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SWIFT ALGORITHM TO PREDICT SEISMIC RESPONSES OF EXTENSIVE BURIED DISTRIBUTION NETWORKS

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SUMMARY

A swift and accurate algorithm is proposed which can simulate nonlinear behavior of a distribution network composed of welded pipes and fittings and subjected to temporary ground deformation. The distribution network is idealized with several segments defined by a straight element and two boundary elements. A nonlinear solution is derived to express longitudinal deformation of the straight element taking into account the relationship of reaction and displacement of the boundary elements. The relationships are obtained with FEA and the results are stored in a database. The nonlinear deformation of the segment can be solved shortly using the nonlinear solution and referring the database. Accordingly the algorithm brings swiftness of design formulas and preserves accuracy of finite element analysis. The algorithm can solve as many as ten thousand segments for a while during the FEA deals with one.

INTRODUCTION

The way of improving seismic integrity of gas and water distribution networks to withstand temporary ground deformation is of a significant interest for lifeline earthquake engineers. In order to perform proper seismic diagnosis to ensure the seismic integrity of the network, responses of the network should be evaluated appropriately. It is generally recognized that FEA is versatile and effective to solve nonlinear deformation of the network subjected to the temporary ground deformation, however, the FEA requires sophisticated expertise and sometimes results in unexpected expenses. Therefore a swift and versatile simulation method is required, which is applicable to evaluate the integrity of the distribution networks.

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A swift and accurate algorithm is proposed in this paper, which method is applicable to simulate nonlinear behavior of a distribution network composed of welded pipes and fittings and subjected to temporary ground deformation [1][2][3]. The distribution network should be idealized with segments defined by a straight element and two boundary elements. The straight element, a straight pipe, has two boundary elements at the both ends, each of which involves a fitting and one or two straight pipes connected to the fitting. A nonlinear solution is derived to express longitudinal deformation of the straight element considering the relationship of reaction and displacement of the boundary elements. The relationships are obtained with FEA and the results are stored in a database. The nonlinear solution for the segments is represented in terms of two unknown parameters, displacements at the both ends of the straight element, therefore the nonlinear deformation of the segment can be obtained shortly through an iterative procedure.

The proposed algorithm provides swiftness of design formulas and preserves accuracy of finite element analysis as the nonlinear solution has only two unknown parameters and the database is made up with information obtained with the FEA. The proposed algorithm can solve as many as ten thousand segments for a while during the FEA deals with one segment. The solutions obtained by the proposed algorithm present quite good agreements compare with those obtained by the FEA, and the discrepancies between them are less than several percent. Therefore the proposed swift algorithm enables us to predict the seismic integrity of the distribution network, brings sufficient information for us to perform seismic diagnosis for the distribution network, even which distribution network spreads over an extensive area.

RESPONSE AND SEGMENTATION OF DISTRIBUTION NETWORK

Response of a Distribution Network to Temporary Ground Deformation

Figure 1 presents a small part of the distribution network with the horizontal length of 100 m and the vertical length of 300 m, which network consists of continuous pipes with the nominal diameters of 150 and 200 mm. The network is deformed by surface wave with the wavelength of 200 m and is composed of straight pipes and pipe bends and tee branches as shown in the figure. FEA using beam elements was performed to obtain responses of the entire network to temporary ground deformation, which responses was appropriate to those obtained by the proposed method in this paper.

Figure 2 shows a schematic illustration of Segment-1 and a traveling wave propagating the straight pipe. Segment-1 consists of the straight pipe with the length of 100 m and two pipe bends and two straight pipes perpendicular to the straight pipe, and the outside diameters of the pipes are assumed to be 200 mm. The node of the traveling wave, with the wavelength of 200 m and the amplitude of 4 cm, locates at a quarter point of the straight pipe. As mentioned above the beam elements were applied to idealize the straight pipes and the pipe bends in Segment-1.

