Preliminary Testing on High-Speed Railway Substructure due to Water Level Changes

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Abstract

Water infiltration into railway subgrade due to heavy rainfall or flood is one of major factors leading to performance degradation in railways. This paper reported a full-scale physical model test on the performance degradation of a ballastless high-speed railway caused by water level changes. The tests were conducted in a dynamic testing apparatus (5 × 15 × 6 m) developed at Zhejiang University. A portion of a real high-speed railway was constructed in the testing box. Train moving loads were simulated by eight high-performance actuators acting in a predefined sequence. The water levels in the railway substructure were controlled in the testing box by a water storage tank. Both dynamic responses and accumulative settlement of the slab track-subgrade system were monitored. Test results showed that water level rising in subgrade could cause significant performance degradation of the railway. Vibration velocities at the track structure and roadbed increased faster and larger with the train speed after water level rising, as well as the dynamic soil stresses in soils. Accumulative settlement of railway subgrade grew remarkably due to water level rising in subgrade soils. That meant for the high-speed railways in service, reducing water infiltration in railway subgrade was very important to keep railway stable.

Keywords: Full-scale model test; High-speed railway; Water level; Vibration velocity; Accumulative settlement

1 Introduction

With the increase of traffic volumes, axle loads and train speeds, higher dynamic wheel loads are exerted on the track structure and underlying subgrade with more repetitions. At the same time extreme weather and intense precipitation have become more frequent and severe intensive. For example, the amount of rainfall in the heaviest 1% of rain events has increased 20% in the United States (Karl et al. 2009). Therefore, railways are likely to be exposed to more rain and even flood that
can cause subgrade submerged in water. Subgrade failures, such as mud pumping, progressive shear failure and excessive plastic deformation, are more easily to occur due to the combined effect of pore water and train loads (Li and Selig, 1998). This will greatly increase the cost of track maintenance and jeopardize the running safety of trains. Based on data derived from Federal Railroad Administration (FRA) statistics, Rossetti (2007) reported that at least 861 railroad incidents were associated with weather conditions over the period 1995~2005. About 23.1% of these incidents were resulted from water infiltration, causing over $48 million losses.

Pore water plays an important role on the performance of railways since it strongly affects the mechanical behavior of the soil-water mixture for saturated soft soils with low permeability, e.g. clay and silt, while in more high-permeable materials water flow may cause internal erosion and material transport (Kettil et al. 2008). This will result in lower strength, lower stiffness, and higher deformation of railway subgrade. As trains run along the saturated soft soils, the speed of the vehicles may approach the Rayleigh wave velocity of the ground, leading to large vibrations and displacements of train-track system. This “resonance-like” condition was observed during the X-2000 high-speed trains running along the West Coast Line in Sweden (Madshus and Kaynia, 2000). The displacements increased drastically when the train speed reached 202 km/h, almost three times larger than the quasi-static displacements. Accumulative settlement would further develop under the long-term running of trains. For example, in the Tokaido Shinkansen line in Japan, whose design speed was 210 km/h, only reinforcement to the track was adopted and reinforcement to the soft clay embankment was neglected. Excessive settlement was accumulated due to the coupled effect of water infiltration and traffic loads, and its running speed was forced to reduce to 110~180 km/h. Moreover, ballast puncture and fine particles divorced from ballast and subgrade may create conditions of poor drainage and retention of water at the bearing surface. Track sleepers start moving up and down in grooves with the movement of wheel loads, leading to suction of fines into the groves and pumping out. The mud pumping occurred in more than 13% mileages of railways in China. A Japanese survey carried out in 1975 found that out of 17,000 km of frequently used rails in Japan, more than 700 km suffer from mud pumping. When the pore water pressure is high enough (usually caused by heavy rainfall and dynamic loadings), the effective stress in the soil decreases, which may reduce its ability to transfer shear stresses by friction. The shear failure of subgrade will occur, and the subgrade may even collapse. For example, large deformation up to 64.2 cm was observed in the Shitai railway in China during continuous heavy rainfall. Subgrade collapses were also reported in Xiaoyong and Jingjiu railways in China due to the water infiltration.

