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Model Test Analysis of the Plastic Energy Dissipation Effect of Pile Foundation for Bridge Structure

Changfeng Wang[a], Jikang Zhao[b], Mingbo Ding[b]

[a] School of Civil Engineering, Yantai University, Yantai, China,
[b] School of Civil Engineering, Lanzhou Jiaotong University, Lanzhou, China.

wangchang-f@126.com

To study the plastic energy dissipation effect of foundation soil on nonlinear seismic response of bridges with pile foundations, a scaled pseudo-static model test of single pier bridges with pile foundations is performed. Based on the test result and motion features of piles with reciprocating loading, the analysis model of nonlinear seismic response of bridges with pile foundations has been built and pseudo-statically examined with reciprocating loading. This model has been built with the consideration of horizontal compression-only nonlinearity and vertical friction effect of pile side soil and nonlinear indentation and lift-off effect of pile tip soil. The test has showed that, on the condition that bearing capability of the pier is high, foundation soil enters the plastic deforming stage, which produces the plastic energy dissipation effect when the earthquake occurs. The result of theoretical analysis has great similarity with the test result on bearing capability and hysteresis loop features, which shows that the analysis model of nonlinear seismic response of bridges with pile foundations can be applied to analyze nonlinear seismic response.

1. Introduction

High-speed railway bridges often use gravity piers with less reinforced concrete which are high in rigidity but low in ductility. However, records data of the seismic damage survey shows that gravity piers can sometimes resist high-intensity earthquakes. Obviously, strength of piers cannot bear the heavy loading. Pile foundations which are widely used in bridge construction may break down in strong earthquakes. Since bearing capability of pile foundations and foundation soil is lower than that of bridge piers, which tends to enter the plastic stage in strong earthquakes, seismic resistance of foundation soil should be studied in terms of its energy dissipation effect.

In recent years, pile-soil-structure interaction has been explored in depth and its study has made many meaningful achievements (Kim et al (2004). Apostolou, Gazetas and Garini (2007). Foriero, St-Laurent and Ladanyi (2005). Narasimha, Ramakrishna and Babu (1998). Hajialilue-Bonab, Sojoudi and Puppala (2013). Shivani and Amit (2014)). Penzien Model (Peizien (1964)) is a computational model which is widely applied in the theory of pile-soil-structure interaction. Scholars have built different improved Penzien Models. When analyzing pile-soil dynamic interaction, it is important to properly describe the mechanical state of soil around piles and take into account dynamic impedance of pile side soil against pile foundations (Musharraf-uz et al (1984)). Dynamic Winkler Model is a convenient and effective lumped parameter computational mechanics model, which is represented by Matlock Model, Novak Model (Novak, Aboul-Ella and Impedance (1978)), and Nogami Model (Nogami, Otani and Konagai (1992)). Thereinto, Nogami model is more used in the nonlinear analysis of pile-soil interaction.

The current analysis models of soil-structure interaction seldom take into consideration contact of pile-soil separation and material coupling nonlinearity. Seismic design standards for railway structures of Japan (Japan Railway Technical Research Institute (2000)) noticed material nonlinearity of piles, soil and piers and put forward the analysis model of static pushover elastic-plasticity, but neglected the hysteretic process of soil with reciprocating seismic loading and also neglected the possible effect of soil-pile foundation separation when earthquakes occur.

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To provide experimental basis for the analysis model of bridges with pile foundations in terms of soil-structure dynamic interaction, this paper made a model trough and scaled piers with pile foundations, conducted a pseudo-static loading test and worked out the failure mode of gravity piers with pile foundations as well as the analysis model of nonlinear soil-structure interaction of bridges with pile foundations.

2. Model Building for the Test

2.1 Construction background and test model

This paper chooses the simply supported double-line box girder bridge as the research object. Round ended pier, loess foundation, end-bearing piles, piers and pile foundations are shown in Figure 1. Piers in the test model are 1:5 scaled. In Figure 2, due to the fact that stress of pile foundations decreases sharply at a certain depth (Reese (1997)). Reese, Van and W.F. (2001)), the length of the pile foundation is set 1.8m.

