JFE TECHNICAL REPORT
No. 8 (Oct. 2006)

Fast Simulation Method for Seismic Diagnosis of Extensive Distribution Networks†

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Abstract:

A newly-developed simulation program, NeEX, enables quick prediction of the nonlinear seismic response of buried distribution networks in gas and water supply systems, which are characterized by geometry in a complex linear form. As a key feature of NeEX, the novel algorithm which is used to simulate the seismic response of the network idealizes the network in segments. Idealization of networks in segments makes it possible to model networks using far fewer elements than in finite element analysis (FEA). While the accuracy of NeEX is on the same level as FEA, computational time is only 1/5 000–10 000 that with FEA. The high accuracy and high speed performance of NeEX in simulations enables seismic diagnosis of extensive buried distribution networks.

1. Introduction

Distribution systems of pipelines which supply gas and water cover extensive supply areas in a network form. These distribution networks have developed in a way similar to the network of streets. Because distribution networks cover an extensive area and have a complex form, simulation of seismic response by finite element method (FEM) had been considered impossible[1)].

To solve this problem, the JFE Group developed a program called NeEX (Network EXpress) which enables fast simulation of the seismic response of extensive distribution networks[2–4)]. NeEX employs a method in which the network is divided into segments and the deformation of these segments is simulated individually. A segment comprises a straight section of the network (straight element) and two fittings (boundary elements), which are connected to the ends of the straight element.

The simulation accuracy of NeEX is equal to that of FEA, but its computational speed is 5 000 to 10 000 times faster. Accordingly, while maintaining the simulation accuracy of FEA, NeEX enables quick computation of deformation of a number of segments which comprise a network. And thus makes it possible to carry out seismic diagnoses and examinations of the seismic integrity of networks in a greatly reduced time.

2. Modeling of Networks

2.1 Outline of Networks

A schematic diagram of part of a general buried pipeline network is shown in **Fig. 1**. As illustrated in this

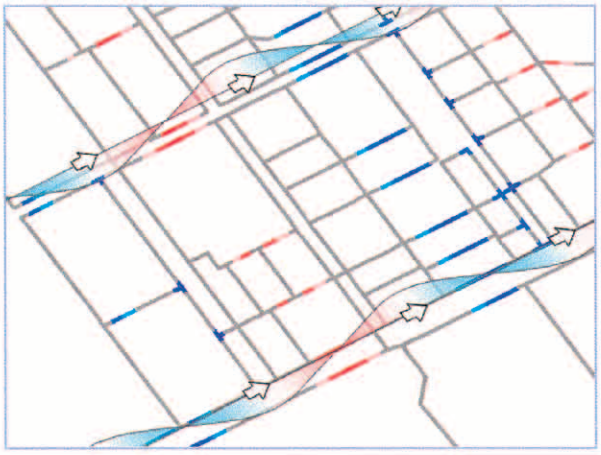

Fig. 1 A part of a distribution network

† Originally published in *JFE GIHO* No. 11 (Apr. 2006), p. 39–43

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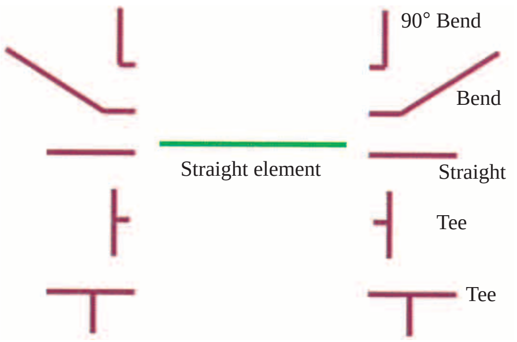

Fig. 2 Definition of segments to idealize distribution network

figure, the network comprises straight pipes and the various types of fittings, such as bends and junctions, which are used to connect the straight pipes. The figure shows a condition in which the respective parts of the network have deformed as a result of propagation of a seismic wave along the network. In deformation of a network by a seismic wave, axial deformation predominates in the straight pipe sections and bending deformation predominates in the fitting parts.

