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SEISMIC RESISTANCE OF WATER-SUPPLY PIPE IN THE TRANSVERSE DIRECTION DUE TO THE DIAMETER EFFECT

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Abstract

Since majority of water-supply pipes are small-diameter pipes, the influence of external force on the cross section is considered to be small, and they have not been fully studied so far in seismic design. On June 18, 2018, an earthquake in northern Osaka, Japan with a maximum seismic intensity of 6 on the JMA scale occurred. Although the earthquake was a relatively small earthquake with M6.1, water supply to large-diameter pipes was damaged and water supply to the surrounding residents was stopped. Damage to other infrastructure such as roads and railways was minor. Even in buried water and gas pipes, damage to small-diameter pipes was minor. In addition, there was almost no damage such as joint disconnection, which is a general earthquake damage of pipeline. The damage to ductile cast iron pipe with a large diameter of 800 to 900 mm was significant having large cracks on the pipe body. The several factors were considered: the tensile strength was not as high as the current one because it was an early period of transition from cast iron pipe to ductile cast iron pipe. The pipe thickness was not constant due to external corrosion. Abnormal water pressure in the pipe occurred during the earthquake.

With respect to the seismic resistance of the cross section of the water-supply pipe, as the diameter becomes large, the seismic response of pipe is more affected by seismic ground displacement and water pressure. According to the study of the sewer pipe considering diameter effect, it was confirmed that the smaller diameters are more prone to slip between pipe and ground and so large diameter pipes with a diameter of 800 mm or more are less likely to cause slip, and are more susceptible to the effects of seismic external forces generated in the cross-section. The objective of this study is to clarify the diameter effect of seismic resistance in the cross-section of water-supply pipe by the seismic coefficient method.

Under the same buried depth of pipes, the generated section forces of the pipes with different dimeter were compared between the case with joint element and the case without the joint element. As far as the analytical conditions assumed in this study, the effect of peripheral shear stress was not remarkable. The edge stress of cross section of the pipe became large if the diameter of pipe is more than 500 m. It is considered that seismic resistance check of cross section is necessary for the pipe with the dimeter more than 500 m.

Keywords: buried pipe; seismic resistance, diameter effect

1. Introduction

Since majority of water-supply pipes are small-diameter pipes, the influence of external force on the cross section is considered to be small, and they have not been fully studied so far in seismic design. On June 18, 2018, an earthquake in northern Osaka, Japan with a maximum seismic intensity of 6 on the JMA scale occurred. Although the earthquake was a relatively small earthquake with M6.1, water supply to large-diameter pipes was damaged and water supply to the surrounding residents was stopped. Damage to other infrastructure such as roads and railways was minor. Even in buried water and gas pipes, damage to small-diameter pipes was minor. In addition, there was almost no damage such as joint disconnection, which is a general earthquake damage of pipeline. The damage to ductile cast iron pipe (DIP) with a large diameter of 800 to 900 mm was significant having large cracks on the pipe body. According to the report of the Osaka Regional Water Supply Corporation[1], several factors were considered: (1) the tensile strength was not as high as the current one because it was an early period of transition from cast iron pipe to ductile cast iron pipe. (2) The pipe thickness was not constant due to external corrosion. (3) Abnormal water pressure in the pipe occurred during the earthquake.

The damaged DIPs had been used for more than 50 years, and the pipe body was severely corroded. Generally, DIPs have high strength and high toughness. However, according to a report from the Japan Ductile Iron Pipe Association, it was found that the manufacturing method of the damaged pipe was different from that of the current one, and a part where spheroidal graphite was not formed well led to a decrease in strength. Moreover, the pipe thickness was not constant due to external corrosion. Moreover, it was found that the pipe thickness was under the standard value due to corrosion even at the fracture surface and other than the fracture surface. Regarding to the abnormal water pressure, the characteristics of this seismic ground motion were analyzed, and the hydraulic pressure in the pipe was calculated using a logical formula and estimated that a total of 3.48 MPa was acting in the pipe during the earthquake.

Although the external force in the cross-sectional direction is not considered as the main factor in the report, most of the pipes damaged at the earthquake are large-diameter pipes. With respect to the seismic resistance of the cross section of the water-supply pipe, as the diameter becomes large, the seismic response of pipe is more affected by seismic ground displacement and water pressure.

