Influence of differential settlement on pavement structure of widened roads based on large-scale model test

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Received 29 December 2010; Received in revised form 5 February 2011; accepted 15 February 2011

Abstract: This study introduced at first the background of numerous highway widening projects that have been developed in recent years in China. Using a large ground settlement simulator and a fiber Bragg grating (FBG) strain sensor network system, a large-scale model test, with a similarity ratio of 1:2, was performed to analyze the influence of differential settlement between new and old subgrades on pavement structure under loading condition. The result shows that excessive differential settlement can cause considerable tensile strain in the pavement structure of a widened road, for which a maximum value (S) of 6 cm is recommended. Under the repetitive load, the top layers of pavement structure are subjected to the alternate action of tensile and compressive strains, which would eventually lead to a fatigue failure of the pavement. However, application of geogrid to the splice between the new and the old roads can reduce differential settlement to a limited extent. The new subgrade of a widened road is vulnerable to the influence of dynamic load transferred from the above pavement structures. While for the old subgrade, due to its comparatively high stiffness, it can well spread the load on the pavement statically or dynamically. The test also shows that application of geogrid can effectively prevent or defer the failure of pavement structure. With geogrid, the modulus of resilience of the subgrade is increased and inhomogeneous deformation can be reduced; therefore, the stress/strain distribution in pavement structure under loading condition becomes uniform. The results obtained in this context are expected to provide a helpful reference for structural design and maintenance strategy for future highway widening projects.

Key words: widened subgrade; differential settlement; fiber Bragg grating (FBG) strain sensor; model test

1 Introduction

Currently, more and more highway projects are launched out to widen or reconstruct the old roads. However, a large number of defects such as longitudinal cracks or lane-to-lane staggering were observed in the pavement shortly after the road construction [1]. These defects are believed, according to field investigation, to be caused mainly by the differential settlement between the new and the old roads [2–6]. Therefore, it is of great practical significance to study the effect of differential settlement on pavement structure of a widened road. Up to now, a lot of research programs have been fruitfully developed on this subject at home and abroad. For example, Huang et al. [7] conducted their laboratory tests on a widened subgrade. In the tests, a layer of soluble chemical fertilizer at the bottom of embankment fill was employed. By doing so, the differential settlement was simulated. By employing a large centrifugal tester and finite element program PLAXIS, Hortnxs-Pedersen and Broers [8] analyzed the mechanical properties and deformation characteristics of soft foundation during subgrade widening construction. Similarly, Allersma et al. [9] used a small centrifugal tester and PLAXIS to analyze the destabilization of widened subgrade and to evaluate two different methods of embankment filling. However, it should be pointed out that the technical problems, encountered in all these research programs, should focus on the unsystematic model test and the lack of observation data of the prototype. As a result,
these research programs, unfortunately, are unable to provide powerful data support for the analysis of failure mode and mechanism of pavement structure caused by differential settlement. In addition, the stress condition and deformation distribution in widened subgrade are so complicated that it would be very difficult to establish an analytic relation and to achieve a numerical solution between stress and deformation. As for the conventional model test, due to size limit of the model box, it cannot truly represent the prototype as far as mechanical properties are concerned. In view of this point, a large-scale model test was performed for the first time to study the stress and deformation characteristics of the pavement structure of a widened road under the influence of differential settlement. The result of this study is expected to provide a helpful reference for the design and maintenance strategy of widened highways.

2 Model test design

2.1 Similarity ratio of model

A test model is placed on a controllable settlement platform to simulate the effect of differential settlement of a widened road on the stress and deformation characteristics of pavement structure. The deformation and failure of pavement structure under the combined action of bending-tensile stress and fatigue traffic load can be observed by adjusting the settlement of the platform. The model test in this study employed a large-scale model with geometrical similarity ratio $C_l$ preset at 2 and weight similarity ratio $C_\gamma$ at 1, where $\gamma$ is the unit weight. The similarity ratios of other basic parameters of the prototype, according to the similarity theory [10], are calculated as follows: $C_{E_1} = 1$, $C_\mu = 1$, $C_c = 1$, $C_\sigma = 1$, $C_\phi = 1$, $C_\sigma = 1$, $C_\varphi = 2$, $C_\varepsilon = 1$, where $E_1$ is the elasticity modulus of subgrade, $\mu$ is the Poisson’s ratio, $c$ is the cohesive strength, $\varphi$ is the internal friction angle, $\sigma$ is the soil stress, $E$ is the elasticity modulus of pavement, and $\varepsilon$ is the strain of pavement.