Figures 3 and 4 express the results obtained by FEA regarding axial force and bending moment induced in

Segment-1. Figure 3 represents the longitudinal strain distribution, which is distributed along the straight pipe, and the maximum strain of about 0.1 % is observed near the node of the propagating wave. Figure 4 presents bending strain distribution, in which the maximum bending strain of 0.1 % is observed along the straight pipes near the left hand side pipe bend. Based on the above-mentioned strain distributions, it can be recognized that the longitudinal strain distributes along the straight pipe between the pipe bends. And the bending strain distributes along the straight pipes connected to the pipe bends, which bending strain diminishes rapidly within 10 m from the pipe bends.

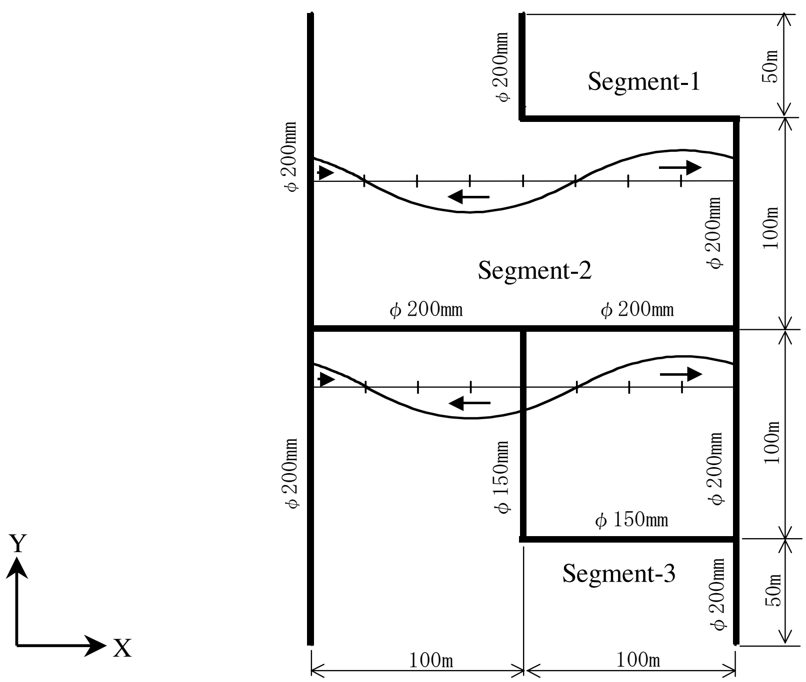

Fig. 1 A part of a distribution network consisted of straight pipes and pipe bends

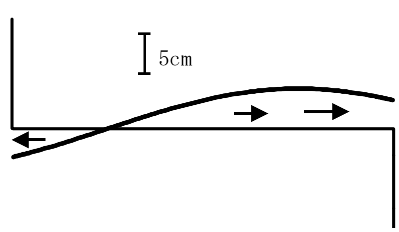

Fig. 2 Segment-1 and traveling wave with the wavelength of 200m propagating along the segment

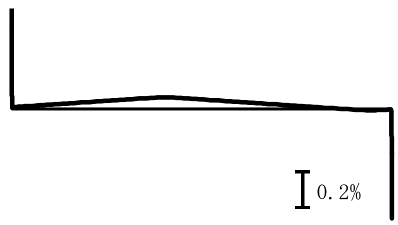

Fig. 3 Longitudinal strain distribution in Segment-1

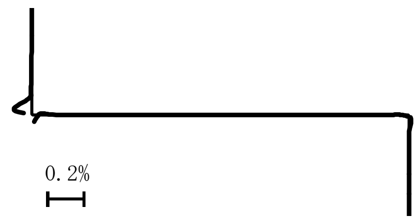

Fig. 4 Bending strain distribution in Segment-1

Definition of Segments to Idealize the Distribution Network

Segment-1 and two other segments, Segment-2 and Segment-3, are presented in Fig. 5, which can be defined in order to investigate the responses of the network due to the traveling waves. The components of Segment-1 are already mentioned above. Segment-2 consists of a straight pipe and two tee branches and Segment-3 is composed of a straight pipe and a pipe bend and a tee branch.

