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Hysteretic behaviors of pile foundation for railway bridges in loess

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Abstract. Pile foundation is widely used for railway bridges in loess throughout northwestern China. Modeling of the loess–pile interaction is an essential part for seismic analysis of bridge with pile foundation at seismically active regions. A quasi-static test is carried out to investigate the hysteretic behaviors of pile foundation in collapsible loess. The failure characteristics of the bridge pile-loess system under the cyclic lateral loading are summarized. From the test results, the energy dissipation, stiffness degradation and ductility of the pile foundation in loess are analyzed. Therefore, a bilinear model with stiffness degradation is recommended for the nonlinearity of the bridge pier-pile-loess system. It can be found that the stiffness of the bridge pier-pile-loess system decreases quickly in the initial stage, and then becomes more slowly with the increase of the displacement ductility. The equivalent viscous damping ratio is defined as the ratio of the dissipated energy in one cycle of hysteresis curves and increases with the lateral displacement.

Keywords: high-speed railway bridges; pile foundation; hysteretic behaviors; loess; loess-pile interaction

1. Introduction

Along with the improvement of transportation facilities and the implementation of “The Belt and Road” initiative, a large number of railway construction projects have been carrying out in Northwest China. The land of the Northwest China is covered by large area of loess and also one of the most seismically active regions (Wang *et al.* 2018). The loess typically has a loose honeycomb-type meta-stable structure that is susceptible to a large reduction in total volume or subsidence upon ground motion (Mei *et al.* 2016). Because of the special geological phenomenon of collapsible loess when penetrated by water, a pile is a popular foundation used in loess (Grigoryan 1991, Gao *et al.*, 2007). There are many cases where piles are subjected to indirect loads due to the lateral movement of the surrounding ground (Toma Sabbagh *et al.* 2019), such as earthquakes. The inherent variability of loess parameters may lead to a considerable effect on seismic response of foundation and superstructure elements (Chanda *et al.* 2019). The performance of pile foundations during an earthquake significantly influences the integrity of structures supported by surrounding soils (Gerolymos *et al.* 2009, Dehghanpoor *et al.* 2019). Therefore, in the overall seismic design process of the structures, modeling of the soil–pile interaction is an essential part (Liyanapathirana and Poulos, 2005, Kim and Choi, 2017). And for the railway bridges in the northwest region of China, the hysteretic behaviors of pile foundation in loess are the key factors for seismic analysis.

In early days, Gazetas *et al.* (1993) outlined the recorded response to numerous earthquakes of the pile foundation, the supporting soil, and the superstructure of the main pier of a road bridge. In recent years, there have been large numbers of researches focused on the soil-pile interaction mechanism and its effects on the seismic response of bridges with pile foundation. A method of analysis is presented for determining the dynamic response of bridges supported on deep piles extending through deep sensitive clays. Makris *et al.* (1994) presented a simple integrated procedure to analyze the problem of soil-pile foundation-superstructure interaction. The procedure combines the available theories for the computation of the dynamic impedances and kinematic-seismic response factors of pile foundations with a simple six-degree-of-freedom structural model. Kaynia and Mahzooni (1996) found that the seismic shear force and bending moment in a pile are strongly contributed by the kinematic seismic interaction, except in a band approaching the natural frequency of the pile-soil-structure system. Mylonakis and Nikolaou (1997) has been implemented a substructuring method for the seismic analysis of bridge piers founded on vertical piles and pile groups in multi-layered soil. The method reproduces semi-analytically both the kinematic and inertial loess-structure interaction, in a simple realistic way. Several types of models may be used for the seismic analysis of bridges with pile foundations. These range in complexity from detailed models where each pile is modeled down to its tip and depth-variable ground motions are input along the length of the pile through elastic or inelastic soil springs, to models where a complete foundation is modeled with a single set of impedance (stiffness and damping) matrices (Ingham *et al.*, 1999). To investigate more precisely the seismic response of interactive soil–pile–structure systems, Cai *et al.* (2000) developed a three-dimensional finite element subsystem methodology with an advanced plasticity-based constitutive model for soils. Yang and Jeremić (2002) presents results

