FAST SIMULATION METHOD FOR SEISMIC DIAGNOSIS OF EXTENSIVE GAS NETWORKS

Takeshi MORI & Yoji TSUNASAWA
JFE Engineering Corporation,Yokohama,Japan

Nobuhisa SUZUKI
JFE Techno-Reseach Corporation,Kawasaki,Japan

SUMMARY:
A fast simulation program enables us to conduct seismic diagnosis of an extensive gas distribution network. A hypothetical distribution network is assumed in Kobe city to simulate the damage to buried pipelines caused by the 1995 Kobe earthquake. The simulation result was calibrated using the actual damage. Moreover another hypothetical distribution network is provided in Sendai city to simulate damage to an extensive network shortly. Three types of supposed seismic motion and one actual earthquake the 2011 Tohoku earthquake are used in this simulation; the former have each different destruction mode of fault.

Keywords: buried distribution network, seismic diagnosis

1. INTRODUCTION

Pipeline network is indispensable facilities for our life in highly developed metropolis. In case the network damaged by big earthquake it causes not only obstacles in people's lives but also harm to us such as fire. Pipeline industry, as city gas companies has been progressed quake-resistant design and preventive measures.

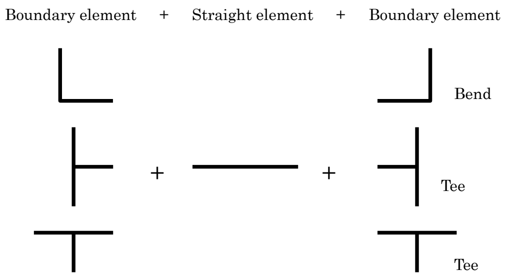
Although such effort pipeline network suffered damage due to mega-quakes such as the 1995 Kobe earthquake and the 2011 Tohoku earthquake. The risk of earthquake damage to pipeline is expected to go down in the future because of continuous improvement in quake-resistant design. Preventive measures against earthquake are essential from now on without a break. The damage estimation is required as a practical method for detecting some points to be fixed in widespread distribution network.

2. BASIC THEORY OF THE SIMULATION METHOD

In case of widespread pipeline network it takes too much time to calculate. Other general method for seismic diagnosis is the judgment at each certain zone by the law of damage estimate constructed on the case study. This method, however, doesn't specify the point where the damage will break out in that zone. That is also useless to diagnose an unprecedented massive earthquake.

The fast simulation program for seismic diagnosis is the deformation analysis of distribution network against seismic wave and the comparison with the strength of each pipe. That method makes the analysis of pipeline deformation rapidly while keeping accurate, and taking into account not only stress-strain relationship of pipe but the shapes of network or the difference of soil solidity around the buried pipe. A distribution network can be idealized with many segments which are composed of a straight line and two boundary elements (Fig.1).

Dividing the entire network into segments makes the analysis drastically quick (Fig.2). The relationship between force and displacement in each segment is obtained by FEA, and in advance results of FEA are stored in a database. As calculation condition of FEA, the nonlinear pipe-soil interaction and the nonlinear stress-strain relationship of the pipe are considered. Accuracy of the analysis is guaranteed by using the database constructed with the results of FEA.



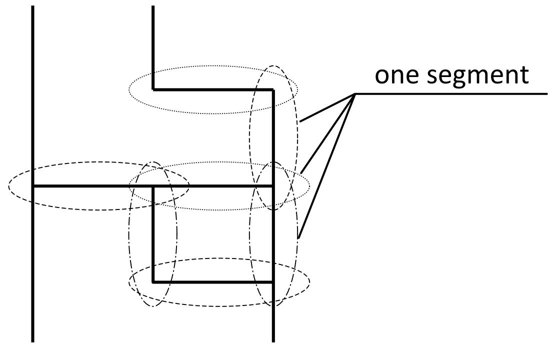


Figure 1. Definition of a segment **Figure 2.** Image of a network and segments

3. SEISMIC DIAGNOSIS OF THE HYPOTHETICAL NETWORKS

3.1. Definition of Segments to Idealize the Distribution Network

The main distribution networks, such as town gas, usually have many long straight lines. On the other hand, the lower networks below the main distribution ones spread widely to various areas. The straight line is often shorter than the seismic wavelength and the fitting pipes such as bend or tee are connected to that straight part. In this study the network is not the same shape as actually buried in urban area of Kobe city, but the imaginary shape based on the road map in Kobe city. In supposed network the straight line length is set to be shorter than the seismic wavelength and the diameter of each pipe are decided considering the typical distribution in actual network. The standard depth of pipe is to be 1.5 meter.

