Non-linear Pushover Analysis of Water Pipelines under Soil Liquefaction

Lap-Loi Chung[1,2] Yu-Hsuan Chiu[2] and Gee-Yu Liu[1]

[1]National Center for Research on Earthquake Engineering (NCREE), Taiwan
[2]Department of Civil Engineering, National Taiwan University (NTU), Taiwan

ABSTRACT

Soil liquefaction may be induced during earthquake. In this situation, bearing capacity of soil under water pipelines will be reduced or vanished. If the joint or the pipe itself is not strong to withstand the gravity load of the pipes and water inside, the pipeline will be damaged or disengaged and water supply is affected. In this paper, the behavior of pipeline under soil liquefaction is investigated. Parameters of plastic hinges are adopted from previous study and they are allocated on the pipes and at the joints. It is assumed that the bearing capacity of soil in the liquefaction area vanishes. Pushover analysis is conducted such that the uniform distributed load on the pipeline is increased gradually. If the capacity of the pipelines is larger than the demand (weights of pipes and water), the water pipeline are safe. Otherwise, damage or disengagement may happen. The process of pushover analysis of water pipelined under liquefaction is illustrated by ductile iron pipes with K-type joints. The behavior of pipelines highly depends on the extent of soil liquefaction. If the area of liquefaction is limited to 16 m along the pipelines, the pipelines will not damage.

Keywords: water pipeline, soil liquefaction, pushover analysis

1. INTRODUCTION

Taiwan is located in seismically active area and disastrous earthquake may happen in every 10 years so people in Taiwan have to live with earthquakes. Water pipeline may be ruptured during earthquakes and water supply may be disrupted. However, water is very important for human beings and water system is an important lifeline. Therefore, seismic performance of water pipeline is very crucial. Earthquake may be followed by soil liquefaction. Under soil liquefaction, bearing capacity of soil is greatly reduced and underground water pipeline may be settled and failure occurs.

Nonlinear behavior of underground structures such as pile has been studied by nonlinear pushover analysis. The pile is modeled by beam element and its nonlinear properties are represented by plastic hinges. Soil is modeled by spring with perfectly elastic plastic properties. Displacement and force relationship of ductile iron pipes was developed from experimental and numerical studies [1]. According to the experimental and numerical results, axial (including tension and compression) and bending nonlinear plastic hinges were established. In addition, since the K-type joint is highly nonlinear, the axial (including tension and compression) and bending plastic hinges were solely derived from laboratory tests

[2]. In this paper, the behavior of underground water pipeline under soil liquefaction is investigated. In the region where liquefaction occurs, the bearing capacity is assumed to vanish and in the region where no liquefaction, the soil is modeled by nonlinear spring. The extent of liquefaction is assigned and the loading pattern is uniformly distributed load to simulate the weight of pipe filled with water. The displacement of pipeline increases gradually and the corresponding load is acquired. From the relationship between uniformly distributed load and displacement, the maximum one is the capacity of the pipe. If the capacity is larger than the demand, the pipeline survives. The critical situation can be obtained by varying the extent of soil liquefaction.

2. PUSHOVER ANALYSIS

In this paper, ductile iron pipes with K-type joints are investigated. The diameter D is 407 mm and the thickness t is 7 mm. The pipes buried under the ground are simulated by beam elements. It is assumed that the bearing capacity of soil completely vanishes during soil liquefaction. Therefore, the weight of the pipes with water becomes the external force of the structural system. The sketch of the analysis model for the system is shown in Figure 1 where L is length of soil liquefaction region along the pipeline and l is the length of beam element of the pipes. It is found that analysis results are accurate enough if the size of beam element is as small as 0.2 times the pipe diameter, that is, $l = 0.2D$. At the nodes of the beam element, nonlinear axial (including tension and compression) and moment plastic hinges for the pipes are assigned. Since the ductile iron pipes are fabricated in segments with length 6 m, there is a joint at every 6 m of the pipeline. Nonlinear axial (including tension and compression) and moment plastic hinges are also assigned at the joints.