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from a finite element study on the behavior of a single pile inelastic–plastic soils, which can be used to generate *p–y* curves and can predict the pile head deflection with very good accuracy. Ju (2013) developed a finite element model includes bridge girders, piers, foundations, soil, and water, and it can consider the effect of soil–fluid–structure interaction on bridge natural frequencies. A three-dimensional method of analysis is presented for the seismic response of structures constructed on pile foundations (Maheshwari *et al.* 2004). The use of non-linear analysis of structures in a functional way for evaluating the structural seismic behavior has attracted the attention of the engineering community in recent years (Ahmadi *et al.* 2019). The pseudo-static beam-on-nonlinear-Winkler foundation approach has been successfully applied in modeling pile foundations (Zhang and Yang 2018). Nonlinear static and dynamic analyses were used to evaluate the inelastic seismic response of bridge and viaduct structures supported on extended cast-in-drilled-hole (CIDH) pile shafts. The nonlinear dynamic analyses used a beam-on-nonlinear-Winkler foundation (BNWF) framework to model the soil-pile interaction, nonlinear fiber beam-column elements to model the reinforced concrete sections, and one-dimensional site response analyses for the free-field soil profile response (Hutchinson *et al.*, 2004). It is of great interest to investigate the layering effects since in practice, most of soil deposits are layered systems. Yang and Jeremić (2005) found that the layering effects are two way, not only are the lower layers affected by the upper layers, but the upper layers are also affected by the lower layers. (Biswas *et al.* (2013)) developed a three-dimensional (3D) finite element (FE) model to predict the nonlinear dynamic response of full-scale pile foundation in a layered soil medium using ABAQUS/CAE.

In general capacity design concept, bridge pier supported by foundation is usually designed to have less capacity than that of foundation so that a ductile plastic hinge occurred at the bottom of the pier can absorb input seismic energy. Damage in foundation is avoided as much as possible because it is hard to be inspected and repaired after earthquakes. Many existing railway bridges with gravity pier used in western China, the large stiffness in the pier can cause the failure position shift from the pier down to the pile foundation. Most of these bridges designed by old design codes, so the bridge pier and pile foundation have low longitudinal reinforcement ratio. However, with the railway speed raising in China, it is essential to investigate the structural safety of these existing bridges under earthquakes. The nonlinearity of the pile-loess system should be considered in seismic analysis of railway bridge pier with pile foundation. In this study, a scaled model test of the railway bridge pier-pile-loess system is carried out and the hysteretic behaviors of the pile foundation in loess are investigated.

2. Experimental design

2.1 Testing model

A bridge pier with pile foundation from Jinghe-Yining-Huocheng Railway in Xinjiang province of China is

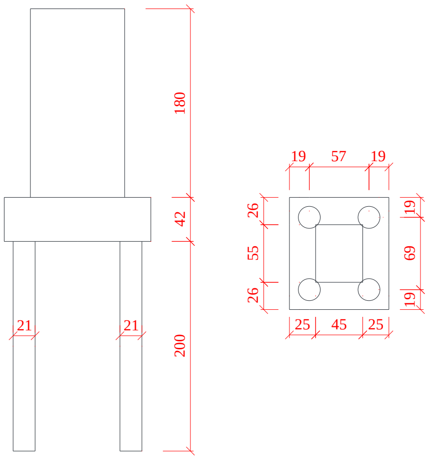


Fig. 1 Scaled model of the prototype

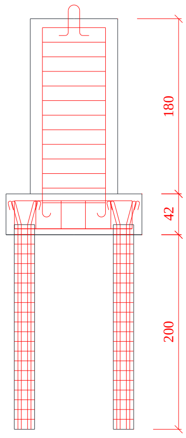


Fig. 2 Reinforcement cage of the pier and pile

Table 1 Mechanical parameters of the remolded loess

Parameter	Water content/%	Bulk density/$g\cdot cm^{-3}$	Deformation modulus/MPa	Cohesion/ kPa	Internal friction angle/°
loess	14.5	2.1	25.1	49.3	30.1

