The Preliminary Study of the Impact of Liquefaction on Water Pipes

Jerry J. Chen and Y.C. Chou

ABSTRACT

Damages to the existing tap-water pipes have been found after earthquake. Some of these damages are derived from the soil liquefaction. Excess pore water pressure generated due to shear wave has been studied by way of the well-known numerical software PLAXIS in this article. The dissipation of pore pressure after soil liquefaction will cause ground subsidence. The loose sand can easier generate pore water pressure and cause a larger settlement. A greater liquefaction thickness will cause a larger ground settlement and will result in a more severe damage to DIP tap-water pipes. The numerical calculations reveal that the damage of tap-water pipe occurs mainly at the border between soil with and without liquefaction. Elongation and bending are the most common damage type happened in the existing tap-water pipes during earthquake. The installation of flexible joints has also mentioned to reduce the damage to the tap-water pipes. It is expected that the concept and calculation described in this paper would be helpful for the engineer in gaining the ability of analysis so that the more effective design can be developed for such problem in the future.

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Introduction

The dissipation of excess pore water pressure after soil liquefaction will cause ground subsidence. The uneven ground subsidence may cause damage to the existing tap-water pipe. The magnitude of ground subsidence is mainly related to the depth of soil liquefaction, thickness of soil liquefaction and inclination distribution of soil liquefaction layer. The impact of the above factors on existing tap-water pipes is studied in this article. The preliminary numerical calculation shows that the damage to tap-water pipes occurs mainly at the border between soil with and without liquefaction. In general, the uneven thickness of soil liquefaction layer and the inclined distribution of soil liquefaction layer will have a greater damage to the tap-water pipes. In addition, the numerical results reveal that the greater thickness of the soil liquefaction layer, the greater subsidence of tap-water pipe after the dissipation of excess pore water pressure caused by the soil liquefaction. To reduce the damage to the tap-water pipes, flexible joints are also introduced in this article.

Excess pore water generation due to SH shear wave

PLAXIS has options to deal with undrained behaviour in an effective stress analysis. In PLAXIS, it is possible to specify undrained behaviour in an effective stress analysis using effective model parameters. The presence of pore pressures in a soil body, usually caused by water, contributes to the total stress level. According to Terzaghi's principle, total stresses σ can be divided into effective stress σ', and pore water pressures σ_w. However, water is supposed not to sustain any shear stress, and therefore the effective shear stresses are equal to the total shear stresses. Accordingly, the excess pore water pressure is related to isotropic stress.[1]

$$\Delta\sigma = \frac{1}{3}(\Delta\sigma_1 + \Delta\sigma_2 + \Delta\sigma_3)$$

Total stress $\sigma = K_u \varepsilon_u$

Excess pore water pressure $\sigma_{excess} = B\sigma = \frac{\alpha\varepsilon_v}{nC_w + (\alpha - n)C_s}$ $C_w = 1/K_w$ $C_s = 1/K_s$

Effective $\sigma' = (1 - \alpha B)\sigma = K'\varepsilon_v$

In which K_W is the bulk modulus of water; K_S is the bulk modulus of soil material; n is the soil porosity; B is the Skempton parameter.

In PLAXIS it is possible to simulate pore pressure generation derived from SH wave excited at ground bottom, as shown in Figure-1a. The finite element mesh in calculation is shown in Figure.-2a. The pore pressure generation at different depth of ground is given in Figure.-2a, which reveals that the pore pressure generated during the course of earthquake seems not much difference.