As a study on underground pipes, Takada et al.[2] evaluated the peripheral shear stress of a circular pipe cross section, which is not considered by the current seismic calculation method (response displacement method), and they conducted a comparison between pipe responses by the response displacement method and those by the seismic coefficient method. The latter is a quasi-dynamic FEM analysis method. Joint elements that can take into account slippage and separation that may occur in the pipeline and ground were introduced. It was clarified that the larger the diameter, the greater the effect of the peripheral shear force. As a study of the diameter effect on the peripheral shear stress of underground structures, Sato et al.[3] found that the effect of the peripheral shear stress was examined by the seismic coefficient method, focusing on the difference in the effect of the size of the structure. The increase in local strain in the ground around the pipe is larger as the pipe diameter is larger, and the smaller the diameter is, the smaller the amount of strain in the surrounding ground is, and the greater the shear force acting on the joint element is. In addition, comparing the case where slip / separation was considered with the joint element and the case where the slip / separation was not considered, the bending moment and shear force were reduced by providing the joint element only for small-diameter pipes. The sectional forces were almost the same regardless of the presence or absence of joint elements. Morisaki et al.[4] conducted a comparative study on the diameter effects of the peripheral shear stress using sewer pipes, considering parameters such as ground conditions, diameter sizes, burial depth, and the presence or absence of slipping / separation effects. Then, the difference in the effect of the pipe diameter was determined by the seismic coefficient method. The sliding phenomenon due to the size of the pipe diameter tended to occur in the case of small diameter. Regarding the generated cross-sectional force, the smaller the pipe diameter, the smaller both the axial force and the shearing force due to the slip of the circumferential surface of pipes. When the generated shear force decreased below 800 mm in diameter, the rate of decrease was almost constant. In the case of small diameter, it is necessary to consider slip and peel between ground and structure.

It is thought that the influence of external force on a cross section of pipe is small because most of the water pipes are small-diameter pipes. Even in the earthquake, the above-mentioned report did not consider the external force in the cross section as the main factor. However, most of the damaged pipes are large-diameter pipes and the seismic resistance in the cross section of the water pipe is larger. The objective of this study is to clarify the diameter effect on the seismic resistance of water pipeline by the seismic coefficient method.

2. Calculation Method on a Cross Section of Pipe by Seismic Coefficient Method

The response displacement method, which is generally used as a seismic calculation method for buried pipelines, supports a structure with a tangential spring and a normal spring that represent the interaction between the ground and the structure. By applying these loads to the structure, such as inertial force and hydrodynamic pressure caused by ground shear stress and the ground displacement, response such as displacement and section force generated in the structural members are obtained. On the other hand, the seismic coefficient method enable to calculate seismic response by applying the inertia force of the ground to an overall model of the ground-structure system modeled by two-dimensional finite element etc.

Buried pipes are generally longer in the axial direction of the structure than the outer circumference of the cross section, and their apparent weight is relatively lighter than the surrounding ground. It is considered that the pipe does not vibrate independently and is governed by the movement of the surrounding ground. Therefore, the response displacement method that reflects the response characteristics of the ground has been used in seismic design of buried pipelines. By the way the beam-spring model in the response displacement method is unable to represent the nonlinearity of the surrounding ground.

2.1 Analysis cases

The target buried pipe is a DIP (JDPA G 3004) [5] and its characteristics are shown in Table 1. In order to study from the relatively small diameter of pipes to the large diameter, six types of nominal diameters of 75, 100, 250, 500, 900 and 1500 mm were used. The pipe with 900 mm in diameter is the one damaged in the earthquake. The nonlinearity of the pipeline material was not considered in this study. Young modulus of DIP is 1.6×10^6 kN/m^2 and unit weight is 70.7 kN/m^3.

Table 1 – Ductile cast iron pie (JDPA G 3004)

Nominal diameters	ϕ 75	ϕ 100	ϕ 250	ϕ 500	ϕ 900	ϕ 1500
Outer diameter (mm)	93	118	272	528	939	1554
Thickness (mm)	7.5	7.5	7.5	9.5	15	23.5

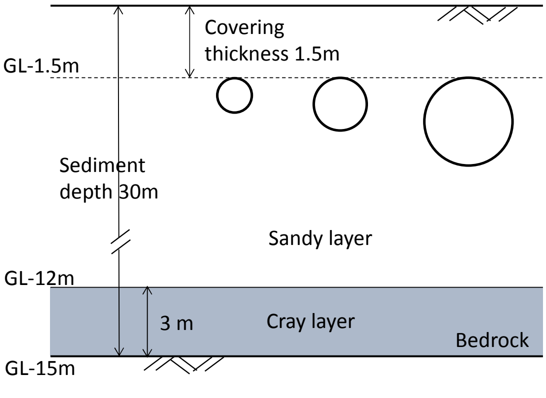


Fig.1– Schematic model of pipe-ground system

Table 2 – Parameters of ground

Layer	Vs (m/s)	Unit weight (kN/m^3)	C (kN/m^2)	ϕ (deg)
Sandy	72	16.7	0	30
Cray	135	16.7	38	0

Analytical model is set as shown in Fig.1. The sediment is 15 m in depth and composed upper sandy layer with 12 m and lower cray layer with 3 m. The covering thicknesses of pipes are the same as 1.5 m. The ground condition is assumed as listed in Table 2.