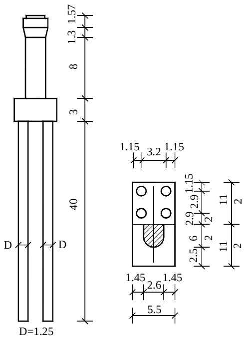


Figure 1: Structural map of practical structure (unit: m)

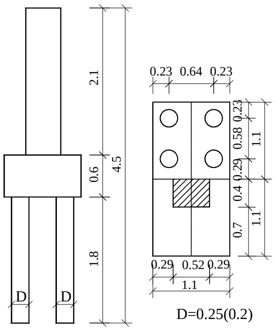


Figure 2: Structural map of test model (unit: m)

2.2 Test model building

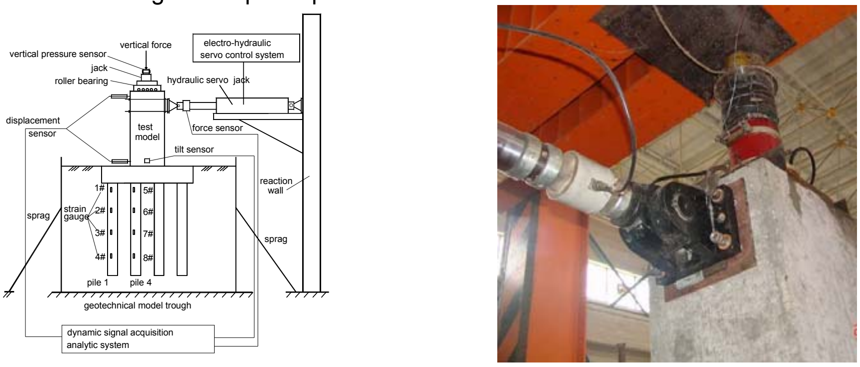
The model trough is made of stiffened plates which include angle steel and PMMA. The size of this trough is 3×4.2×2.8m. PMMA is used in one side to observe the change of soil, while the other sides use ribbed plates. Soil in the trough is remolded loess. To ensure compactness of soil, when soil is close to its optimum moisture content (around 11%-13%), soil is tamped in 21 layers from the bottom to the top. The pore-forming process of the pile foundation is shown in Figure 3. After the static triaxial test on soil sample, it has been concluded that deformation modulus of soil E = 25.0MPa, cohesion force C = 78.4kPa, internal friction angle φ = 32º.

Figure 3: The pore-forming process of the pile foundation

3. The loading system of the test

The whole loading system is made up from three parts: (1) the horizontal and vertical loading system; (2) the data testing and collecting system; (3) the servo control loading system. The vertical loading system is made from the afterburning frame, test bed, roller bearing and hydraulic jack. The test uses the roller bearing to exert vertical force on the pier top, which simulates the condition that the bridge exerts vertical loading force on the piers and thus reduces the additional moment effect of vertical loading on the pier top. The horizontal loading system is made from the afterburning frame, reaction wall and electrohydraulic servo loading system. Test device is laid out in Figure 4.

The test uses force-displacement to control the loading, with force controlling the loading before the structure yields and displacement controlling the loading after the structure yields until the device breaks down. Data mainly collected is pier top displacement, pile cap displacement, pile foundation strain, pile cap angle and horizontal loading on the pier top.