2.2 Definition of Segments

The segments shown in **Fig. 2** are defined in order to idealize the network shown in Fig. 1. A straight element is shown in the center of the segments in Fig. 2. The various boundary elements presented in the figure can be connected to two ends of this straight element, one boundary element being connected to each of the right and left ends. The boundary elements connected to the right and left ends of the straight element can be used in any desired combination.

The network in Fig. 1 can be idealized using the segments in Fig. 2. The number of segments is equal to the number of straight elements, and the boundary elements are defined as being duplicated in the adjoining straight elements.

3. Deformation Analysis of Segments

3.1 Assumptions of Analysis

The following assumptions are used in analyzing the deformation of segments.

(1) Pipe Stress-Strain Curve

A round-house stress-strain curve is adopted, and can be expressed by the Ramberg-Osgood equation[5], as follows:

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

where, E: Young's modulus, σ_0: Yield stress (In the case of API materials, stress at 0.5% strain), α, N: Ramberg-Osgood constants determined by the strain-hardening property of the material.

(2) Soil Spring Property

(a) For the soil spring property in the pipe axial direction, a solid-perfect plastic model which considers only friction force is adopted.

(b) For the soil spring property in the transverse direction, a bilineal model of an elastic-perfect plastic model is adopted.

(3) Temporary Ground Displacement

The distribution of temporary ground displacement is assumed to depend on the primary wave component of the surface wave, which was adopted in Seismic Design Codes for High Pressure Gas Pipelines (2000)[6]; the direction of wave propagation is assumed to be the pipe axial direction.

3.2 Analytical Model

As shown in **Fig. 3**, a segment having 90° bends as the boundary elements at its two ends is used as an example of the analytical model.

The upper drawing in Fig. 3 shows the relationship between the basic composition of the segment and ground displacement. The drawing in the center shows the results of modeling by simple nonlinear spring using the bends at the two ends and the straight pipe connected to the bends as boundary elements. The lower drawing expresses the fact that a certain friction force acts on the pipe because a solid-perfect plastic model is assumed for the soil spring property in the pipe axial direction.

3.3 Analysis of Segment Deformation

When expressing the deformation of the segment shown in Fig. 3, there are two unknown parameters, namely, the displacement of the boundary elements on the right and left sides, δ_{BR} and δ_{BL}. F_{BR} and F_{BL}, which

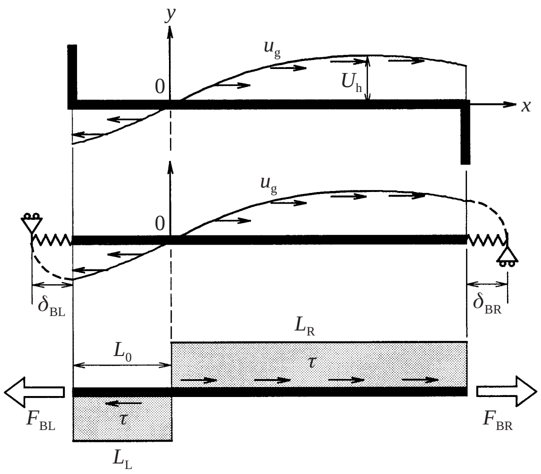

Fig. 3 Analytical model of a segment

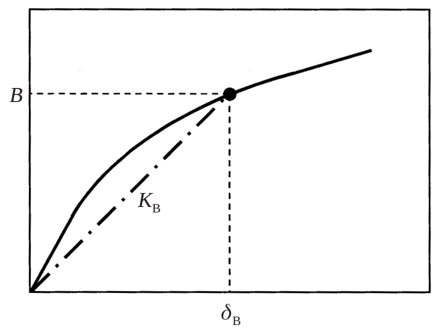

Fig. 4 Force-displacement relation of a boundary element

are the external forces acting on the straight element from the boundary elements, are functions of δ_{BR} and δ_{BL}, respectively, as will be described in the following.