The region of soil liquefaction is unknown in advance so that the distribution of joints with respect to the liquefaction region is arbitrary. Therefore, two types of joint distribution pattern are considered. In joint distribution type a (Figure 2), a joint is located at the center of the liquefaction region. In joint distribution type b (Figure 3), the midpoint of a pipe segment is located at the center of liquefaction region. In the region of soil liquefaction, soil springs are removed and the pipes are not supported (Figure 1). Beyond the region of soil liquefaction, the pipes are supported by soil springs in the longitudinal and lateral directions. It is found that analysis results are accurate enough as long as the length of the model is 3 times the length of liquefaction ($3L$). In this situation, the reactions (shear forces, axial forces and bending moments) at the two far ends of the model are small enough to be neglected.

The external force for pushover analysis is uniformly distributed load, simulating the weight of pipe with water. The center of liquefaction region is assigned as the control point. The displacement of the control point increases by one step and the uniformly distributed load is adjusted such that the displacement can be achieved. The above-mentioned process repeats again and again until the displacement cannot be increased any more. The pushover curve for case with the length of liquefaction L equal to 20 m is shown in Figure 4. The uniformly distributed load increases linearly when the displacement is small and becomes nonlinear when the displacement is large enough. After reached the maximum point, the uniformly distributed load attenuates. The maximum uniformly distributed load is different for different joint distribution types. Between joint distribution types a and b, type a has lower maximum uniformly distributed load, $w_{\max} = 1.288\,\mathrm{kN/m}$ which is the capacity of the pipe under soil liquefaction with region $L = 20\,\mathrm{m}$. The weight of the pipe with water per unit length is $w_t = 1.8716\,\mathrm{kN/m}$, which is the demand of the pipe. Since the capacity is less than the demand, the pipes fail under this situation.

The procedures mentioned above are repeated for other cases (length of liquefaction region L equal to 12, 14, 16, 18, 20, 21, 22, 23, 24, 26, 28 and 30 m). Joint distribution types a and b are considered. The maximum uniformly distributed loads $w_{\max}$ are plotted against the lengths of liquefaction region L as shown in Figure 5. The capacity (maximum uniformly distributed load $w_{\max}$) decreases as the length of liquefaction region L increases. When the region of liquefaction exceeds 16 m, the lower of the maximum loads of joint distribution types a and b becomes less than the unit weight $w_t = 1.8716\,\mathrm{kN/m}$.

Joint distribution type b can be considered as type a shifted by 3 m. Since the capacity of the pipe under soil liquefaction is highly dependent on the way the joints are distributed in the liquefaction region, three more joint distribution types c, d and e are taken into account. Types c, d and e are type a displaced by 0.75, 1.5 and 2.25 m, respectively. Since the length of pipe segment is 6 m, all the joint distributions are varied from type a by shifting no more than 3 m. Figure 6 shows the pushover curves of pipeline with joint distribution types a, b, c, d and e under liquefaction length of 17 m. The maximum uniformly distributed loads of types b and e are less than $w_t = 1.8716\,\mathrm{kN/m}$. Therefore, the pipeline fails under soil liquefaction of length $L = 17\,\mathrm{m}$. Similarly, 5 pushover curves can be constructed for $L = 16\,\mathrm{m}$. All the five maximum uniformly distributed loads exceed the demand w_t. In a word, the pipeline can sustain soil liquefaction of length L not greater than 16 m.

3. CONCLUSIONS

In this paper, a method is developed to investigate the behavior of water pipeline under soil liquefaction. It is assumed that bearing capacity of soil completely vanishes within the region of liquefaction. The weight of pipe with water is simulated by uniformly distributed load which is the load pattern for pushover analysis. The nonlinear characteristics of pipe and its joint are represented by plastic hinges. Maximum uniformly distributed load are obtained from pushover analysis. If the capacity (maximum uniformly distributed load) is higher than the demand (weight of pipe with water), the pipeline survives. Otherwise, the pipeline fails. The process repeats for various extents of liquefaction so that the critical situation can be found.

