8th Canadian Conference on Earthquake Engineering / 8ième Conférence canadienne sur le génie paraséismique
Vancouver - 1999

Seismic Response Analysis of Water Supply Pipe Network During the 1995 Hyogoken Nambu Earthquake

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ABSTRACT

The present study proposes a method of seismic response analysis of water supply pipe network for seismic diagnosis. The water supply system in Kobe city has been completely disrupted and its principal functions have been lost in the 1995 Hyogoken Nambu earthquake (Kobe earthquake) in Japan. First, the pipelines constructed closely to Egeyama fault system were analyzed. Next, the pipelines installed in Fukaehama which was a manmade reclaimed land were analyzed. The method of analysis was verified through comparison of the analytical results with the actual pipeline damage.

INTRODUCTION

The water supply system in Kobe city was completely disrupted and its principal functions were lost in the 1995 Hyogoken Nambu earthquake (Kobe earthquake). This earthquake has produced significantly great ground motion and extensive liquefaction. Ground failure has been also caused at fault topographical lands. The characteristics of damage to water supply pipelines during the earthquake are summarizes as follows; (1) Damage to distribution pipelines was markedly hard. (2) Joint separations for cast iron pipe occurred in the older mechanical joints. (3) Liquefaction strongly affected the damage to pipeline. Since the ductile cast iron pipelines with earthquake-proof joint did not suffer damage even in the liquefied area, the effect of earthquake proof joint was confirmed. (4) Damage to the pipe fittings such as valves, hydrants, etc., was extensive. Although it is not realistic that these damages were perfectly prevented, strengthening of the system based on seismic diagnosis is very important.

The present study proposes a method of seismic response analysis of water supply pipe network for seismic diagnosis. Since permanent ground displacements induced by liquefied ground flow and fault movement were measured by using aerial photographs taken before and just after the earthquake (Hamada et al. 1995, Takada 1997), these displacements were used as input data of the seismic response analysis. First, the pipelines constructed closely to Egeyama fault system were analyzed. The relation of the residual ground displacements induced by movement of the fault to the damage were studied. Next, the pipelines installed in Fukaehama which was a manmade reclaimed land were analyzed. The liquefaction has occurred extensively and liquefied ground flow has been induced there. The relation among the strain of ground, stiffness of ground which was treated as soil spring constants, and damage to pipelines was investigated. The method of analysis was verified through comparison of the analytical results with the actual pipeline damage. Moreover, effects of the shape of pipe network to damage to pipelines were also studied.

ANALYTICAL PROCEDURES

Analytical models are constructed under the following assumptions:

(1) Quasi-static analysis can be applied, i.e. the effects of inertia force and damping are assumed to be negligible because the ground movement is slow in terms of the dynamic characteristics of pipe-spring system.

(2) Buried pipelines are treated as a series of beams constructed of a material that has an elastic nature. These beams are connected longitudinally with joints which function as a spring for both axial and bending motions.

(3) Ground displacement acts on the pipe body through the soil spring.

(4) A perfect elastic behavior is assumed for the pipe material. Both the joint and soil springs are assumed to be bi-linear elastic.

Fig. 1 shows the spring characteristics of soils assumed here. Joint resistant characteristics depend on the joint type and diameter of pipe. Although the joint resistant characteristics of earthquake-proof joint (S, SII types) have been clarified by laboratory tests, those of mechanical joints (A, K, T types) have not obtained yet. These values were assumed based on the following considerations. When the water pressure in a pipe reaches 98 kPa, pull-out of pipe at joint reaches 3 mm. Then the slippage at joint occurs when the force of pull-out is over 98 kPa. Displacement of joint for compression

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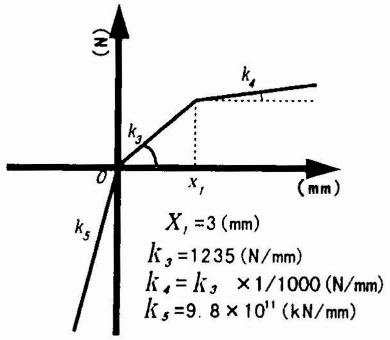