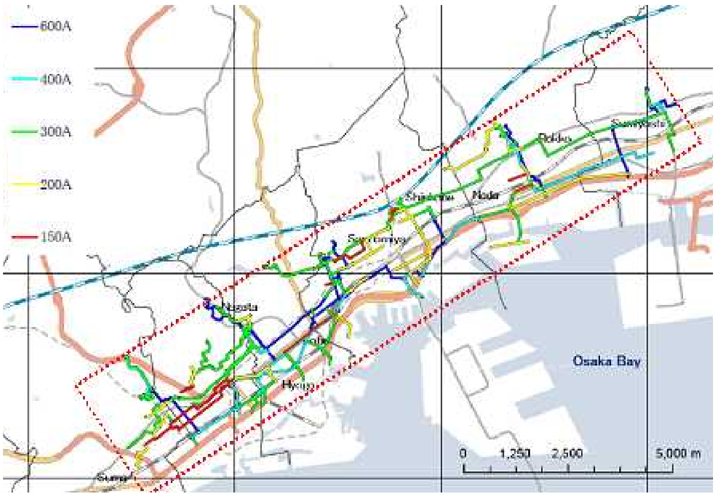


Figure 3. Hypothetical distribution network in Kobe city

Table 1. Number of the segments of the hypothetical network in Kobe city

DIA	0	100	200	300	400	500	600	700	800	900	1000	1100	1200	1800	Total
150	102	25	6	6	3	1			1	1					145
200	173	54	24	9	3	1		1		1		1		1	267
300	456	158	39	14	10	4	4	1	1				1		687
400	130	54	20	8	2	2	2	2			1		1		221
600	206	86	27	13		1	1		1	1		1			338
Total	1067	377	116	50	18	9	7	2	3	3	1	2	2	1	1658

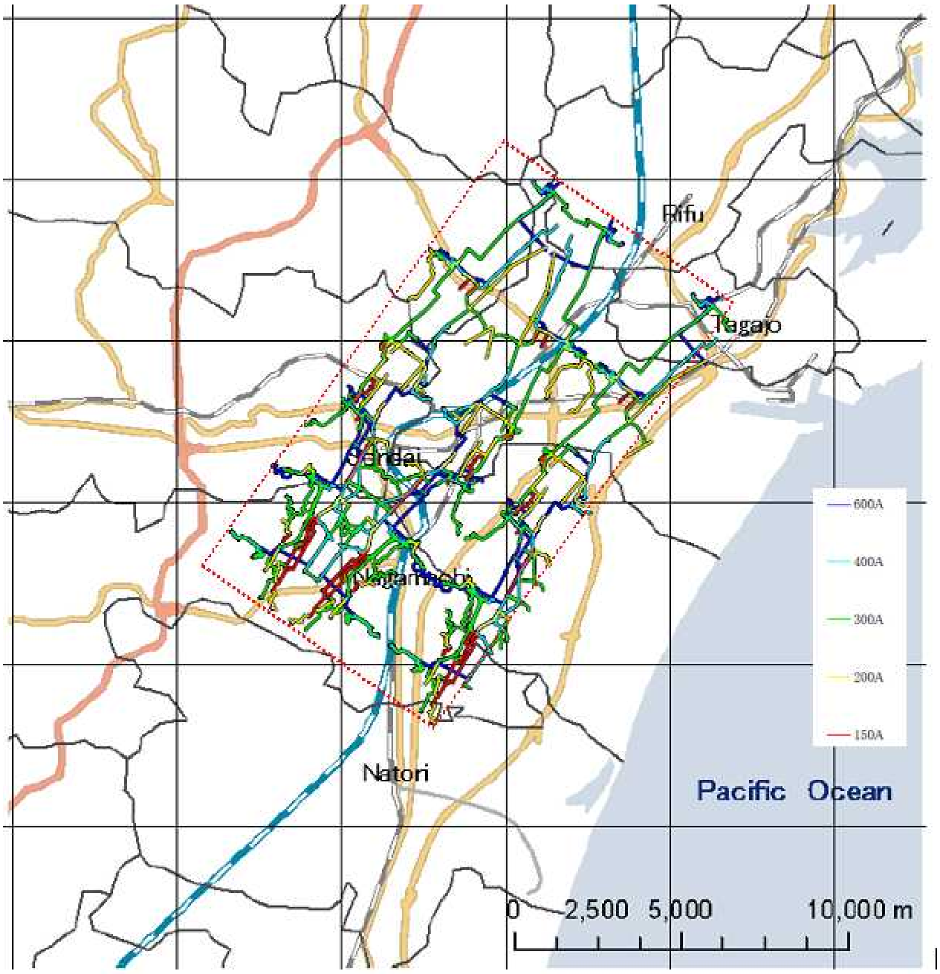


Figure 4. Hypothetical distribution network in Sendai city

Table 2. Number of the segments of the hypothetical network in Sendai city

DIA	0	100	200	300	400	500	600	700	800	900	1000	1100	1200~	Total
150	312	81	19	17	11	3	1	2	1	1				448
200	527	175	69	25	10	4			1	1		3	3	818
300	1380	461	115	38	33	13	11		3	3			3	2060
400	391	156	62	28	13	3	6	3	1	1	3			666
600	595	254	76	40	2	4	4	4	3	3		1		986
Total	3205	1127	341	148	69	22	22	9	9	9	3	4	6	4978

The supposed network as stated above is also used as a network in urban area of Sendai city, for seismic diagnosis against the 2011 Tohoku earthquake. The distribution area in Sendai city is about three times as large as that in Kobe city, then the supposed network is increased the size by three and applied as a hypothetical network in Sendai city.