As water infiltration is one of the main causes of deterioration and premature distress of the geotechnical structures, a study team from 18 European countries carried out a 3.5 years program to investigate the effect of water infiltration on the road pavements and earthworks (Dawson 2009). It was reported that clear and significant variations of moisture in subgrades were observed in the field. The mechanical behavior, as observed in situ, was strongly affected by moisture variations: the wetter the state the lower the stiffness (up to a factor 2 or more), the lower the strength and the higher the deflection. Accelerated pavement tests showed that rutting depth increased fast after the soil was added by water, which accelerated deterioration by a factor of 4.0.

To investigate the combined effect of traffic loads and water infiltration on the performance of railways, a new research study sponsored by the National Natural Science Foundation and the Ministry of Railway has been undertaken at Zhejiang University. The research project scope involves conducting triaxial tests on the mechanical behavior of soil-water mixtures, carrying out full-scale physical model tests on the dynamic performance of high-speed railways under the coupled effect of water infiltration and traffic loads, and modeling a vehicle-track-subgrade dynamic interaction model. This paper presented first a summary of previous research studies on the degradation mechanism of railways under the coupled action of water infiltration and traffic loads. Then a full-scale physical model for ballastless railways was constructed, and a loading system with eight actuators was used to simulate train moving loads at various speeds. The water levels in the subgrade were lifted or lowered.

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by a water storage tank. Dynamic loading tests under train moving loads were carried out before and after water level rising. Dynamic responses of the slab track-subgrade system, such as vibrations and dynamic soil stresses were monitored and described. The long-term settlement caused by train moving loads was also measured.

2 Degradation Mechanism of Railways Caused by Water Infiltration

The detrimental effects of water infiltration on the performance of railways are mainly behaved on three aspects: degrading the mechanical behavior of soils, particle migration and erosion, aggravating the dynamic interaction of vehicle-track-subgrade systems.

2.1 Mechanical Behavior of Soil-Water Mixtures

The moisture content has been found to affect both the resilient response and residual deformation of the soil materials. Haynes (1961) observed a 50% decrease in the resilient modulus in gravel as the degree of saturation increased from 70 to 97%. Hicks and Monismith (1971) showed that the resilient modulus decreased steadily as the moisture content increased above its optimum value. The presence of moisture in an aggregate assembly has some lubricating effect on particles, which will increase the deformation with a consequent reduction of the resilient modulus, even without generation of any pore water pressure (Thom and Brown 1987). Li et al. (2006) carried out a series of dynamic triaxial tests to study the effect of moisture content on the dynamic properties of soft soil. They found that below the moisture content of the plastic limit, dynamic strength of soils decreased fast with the increase of moisture content. This was mainly resulted from the reduction of soil cohesion rather than the friction angle. For soft soils with low permeability, the excessive pore water has vital influence on the mechanical behavior of the soil-water mixture. Under cyclic loadings, the pore water pressure increases and the effective stress in the soil decrease, which will reduce the shear strength and lead to large deformation. Even for the well-graded unbound aggregates with a high proportion of fines, the pore water pressure plays a significant role on their mechanical behavior. Dawson et al. (1996) studied a range of well-graded unbound aggregates and found that below the optimum moisture content, stiffness increased with the moisture content due to development of suction. While beyond the optimum moisture content, excess pore water pressure was developed as the material became more saturated, and the soil stiffness started to decline rapidly.