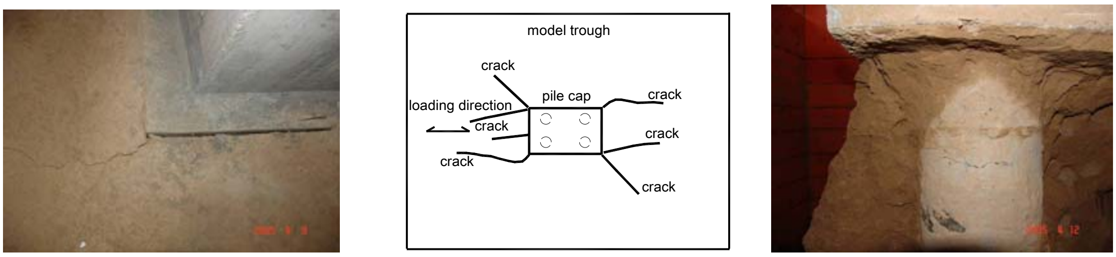


(a) layout of the test device *(b) the horizontal and vertical loading system*

Figure 4: layout of the test device

4. The test result

Phenomena in the test are illustrated as bellow:
(1) When the displacement loads ±3.0mm, foundation soil does not crack, soil is in an elastic state, and the maximum horizontal loading force of the pier top is 92kN; when the displacement loads ±4.5mm, foundation soil cracks and the maximum loading force is 118kN. When the displacement loads ±6.0mm, apparent cracks appear on foundation soil and the maximum loading force is 150kN. With reciprocating horizontal loading, soil under the pile cap enters the plastic stage and the piers sink vertically by about 0.5mm.
(2) With reciprocating horizontal loading, soil of four angles of the pile cap cracks. The cracks are up to 2mm wide and 70cm long. The cracks do not reach the boundaries of the trough, showing that its size is big enough and meets the boundary conditions of soil. The layout of cracks is shown in Figure 5 (a) and (b).
(3) The pile cap separates from lateral soil, with the crack up to 1.5cm wide. Soil at the bottom of the pile cap separates from the cap, with the crack 0.5cm wide and 10-15cm long, which tilts the pier.
(4) Annular cracks appear on all piles, 12-16cm away from the pile cap, with cracks up to 2.5mm wide. Pile side oil separates from the pile, with the separation around 36cm high.



(a) The lateral crack of the pile cap *(b) the distribution map of cracks* *(c) Pile 2# cracking and soil separating*

Figure 5: Soil crack pattern

5. Improved Analysis Model of Bridges with Pile Foundations

5.1 Analysis model of bridges with pile foundations

Seismic design standards for railway structures of Japan (Japan Railway Technical Research Institute, 2000) built a static nonlinear computational model of piers with pile foundations, and used three types of springs of the ideal elastic-plastic model - the horizontal spring against the pile side, vertical friction spring and spring on the pile top to analyze the unidirectional pushover (Brandenberg and Boulanger (2007). Li, Zhang and Yang (2011)). But it did not take into account the hysteretic process of soil with seismic reciprocating loading or the possible pile-soil separation effect. On the basis of this model, this paper has improved the nonlinear analysis model of bridges with pile foundations, making it more applicable to pseudo-static and dynamic analysis with reciprocating loading. The improvements are listed as Figure 6 shows:

(1) Take into account horizontal contact of soil and material nonlinearity; the horizontal spring is the compression-only bilinear spring element; the bidirectional crack between soil and pile foundations is also taken into consideration.
(2) Consider vertical friction effect; the vertical spring is supposed to be bilinear.
(3) Consider impact of soil damping on dynamic response of bridges with pile foundations.
(4) Use Takeda trilinear model to simulate nonlinearity of reinforced concrete piles.
(5) Use unidirectional compression-only bilinear Winkler foundation spring to simulate the spring for nonlinear indentation and lift-off of pile tip soil (Wang and Chen (2014)).

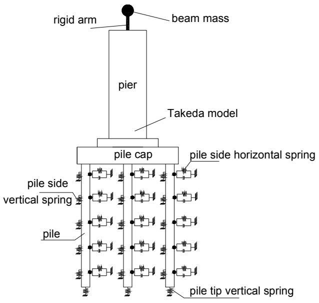


Figure 6: The improved model

5.2 The Bidirectional compression-only bilinear spring

In the vibrating process, soil and piles may separate and enter different nonlinear stages in terms of material and states: soil and piles may bond together, soil becomes nonlinear, soil and piles separate and recontact. Additionally, soil and piles may vertically slip. All these elements have impact on dynamic response as well as dynamic impedance calculation of pile foundations.
Since horizontal movement of pile foundations can be both positive and negative in the earthquake, the bidirectional compression-only bilinear spring element is built as Figure 7. This spring element takes into account the bilateral cracks between soil and pile foundations.