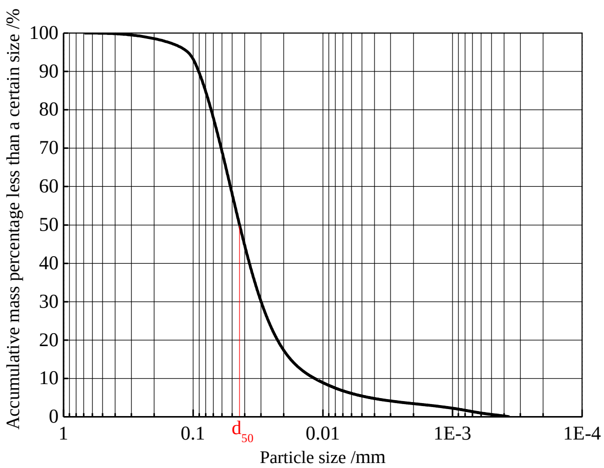
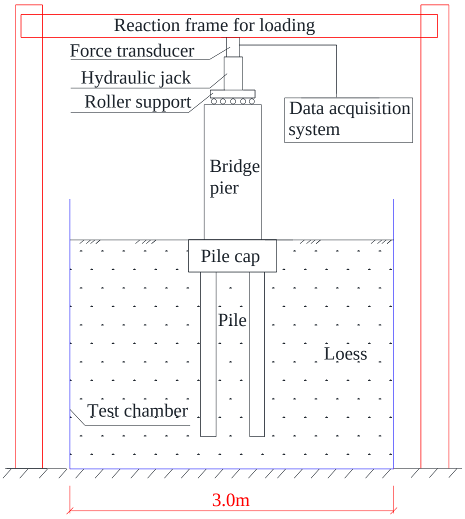
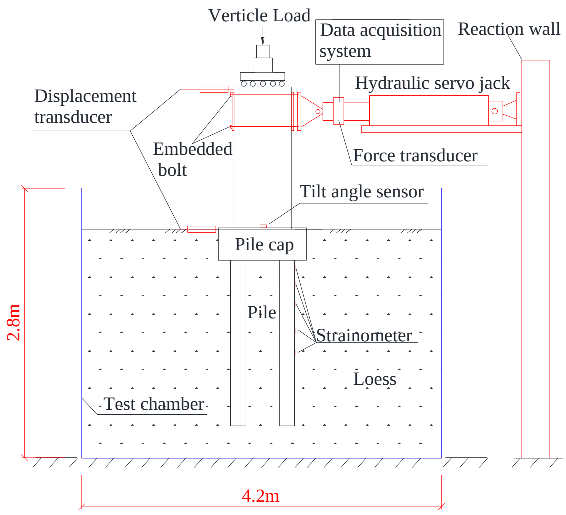


Fig. 3 Particle size distribution curve of loess

Fig. 4 Steel tubes for pile hole



(a) Vertical loading system



(b) Lateral loading system

Fig. 5 Loading system for bridge pier-pile-soil system

Fig. 6 Photo of the loading control system

selected as the prototype. A 1/6 reduced-scale model is constructed for quasi-static test, its size is shown in Fig.1. The cube compressive strength of the concrete used for the model is 20 MPa. 4 longitudinal steel bars with the diameter of 6mm constitute a 0.33% reinforcement ratio in the model pile, as shown in Fig. 2. The size of the pier is 55 cm×45 cm×180 cm(length, width and height), 4 longitudinal steel bars with a diameter of 6 mm, constitute a 0.05% reinforcement ratio (as seen in Fig. 2).