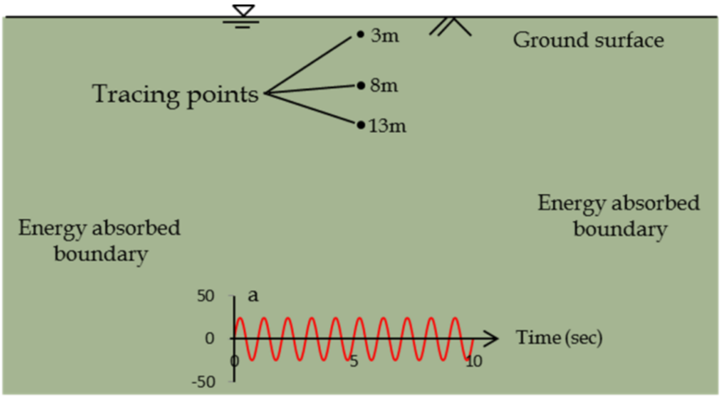

Figure-1a Layout and tracing points of pore pressure

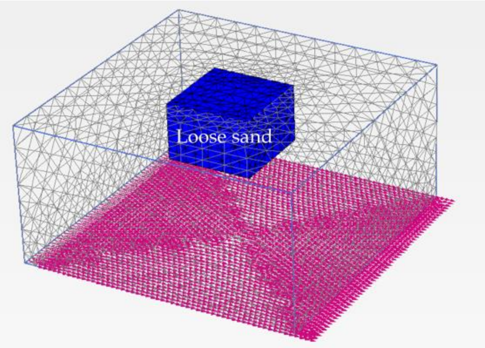

Figure-1b Finite element mesh in calculation

However, the excess pore pressure stress ratio r_u is obviously difference, where the stress ratio r_u is defined as the pore water pressure (u_w) divided by its effective overburden pressure (σ'_v), i.e. $r_u = u_w/\sigma'_v$, as shown Figure-2b. In the liquefied zone, $(u_w)_{max}$ would always equal to the effective overburden pressure (σ'_v), i,e. r_u=1.0

$$\text{Excess pore pressure ratio } r_u = \frac{\text{excess pore water pressure } (u_w)}{\text{effective overburden pressure}(\sigma'_v)}$$

Figure 3 is the typical time history of excess pore pressure generated by the shock wave at various depths below the ground surface. The pore pressure ratio $r_u = u_w/\sigma'_v$ was used to estimate the liquefaction during earthquake.

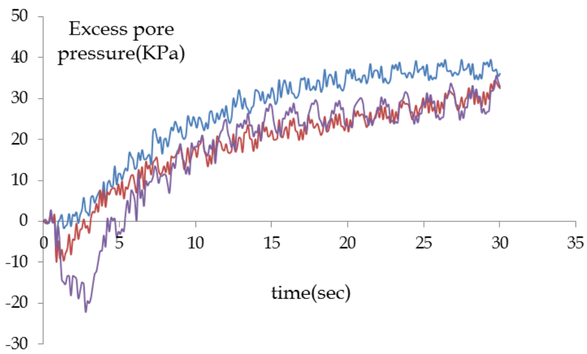

Fig-2a Excess pore pressure at various depth

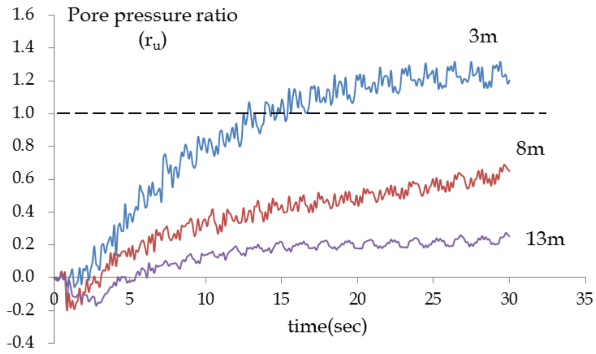

Fig-2b Excess pore pressure ratio at various depth

Excess pore water generation in various underground water tables

The location of ground water table below the ground surface will dramatically affect the liquefaction potential of soil. The lower ground water will not easy to generate excess pore pressure during earthquake. Figure-3 indicates the pore pressure generation at various ground water tables below the ground surface. It can be seen that the pore pressure generation is quite sensitive to the ground water table. The numerical calculations show that it is difficult to bring about liquefaction if the underground water located at more than 5m below the ground surface.