3.2. Characteristic of the earthquake wave

Seismic waves in this diagnosis are as follows;

(1) seismic intensity distribution in the 1995 Kobe earthquake" (January 17, 1995) (M=7.3) : **Kobe Model**

(2) seismic intensity distribution in the 2011 Tohoku earthquake(March 11, 2011) (M=9.0) : **The great earthquake on March 11th of 2011**

(3) seismic intensity distribution based on a simulation in case of single destruction of fault at the boundary of plate in an earthquake off Miyagi prefecture (M=7.5) : **Sendai Model 1**

(3)＋(4) seismic intensity distribution based on a simulation in case of consecutive destruction of fault at the boundary of plate in an earthquake off Miyagi prefecture (M=8.0) : **Sendai Model 2**

(5) seismic intensity distribution based on a simulation in case of the earthquake on Nagamachi-Rifu fault belt (M=7.5) : **Sendai Model 3**

(1) and (5) are inland earthquake and the predicted maximum intensity on the Japanese seven-stage seismic scale is 7 near the fault. (3) and (3)+(4) are small-scale earthquake of . (2) is, on the contrary, relatively large-scale trench type earthquake of trench type.

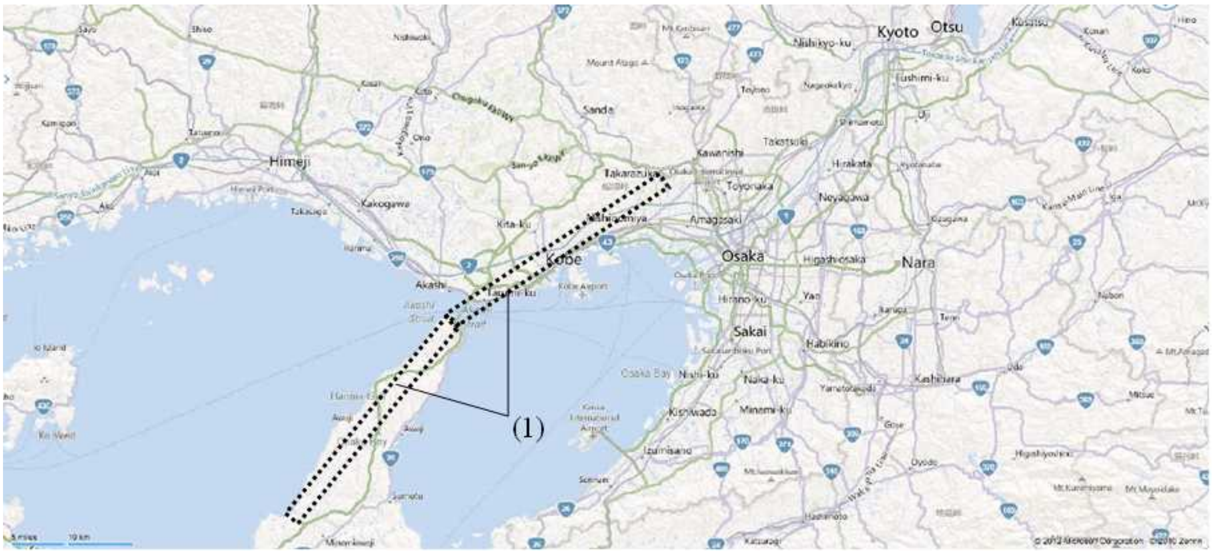


Figure 5. Fault position figure (Kobe city, Hyogo prefecture)