Similar responses to Segment-1 were observed for Segment-2 and Segment-3, which were obtained regarding the FE model of the entire distribution network as mentioned above. In other words, it is recognized that the deformation of Segment-1 does not affect those of Segment-2 and Segment-3. Namely the deformation of one segment does not propagate to the other two segments, and the deformation of each of the segment is independent each other. Therefore we can obtain the responses of the network with sufficient accuracy by solving each of the segments separately instead to solve the entire distribution network.

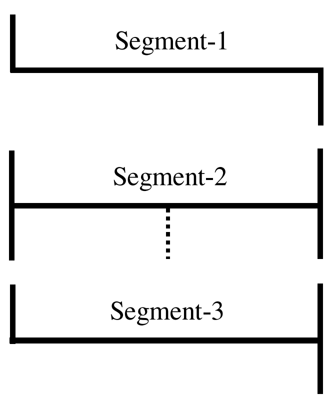

Fig. 5 Definition of network segments to idealize the pipeline network

ALGORITHM TO SOLVE RESPNSE OF SEGMENT

Description of the Response of a Segment

The simulation procedure to solve deformation of the network segments can be explained as follows taking Segment-1 presented in Fig. 1 for example. The top figure in Fig. 6 illustrates Segment-1, along which a seismic wave is propagating, and the amplitude of ground displacement in the longitudinal direction is written as U_h. The middle figure shows an analytical model of the segment, where the pipe bends and the straight pipes connected to the bends are represented by nonlinear springs. Therefore the nonlinear springs are recognized to be boundary elements of the straight element, the straight pipe. And the bottom figure represents external forces acting on the straight element in the longitudinal direction, which are friction forces induced by the pipe-soil interaction and reaction forces associated with the corresponding boundary elements.

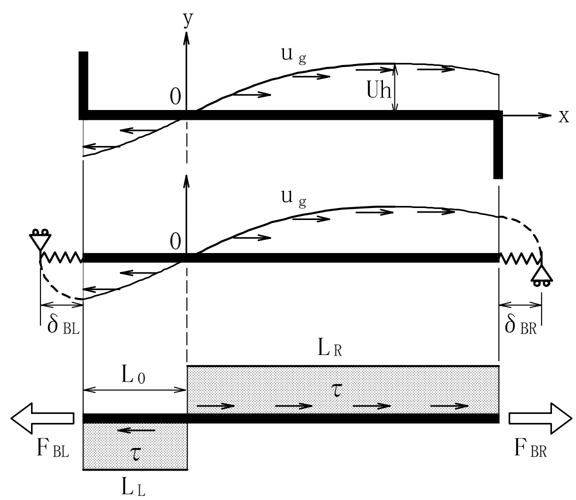

Fig. 6 Analytical model of a network segment

Assumptions for Derivation of Fundamental Solution

The following assumptions are taken into account to derive the fundamental solution of the network segments.

- **Stress-strain relationship of pipe**

  The stress-strain relationship for the pipe is assumed to be a Round-House model which can be represented by the following Ramberg-Osgood formula [4].

$$\varepsilon = \frac{\sigma}{E} + \frac{\alpha\sigma_0}{E}\left(\frac{\sigma}{\sigma_0}\right)^N \tag{1}$$

  Where E represents Young's modulus and σ_0 represents yield stress correspond to specified stress at 0.5 % strain. The parameters α and N are the R-O constants depend on hardening property of materials.

- **Pipe-soil interaction**

  A rigid-perfectly plastic soil spring and an elastic-perfectly plastic soil spring are assumed in the longitudinal and the transverse directions, respectively [5].

- **Temporary ground deformation**

  Temporary ground deformation to be introduced in the fundamental solution is expressed by surface waves [5], in which the direction of the ground displacement is parallel to that of wave propagation. The temporary ground deformation is represented by a design spectrum in the Seismic Design Codes for High-Pressure Gas Pipelines in Japan (2000) [5] and the surface wave is assumed to propagate along a buried pipeline.