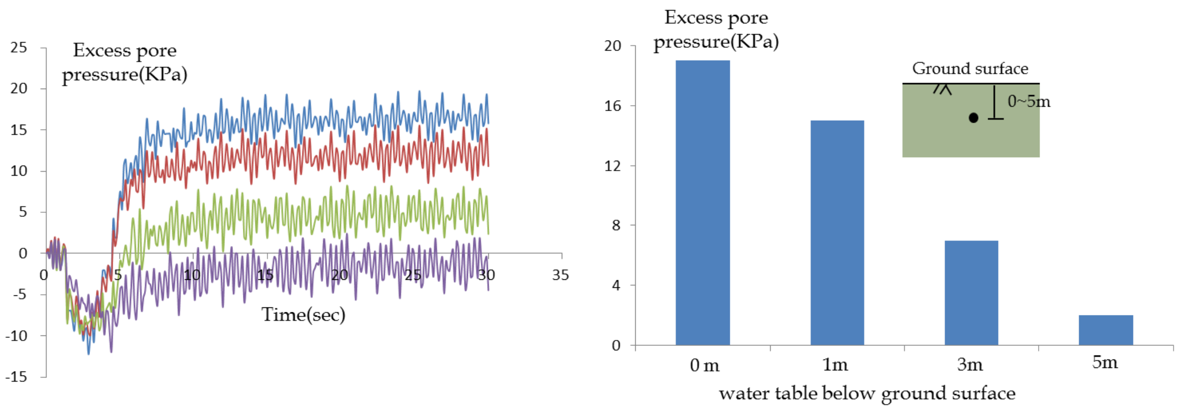

Figure-3 Pore pressure generated with various water table

Ground settlement due to liquefaction

The pore pressure generated during earthquake has to be dissipated to equilibrium the pore water pressure in the surrounding liquefaction area. According to the theory of consolidation, the ground located at liquefaction area will be settlement after the dissipation of the excess pore water pressure. The dissipation of excess pore pressure will result in the consolidation of the ground. In the liquefied zone, the excess pore pressure would always equal to the effective overburden pressure (σ'_v) so that it will induce a liquefaction. Accordingly, the settlement derived from the liquefaction means that the liquefaction layer below the ground subjected to another the effective overburden pressure, which is only limited to at the range of liquefaction. A higher excess pore pressure generated corresponds to a larger settlement. In general, the loose sand can easier generate pore water pressure and cause a larger settlement, as shown in Figure.-4. Also, a greater liquefaction thickness will cause a larger ground settlement.

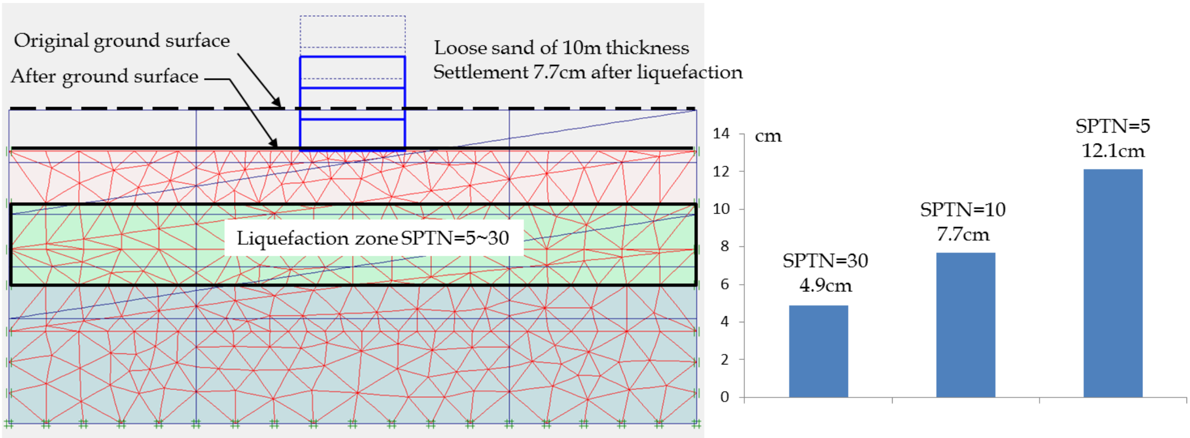

Figure-4 Settlement in different sand properties after liquefaction.

In addition, the distribution of liquefaction zone will affect the distribution of ground settlement. Figure-5 shows the incline liquefaction zone will lead to the building tile after earthquake if liquefaction happened.