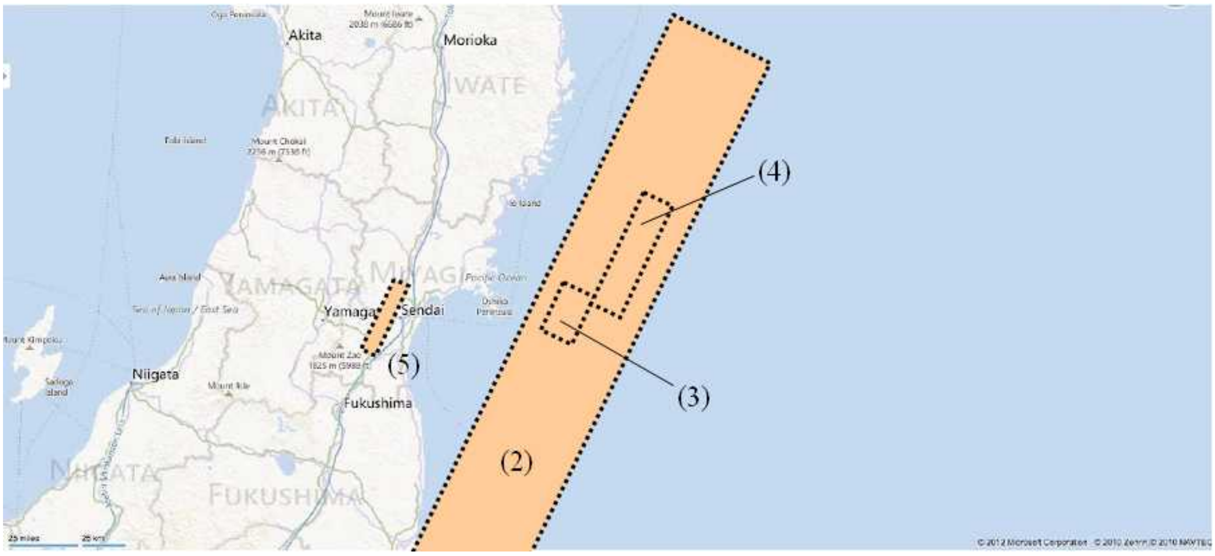


Figure 6. Fault position figure (Sendai city, Miyagi prefecture)

Table 3 shows the relationship between JMA scale and maximum acceleration. Figure 7 shows the frequency distribution of the Japanese seven-stage seismic scale for each earthquake.

Table 3. Relationship between JMA scale and maximum acceleration

the Japanese seven-stage seismic scale	maximum acceleration (Gal)
5.0～5.5	240～520
5.5～6.0	520～830
6.0～6.5	830～1500
6.5～	1500～

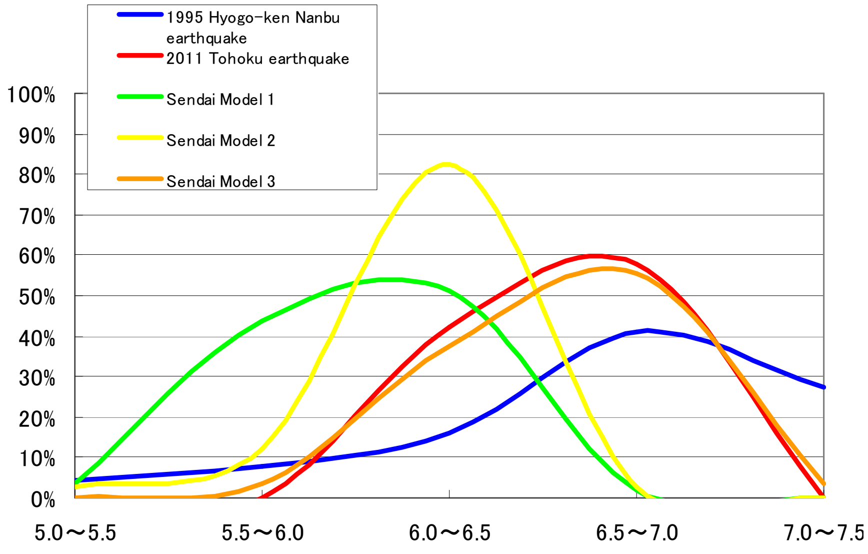


Figure 7. Tendency of the JMA scale for each earthquake

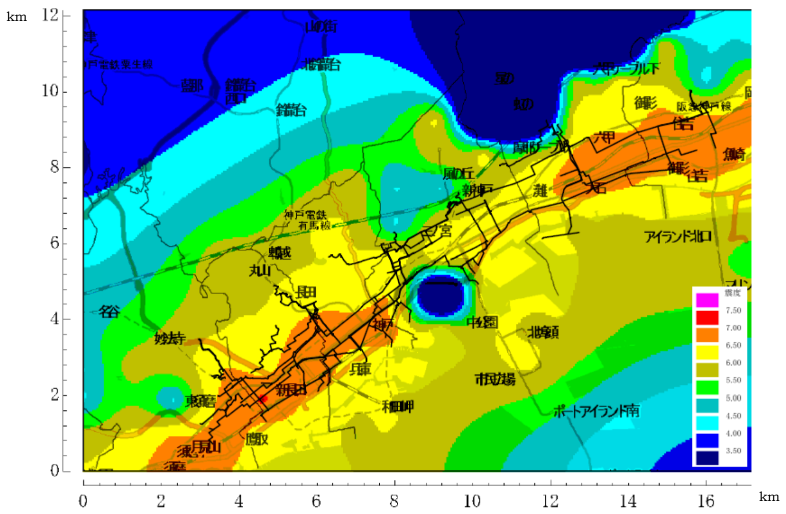
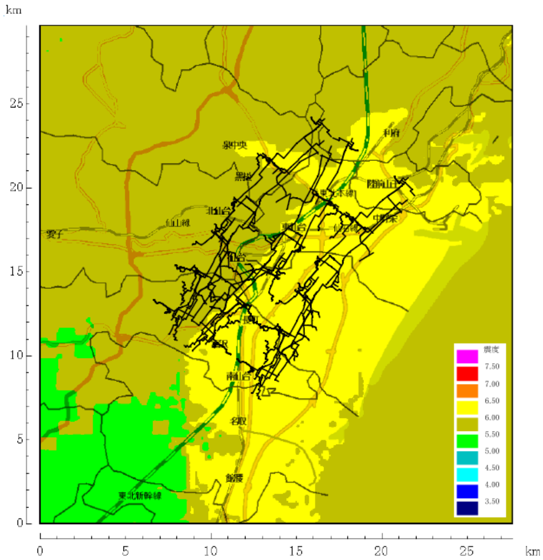