Fig. 1 Soil spring characteristics

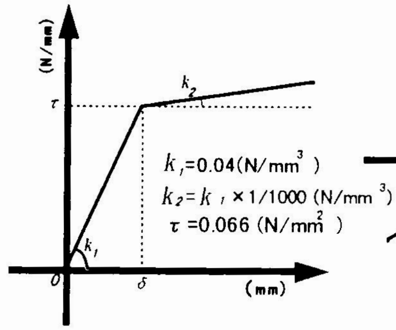

Fig. 2 Joint resistant characteristics for expansion and contraction (Mechanical joint, ø200mm).

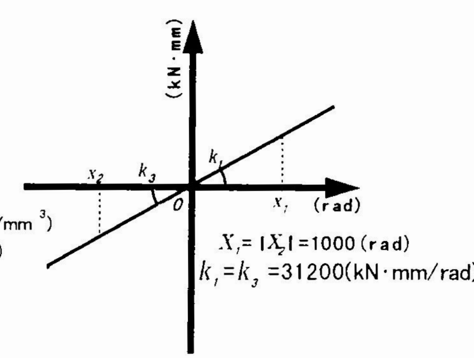

Fig. 3 Joint resistant characteristics for bending (Mechanical joint, ø200mm).

hardly occur and failure of joint is caused when the compression force reaches the allowable value for compression of pipe body. Fig. 2 shows an example of the joint resistant characteristics for expansion and contraction of mechanical joint (A type) with diameter of 200 mm. Fig. 3 shows that for bending. It is assumed based on the results of laboratory tests of an earthquake-proof joint because the mechanism of resistant characteristics for bending of the mechanical joints is similar to that of the earthquake-proof joint.

A modified transfer matrix method (Nakamura 1979) which minimizes the accumulative error in the numerical computations was employed here . The pipeline network was composed by straight pipes, T-shape pipes, cross pipes and bent pipes. The simulation was three dimensional analysis (Takada 1991). Since it is impossible to calculate all water supply pipeline network of Kobe city at a time, a part of network was selected for calculation. The end of pipe was treated as fixed end but the displacement of pipe was given as equal to the displacement of the surrounding ground in calculation.

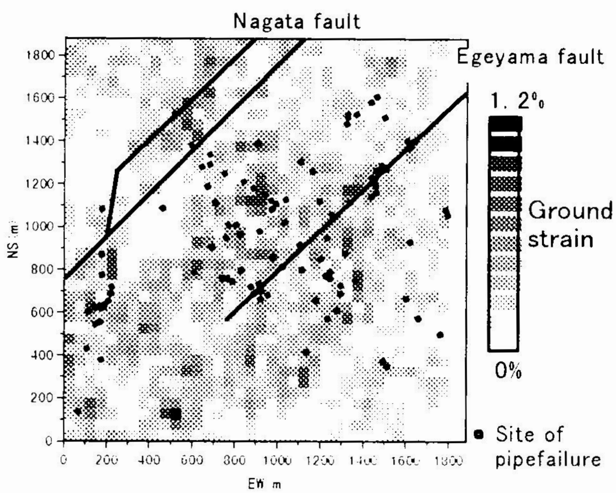

Fig. 4 Distribution of principal ground strain in Egeyama area.

ANALYSIS OF PIPELINE DAMAGE IN FAULT TOPOGRAPHICAL LANDS, EGEYAMA

Target area of analysis and ground displacement

The permanent ground displacement at fault topographical lands were estimated with the aid of aerial photographs before and after the earthquake at Egeyama area in Kobe city by Takada (1997). The principal ground strains were evaluated by using the permanent ground displacements in each 50m mesh. Fig. 4 shows the principal ground strains, location of active faults and sites of pipe failures. According to this figure, large ground strains appeared close to the active faults.