If the axial deformation of the straight element is obtained and the compatibility condition and the equilibrium condition with the right and left boundary elements are satisfied, δ_{BR} can be obtained as shown in Eq. (2). Although the unknowns in Eq. (2) are δ_{BR} and K_{BR}, because K_{BR} is a function of δ_{BR}, as shown in **Fig. 4**, Eq. (2) can be solved as a nonlinear equation for δ_{BR}.

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

where, K_{BR} is a nonlinear spring coefficient expressing the deformation property of the boundary element shown in Fig. 4 and is obtained by synthesis of the nonlinear reaction property of the soil and the nonlinear deformation property of the pipe.

A similar calculation is also made for the boundary element on the left side, and the displacement of the boundary element, δ_{BL}, is obtained using the following equation:

$$\delta_{BL} = \frac{1}{EA + K_{BL}L_0}\Big[-EAu_g(L_L) - \frac{f_\tau}{2}L_L{}^2 - \frac{\alpha\{(f_\tau L_0 + K_{BL}\delta_{BL})^{N+1} - (K_{BL}\delta_{BL})^{N+1}\}}{(N+1)f_\tau(A\sigma_0)^{N-1}}\Big] \cdots (3)$$

where, K_{BL} is a nonlinear spring coefficient expressing the deformation property of the boundary element shown in Fig. 4 and is also obtained by synthesis of the nonlinear reaction property of the soil and nonlinear deformation property of the pipe.

3.4 Features of NeEX

As described in the previous section, a nonlinear solution for the deformation of the central straight element, in which the displacements of the boundary elements are the unknowns, was obtained as shown in Eqs. (2) and (3). Although this nonlinear solution is a complex equation, the solution can be converged after some iterations. Considering space limitations, a detailed explanation of the nonlinear solution will be omitted in this paper.

As the deformation properties of the boundary elements shown in Fig. 4, the relationship between axial force and displacement was obtained by FEA, and the results were incorporated in a database. Regardless of the size of the network, the types of boundary elements are basically as shown in Fig. 2. Moreover, the parameter of pipe diameter comprises at most approximately 10 types.

In calculating the deformation of a network, computational time can be shortened by avoiding redundant calculations, which is possible by using the above-mentioned DB of the deformation properties of the boundary elements. This is a distinctive feature of network deformation analysis with NeEX, and is the most important merit of the new system in seismic diagnosis of extensive networks.

4. Computational Accuracy and Speed of NeEX

4.1 Calculation Model

In order to investigate the computational accuracy and speed of NeEX, the network model shown in **Fig. 5** was created. The pipes comprising the network model have nominal diameters of 150 mm and 200 mm, and