Figure 8. Distribution of the JMA scale in the 1995 Kobe earthquake" (January 17, 1995) *1



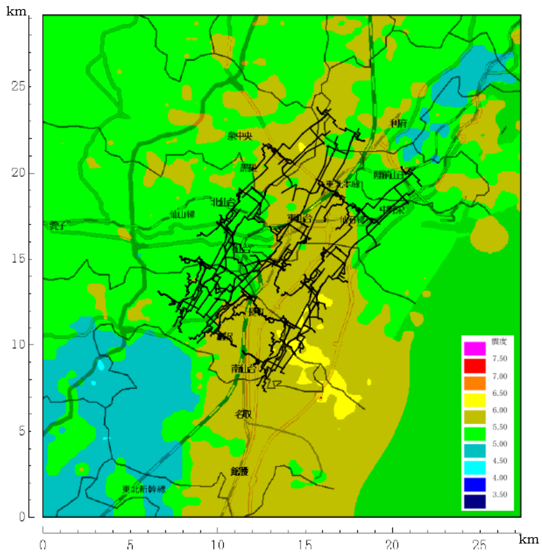
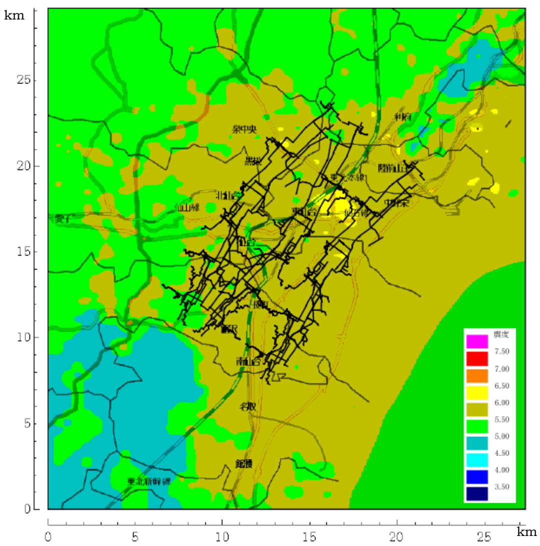


Figure 9. Distribution of the JMA scale in "2011 Tohoku earthquake"*2

Figure 10. Distribution of the JMA scale in Sendai Model 1 *3



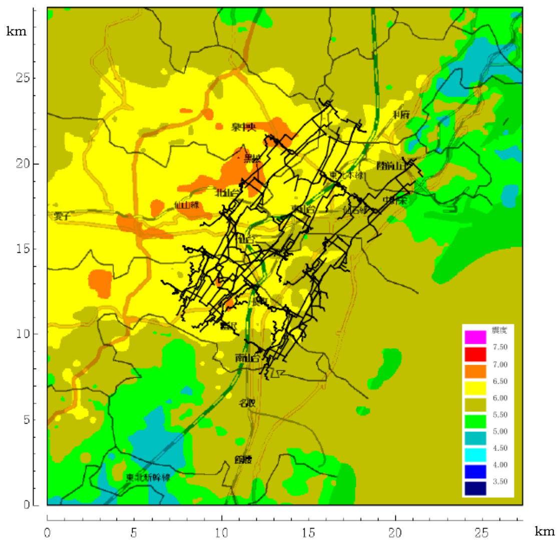


Figure 11. Distribution of the JMA scale in Sendai Model 2 *3

Figure 12. Distribution of the JMA scale in Sendai Model 3 *3

*1 The contour figure which made from the data created by “Institute of Industrial Science, the University of Tokyo”
*2 The contour figure which made from the data created by “The National Institute of Advanced Industrial Science and Technology”
*3 The contour figure which made from the data created by “The Headquarters for Earthquake Research Promotion, the Ministry of Education, Culture, Sports, Science and Technology”

3.3. Evaluation method

The swift and accurate algorithm, NeEX, which method is possible to analyze the stress and strain of buried pipes regardless of shape. The strength of each pipe and fittings is necessary for seismic diagnosis to any part in a network. In this paper safety factor is used for diagnosis. Safety factor equals to a ratio of strain on focus and that at critical state, and they are calculated according to tensile strength of straight pipe. The calculation formula of safety factor can be expressed as follows;

$$S_F = \varepsilon_{cr} \,/\, \varepsilon_p \tag{3.1}$$

S_I : Safety index
ε_{cr} : Strain to reach to the limit state
ε_p : Strain to occur at the point concerned

4. RESULT

4.1. Seismic Diagnosis in Kobe city

As an example of calculation results, Figure 13 shows the strain of pipe in Kobe city. The red lines represent where the strain exceeds the tensile strength determined in advance.