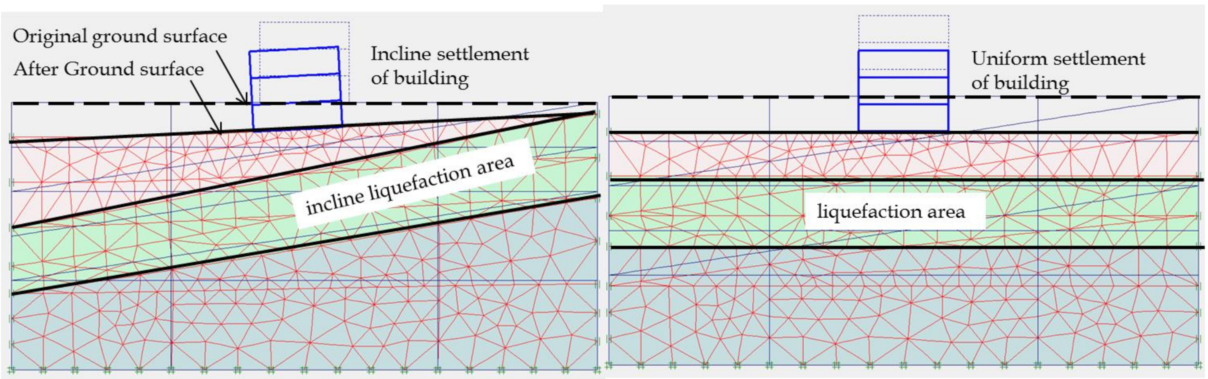

Figure-5 Ground settlement due to incline liquefaction area

The allowable elongation and rotation angle of ductile cast-iron pipe (DIP)

The DIP tap-water pipe buried in the ground is not a one-piece molding. In general, the DIP tap-water pipe is made up of multiple ductile cast iron pipes (DIP). The connection of each cast iron pipe possesses a certain allowable rotation angle and expansion or compression. Accordingly, the ductile cast iron pipes (DIP) is allowed to be constructed in the road turn or climb up and down.

The K-type DIP of 6m in length is widely used in the underground tape-water pipe. The allowable amount of expansion/compression and rotation angle is 3.4cm and 1.5^o, respectively, which corresponds to the rate of change in the vertical and horizontal is 0.0262, H/V=0.0262, as shown in Figure-6. The deformation and rotation angle of cast iron pipes (DIP) due to the liquefaction settlement shall be less than the allowable value. [2][3]

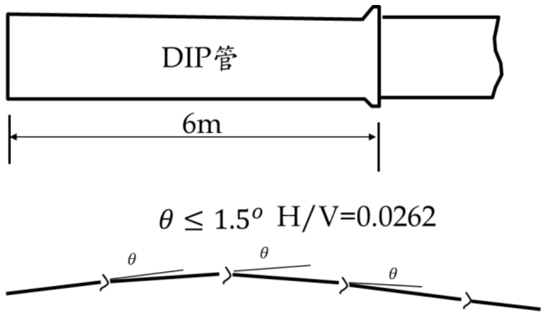

Figure.-6 Allowable rotation angle of ductile cast-iron pipe (DIP)

The engineering properties of ground and DIP tap-water pipe

By way of numerical calculation, the impact of liquefaction settlement on the DIP tap-water pipe will be studied in this article. The engineering properties of ground and DIP tap-water pipe have to be included in the FEM analysis. In accordance with the geological investigation, the ground in this analysis consists of saturated loose sand and dense sand. The engineering parameters adopted in the numerical calculation are given in Table-1.

Table-1 Engineering properties adopted in numerical analysis

	SPT-N	E (KPa)	υ	c (KPa)	φ (degree)	Remark
Sand_1	5	10000	0.35	5	29	Loose sand
Sand_2	35	70000	0.32	5	38	Dense sand
DIP	-	1.67E8	0.33	-	-	

Configuration and finite element mesh in numerical calculation

In accordance with the preliminary evaluation, the saturated loose sand is prone to liquefaction. The whole area includes soil with different natures, such as clay, loose sand and dense sand. Accordingly, the DIP tap-water pipe may pass through possible liquefaction area and non-liquefaction area. The liquefaction zone will cause settlement after the earthquake, whilst the non-liquefied zone will remain unchanged. Thus, the area located at boundary of liquefaction zone and non-liquefaction zone will undertake an uneven settlement, which will damage to the DIP tap-water pipe. The uneven settlement due to liquefaction will stretch and twist the DIP tap-water pipe. The numerical analysis in this paper aims to study the elongation and rotation angle in DIP tap-water pipe when liquefaction happened. Therefore, whether the designed DIP can meet the requirement will be examined.