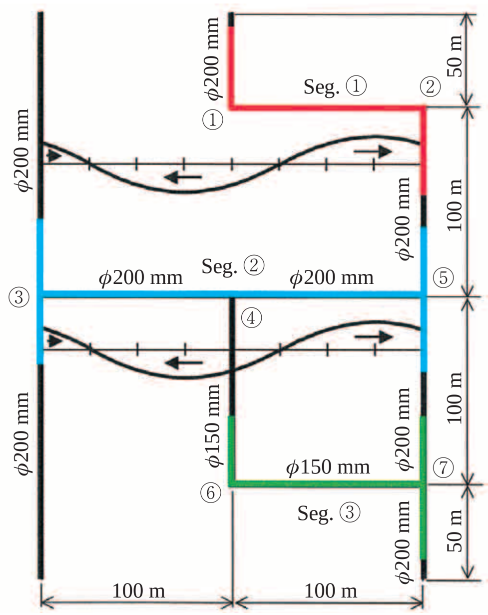

Fig. 5 Distribution network model for verification of NeEX

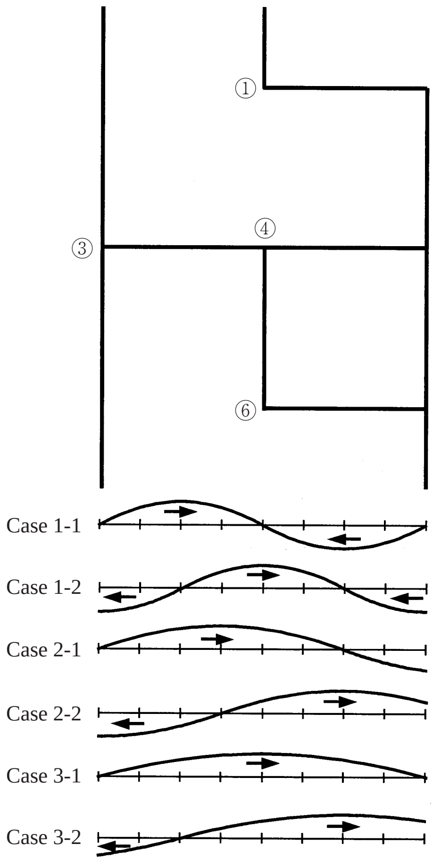

Fig. 6 Node definition of the network model and seismic waves considered for the analysis

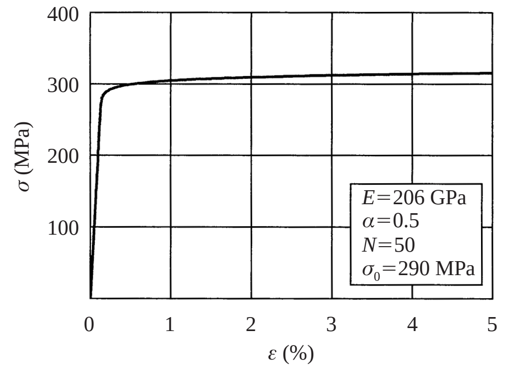

Fig. 7 Stress strain relationship of pipes

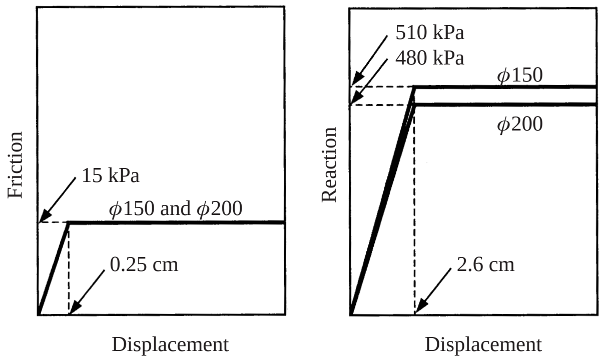

Fig. 8 Soil springs for 150 mm and 200 mm diameter pipes

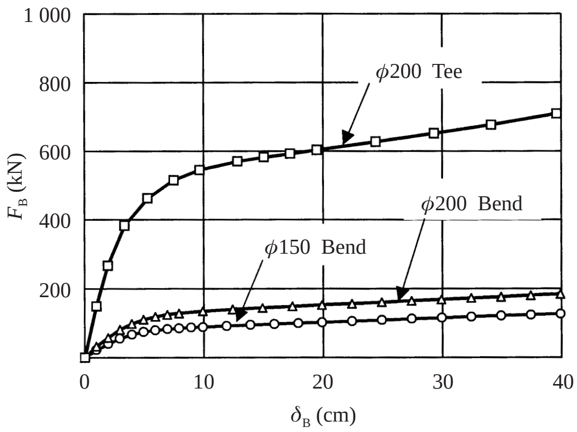

Fig. 9 Load displacement relationship of boundary elements

the basic length of the straight pipes is 100 m. The case of a wavelength of 200 m is presented, supposing wave propagation from the left to the right side of the network model.

In a case where the wave motion propagates from left to right in the network model, the network can be modeled by the three segments shown in red, blue, and green. Both boundary elements are bends in Segment ① and junctions in Segment ②; Segment ③ has one bend and one junction as its boundary elements.

Figure 6 shows the node definition of the network model corresponding to the calculation conditions, assuming three wavelengths (200 m, 300 m, 400 m) as the input ground displacement.