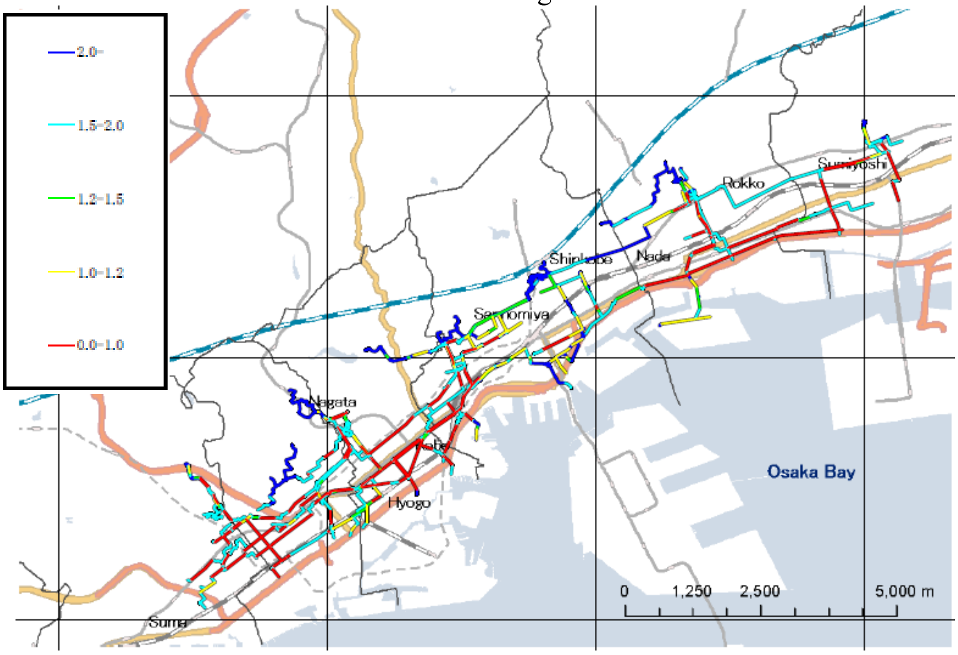


Figure 13. Safety factor and the conduit network diagram: (1) the 1995 Kobe earthquake

Table 4 shows the relationship between damage and pipe diameter or straight line length.

Table 4. Relationship between the length of the segment and safety factor: (1) the 1995 Kobe earthquake

Frequency distribution	Safety-Index Safe($S_I \geqq 1$) DIA					Safe total	Damage($S_I < 1$)					Damage total	Sum total
Extension(m)	150	200	300	400	600		150	200	300	400	600		
0～100	113	200	559	164	263	1299	1	6	12	5	4	28	1327
100～200	13	25	50	25	40	153	4	9	11	4	2	30	183
200～300	2	10	13	5	10	40	3	3	18	6	8	38	78
300～400		7	3	1	4	15	3	3	3	2	1	12	27
400～500			7	1	1	9	4		4	1		9	18
500～600			3	2		5		1	1	1	1	4	9
600～700			1			1				1	1	2	3
700～800							1			1		2	2
800～900					1	1	1		1		1	3	4
900～1000		1				1				1		1	2
1000～1100											1	1	1
1100～1200			1			1		1		1		2	3
1700～1800								1				1	1
Sum total	128	243	637	198	319	1525	17	24	50	23	19	133	1658

That indicates few parts are damaged in the area where straight pipe length is less than 100 meter. This is because the strain of pipe is limited in such area. Pipe length is shorter than the seismic wave length, therefore the frictional force on pipe surface is weak. We compare the result of seismic diagnosis to actual damage case next. The number of damage case on town gas network with middle pressure was 106 in the 1995 Kobe earthquake". This corresponds well with the result of analysis.

4.2. Seismic Diagnosis in Sendai city

Figures 14 to 17 show the strain of pipe in Sendai city. As the same way as previous section, red lines are where the strain exceeds the tensile strength. The distribution where strain exceeds the criteria is different at each seismic wave. Both seismic waves (3) and (3)+(4) have few damage cases. Meanwhile there are more damage cases on seismic waves (2) and (5), but the distribution of damaged spots differs according to seismic wave. The safety factor is also various according to the difference of pipe shape, mainly the straight length, even where the seismic intensity is similarly large.