2.2 Particle Migration and Erosion

When water flows from a finer to coarser materials among different soil layers (inside the subgrade) or emerges from soils into an open space (outside the subgrade), the potential exists for some particles to migrate out of the finer materials. The migration may cause the clogging of packing or the formation of erosion tunnels (Terzaghi 1996). When the fine particles hinder the subgrade drainage, excessive pore water pressure will develop under repeated traffic loadings. Thus the effective stress and the shear strength of soils will decrease, aggravating progressive shear failure of railway subgrade. Flowing water may carry away the eroded particles, usually happening in the granular layers. This will change the grain grading of granular materials. As the finer particles are washed out, the void of soil skeleton is filled with water. The contact areas between soil particles get small, and more stresses will be supported by these particles. If the contact force is large enough, soil particles may re-orientate and cause an unstable aggregate skeleton, leading to large resilient and residual deformations (Werkmeister et al. 2002). Moreover, when the eroded fines settle down at the soils with larger grain sizes, e.g. from the subballast layer to the ballast layer, these added fines may also have some impact.
on the mechanical behavior of the larger grain-size soils. Hicks and Monismith (1971) observed some reduction in resilient modulus with increasing fines content for the partially crushed aggregates tested, whereas the effect was reported to be the opposite when the aggregates were fully crushed. Hicks (1970) reported that the fines content have a minor influence on resilient modulus when the percentage of fines was below 10%. However, a dramatic drop of about 60% in resilient modulus was reported by Barksdale and Itani (1989), when the amount of fines was increased from 0 to 10%.

2.3 Dynamic Interaction of Vehicle-Track-Subgrade Systems

Dynamic responses such as vibrations and dynamic soil stresses are largely dependent on the relationships between train speeds and Rayleigh wave velocities of the subgrade. Responses of railways form a slow-moving train can be explained by quasi-static analysis. However, as train speeds increase, dynamic phenomena gradually dominate the vehicle-track dynamic interactions. Water infiltration causes the railway subgrade softer, resulting in the reduction of the Rayleigh wave velocities of soils. It is known that resonance-type effects might result in excessive ground movements if the train speed approaches the Rayleigh wave velocity of soils (Krylov 1995). Priest and Powrie (2009) measured the track displacements at different train speeds in the railway field. Testing results showed that track displacement increased with increasing train speeds, and the dynamic stiffness of railway track under fast trains was about 20% less than that for the slow trains. Yang et al. (2009) built a two-dimensional dynamic finite-element model to study the effect of train speed on dynamic soil stresses. Results indicated that dynamic effects started to become apparent when the train speed was greater than 10% of the Rayleigh wave velocity of the subgrade, and at a train speed of 50% of the Rayleigh wave velocity, the shear stresses was underestimated by 30% in a static analysis. Bian et al. (2008) developed a 2.5D finite model to analyze train induced track and ground vibrations, and concluded that significant response can be generated when train speed is close to the wave propagating velocity in the underlying soil.

Physical model testing provides an effective way to understand the dynamic performance of track-subgrade systems. Muramoto et al. (2006) developed a full-scale physical model of a ballastless track (6.5 × 3.5 × 1.5 m deep) over a saturated roadbed, and used cyclic loads of 1 Hz in the test. The settlement developed fast because the roadbed became softer after being weakened by the pore water. Jiang et al. (2008) built a large scale model of a ballastless railway with sizes of 2.6 × 1.12 × 2.2 m deep to study the static and dynamic characteristics of the ballastless track subgrade before and after rainfall under a stationary loading. Results showed that owing to the rainfall, the dynamic soil stress at subgrade surface, acceleration and resilient deformation at the track increased by 3%, 35% and 13%, respectively. Bian et al. (2014 a) and Jiang et al. (2014) developed a full-scale model testing device for ballastless high-speed railways, and carried out plenty of dynamic tests to explore the dynamic performance of railways under simulated train moving loads. The vibration velocities of the track structure and the underlying soils presented almost monotonically increasing tendency with the train speed. While for the dynamic soil stresses, they generally exhibited slow ascendant tendencies when the train speed was lower than 150 km/h, but these values grew quickly with the train speed in the range of 150~300 km/h. The dynamic loading tests with water level rising described in the following sections were conducted based on this full-scale physical model.

3 Test Materials and Setup

3.1 Materials

The full-scale physical model of a ballastless railway was developed according to the high-speed railway design code used in China, including the dimension of the track structure and substructure,
selection of materials, and requirement of compaction quality. Therefore, the experimental results from the model tests can be applied to evaluate the actual performance of high-speed railways. Fig. 1 shows the established full-scale physical model, consisting of the slab track structure and a 0.4 m thick roadbed, a 2.3 m thick subgrade and a 2.5 m deep subsoil.