2.2 Modeling

The cross section of the buried pipe is modeled in two-dimension in order to use the seismic coefficient method. Generally, structural members are modeled using beam elements, and the ground is modeled using continuum elements such as ground springs or plane strain elements that support the structure. During an earthquake, the cohesion between the ground and the structure is not so high that there is a possibility of slip and separation between the ground and the pipe. Considering this phenomenon, the section force generated in the pipe may change. Therefore, in order to represent the behavior of this discontinuous surface is represented by the finite element method, a bilinear joint element having nonlinearity was used. For the yield stress of the shear spring, the Mohr-Coulomb failure criterion was adopted. The values of c and tanφ used in this case are shown in Table 2. The normal spring was set so that the compression region was linear and the tension region was separated in which its stress was zero. The ideal configuration of the contact surface is to make the spring constant infinite, but this involves difficulties in numerical calculations. The finite spring constant is set to be as large as possible. The pipe is divided into 36 beam elements and edges of each beam is arranged with these ground springs.

The sediment and pipe is modeled as shown in Fig.2 and Fig.3. The bottom boundary of the sediment model is assumed to be fixed, and its side boundary is assumed to be lateral roller. The sediment near the pipe is divided into small mesh. Analytical model of sediment has enough length from the side boundary. The ground stiffness is assumed to be a linear analysis except the joint element above mentioned. The pipe stiffness is also a linear analysis. In addition, a study was conducted using the ground as a non-linear material.

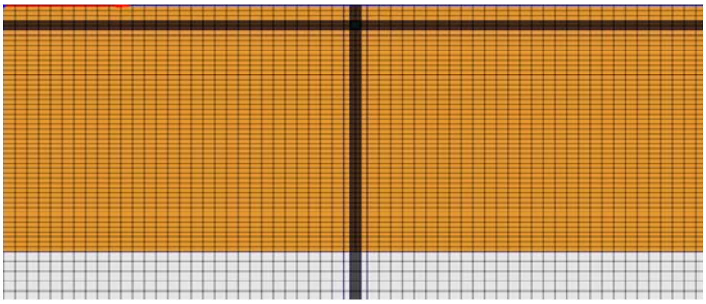


Fig. 2 – Analytical model by FEM

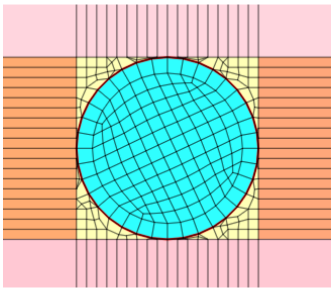


Fig.3 – Analytical model near pipe

2.3 Loads

The seismic load used in the response seismic intensity method was calculated by one-dimensional seismic response analysis. The ground stiffness and damping are equivalent linear model. Fig. 4 shows the time history of input ground motion. This is level 2 seismic motion for rock used for the seismic design of bridge in Japan and input at the bedrock. The acceleration distribution to the depth is determined by the acceleration at the time when the maximum relative displacement between the upper and lower level of the pipe is obtained as shown in Fig.5. The acceleration distribution was input using the load increment method in order to consider the nonlinearity of slip and separation between pipe and ground.

The load due to internal water pressure is determined from the guideline on the maximum operating pressure of the general distribution pipe as 0.74 MPa. This is an allowable value from the viewpoint of protection of the water supply equipment currently used. The pressure is applied to the beam element of pipe to the normal direction.