The method is illustrated by an example of ductile iron pipe with nominal diameter 400 mm and thickness 7 mm. It is found that the performance of pipeline under soil liquefaction depends on the distribution of joints relative to the center of liquefaction region. After considering all joint distributions, the pipeline can survive if the length of pipeline in the liquefaction is no more than 16 m. The proposed method can be readily extended to other cases once the nonlinear properties of pipe section, pipe joint and soil.

REFERENCES

1. Chung, L.L., Chen, Z.H., Huang, G.L., Liu G.Y., and Wu, L.Y. (2011), 'Nonlinear pushover analysis of buried water pipelines under faulting', Proceedings of the 7th Japan-US-Taiwan Workshop on Water System Seismic Practices, paper no. 42, October

12-15, Japan Water Works Association, Niigata, Japan.

2. Chung, L.L., Liu, G.Y., Chou, P.C., Uang, P.Y., Huang, C.S., Cheng, C.T., and Chou, C.J. (2013), 'Experimental study on seismic behavior of ductile iron pipes and their joints for water supply system', Proceedings of 8th WRF/JWWA/CTWWA Water System Seismic Conference, Oakland, USA.

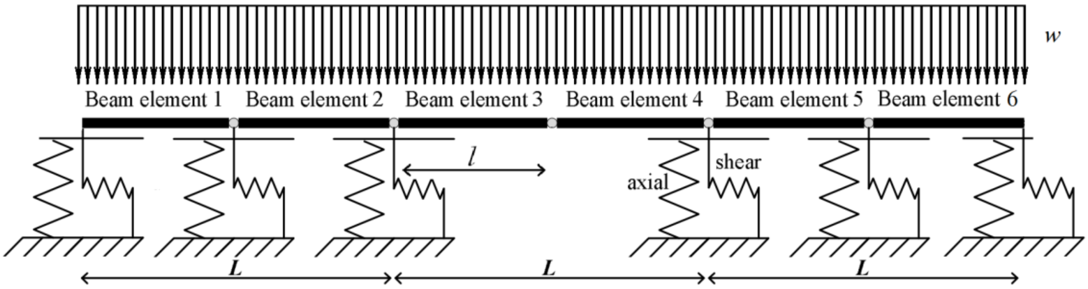

Figure 1 Pushover analysis model of pipelines under soil liquefaction

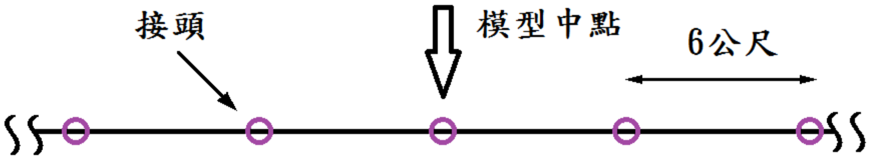

Figure 2 Joint distribution type a (joint located at center)

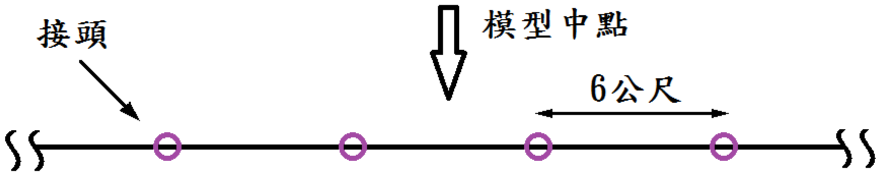

Figure 3 Joint distribution type b (pipe midpoint located at center)