Implicit Solution for Longitudinal Deformation of Straight Pipe

Deformation of the network segment represented in Fig. 6 can be derived as follows when the value of x is positive. Relationship between the axial force and the friction force has to satisfy equation (2) and if we substitute equation (2) into equation (1), longitudinal stress can be expressed as equation (3).

$$F_R(x) = f_\tau (L_R - x) + F_{BR} \tag{2}$$

$$\sigma_R(x) = \frac{F_R(x)}{A} = \frac{f_\tau}{A}(L_R - x) + \frac{F_{BR}}{A} \tag{3}$$

Where $F_R(x)$ represents longitudinal stress when the value of x is positive and F_{BR} expresses a reaction force from the right side boundary element. The friction force per unit length acting on the pipe can be expressed as $f_\tau = \pi D \tau$.

Longitudinal strain of the pipeline can easily be obtained as equation (4) by substituting equation (3) into equation (1) and longitudinal displacement can be represented as equation (5) after integrating equation (4). Equation (6) gives the solution regarding the longitudinal displacement which was derived from equations (5) and (4). Substituting $x = 0$ into equation (6), we can obtain equation (7) and the equation represents longitudinal displacement at the origin. If we substitute $x = L_R$ into the same equation, we can obtain equation (8) which represents the longitudinal displacement at the right side end of the pipe.

$$\varepsilon_R(x) = \frac{\sigma_R(x)}{E} + \frac{\alpha \sigma_R(x)^N}{E \sigma_0^{N-1}} \tag{4}$$

$$u_{pR}(x) = \int_0^x \varepsilon_R(x) dx \tag{5}$$

$$u_{pR}(x)=\frac{1}{EA}\left\{f_\tau(L_R-\frac{x}{2})+F_{BR}\right\}x+\frac{\alpha\left[\{f_\tau L_R+F_{BR}\}^{N+1}-\{f_\tau(L_R-x)+F_{BR}\}^{N+1}\right]}{(N+1)f_\tau EA^N\sigma_0^{N-1}} \tag{6}$$

$$u_{pR}(0)=0 \tag{7}$$

$$u_{pR}(L_R)=\frac{L_R}{EA}\left\{f_\tau\frac{L_R}{2}+F_{BR}\right\}+\frac{\alpha\left\{(f_\tau L+F_B)^{N+1}-F_B{}^{N+1}\right\}}{(N+1)f_\tau EA^N\sigma_0^{N-1}} \tag{8}$$

Furthermore, equation (9) represents reaction of the right side boundary element applied to the straight pipe. The parameter K_{BR} used in the equation represents a nonlinear spring coefficient of the boundary element that can be obtained taking into account the combined effect of the nonlinear pipe-soil interaction and the nonlinear stress-strain relationship of the pipe.

$$F_{BR}=K_{BR}\left\{u_{gR}(L_R)-u_{pR}(L_R)\right\} \tag{9}$$

The longitudinal relative displacement between the pipe and the ground can be written as equation (10), if we rewrite the equation as equation (11) and substitute that into equation (8), we can obtain a nonlinear solution as equation (12) in terms of the relative displacement δ_{BR}.

$$u_{gR}(L_R)-u_{pR}(L_R)=\delta_{BR} \tag{10}$$

$$u_{pR}(L_R)=u_{gR}(L_R)-\delta_{BR} \tag{11}$$

$$\delta_{BR}=\frac{1}{EA+K_{BR}L_R}\left[EAu_g(L_R)-\frac{f_\tau}{2}L_R^2-\frac{\alpha\left\{(f_\tau L_R+K_{BR}\delta_{BR})^{N+1}-(K_{BR}\delta_{BR})^{N+1}\right\}}{(N+1)f_\tau(A\sigma_0)^{N-1}}\right] \tag{12}$$

The unknown parameters involved in equation (12) are δ_{BR} and K_{BR}, however, we can solve the nonlinear equation as K_{BR} is dependent on δ_{BR} as shown in Fig. 7. Moreover, similar reduction to that mentioned above can be performed about the left side boundary element and the solution is written as equation (13) in terms of the left side relative displacement δ_{BL}.