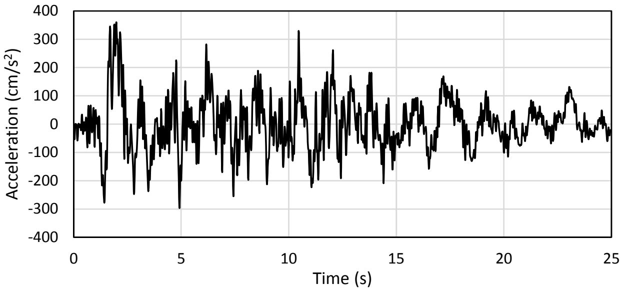


Fig.4 – Input seismic motion

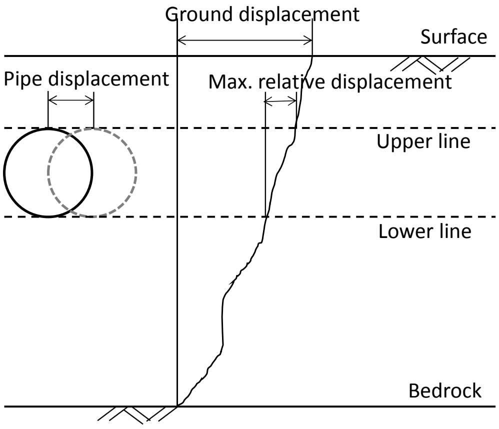
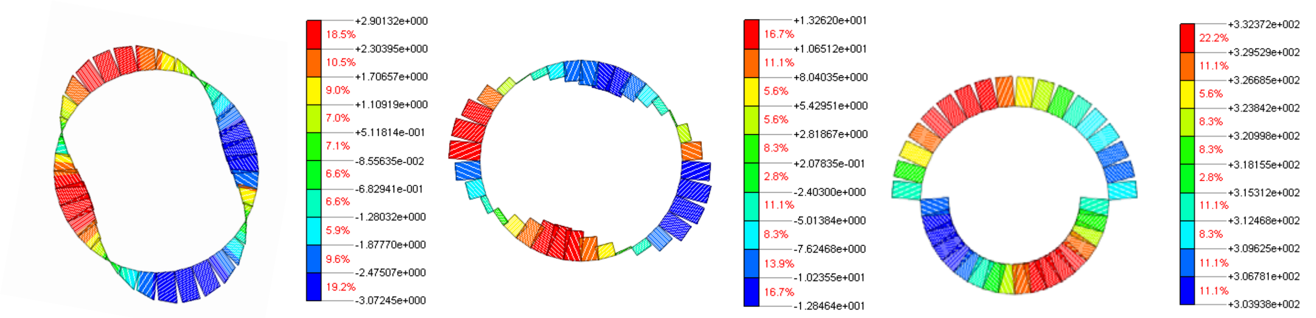


Fig.5 – Concept of max. relative displacement

3. Calculation Results

3.1 Section force

Fig. 6 shows an example of the distribution of the axial force, shear force and bending moment in section force distribution for the case of a pipe diameter of φ900 with joint element. The bending moment and shear force are dependent to the lateral seismic inertia force, while the axial force is dependent to the water pressure.



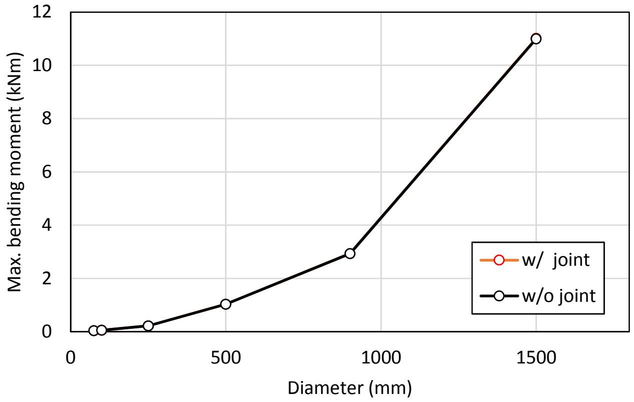
(a) Bending moment (b) Shear force (c) Axial force

Fig.6 – Section force distribution of the case of pipe diameter of φ900 with joint element

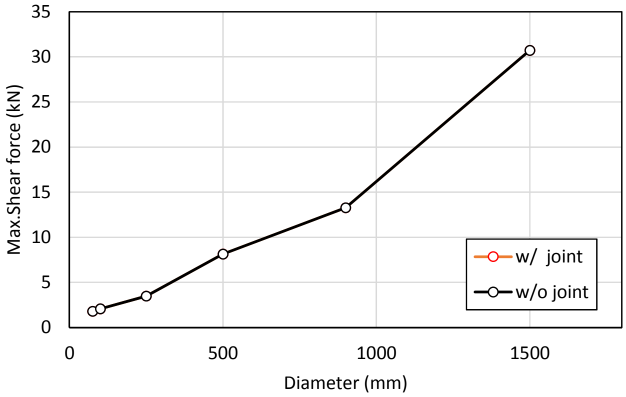
3.2 Effect of shear stress due to diameter

In seismic coefficient analysis, the ground condition and pipe diameter were changed. The case where slip and separation between the pipe and the ground were not taken into account is hereinafter referred to as "without joint" and the case considered is hereinafter referred to as "with joint". Fig.7 shows the maximum bending moment, shear force and axial force to the nominal diameter with and without the joint consideration. The maximum section forces increase to the diameter. The maximum bending moment and maximum shear force gives the same responses between the cases with and without the joint element and the effect due to the shear stress is not effective. The difference from the previous studies [3][4] is that the buried depth of water pipe in this study is close to the surface. The relative displacement of ground provided by the inertia force became smaller.

