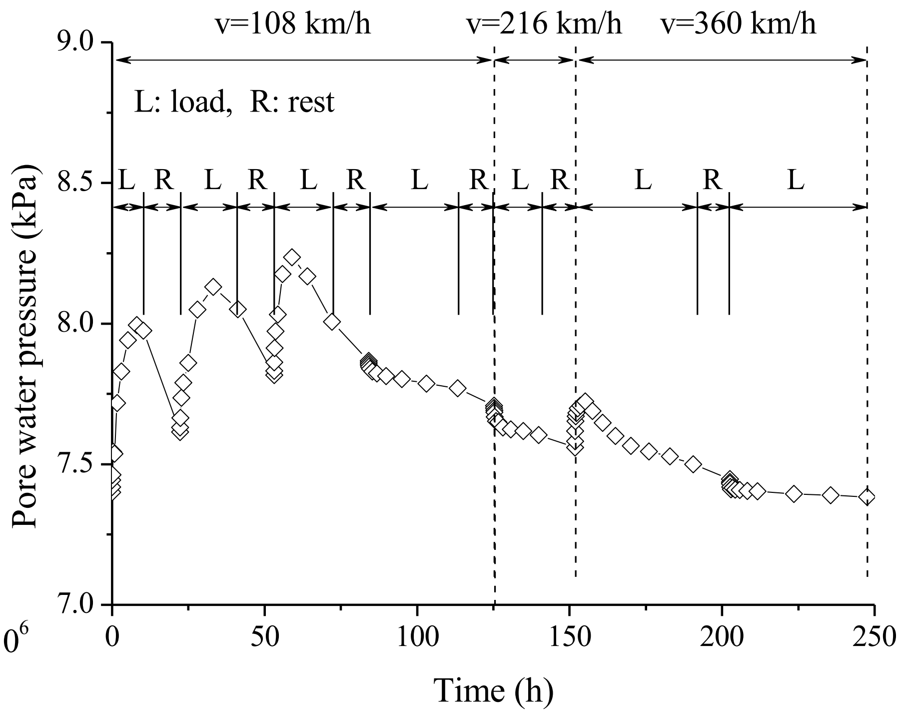
- Increasing train speed leads to additional settlement development.
- The accumulated settlement is easier to reach a stable state under repeated train moving loads when train speed is below 216 km/h, while it increases faster at train speed of 360 km/h.
- Total accumulated settlement is only 2.5 mm for the normal subgrade.