2.2 Test materials

The subgrade soils for the model test were taken from the suburb of Xi’an City, with basic physico-mechanical properties shown in Table 1. The optimum water content of soil is determined at 13.2% as the result of compaction test. To truly simulate the difference in stiffness and deformation between the new and the old subgrades, quicklime was added to the filling soil at a percentage of 4% in placing the old subgrade. Meanwhile, strict control must be exercised on water content, ensuring a value of compactness over 0.98. According to field test, the filling soil had an average water content of 13.3% and a maximum dry density of 1.28 g·cm$^{-3}$ after compaction, which could approximately meet the aforementioned requirement.

The new and the old subgrades had a half-width of 4 and 7 m, respectively, with a length of 3 m. The filling soil was placed closely against the concrete wall of the test platform that was taken as the central line of the old subgrade. The original design for the new subgrade and pavement was followed in building the test model, which contained a 4 cm upper layer of asphalt concrete AK-13C, a 6 cm bottom layer of AC-25, and a 9 cm base course of cement-stabilized gravel that was placed and compacted by 3 layers (Fig.1). It was assumed that the maximum settlement of the new subgrade occurred on the shoulder, which could be expressed as

$$S = S_2 - S_1$$

where $S_2$ and $S_1$ are the settlements on the shoulder of the new subgrade and at the central line of the old subgrade, respectively.

2.3 Test device for foundation settlement

The model test was conducted in the laboratory of large-scale testing device for foundation settlement in Chang’an University. The tester is mainly composed of the jacking system, the supporting system and the monitoring system. The jacking system can simulate the amount and the rate of subgrade settlement; apart from a number of industrial computers and sensors, it employs more than 100 self-lock jacks that were uniformly spaced in rows. The test platform forms the supporting system by itself, and the monitoring system
is made up of monitoring elements and data acquisition system (DAS). Figure 2 shows the jacking system for simulation of foundation settlement. The platform is used to simulate the ground surface; it consists of a number of panels that exhibit certain dynamic effect when assembled together. The points at the corner or the joints of panels are regarded as the settlement nodes on curve. The lift of jacks at different positions can be adjusted to achieve required settlement at different locations of the foundation.

2.4 Measuring system

To analyze the stress variation in subgrade caused by the deadweight of filling soil and the cyclic load of fatigue test, pressure cells YL1, YL2, YL3 and YL4 were installed at the bottom of the new and the old subgrades, where geogrid was applied; and YL5, YL6, YL7 and YL8 were installed at the bottom of the new and the old subgrades, where no geogrid was applied.

This study employed a fiber Bragg grating (FBG) strain sensor that was able to fully reflect the stress variation of all measuring points in pavement structure under the combined action of traffic load from above and differential settlement from beneath. The FBG strain sensor used an optical fiber for data transmission that, in comparison with the traditional sensor technology, had the features of sound durability, sensitivity and repeatability, quick response, small size, wide range of application temperature, and non-electromagnetic interference [11–16]. The main specifications for the FBG strain sensor (Fig.3) used in this context are given below:

1. Resolution: $0.1 \leq F_S$.
3. Temperature range of application: $-20 ^\circ C$–$50 ^\circ C$.
4. Measurement range: $-2 000$–$2 000 \mu \varepsilon$.

Figures 4 and 5 show the FBG strain sensor network analyzer SM-125 and the strain sensing modules, respectively, that are used in the model test.

2.5 Loading system

To describe strain characteristics of the pavement structure in the splice between the new and the old subgrades, in which differential settlement was experienced, a single point loading system was employed to simulate the traffic load on the pavement.

The fatigue test on model subgrade was performed by using a hydraulic pulsating fatigue tester PME-50A with the following major specifications:

1. Maximum static/dynamic load: 500 kN.
2. Operating frequency of dynamic load: 100–500 times per minute (or 1.6–8.3 Hz).

Another set of major equipment employed in the
fatigue test was a dynamic strain measurement and analysis system, typed DH5937. It was used to measure the strain on the surface of asphalt concrete layers and cement-stabilized gravel layers and to identify their variation tendency against the duration and times of the loads. The magnitude of dynamic load was determined with consideration of the change in strain during fatigue test. Normally, it was set between 20.0 and 90.0 kN, corresponding to an average pressure of 0.28–1.27 MPa on the contact surface.

Load was imposed on the area with and without application of geogrid to assess its effect on the widened subgrade separately. Loading points JZ1 and JZ2 were chosen in close proximity to the intersection between the splicing line and FGB wires (Fig.6). Figure 7 illustrates the times and duration of the load at these two points.