The slab track structure was composed of rails, fasteners, track slab, CAM (cement asphalt mortar) layer and concrete base. Type of CRTS (Chinese railway track system) I slab was used in the experiment with sizes of 5.0 m×2.4 m×0.19 m. CHN60-type rails were connected to the track slab with WJ7-type fasteners, whose static stiffness was 2.85×10⁷ N/m. Concrete base with sizes of 5 m×3 m×0.3 m was poured in situ with steel reinforcement. CAM was poured into an infusion bag pre-placed between the track slab and concrete base.

The substructure consisted of roadbed, subgrade and subsoil, which were filled with gravel, medium sand, and silty soil, respectively. The grain-size distributions of these three geomaterials are shown in Fig. 2 (Bian et al. 2014 a). The maximum dry densities of the roadbed, subgrade and subsoil were 2.21 g/cm³, 2.11 g/cm³ and 1.62 g/cm³, which corresponded to the optimum moisture contents of 4.2%, 4.0% and 18%, respectively. The subgrade and the subsoil were compacted at their optimum moisture contents. After the compaction of the roadbed and subgrade, soil was sampled at five locations at their surface to verify the soil density, moisture content, and relative compaction K (defined as the ratio of the dry density of the compacted soil to its maximum dry density). The stiffness parameters in terms of soil reaction k₃₀ value and the second deformation modulus Eᵥ₂ were also determined based on the static plate load tests using a circular plate with a diameter of 30 cm. For roadbed, tested values of foundation coefficient k₃₀, the second deformation module Eᵥ₂, Eᵥ₂/Eᵥ₁, and compaction coefficient K were 306~402 MPa/m, 143~157 MPa, 1.7~2.3, and 0.97~0.98, respectively. For subgrade, these tested values were 272~309 MPa/m, 134~160 MPa, 1.8~2.1, and 0.95~0.97, respectively.
Fig. 2: Grain-size distributions of geomaterials

3.2 Test Setup

Bian et al. (2014 b) presented a detailed description of the loading system for simulating train moving loads. The loading system was composed of a reaction frame, eight servo hydraulic actuators and eight spreader beams, as shown in Fig. 1. The rail was cut into eight separate segments. Simulated train loading was achieved by applying pre-programmed loads with maximum magnitude of 58 kN and $9^\circ$ phase lag between each actuator. Fig. 3 shows the input load for an individual actuator, which was obtained from a train-slab track-subgrade coupled analysis model. Due to the oil pressure and flow capacity of the hydraulic pump in the laboratory, the simulated train speed was up to 360 km/h.

Water levels in the physical model were raised and lowered using a movable water storage tank connected to a network of branch tubes at the bottom of the subsoil with a main supply tube as shown in Fig. 4. Water levels rose gradually from the subsoil bottom to the subgrade surface, and then fell back to the subsoil surface. The performance of the railway infrastructure was evaluated at four typical water levels, i.e., (1) water level at the subsoil bottom, (2) water level at the subsoil surface, (3) water level at the subgrade surface and (4) water level falling back to the subsoil surface. The first and third cases were presented and compared in this paper, which represent the normal situation that trains run along normal railways and the extreme situation caused by excessive precipitation or flood. Cyclic loads at different frequencies and moving loads at different train speeds were applied to the ballastless...
track. Details of the configuration and measurement of the instrumentation in the railway substructure during the water level changes were described by Jiang et al. (2015).

Fig. 4: Model layout and configurations of instrumentations in the testing (Unit: m)

4 Test Results and Discussion

Before the water level rising, the performance of slab track-subgrade system was investigated under train moving loads at different speeds, including the short-term dynamic responses and long-term accumulated settlement. When the subgrade was submerged under the water, simulated train moving loads at speeds of 5~360 km/h were applied to investigate the dynamic performance of ballastless railways. Test results such as vibration velocity, dynamic soil stress and accumulated settlement were presented and compared with those before water level rising.