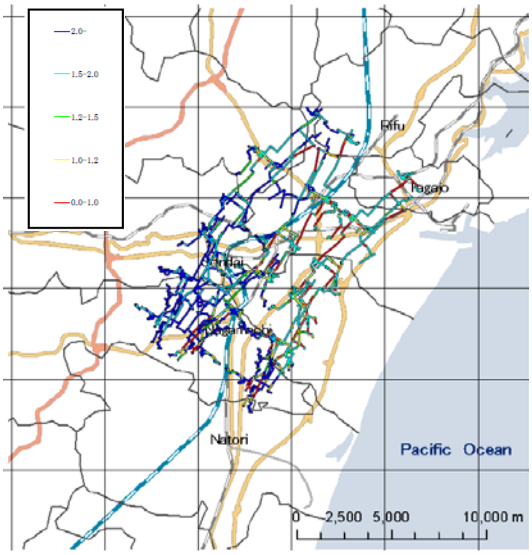


Figure 14. A safety factor calculation result: (2) the 2011 Tohoku earthquake

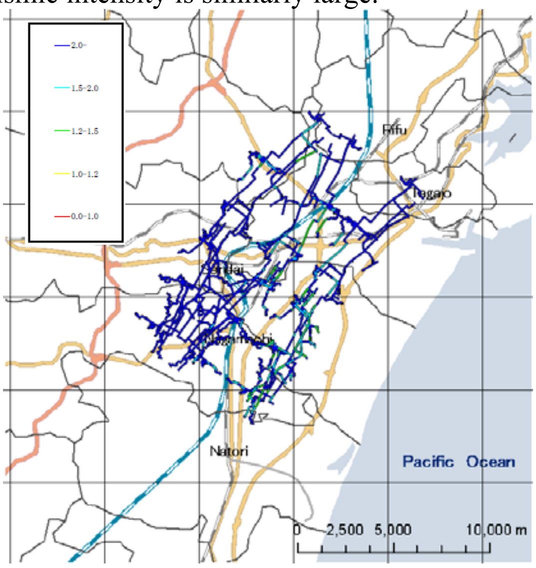


Figure 15. A safety factor calculation result: (3) Sendai Model 1

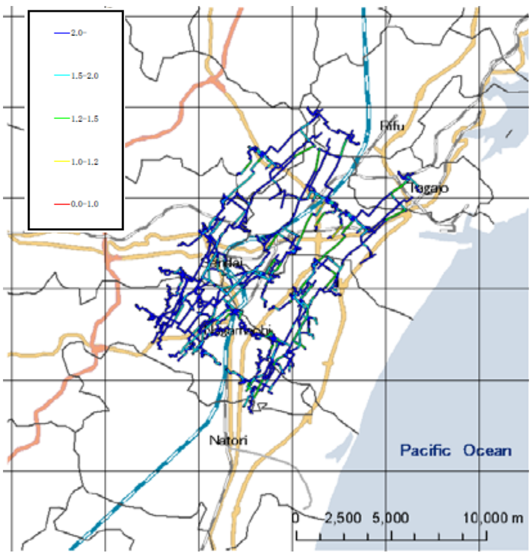


Figure 16. A safety factor calculation result: (3)+(4) Sendai Model 2

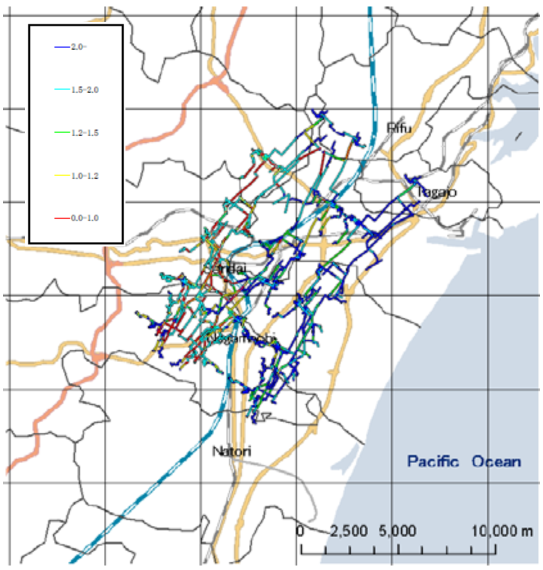


Figure 17. A safety factor calculation result: (5) Sendai Model 3

Table 5. Relationship between the length of the segment and safety factor : (2) the 2011 Tohoku earthquake

Frequency distribution	Judgment		Sum total
Extension(m)	Safe $S_I \geqq 1$	Damage $S_I < 1$	
0～100	3903	73	73
100～200	499	51	51
200～300	207	21	21
300～400	81	15	15
400～500	47	7	7
500～600	20	9	9
600～700	7	2	2
700～800	7	0	0
800～900	10	0	0
900～1000	6	2	2
1000～1100	2	0	0
1100～1200	3	3	3
1400～1500	1	0	0
1600～1700	1	0	0
1700～1800	1	0	0
Sum total	4795	183	183

Table 6. Relationship between the length of the segment and safety factor : (3) Sendai Model 1