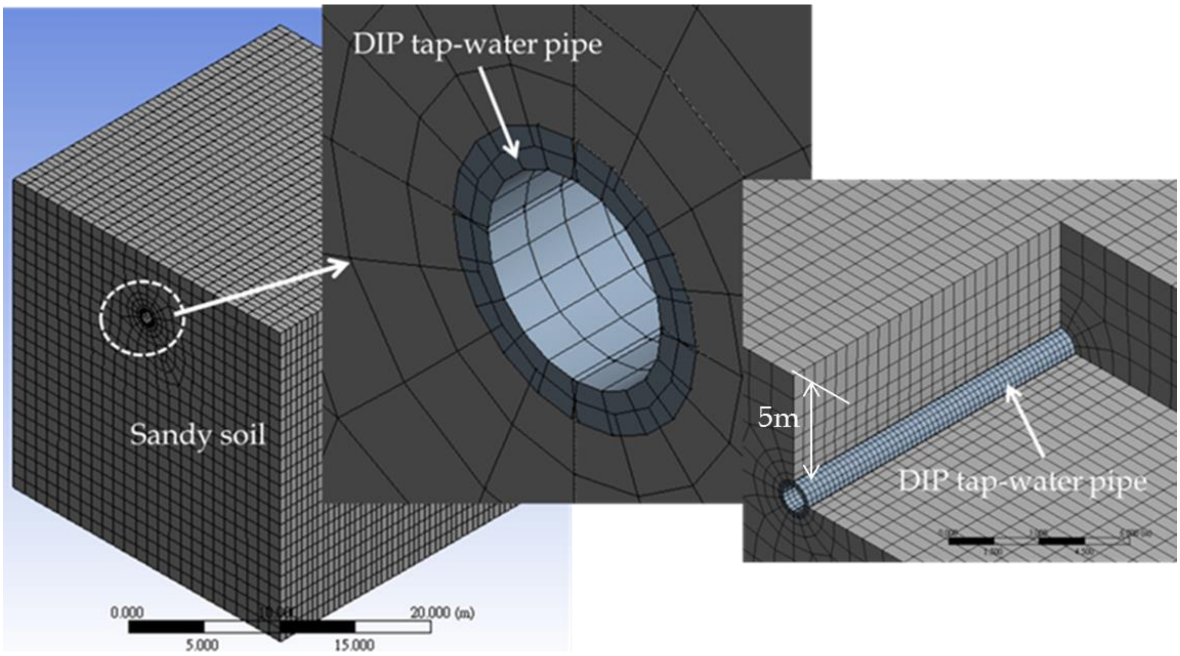

Figure.-7 Configuration and finite element mesh in numerical calculation

To avoid the difficult selection of soil spring parameters in the calculation of soil-structure interaction, it has been suggested that soil and DIP tap-water pipe shall be simultaneously considered in the three-dimensional numerical calculations. In the finite element calculation, block elements are used to simulate the ground settlement in the whole area. The block element can only provide stress tensor $\sigma_x, \sigma_y, \ldots \tau_x, \tau_y, \ldots$, which is not available for the design so that shell elements will be adopted to simulate ductile cast-iron pipes to obtain the axial force, shear force and bending moment in the DIP tap-water pipe. The block element and shell element are different attributes. Therefore, the contact behaviour has to be experienced to bond these two different types of elements. [4]

Results of finite element calculation

The DIP tap-water pipe is buried at 5m beneath ground surface. The configuration and finite element mesh in numerical calculation is given in Figure.-7. Based on the engineering parameter given in Table-1, the FEM numerical approach reveals that the soil liquefaction results in around 8cm ground settlements. The results of numerical calculation are depicted as follows

Except for the DIP tap-water pipe located at boundary between liquefied and the non-liquefied zone, the displacement of tap-water pipe presents uniform since the thickness of the liquefaction layer is uniform as well. The ground settlement and DIP's deformation due to liquefaction are given in Figure-8, which shows that large settlements will occur in the range of liquefaction area. Moreover, the liquefaction settlement will affect a nearby range where the DIP tap-water pipe will be subjected to an extra elongation and will lead to an extra axial force and bending moment.