The loess used in this study is collected from the northwest of china, the mechanical parameters of the remolded loess are listed in Table 1. Fig. 3 shows the particle size distribution curve of loess.

2.2 Model preparation

During model preparation, the soil was cracked firstly and then moistened. Considering the similarity relationship

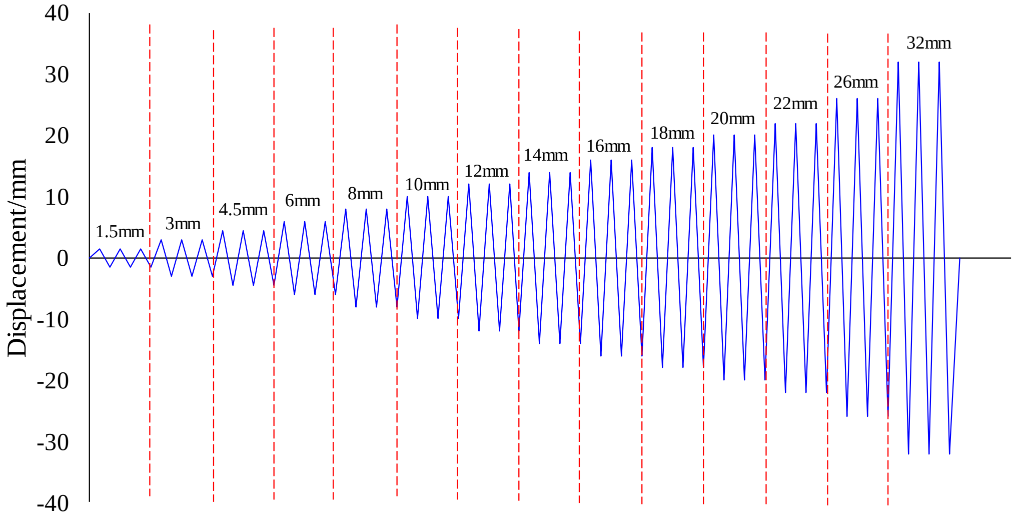


Fig. 7 Loading protocol with displacement control method

Fig. 8 Loess cracking at the corner of pile cap

between actual structures and scaled model, the optimum water content was used to increase the density of remolded soil as optimal as possible. At first, a 30 cm layer of loess is filled at the bottom of the test chamber, above which 4 steel tubes with an inner diameter of 22 cm are fixed at the designed positions (Figs. 1 and 4). Then, the prepared loess is packed into the test chamber and compacted layer by layer, and the steel tube can be pulled out to form the pile hole. The prepared reinforcement cage is inserted into the pile hole and the following is the concrete pouring. The steel bar extends from pile top to the pile cap.

2.3 Testing equipment

The quasi-static test is conducted at the structural laboratory of Lanzhou Jiaotong University. The size of the test chamber for loess is 3 m×4.2 m×2.8 m (width, length and height), made of plexiglass and stiffened with angle iron. The electro hydraulic servo system is used for lateral and vertical loading, as shown in Fig. 5(a) and 5(b). A constant load (172kN) in vertical direction is applied at the top of bridge pier as a consideration of the weight of the superstructure, as shown in Fig. 6. To and fro load in lateral direction is applied with the displacement control method, the maximum loading displacement is 32 mm, as shown in Fig. 7.

3. Results analysis

3.1 Failure characteristic

3.1.1 Foundation loess

There is no loess crack when the lateral displacement is small, i.e., 1.5 mm and 3 mm. By this stage, the lateral force at the pier top is less than 43 kN, that is to say the bending moment at the pile top is less than 77.4 kN·m. The micro cracks appear at loess surface when the lateral displacement increases to 4.5 mm with a lateral force of 55 kN. Loess cracks start to propagate and become more visible when the lateral displacement increases to 6mm with a lateral force of 67 kN. After testing, it can be found that the loess cracks mainly distributed at the four corners of the pile cap, as shown in Figs. 8 and 9. The maximum width of the loess cracks is about 2mm, and length is about 70cm. The vertical settlement of the bridge pier is about 0.5mm, which induced by the plastic deformation of the foundation loess beneath the pile cap. The differential settlement lead to an incline of the bridge pier.