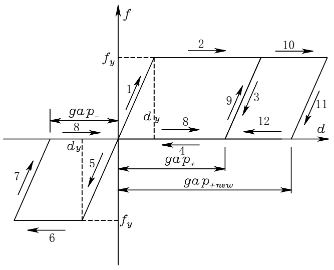


Figure 7: The improved bidirectional compression-only bilinear spring model

The force-displacement process of the bidirectional compression-only nonlinear spring is shown as follows:
(1) In the elastic stage, loading and unloading of this spring is the same with the general spring.
(2) In the plastic deforming stage, the force-displacement curve is 1→2→3→4. After unloading, the unrecoverable plastic deformation is gap_+, meaning a positive gap between soil and piles. When resilience is 0, the curve coincides with the lateral axis in the negative direction, thus stopping providing resilience for the whole system.
(3) When the negative loading spring yields, the force-displacement curve is 4→5→6→7→8, the same with that in the positive direction. After unloading, the unrecoverable plastic deformation is gap_-, meaning a negative gap between soil and piles. After unloading, the curve coincides with the lateral axis in the positive direction, thus stopping providing resilience for the whole system.
(4) When the force-displacement curve moves along the lateral axis in the positive direction and arrives at gap_+, soil and piles contact. Then the spring works and the force-displacement curve is 8→9→10→11→12. After unloading, a new positive gap_{+new} appears.
The bidirectional compression-only nonlinear spring takes into consideration the impact of soil stratification. Therefore, in different depths of piles, this spring can be used with different rigidity and yield force.

6. Comparative analyses of results

To rationalize this improved model, with reciprocating loading, the paper uses nonlinear static pushover analysis to examine the test model of the single-pier with the pile foundation. Parameters of pile side soil are calculated according to Seismic design standards for railway structures of Japan (Japan Railway Technical Research Institute (2000)). The hysteretic curve of the bidirectional compression-only soil spring around the pile cap is shown in Figure 8.

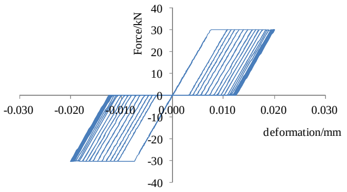
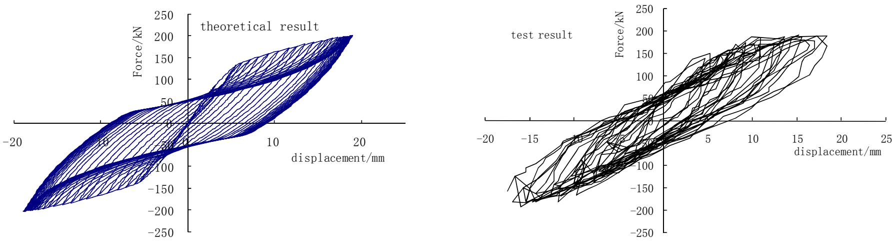


Figure 8 the hysteretic curve of the soil spring on the pile top

As Figure 8 shows, the bidirectional compression-only nonlinear spring can be used to simulate the nonlinear energy dissipation and simulate the gap between soil and piles when vibrating. According to the theoretical analysis, a residual gap appears between soil and the pile top, with the gap up to 13mm long, which is close to the test result.

The result of theoretical analysis of the force-displacement curve of the pile top with reciprocating loading is shown in Figure 9(a), while the test result is shown in Figure 9(b).



(a) the result of theoretical ananlysis *(b) the test result of the force-displacement curve of the pile top*

Figure 9: Comparative analyses of results

From Figure 9, it can be seen that the result of numerical analysis of the improved model is close to the test result in terms of data and the shape. As reciprocating loading force increases, a gap appears between soil and piles and the original rigidity of the unloading curve is relatively high; as soil and piles separate, its rigidity lows down. In the negative recontact process, as the contact range between soil and piles increases, the rigidity increases, indicating that the improved scattered spring model can simulate the state of contact-separation of soil and piles and material nonlinearity.

7. Conclusions

This paper studies and examines the pile-soil-structure interaction of bridges with pile foundations with pseudo static test study and theoretical analysis. Conclusions are as follows:

The plastic energy dissipation of foundation soil is examined in the pseudo static model test. The test shows that, when the strength of the pier is high, cracks appear between soil around the pile cap and soil around pile. Then foundation soil enters the nonlinear deforming stage, which has great impact on hysteresis of the whole bridge. This will consequently affect the seismic response of its upper structure when the earthquake occurs.