In this study case, the thickness of loose sand is 8m. The DIP tap-water pipe is buried at 5m below ground surface. The numerical analysis shows that the liquefaction settlement is around 0.8cm.. The DIP subsidence derived from liquefaction will stretch and twist the DIP tap-water pipe rested on the border of liquefied and non-liquefied zone.

Examination of rotation angle and elongation in ductile cast iron pipe (DIP)

Earthquake shaking will generate excess pore water pressure and even cause soil liquefaction. After earthquake, the dissipation of excess pore water pressure will lead to a ground subsidence.

The DIP tap-water pipe located not at the liquefaction zone would not be damaged. However, the DIP tap-water pipe may be damaged if the pipes are rested on the liquefaction area. The larger ground settlement will result in a more severe damage to DIP tap-water pipes, in particular, when the DIP tap-water pipes are located at the boundary between liquefied and non-liquefied areas. The numerical calculation shows that the DIP tap-water pipe located inside the liquefaction zone presents an uniform deformation. Nevertheless, the DIP tap-water pipes will undertake a serious distortion if the pile is located at border of liquefied and non-liquefied areas.

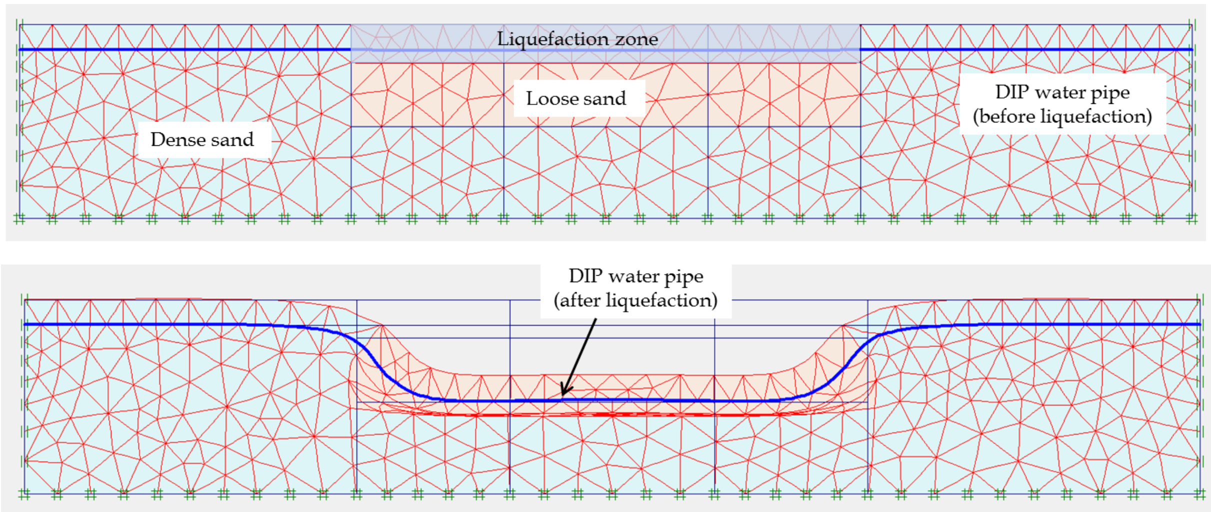

Figure.-8 Deformation of DIP tap-water pipe before and after earthquake

The ground settlement will draw the tap-water pipes. The shape of pipe elongation due to pulling out presents a similar to that of hyperbolic secant curve, as shown in Figure.-9. The rate change of elongation indicates the bending angle of DIP tap-water pipe and it looks like a similar to Gauss curve, as shown in Figure.-10. The overall shape of the stretched tap-water pipe looks like a hyperbolic secant curve. The largest deformation and bending angle of the tap-water are all at in the middle of the stretched curve. In general, a larger liquefaction settlement will cause a more severe elongation and bending angle in DIP tap-water pipes. Accordingly, the axial elongation and bending angle due to the large settlement derived from liquefaction have to be calculated to examine whether the liquefaction will cause the damage to the DIP tap-water pipe.