3.1.2 Bridge piles

After applying each loading-unloading cycle, the pile group cannot move back to its original location. It implies that residual movement and bending strain are induced in

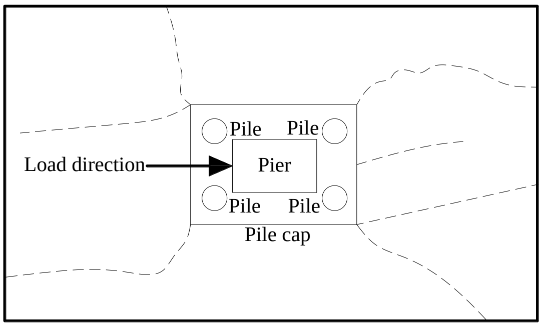


Fig. 9 Loess cracking distribution after test

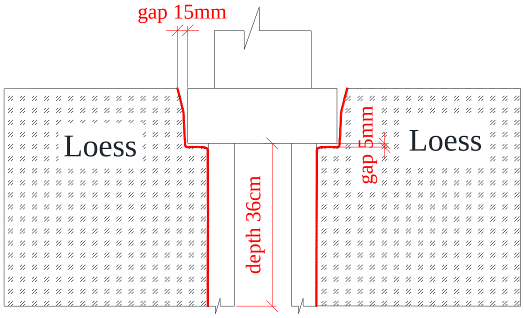


Fig. 10 Sketch of the soil-pile interface separation

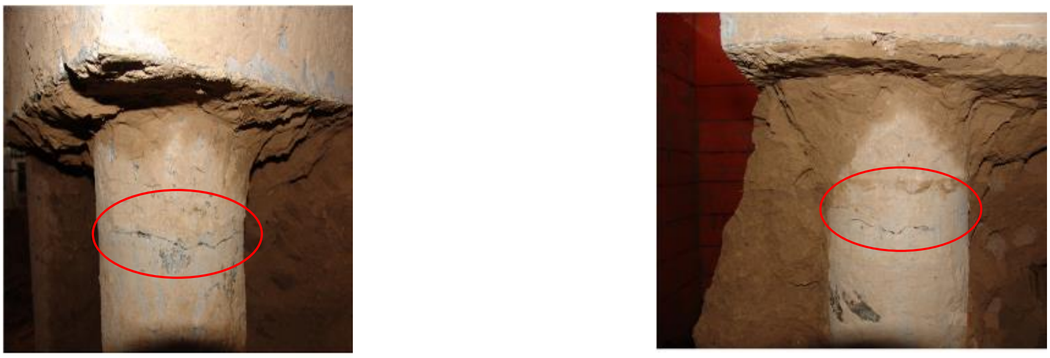


Fig. 11 Radial through cracks at the pile shaft

the pile (Shi *et al.* 2018). After test, the foundation loess is cleared away from the test camber in order to observe the failure characteristics of the piles, as shown in Fig. 10. It can be found that the loess and pile cap is separated at the lateral direction and the separation distance is about 15 mm, the separation between the bottom of the pile cap and loess is about 5 mm. Radial cracks appear at 12-16 cm depth of the four piles from the bottom of the pile cap and cut through the pile shaft, as shown in Fig. 11. The width of the crack is around 1 mm-2.5 mm. The separation between pile and the surrounding loess extends from the pile top to about 36cm depth.