$$\delta_{BL}=\frac{1}{EA+K_{BL}L_L}\left[-EAu_g(L_L)-\frac{f_\tau}{2}L_L^2-\frac{\alpha\left\{(f_\tau L_L+K_{BL}\delta_{BL})^{N+1}-(K_{BL}\delta_{BL})^{N+1}\right\}}{(N+1)f_\tau(A\sigma_0)^{N-1}}\right] \tag{13}$$

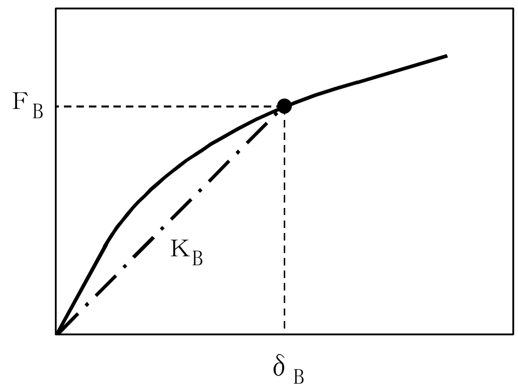

Fig.7 Force-displacement relationship of a boundary element

How to Update the Friction Zones

We can calculate the relative displacements δ_{BR} and δ_{BL} by equations (12) and (13) which are derived referring the bottom figure in Fig. 6. The corresponding reaction forces F_{BR} and F_{BL} can be expressed knowing δ_{BR} and δ_{BL}. Then we can derive an equation that satisfies static equilibrium of the network segment in the longitudinal direction.

Total amount of the external forces can be written as equation (14) and the equation gives the location of the point as equation (15) where the sign of the friction changes as shown in Fig. 8, which means the change of direction of the friction force. The variable s represented by equation (15) is a correction parameter for L_R and L_L, which shall be updated successively in accordance with equations (16) and (17).

$$F_{BR} + f_\tau L_R - F_L - f_\tau L_L = f_\tau s \tag{14}$$

$$s = \frac{F_R - F_L}{f_\tau} + L_R - L_L \tag{15}$$

$$L_{R(i+1)} = L_{R(i)} - s_{(i)} \tag{16}$$

$$L_{L(i+1)} = L_{L(i)} + s_{(i)} \tag{17}$$

After updating the neutral point where the direction of the friction force changes, the first step simulation procedure mentioned above should be conducted again in order to investigate the static equilibrium of the external forces. The first step and the above-mentioned updating procedure shall be repeated until the parameter s converges when the solution has a required accuracy. The converged value of s gives the final solution of δ_{BR}, δ_{BL}, F_{BR} and F_{BL}.

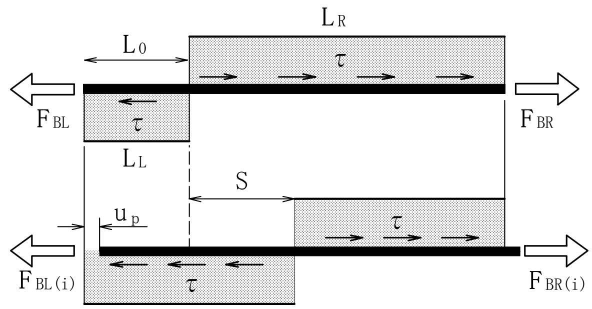

Fig. 8 Updating friction zones considering static equilibrium of external forces

VERIFICATION OF THE PROPOSED SWIFT ALGORITHM

Distribution Network Provided for Verification

In order to verify the accuracy of the results obtained by the proposed simulation method, the results are compared to those obtained by the FEA. The distribution network to be discussed in this section is represented in Fig. 9 whose geometry is the same as the small example network presented in Fig. 1. Figure 9 shows additional information regarding node numbers of the network model in order to compare the results with respect to displacement at every node. The wavelengths of 200, 300 and 400 m are considered for the comparison and the location of the surface waves are also explained in the figure. Therefore the lengths of network segments will vary in accordance with the wavelength.