3 Discussion on test results

3.1 Variation in lateral strain in pavement structure with differential settlement

Figure 8 shows the variation curves for the lateral stress on the top of each layer of pavement structure in different cross-sections of the model. It can be observed that they exhibit basically the same deformation features, which demonstrates the sound stiffness and structural integrity of the combination of flexible surface course and semi-rigid base course. According to Fig.8, most parts of the 5 pavement layers, in the new or the old road, were subjected to the tensile deformation on the top. However, at the point 5 m away from the central line of the old road, the deformation of pavement structure began to change from tension into compression. This indicates that the...
differential settlement between the new and the old subgrades could cause considerable tensile strain upon the pavement structure, but near the central line of the old road, the pavement structure was instead subjected to compressive strain in compensation for the differential settlement that occurred in the outer part of the road. The strain of pavement structure increased smoothly with differential settlement $S$. In case of $2 \text{ cm} \leq S \leq 6 \text{ cm}$, the strain in pavement structure experienced obvious changes while it remained at a low level; but when $6 \text{ cm} < S \leq 10 \text{ cm}$, the strain in pavement structure would be elevated to a high level without obvious changes. That is why a maximum differential settlement of $6 \text{ cm}$ is recommended for a widened road.

It can also be observed in Fig.8 that the peak stress does not occur near the splice between the new and the old subgrades. Instead, it occurs at both sides of the splices symmetrically, which implies that differential settlement with a large magnitude could cause subgrade deterioration to a much wider area.

### 3.2 Results of fatigue test

Figure 9 shows the earth pressure measured in different locations at different depths of widened subgrade with and without geogrid. It can be observed that in the initial stage, the earth pressure changes slightly with the times of loads applied; but when the latter goes up to the threshold point of $1–2$ million times, the earth pressure increases sharply. In addition, the earth pressure measured at the bottom of subgrade is much lower than that on the top, which could be related to the load alleviation when it is transferred downward from the pavement surface. In Figs.9(a) and (b), we can observe that, without geogrid, the soil pressures on the top and at the bottom of the old subgrade are lower than those of the new subgrade, respectively; if geogrid is applied, they become much closer. This could be explained by the high rigidity of old subgrade and soil hardening effect caused by the geogrid. It plays an active role in spreading and alleviating the traffic load on pavement.

### 3.3 Strain variation on the boundary between new and old subgrades in fatigue test

Figure 10 shows the relations of pavement strain against times of loads at the points JZ1 (with geogrid) and JZ2 (without geogrid). At low times of loads, the pavement surface is subjected to tensile strain that increases with the increment of differential settlement $S$. At $S = 2 \text{ cm}$, the strain goes smoothly with the increase in times of loads and changes slightly with the variation in load applied. But with the further increment of $S$, it grows more rapidly with the increase in times of loads. Especially, when $S$ exceeds $6 \text{ cm}$ and times of loads is greater than $2$ million, the tensile strain of pavement, after growing to a certain extent, will turn into compression. This indicates that differential settlement of excessive amount will place on the top layers of pavement under the influence first of tensile strain and then of compressive strain that will eventually lead to the fatigue failure of pavement.

Comparing Fig.10(a) with Fig.10(b), it can be observed that, on the boundary between the new and the old subgrades, the pavement structure experiences a lower strain with geogrid to the subgrade. This indicates that, however, the geogrid can alleviate the differential settlement and furthermore reduce its influence on the strain of pavement structure to a limited extent. Figure 11 shows the relation between strain of top layer of base course and times of loads. It indicates that the tensile strain increases with the growth of $S$, but unlike that in Fig.10, it increases at a lower rate with the increment of times of loads. According to Figs.11(a) and (b), the application of geogrid to subgrade can reduce the tensile strain...
Fig.10 Relations between strain of pavement surface and times of loads.

(a) Without geogrid.

(b) With geogrid.

Fig.11 Relations between strain of top layer of base course and times of loads.

(a) Without geogrid.

(b) With geogrid.

in the base course structure, which is in agreement with the case of pavement surface.

4 Conclusions

(1) The strain of pavement structure increases smoothly with the growth of differential settlement in the case of \( S \leq 4 \) cm, but rises sharply when \( S \) is larger than 6 cm. Therefore, a maximum value of 6 cm is recommended for differential settlement control on highway widening projects.

(2) Differential settlement with large magnitude between the new and the old subgrades would place on the top layers of pavement under the alternating action of tensile and compressive strain that would eventually lead to the fatigue failure of pavement. Application of geogrid to the splice, however, can relieve the differential settlement and further reduce its influence on the strain of pavement structure to a limited extent.

(3) The new subgrade of a widened road is vulnerable to the influence of dynamic load transferred from above pavement structures. While the old subgrade, due to the high stiffness, can well spread the load on pavement statically or dynamically.

(4) Geogrid reinforcement can increase the modulus of resilience and reduce inhomogeneous deformation of the subgrade, therefore, uniform strain distribution in pavement structure will be formed. As a result, the failures of pavement structures are effectively prevented or deferred.

(5) The controllable settlement platform, featured by high controllability, is an advanced technology for the simulations of differential settlement between the new and the old subgrades. The FBG strain sensing technology employed in the study is proven to be practicable and effective by truly reflecting the strain distribution in pavement structure.

References