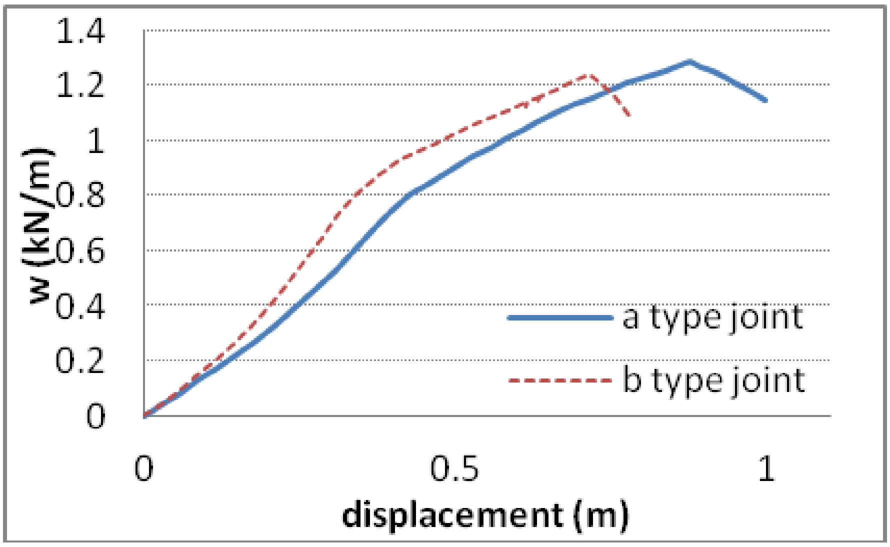

Figure 4 Pushover curve of pipeline under soil liquefaction ($L = 20$ m)

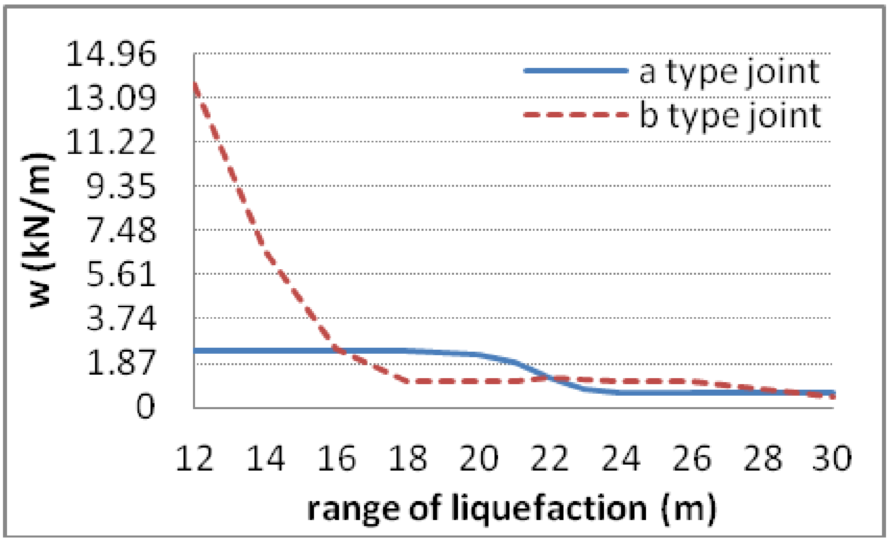

Figure 5 Maximum uniformly distributed load and length of liquefaction

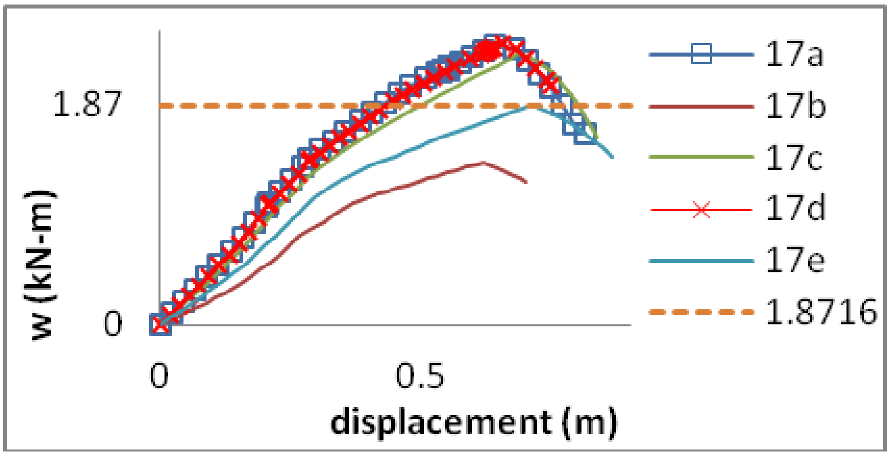

Figure 6 Pushover curve of pipeline with 5 joint distributions under soil liquefaction ($L = 17$ m)