Assumptions for the Verification

The stress-strain relationships of the pipes is shown in Fig. 10 and the soil springs in the longitudinal and the transverse directions were defined as Fig. 11 in accordance with the Seismic Design Codes for High-Pressure Gas Pipelines in Japan (2000) [5]. The material property and the soil springs are the same as those employed in the FEA. The relationships of the reaction force versus displacement of the boundary elements, the database for the boundary elements, were obtained by the finite element analysis and the relationships are presented in Fig. 12. The notations explained in Fig. 12 correspond to the fittings included in the boundary elements.

Verification of the Proposed Algorithm

Tables 1 through 3 compare the results obtained by the proposed method and the finite element analysis, in which longitudinal displacements at the both ends of the straight element are compared and the numbers written in the tables coincide with those presented in Fig. 9. The errors presented in the tables are calculated by dividing the discrepancies between the two methods by the results obtained by the FEA. And the signs of the calculated results in the tables represent the direction of the nodal displacement.

Very good agreements between the results of the proposed method and the finite element analysis can be observed in the tables, in which the errors vary from 0.1 % to 11.1 %. Case 2-2 gives the maximum error of 11.1 %, however, the calculated longitudinal displacement is 0.1 cm, which displacement is small enough for practical use. Besides the comparison mentioned above we can observe that some data have the error of 5 to 7 %, however, their longitudinal displacements are approximately 0.3 cm and the displacements are also enough small to neglect.

Besides the network model shown in Figs. 1 and 9, an extensive distribution network spreading over a rectangular area of 1x2 km was analyzed to compare with the efficiency of the proposed method and the FEA. The computing time of the proposed method is 1/8000 times as short as that of the finite element analysis. Taking into account the other results, the computing time of the proposed method is very short compare with the FEA, which can be estimated between 1/5000 and 1/10000. Based on the comparison with respect to the computing time, we can conclude that the proposed method is extremely swift compare with the FEA.

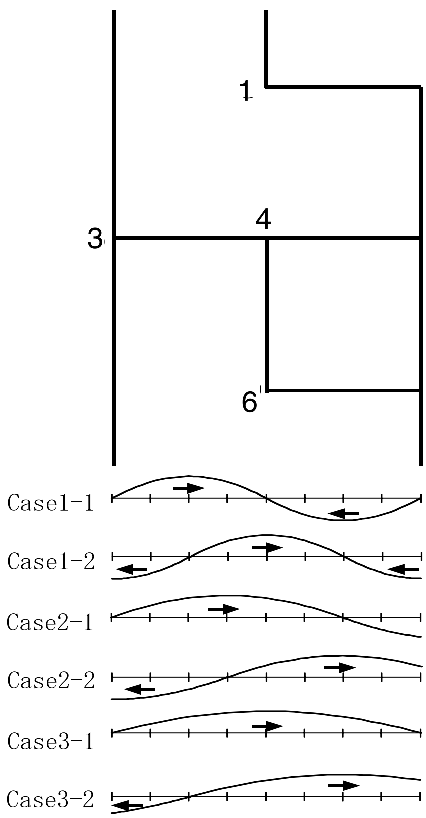

Fig. 9 Definition of nodes of the network and locations of propagating surface waves