3.2 Hysteretic characteristics

In order to investigate the nonlinearity and energy dissipation behavior of the pier-pile-loess system, the force-displacement curves (defined as hysteretic curves) under

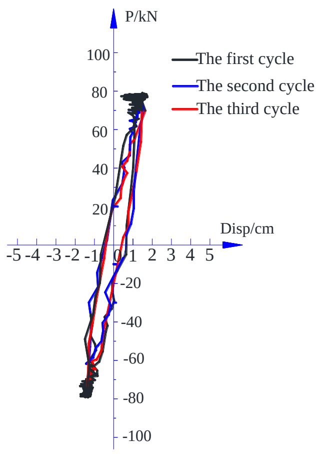


Fig. 12 hysteretic curves at 1.8 cm

relatively large to-and-fro displacements (1.8 cm, 2.2 cm,

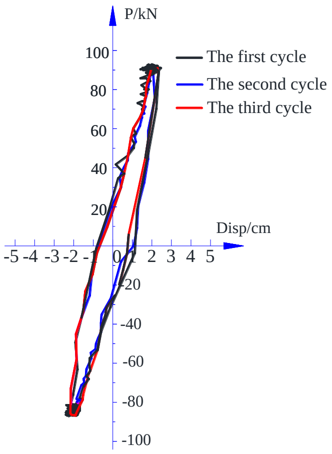


Fig. 13 hysteretic curves at 2.2 cm

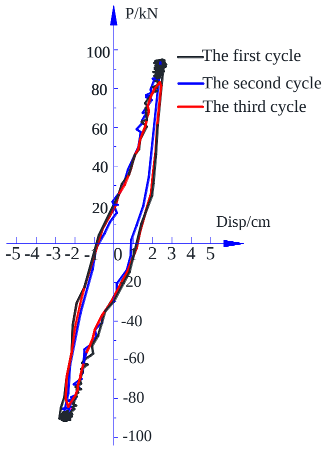


Fig. 14 hysteretic curves at 2.6 cm

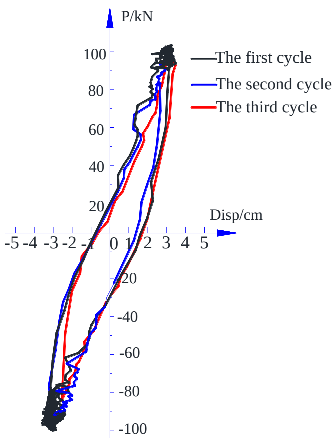


Fig. 15 hysteretic curves at 3.2 cm

2.6 cm and 3.2 cm) are shown in Figs. 12-15. It can be found that hysteretic hoops gradually evolve into spindle shape with the increase of lateral displacement. The increase of the hysteretic area and peak force indicates that the pier-pile-loess system exhibits good energy-dissipating and load-bearing capacity even though the pile concrete is failed with through cracks. The main contribution is the constraint of the pile-surrounding loess and the reinforcement of the pile. Therefore, the nonlinearity of the

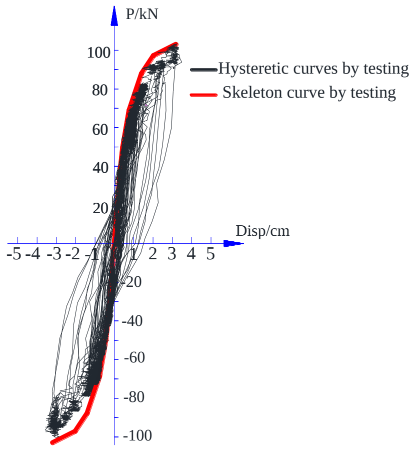


Fig. 16 Skeleton curve of the testing model

pile and surrounding soil is essential for the seismic design of the bridges with pile foundation.

The skeleton curve derived from the enveloping of the hysteretic curves is shown in Fig.16, it reflects the stiffness characteristics, yielding and ultimate strength. It can be found that no significant reduction of the loading-resistance capacity during the cyclic loading.