4.1 Vibration Velocity

Time histories of vibration velocity at the track slab and roadbed are plotted in Fig. 5, taking train speed of 216 km/h as an example. The positive sign indicates the downward vibrations. The locations of the train axles can be identified from the peaks and troughs in the dynamic response of the track slab, as shown in Fig. 5(a). With transmission of the vibrations from the track slab to the roadbed, vibration velocity response of the roadbed gradually became dominated by train bogies, instead of the train axles, as shown in Fig. 5(b). When train wheels moved away, some apparent fluctuations were found in the velocity curve of the roadbed, indicating that the vibrations at the roadbed attenuated slowly. The water level rising increased the vibrations both at the track structure and the roadbed under train moving loads. The amplitudes of vibration velocity at the track structure and roadbed were 7.1 mm/s and 2.7 mm/s at the train speed of 216 km/h at the normal condition. These values reached 9.6 mm/s at the track structure and 5.6 mm/s at the roadbed after water level rising, increasing by 35.2% and 107.4%. It seemed that water level rising had more influence on the degradation of the underlying soils.
Fig. 6 presents an increasing trend for the vibration velocity magnitude as train speeds increase from 5 km/h to 360 km/h. The vibration velocities at the track structure and roadbed presented almost linearly increasing tendency with train speeds before water level rising. These linear increasing rates at the track structure and the roadbed were approximately equal to 0.3 mm/s and 0.2 mm/s per 10 km/h. When train speeds increased to 360 km/h, the vibration velocities reached the maximum values of 11.6 mm/s at the track structure and 5.6 mm/s at the roadbed. After water level rising, it was observed that the velocity magnitudes grew faster with the increase of train speeds, which can be divided into three stages. In the first stage (below 150 km/h), the growth rates of the velocity magnitudes at the track slab and roadbed were 0.34 mm/s and 0.19 mm/s per 10 km/h, which were very close to the values at the normal situation. When train speeds increased from 150 km/h to 270 km/h in the second stage, the growth rates increased to 0.46 mm/s per 10 km/h at the track structure and 0.27 mm/s per 10 km/h at the roadbed, increasing by 35.3% and 42.1% compared with the first stage. At the end of the second stage, the velocity magnitudes at the track structure and roadbed were 11.4 mm/s and 6.4 mm/s, which were equal to the values at train speed of 360 km/h before water level rising. However, the velocity magnitudes at the track structure and roadbed presented a rapid growth in the last stage (train speed varying from 270 to 360 km/h). The growth rates reached 0.72 mm/s and 0.87 mm/s per 10 km/h, increasing by 56.5% and 222.2% than the second stage. The maximum velocity magnitudes at the track structure and roadbed were 17.9 mm/s and 14.2 mm/s when train speeds reached 360 km/h. The increase in vibration velocity at the roadbed was much larger than that at the track structure, indicating that water level rising resulted in greater adverse influence on the underlying soils than the track structure. It will get even worse for the roadbed and subgrade under long-term traffic loadings, because larger deformations may develop at such high vibrations.
4.2 Dynamic Soil Stress

Fig. 7 shows typical recorded time histories of dynamic soil stress at the roadbed surface at train speed of 216 km/h, which presented a similar shape of the letter M to the applied loads on the fasteners. But the dynamic stresses at the roadbed surface were dominated by train bogies instead of train axles. The maximum dynamic soil stress at the roadbed surface was 18.7 kPa for the normal subgrade, which increased by 29.4% to 24.2 kPa for the submerged subgrade. The maximum dynamic soil stresses occurred under the train bogies, and they decreased to the first trough as the center of two adjacent train bogies arrived. Then the dynamic soil stresses grew again to the peak due to the approaches of the adjacent train bogie. After that, the dynamic soil stresses decreased to the minimum trough until the other train bogie in the same carriage approached. It indicated that the distribution of dynamic soil stresses at the roadbed surface was not uniform in the longitudinal direction in despite of the presence of the rigid concrete track structure.
Fig. 8 shows the test results of dynamic soil stresses at the roadbed surface at different train speeds, which presented ascendant tendencies with the increase of train speeds. The dynamic soil stresses developed relatively slow with train speeds before water level rising, and the growth rate was only 0.042 kPa per 10 km/h. However, dynamic soil stresses increased much faster after water level rising, which can also be divided into three similar stages to the vibration velocities. When the train speed was below 150 km/h, the dynamic soil stresses was not sensitive to the train speed. As train speed increased, the dynamic soil stresses presented a linear increase trend. The growth rate of the dynamic soil stresses was 0.23 kPa per 10 km/h. Then the dynamic soil stresses increased sharply from 26.4 kPa at train speed of 288 km/h to 36.5 kPa at train speed of 360 km/h. The dynamic soil stresses were 18.7 kPa, 19.5 kPa and 19.6 kPa at train speeds of 150 km/h, 270 km/h and 360 km/h before rainfall, which increased by 24.6%, 33.8% and 86.2% due to the water level rising, respectively.