The nonlinear analysis model of the bridge with pile foundations is improved. This model takes into account the horizontal nonlinearity and vertical nonlinear frication of pile side soil and nonlinear indentation and lift-off effect of pile tip soil.

The result of numerical analysis of the improved model is close to that of the test in terms of data and the shape. The model test rationalizes the improved analysis model.

This paper puts forward the model of the bidirectional compression-only bilinear spring element and its hysteretic rule. This model can be applied to simulate the horizontal nonlinear effect of pile side soil. It can also exactly simulate the contact between soil and piles and material double nonlinearity in strong earthquakes. It is more practical to apply this spring to simulate the seismic response of the bridges with pile foundations.

Acknowledgements

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References

Aboul-Ella N., Impedance F. 1978. Function of Piles in Layered Media. Journal of the Engineering Mehanics Diviston, ASCE, 104(6): 643-661.

Apostolou M., Gazetas G., Garini E. 2007. Seismic response of slender rigid structures with foundation uplifting. Soil Dynamics and Earthquake Engineering, 27(7), 642-654. Doi: 10.1016/j.soildyn.2006.12.002.

Brandenberg S.J., Boulanger R.W. 2007. Static pushover analyses of pile groups in liquefied and laterally spreading ground in centrifuge tests. Journal of Geotechnical and Geoenvironmental Engineering, 133(9): 1055-1066. Doi: 10.1061/(ASCE)1090-0241(2007)133:9(1055)

Foriero A., St-Laurent N., Ladanyi B. 2005. Laterally loaded pile study in permafrost of Northern Québec, Canada. Journal of Cold Regions Engineering, 19:61-84. Doi: 10.1061/(ASCE)0887-381X(2005)19:3(61).

Hajialilue-Bonab M., Sojoudi Y., Puppala A. J. 2013. Study of strain wedge parameters for laterally loaded piles. Int. J. Geomech., 13(2):143-152. DOI: 10.1061/(ASCE)GM.1943-5622.0000186.

Japan Railway Technical Research Institute. 2000. Seismic design standards and explanations for railway structures. (in Japanese)

Kim Y., Roesset J. 2004. Effect of nonlinear soil behavior on inelastic seismic response of a structure. International Journal of Geomechanics, 4(2): 104-114. Doi: 10.1061/(ASCE)1532-3641(2004)4:2(104).

Li Q., Zhang X., Yang Z. 2011. Analysis of Laterally Loaded Piles in Liquefiable Soils with a Frozen Crust. Proc, GeoCongress 2012, Oakland, CA.

Narasimha Rao S., Ramakrishna V.G.S.T., Babu Rao M. 1998. Influence of rigidity on laterally loaded pile groups in marine clay [J]. Journal of Geotechnical and Geoenvironmental Engineering, 124:542-549.

Nogami T., Otani J., Konagai K. 1992. Nonlinear soil-pile interaction model for dynamic lateral motion. Journal of Geotechnical Engineering, ASCE, 118(1): 89-106.

Peizien J. 1964. Seismic analysis of bridges on long piles. J.Engng.Mech. Div., ASCE, 90(EM3): 223-254.

Rani S., Prashant A. 2014. Estimation of the linear spring constant for a laterally loaded monopile embedded in nonlinear soil [J]. Int. J. Geomech., Doi: 10.1061/(ASCE)GM.1943-5622.0000441.

Reese L.C. 1997. Analysis of laterally loaded piles in weak rock. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 123 (11): 1010-1017.

Reese L.C., Van Impe. W.F. 2001. Single piles and pile groups under lateral loading. Balkema, Rotterdam, Netherlands.

Wang C.F., Chen X.C. 2014. Analytical Model and Experimental study of nonlinear seismic response of bride with pile foundations [J]. Bridge Construction, 44(3): 57-62. (in Chinese)

Zaman M., Desai C., Drumm E. 1984. Interface model for dynamic soil–structure interaction. J. Geotech. Engrg. 1984.110: 1257-1273.