The piles are cracked and then lose the bearing capacity under cyclic lateral loading, and brittle failure happens and no plastic hinge occurs due to the low longitudinal steel ratio (0.33%). Therefore, the skeleton curve in Fig. 16 mainly reveals the nonlinearity of the foundation loess. From Fig. 16, it can be seen that the pile and surrounding loess work in elastic behavior under small lateral displacement (less than 1cm). With the increase of the lateral displacement, the foundation loess enters into plastic state and the pile cracks. The skeleton curve shows that the lateral stiffness of the bridge pier-pile-loess system declines gradually at the later loading stage.

4. Discussion

4.1 Hysteretic model of the bridge pier-pile-loess system

Based on the measured skeleton curve (Fig. 16), a bilinear model with stiffness degradation is presented for the nonlinearity of the bridge pier-pile-loess system, as shown in Fig. 17. The hysteretic model contains two parts, i.e. elastic stage under small lateral displacement (OA) and stiffness degradation stage after yielding (AB). Pushover analysis based on the hysteretic model is conducted to validate the hysteretic model. Fig. 18 shows that the calculated hysteretic behaviors agree well with the measured hysteretic curves from the quasi-static test. Therefore, the bilinear model with stiffness degradation can be applied to simulate the hysteretic behaviors of the bridge pile in loess under earthquakes.

4.2 Stiffness degradation and ductility

Secant stiffness is the slope between the point of the load-displacement curve and the origin point (zero point). It

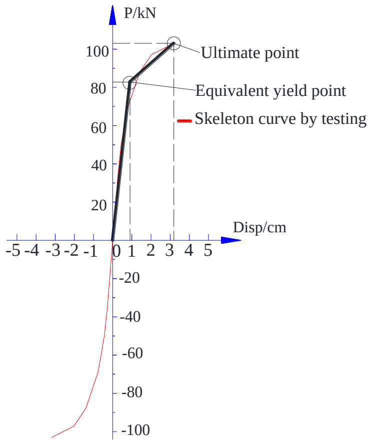


Fig. 17 Suggested hysteretic model of the bridge pier-pile-loess system

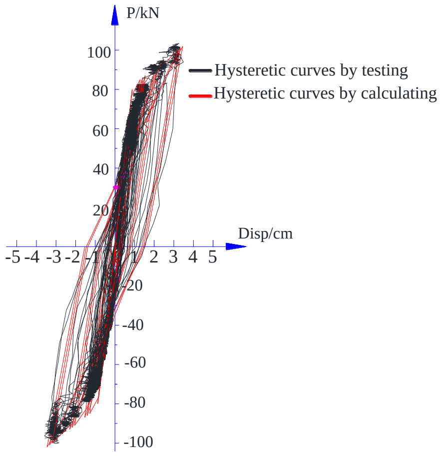


Fig. 18 Measured and calculated hysteretic curves

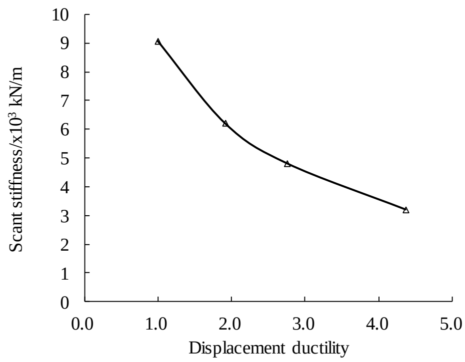


Fig. 19 Variation of secant stiffness with displacement ductility

can be calculated by Eq. (1), as shown：

$$k_s = (|+F_i| + |-F_i|)/(|+u_i| + |-u_i|) \tag{1}$$

Ductility is a measure of the ability of a structure or member to maintain its load-carrying capacity while deforming beyond yielding. The ratio of ultimate and yielding displacement is generally defined by the displacement ductility coefficient (Taheri *et al.* 2017, Bhowmik *et al.* 2017, Wang *et al.* 2016), as follows:

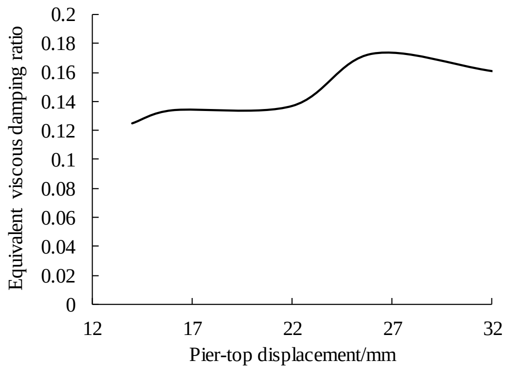


Fig. 19 Variation of secant stiffness with displacement ductility

$$\mu = \Delta u / \Delta y \tag{2}$$

In this study, the ultimate and yielding displacement can be determined by the envelope curve of hysteresis behaviors, as shown in Fig. 17.

The variation of secant stiffness of the testing model with the increase of displacement ductility coefficient, as shown in Fig. 19. It can be found that the stiffness of the bridge pier-pile-loess system decreases quickly in the initial stage, and the decrease of the stiffness becomes more slowly with the increase of the displacement ductility.

4.3 Energy dissipation capacity

Based on the test data of the hysteretic curves, the dissipated energy during testing can be determined by calculating the area enclosed by the hysteresis loop as indicated by Eq. (3) (Han *et al.* 2013).

$$\Delta W_i = \int_{u_{\min}}^{u_{\max}} [F_l(u) - F_{ul}(u)]\,du \tag{3}$$

where, $F_l(u)$ and $F_{ul}(u)$ are the forces at displacement u during the loading and unloading process.

The equivalent damping ratio can be regarded as an index of the energy dissipation capacity and is defined as the ratio of the dissipated energy in one cycle, to the strain energy of an equivalent linear elastic system.

$$\xi_{eq} = \frac{\Delta W_i}{2\pi k u_{\max}^2} \tag{4}$$

where k is the secant stiffness and $u_{\max}$ is the maximum displacement reached in the cycle.

Fig. 20 shows the relationship between the equivalent viscous damping ratio and the lateral displacement. As seen from Fig. 20, the equivalent viscous damping ratio increases with the lateral displacement of the pier-top, and the range is from 0.10 to 0.18.

5. Conclusions

The hysteretic behaviors of the pile foundation in loess are investigated by a scaled model test of the railway bridge pier-pile-loess system. Some primary conclusions are drawn as follows:

• It can be found that the loess cracks mainly distributed at the four corners of the pile cap under cyclic lateral loading. The loess and platform are separated at the lateral direction and the separation is about 15 mm, the separation between the bottom of the pile cap and loess is about 5 mm.

• The piles are cracked and then lose the bearing capacity under cyclic lateral loading, and brittle failure happens and no plastic hinge occurs due to the low longitudinal steel ratio (0.33%). It can be seen that the pile and surrounding loess work in elastic behavior under small lateral displacement (less than 1 cm). With the increase of the lateral displacement, the foundation loess enters into plastic state and the pile cracks.

• A bilinear model with stiffness degradation is recommended for the nonlinearity of the bridge pier-pile-loess system, contains two parts, i.e. elastic stage under small lateral displacement and stiffness degradation stage after yielding.

• The stiffness of the bridge pier-pile-loess system decreases quickly in the initial stage, and the decrease of the stiffness becomes more slowly with the increase of the displacement ductility. The equivalent viscous damping ratio increases with the lateral displacement of the pier-top, and the range is from 0.10 to 0.18.

In this study, we focus on the hysteretic behaviors of the pile foundation in loess and how to simulate the nonlinearity of the pile-loess system under earthquakes. The effect of collapsibility and strength sensitivity of loess on pile-soil interaction should be further studied by in-situ testing in the future.

Acknowledgments

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