![Fig. 8: Dynamic soil stresses versus train speeds](image)

4.3 Accumulative Settlement

Fig. 9 shows the accumulative settlement in terms of number of passing axles measured at the surface of the track structure before and after water level rising. For the normal subgrade constructed at the optimum moisture content, train moving loads were first exerted for 140,000 cycles at speed of 108 km/h as shown in Fig. 9(a). The induced accumulated settlement increased fast in the first 25,000 cycles, followed by slow growth. As the train speed increased to 216 km/h, a similar increasing process was presented to the first loading stage. The growth rate of the last 100,000 cycles in the first loading stage was 0.023mm per 10,000 cycles, which decreased to 0.012mm per 10,000 cycles at train speed of 216 km/h. While the train speed increased to 360 km/h, the growth rate reached 0.034mm per 10,000 cycles, much faster than the first two loading stages. However, the total accumulated settlement was only 2.5 mm after 420,000 cyclic loadings.

When train moving loads were applied to the submerged subgrade after water level rising, the accumulative settlement grew much faster and larger as shown in Fig. 9(b). When the submerged subgrade was subjected to train moving loads at speed of 108 km/h, accumulative settlement kept growing with the loading cycles. After the first 140,000 cycles, the accumulative settlement reached 6.4 mm, which was 5.3 times as much as that before water level rising. It continued increasing to 23 mm after one million cycles. Then the train speed was raised to 216 km/h, and the accumulative settlement developed at a similar growth rate of 1.8 mm per 100,000 cycles to that of the former loading stage. At the end of the second loading stage, the accumulative settlement reached 32.4 mm.
However, a rapid increase of the accumulative settlement occurred when the train moving loads at speed of 360 km/h were applied. The growth rate was almost 5 mm per 100,000 cycles, and the accumulative settlement showed no sign of slowing down. After 700,000 cyclic loadings at train speed of 360 km/h, the total accumulative settlement reached 76 mm, which was nearly 30 times as large as that before water level rising. It seemed that the accumulative settlement would continue growing with the application of traffic loads. After water level rising, dynamic stresses inside soils change not so much when train speed increases from 108km/h to 216km/h, and the accumulative settlement didn’t show faster development speed.

![Graph](image-url)

Fig. 9: Accumulative settlement versus number of train passing axles

5 Conclusions

This paper presented an experimental study on the effect of water level rising on the performance of high-speed railways under simulated train moving loading. A full-scale model for ballastless railways was constructed, and a loading system with eight actuators was used to simulate train moving loads at various speeds. Dynamic loading tests were carried out before and after water level rising. The following conclusions can be drawn from this study:

1. Water level rising resulted in the increase in the vibration velocities both at the track structure and at the roadbed. The growth rates of the vibration velocity were almost identical for these two cases when the train speeds below 150 km/h. However, increasing train speeds led to faster growth rates of vibration velocities for the submerged subgrade, especially beyond 270 km/h.

2. Water level rising resulted in the increase in the dynamic soil stresses, which increased by 75.3% at the roadbed surface, by 50.7% at the subgrade surface and by 61.1% at the subsoil surface. The growth rates of the dynamic soil stresses in the submerged subgrade also increased faster with the increasing train speeds.

3. Water level rising caused significant increase in the accumulative settlement of subgrade, especially under higher train speed of 360 km/h. Before water level rising, the accumulative settlement was only 2.5 mm and it was prone to get stable. However, the accumulative settlement increased by nearly 30 times as large as that before water level rising, and it showed no sign of slowing down.

The water infiltration was vital to the performance of railways both in the dynamic responses and long-term settlement. Special engineering works should be done in railways to protect the subgrade from water infiltration.
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