Frequency distribution	Judgment		Sum total
Extension(m)	Safe $S_I \geqq 1$	Damage $S_I < 1$	
0～100	3976	0	3976
100～200	550	0	550
200～300	228	0	228
300～400	96	0	96
400～500	54	0	54
500～600	29	0	29
600～700	9	0	9
700～800	7	0	7
800～900	10	0	10
900～1000	8	0	8
1000～1100	2	0	2
1100～1200	6	0	6
1400～1500	1	0	1
1600～1700	1	0	1
1700～1800	1	0	1
Sum total	4978	0	4978

Table 7. Relationship between the length of the segment and safety factor : (3)+(4) Sendai Model 2

Frequency distribution	Judgment		Sum total
Extension(m)	Safe $S_I \geqq 1$	Damage $S_I < 1$	
0～100	3976	0	0
100～200	550	0	0
200～300	228	0	0
300～400	96	0	0
400～500	54	0	0
500～600	29	0	0
600～700	9	0	0
700～800	7	0	0
800～900	10	0	0
900～1000	8	0	0
1000～1100	2	0	0
1100～1200	6	0	0
1400～1500	1	0	0
1600～1700	1	0	0
1700～1800	1	0	0
Sum total	4978	0	0

Table 8. Relationship between the length of the segment and safety factor : (5) Sendai Model 3

Frequency distribution	Judgment		Sum total
Extension(m)	Safe $S_I \geqq 1$	Damage $S_I < 1$	
0～100	3903	73	3903
100～200	502	48	502
200～300	202	26	202
300～400	77	19	77
400～500	48	6	48
500～600	26	3	26
600～700	8	1	8
700～800	5	2	5
800～900	9	1	9
900～1000	7	1	7
1000～1100	1	1	1
1100～1200	4	2	4
1400～1500	1	0	1
1600～1700	1	0	1
1700～1800	1	0	1
Sum total	4795	183	4795

4.3. Computation time

Table 9 shows the running time to analyze in previous section. This time corresponds to 0.3 second per one segment, and analysis speed is much faster compared to FEA. One segment model with 150 meters long is usually divided into about 6,000 elements in FEA. In our method a database is prepared in advance gathering the results of analysis for each pipe diameter, and then the deformation of pipe is realized by solving the equilibrium equation of merely three elements.

Table 9. Analysis time

Model	Number of Segment	Analysis time (CPU:Xeon 3.47Gz)
Kobe city, Hyogo prefecture	1658	8 min 32 sec / case
Sendai city, Miyagi prefecture	4978	24 min 41 sec / case

5. CONCLUSIONS

A swift and accurate simulation method is applied to analyze the damage of buried network in 5 cases. This method is effective for seismic diagnosis of large-scale distribution network. The method made it clear these facts as follows:

- The number of damage in Kobe city was almost the same as actual number.
- The distribution of pipe damage due to the seismic diagnosis of network considering various levels of seismic intensity differs according to the distribution of seismic intensity.
- As a result of comparison of the running time, this method is found to be much faster than usual FEA.

ACKNOWLEDGMNTS

The authors wish to thank Mr. Izumi Kubo, Mr. Tatsuya Higuchi for their works to have conducted the simulations and prepared the figures and the tables.

REFERENCES

Nobuhisa SUZUKI,Ken-ichi KOGANEMARU and Yoshihisa SHIMIZU.(2004),Swift Algorithm to Predict Seismic Responses of Extensive Buried Distribution Networks,13thWorld Conference on Earthquake Engineering

Tomohiro YONETA, Takeshi MORI and Nobuhisa SUZUKI.(2009),Seismic Diagnosis of Buried Gas Distribution Networks, 24th World Gas Conference

Nobuhisa SUZUKI, Hiroyuki HORIKAWA, Takeshi MORI, Toshiyuki MAYUMI, Yoshihisa SHIMIZU, Ken-ichi KOGANEMARU, Koji YOSHIZAKI and Yoshito HATSUTA.(2002),A Fast Solver for Buried Pipeline Networks, 11th Japan Earthquake Engineering Symposium

Ken-ichi KOGANEMARU, Yoshihisa SHIMIZU, Koji YOSHIZAKI, Yoshito HATSUTA, Nobuhisa SUZUKI, Hiroyuki HORIKAWA, Takeshi MORI and Toshiyuki MAYUMI.(2002),Development of Evaluation Technique of Pipeline Network Integrity during Seismic Excitations, 11th Japan Earthquake Engineering Symposium

Nobuhisa SUZUKI, Yoshikazu NAKAJIMA and Yoji TSUNASAWA.(2006),Fast Simulation Method for Seismic Diagnosis of Extensive Distribution Networks. JFE TECHNICAL REPORT No.8:80-84

Naoya YAMAUCHI and Fumio YAMAZAKI.(1999),Estimation of Strong Ground Motion in the 1995 Hyogoken-Nanbu Earthquake Based on Building Damage Data. Journal of Structural Mechanics and Earthquake Engineering No.612:I-46,325-336

Japan Gas Association.(2004),JGA Guideline-206-03 Seismic design standard for high-pressure gas pipelnes