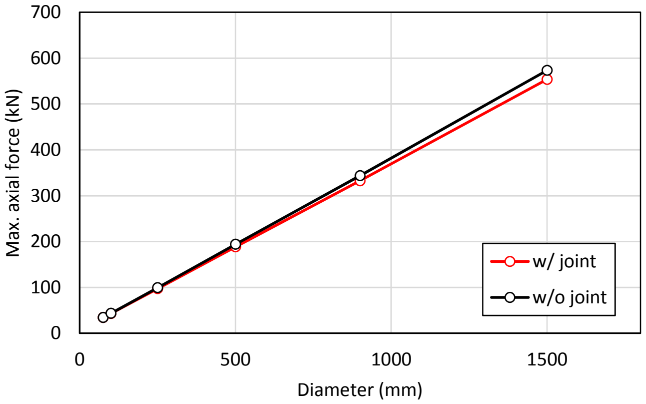
The maximum axial force of the case with the joint element is smaller than that of the case without the joint element, though slightly. The ratio of the generated axial force with the joint to the generated axial force without the joint (hereinafter referred to as the reduction ratio) is range from 96.5% to 99.3%. As the pipe diameter increases, the reduction ratio decreases. In case of water pipe, since the buried depth is shallow, it is considered that the effect of peripheral shear stress is so much to the response.



(a) Maximum bending moment



(b) Maximum shear force



(c) Maximum axial force

Fig.7 – Maximum section force to the diameter of pipe in the cases with and without the joint elements

3.3 Diameter effect of edge stress

The safety to the seismic loads of pipe is checked by the edge stress. The tensile stress at the outer edge of pipe was calculated as shown in Fig.8. The maximum edge stress increases as the pipe diameter increases and the maximum edge stress of the pipe with diameter more than 500 mm becomes around 100 MPa. The tensile strength of DIP is 420 MPa. Though there is safety margin for the seismic load and water pressure given in this study, it is better to check the seismic performance in the cross section of pipe if the diameter is more than 500 mm.

Mentioned above, the water pressure at the earthquake was estimated to be 3.5 MPa, as large as 4 times of that assumed in this study. The tensile strength of damaged pipe was also lower than current specification. Under the consideration of these condition, the large dimeter pipe becomes danger. Since the large-diameter pipe is the core pipeline in the pipeline network, it is necessary to check the seismic resistance in the cross section.

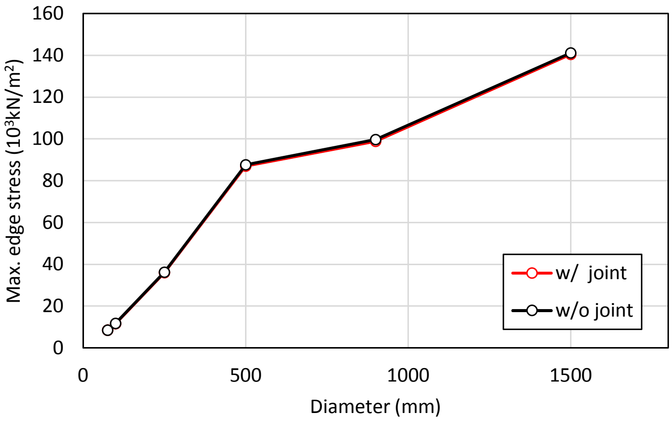


Fig.8 – Maximum edge stress to the diameter of pipe in the cases with and without the joint elements

4. Conclusive Remarks

This study aims to clarify the diameter effect of seismic resistance in the cross-section of water-supply pipe by the seismic coefficient method. Under the same buried depth of pipes, the generated section forces of the pipes with different dimeter were compared between the case with joint element and the case without the joint element. Followings can be summarized as conclusions.

- As far as the analytical conditions assumed in this study, the effect of peripheral shear stress was not remarkable.
- The edge stress of cross section of the pipe became large if the diameter of pipe is more than 500 m. It is considered that seismic resistance check of cross section is necessary for the pipe with the dimeter more than 500 m.

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