4.2 Calculation Assumptions

As assumptions for calculations of the deformation of the network model, the stress-strain curve of the material was set as shown in **Fig. 7**, and the soil springs were set as shown in **Fig. 8**, based on the above-mentioned Seismic Design Codes for High Pressure Gas Pipelines (2000). The nonlinear reaction properties of the boundary elements positioned at the ends of the straight pipes were obtained as shown in **Fig. 9** by finite element analysis, based on the assumed conditions in Figs. 7 and 8.

4.3 Calculation Accuracy

The calculated results for Cases 1–3 are shown in **Tables 1**–**3**. These results represent the displacement of the two ends of the straight pipes. The numbers in these tables are the node numbers in Figs. 5 and 6. The calculation error between NeEX and FEA is the absolute value obtained by dividing the difference between the FEA and NeEX results by the FEA result.

In all of these calculated results, the results obtained with NeEX show good agreement with the FEA solutions, the error being from 0.1 to 11.1%. Although the results include an error of 11.1% in ⑤ under Case 2-2,

Table 1 Examples with 200 m wave length

	Case 1-1			Case 1-2		
	δ_B (cm)		Error (%)	δ_B (cm)		Error (%)
	NeEX	FEA		NeEX	FEA	
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 Examples with 300 m wave length

	Case 2-1			Case 2-2		
	δ_B (cm)		Error (%)	δ_B (cm)		Error (%)
	NeEX	FEA		NeEX	FEA	
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 Examples with 400 m wave length

	Case 3-1			Case 3-2		
	δ_B (cm)		Error (%)	δ_B (cm)		Error (%)
	NeEX	FEA		NeEX	FEA	
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

this calculated result is considered to have sufficient accuracy, as the actual error was small, at only 0.1 cm. Examples of calculations with error on the order of 5–7% can also be seen, but considering the fact that the error was only about 0.3 cm in these cases, this is adequate analytical accuracy for practical purposes.

4.4 Computational Speed

In addition of calculations for the network in Fig. 1, calculations were also performed for a more extensive network, and the computational time was compared. The hardware used was a super computer in the FEA and a personal computer in the NeEX analysis. As a result, the computations in the analysis by NeEX were completed in 1/5 000–1/10 000 of the computational time required for the FEA.

When the response of a network in a 3 km square area was calculated using NeEX, the computational time was approximately 1 min. Calculation of the response of the same network by FEA using a mainframe computer would require 5 000–10 000 min. This means that the computer must be occupied for 3.5–6.9 days, even assuming 24-hour operation.

5. Conclusion

This paper has presented an outline of the newly-developed NeEX program, which enables high efficiency simulation of the nonlinear seismic response of buried pipe networks. The basic performance and distinctive features of NeEX can be summarized as follows.

(1) In calculations of the deformation properties of boundary elements, accuracy equivalent to that in FEA is assured by the development of a database of FEA results. As a result, calculations can be completed more quickly with no reduction in computational accuracy.

(2) As boundary elements, it is possible to consider bends of any desired angle, as well as junctions, cranks, loops free ends, etc. As a result, rapid seismic design, seismic diagnosis, and examination of the seismic integrity of extensive networks is possible.

References

1) Japan Gas Association. Seismic Design Codes for Middle and Low Pressure Gas Pipelines. 1982.
2) Suzuki, N.; Horikawa, H.; Mori,T.; Mayumi, T. Fast simulation method for dynamic responses of buried gas distribution network. 11th Symp. of JAEE. 2002.
3) Suzuki, N.; Mayumi, T.; Hosokawa, N. Seismic Diagnosis of buried gas distribution network performed with a fast algorithm of NeEX. Symp. on Gas Distribution Systems. 2005.
4) Suzuki, N.; Hasegawa, N.; Yabuguchi, T. Seismic diagnosis of extensive water distribution network. 4th US-Japan Workshop on Earthquake Resistant Design of Water Supply System. 2005.
5) Ramberg, W. ; Osgood, W.R. Description of stress-strain curves by three parameters. NACA. TN. 902, 1943.
6) Japan Gas Association. Seismic Design Codes for High Pressure Gas Pipelines. 2000.