Accumulated settlement

❑ **Case 2: water level at the subsoil surface.**



Accumulated settlement

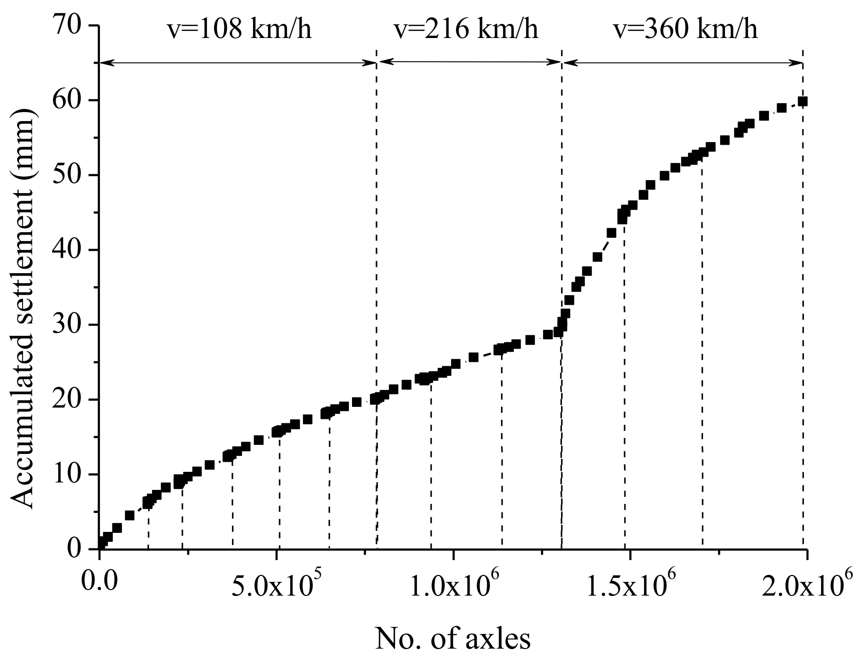


Accumulated pore water pressure at subsoil

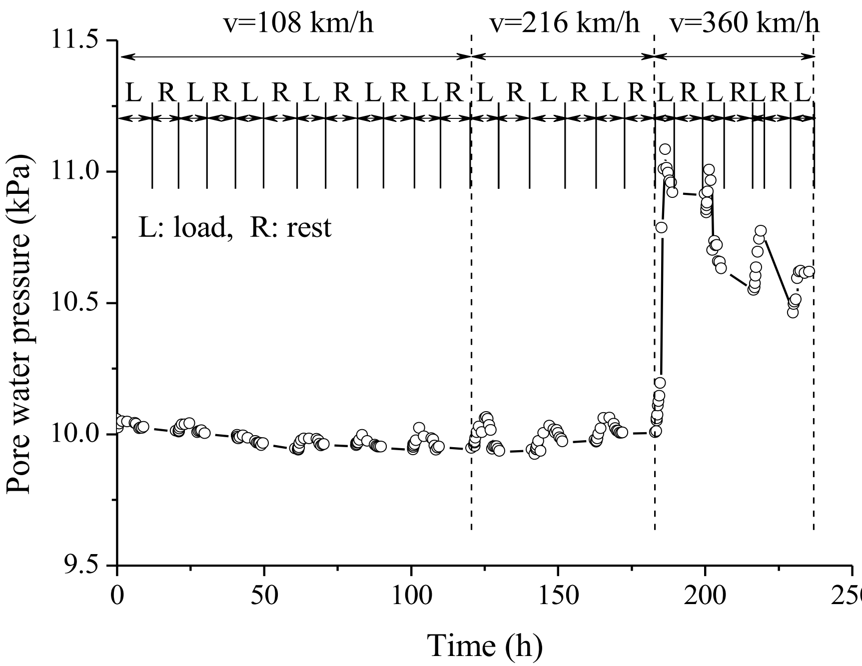
- **Water level rise leads to additional settlement development, which increases to 7.4 mm when the subsoil are under water level.**
- **Settlement development of the subsoil is caused by soil strength reduction and excess pore pressure accumulation and dissipation.**

Accumulated settlement

- Case 3: water level at the subgrade surface.



Accumulated settlement



Accumulate pore water pressure in roadbed

- Accumulated settlement increases to 60mm when water level reaches subgrade surface, and is hard to reach a stable state.
- Settlement development of the subgrade may be caused by soil strength reduction due to water lubrication and decrease in effective soil

Conclusions

- A full-scale model test device has been developed to investigate dynamic performance and long-term deformation of high-speed railway under different water levels. The highest train speed in the model test is up to 360 km/h.
- Variation of water level in the subsoil has little influence on the dynamic performance. However, the resonant frequency of the submerged subgrade decreases from 16 Hz to 12 Hz.
- The transverse distribution of contact pressure under the track structure changes significantly with the variation in water level.
- Water level rise lead to additional track deformation and loss of stiffness.
- Excess pore water pressure accumulates and dissipates in the soils, companied by the development of permanent deformation in soils.

Thanks for your attention !

Xuecheng Bian
Zhejiang University, Hangzhou, China
bianxc@zju.edu.cn

This research is supported by:

- **National Natural Science Foundation of China**
- **China Railway Company General**
- **Newton Advanced Fellowship, the Royal Society of UK**