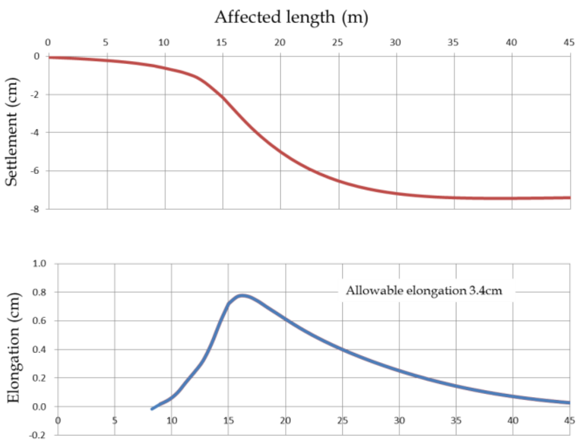

Figure.-9 Elongation of DIP tap-water pipe

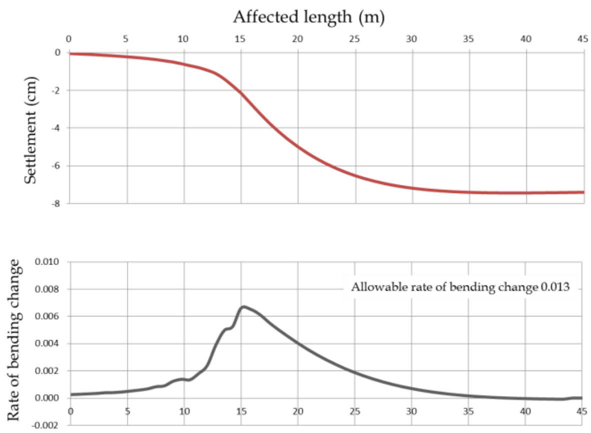

Figure.-10 Bending angle of DIP tap-water pipe

In accordance with the engineering properties of DIP tap-water pipe, the allowable amount of expansion/compression is 1.7cm if the safety factor 2 is taken into account. The numerical calculation shows that the elongation of DIP tap-water pipe resulted in liquefaction settlement is only 0.8cm, which has no exceeding the allowable limit, as shown in Figure.-9. Similarly, the rate change of bending is about 0.0075, which is much less the allowable limit of 0.013. Consequently, the liquefaction settlement is not large enough in the above calculation so that it needs not to install the flexible joint to absorb the large deformation. [5]

Installation of flexible joints if necessary

In this study the liquefaction thickness is 8m below the ground surface and the settlement after earthquake is only about 8cm. It displays no harm to the existing tap-water pipes. However, the liquefaction settlement may result in damage to the tap-water pipe if the liquefaction thickness is large enough. Usually, a larger liquefaction thickness corresponds to a greater ground settlement and the DIP water-pipe will be subjected to a stretch displacement, which will lead to an extra axial force and bending moment on tap-water pipe. To reduce the extra force on tap-water pipes, flexible joints are suggested to be installed to absorb the stretch displacement of water-pipe. In general, the stretch displacement takes place amid the border between the liquefied and the non-liquefied zone and the shape of the stretch displacement presents a similar to the Gaussian curve, as shown in Figure.-9&10. The most elongation of water-pipe is at the middle of the stretch range so that the function of the flexible joint can be fully developed if the flexible joint is installed in the middle of the stretching range.

Conclusions

- The location of ground water below the ground surface will dramatically affect the liquefaction potential of soil.
- The loose sand can easier generate pore water pressure and cause a larger settlement. Also, a greater liquefaction thickness will cause a larger ground settlement.
- To avoid the difficult selection of soil spring parameters in the calculation of soil-structure interaction, it has been suggested that soil and water-pipe shall be simultaneously considered in the three-dimensional numerical calculations.
- The larger ground settlement will result in a more severe damage to DIP tap-water pipes, in particular, when the DIP tap-water pipes are located at the boundary between liquefied and non-liquefied areas.
- Except for the bending of DIP, it also needs to examine the amount of DIP elongation. The flexible joint can absorb the DIP elongation and reduce the bending of DIP.
- The most elongation of water-pipe is at the middle of the stretch range so that the function of the flexible joint can be fully developed if the flexible joint is installed in the middle of the stretching range.

REFERENCES

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[5] *A case study on the deformation behavior of pipe-in-pipe subjected to a fault displacement* detailed report, Dept. of Geotechnical Engineering, CECI, 2012