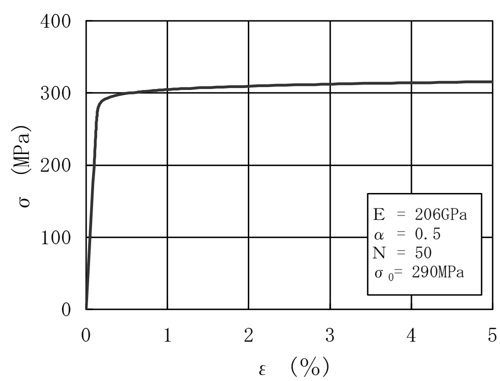

Fig. 10 Stress-strain relationship of pipes

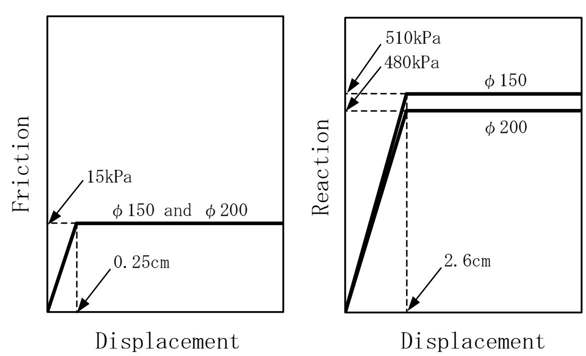

Fig. 11 Soil srings for 150mm and 200mm diameter pipes

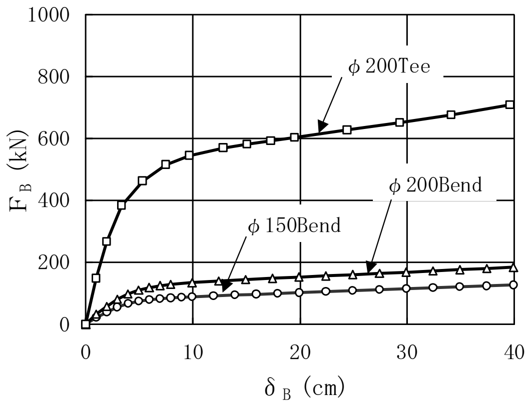

Fig. 12 Load-displacement relationship of boundary elements

Table 1 Results with wavelength of 200 m

	Case 1-1			Case 1-2		
	δ_L (cm)			δ_R (cm)		
	Proposed Method	FEA	Error (%)	Proposed Method	FEA	Error (%)
1	-10.42	-10.55	1.2	-17.59	-17.60	0.1
2	10.41	10.52	1.0	-17.59	-17.60	0.1
3	2.57	2.49	3.2	8.21	8.75	6.1
5	2.57	2.49	3.2	-8.21	-8.74	6.1
6	-7.56	-7.94	4.8	-25.94	-25.47	1.8
7	5.99	5.60	7.0	-6.60	-6.96	5.2

Table 2 Results with wavelength of 300 m

	Case 2-1			Case 2-2		
	δ_L (cm)			δ_R (cm)		
	Proposed Method	FEA	Error (%)	Proposed Method	FEA	Error (%)
1	-14.91	-14.92	0.1	5.56	5.54	0.4
2	-14.91	-14.92	0.1	-5.54	-5.55	0.2
3	5.28	5.41	2.4	12.26	12.27	0.1
5	-15.06	-14.80	1.8	-0.80	-0.90	11.1
6	-20.10	-20.04	0.3	4.76	4.74	0.4
7	-7.06	-7.02	0.6	3.09	-3.07	0.5

Table 3 Results with wavelength of 400 m

	Case 3-1			Case 3-2		
	δ_L (cm)			δ_R (cm)		
	Proposed Method	FEA	Error (%)	Proposed Method	FEA	Error (%)
1	-3.96	-3.97	0.3	11.40	11.41	0.1
2	-11.40	-11.49	0.8	3.98	4.00	0.5
3	7.51	7.89	4.8	5.98	5.94	0.7
5	-7.51	-7.88	4.7	5.98	5.94	0.7
6	-6.04	-6.03	0.2	12.11	12.09	0.2
7	-6.71	-6.54	2.6	1.63	1.64	0.1

CONCLUSION

The swift algorithm and verification of the fast simulation method are presented in this paper. The swift simulation method is applicable to analyze responses of the network consisted of continuous pipes, however, the method is also applicable to the networks consisted of segmented pipes as they behave as a continuous pipes when they undergo compressive deformation. Therefore, the proposed simulation method is effective to conduct seismic design and seismic diagnosis of various buried pipeline networks.

As for the database regarding the deformation property of the boundary element, the accuracy and the quality of the database has been confirmed because the database is constructed based on the results obtained by the FEA. The proposed fast simulation method enables us to predict deformation of an extensive distribution network very shortly maintaining the accuracy of the FEA.

Besides the boundary elements presented in this paper, the pipe bend and the tee branch, other boundary elements can be taken into account such as a pipe bend with an arbitrary bending angle and a single crank and a double crank and a loop for example. Other useful information obtained by the FEA can be stored in the database such as deformation of the straight pipes connected to the pipe bend and the tee branch for example.

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