A part of the water supply pipelines constructed in Egeyama area was analyzed employing the method presented above. A rough sketch of pipelines analyzed here is displayed in Fig. 5. The sites of pipe failure are also shown in this figure. The type of pipes was ductile cast iron and their diameters were 100 mm and 150 mm. The response of the pipelines corresponded to point 6 to point 10 shown in Fig. 5 was investigated in this chapter. The length of pipelines was about 234 m. Fig. 6 illustrates ground displacements along the pipelines. These were interpolated from the measured displacements (Takada 1997) by using the Kriging technique (Isaaks and Srivastava 1989). Since the simulation was three dimensional analysis, the displacement divided into three directions, that is, axial direction of pipe, perpendicular to the pipe axis in horizontal direction and that in vertical direction. The horizontal displacements were remarkably change at the bent part of the pipeline network.

Results of analysis

Fig. 7 illustrates the bending moment of the pipeline that corresponded to point 6 to point 10 in Fig. 5. This figure indicates that the bending moment decreased at each joint. The sites where pipe failures occurred are also illustrated in this figure. Three breaks at the pipe body and one break at the valve occurred. Although the bending moment in this section was under the allowable value, that is, 30 kN m, the bending moment near point 6 is large. The failure of pipe seems to be induced by large bending moment. Fig. 8 shows the joint displacement divided by the allowable value. According to this figure, the ratio of joint displacement to the allowable value is under 1.0. This coincides with no pull-out of pipe at joint. The results of analysis have agreement with the actual behavior of pipelines in this case.

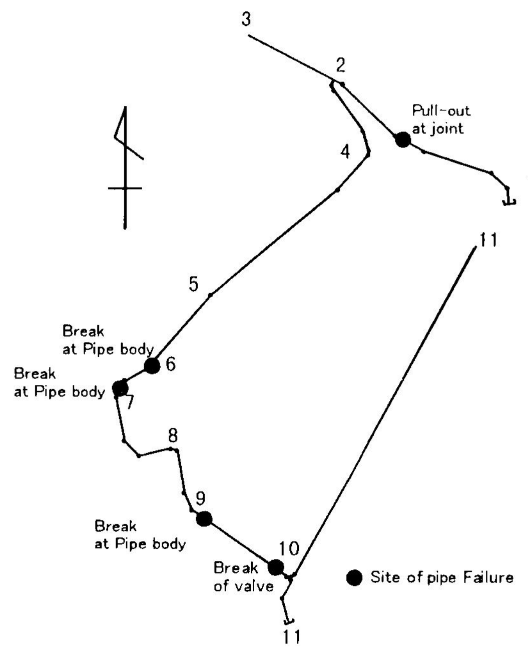

Fig. 5 Rough sketch of pipeline analyzed in Egeyama area.

ANALYSIS OF PIPELINE DAMAGE IN LIQUEFIED GROUND FLOW AREA, FUKAEHAMA

Target area of analysis and ground displacement

The permanent ground displacement induced by liquefied ground flow were measured from aerial photographs before and after the earthquake in Kobe city by Hamada et al. (1995). Fig. 9 displayed the horizontal permanent ground displacement (Hamada et al. 1995) and damage to water supply pipelines (Japan Water Works Association 1996) plotted on the pipeline network in Fukaehama. The length of arrows in this figure means the magnitude of permanent ground displacement and they were transformed from the actual measured data to cell data of 50 m x 50 m. Great permanent ground displacement occurred near the coastlines. The quay wall line moved toward the sea with a maximum magnitude of about 4 m, and also largely subsided. The principal ground strains were evaluated by using the permanent ground displacements in each 50m mesh. Fig. 10 shows the principal ground strains and sites of pipe failures. According to this figure, pipe failures were occurred at sites where the large ground strains appeared. The ground strains in Fukaehama were less than those in Egeyama presented shown in Fig. 4.

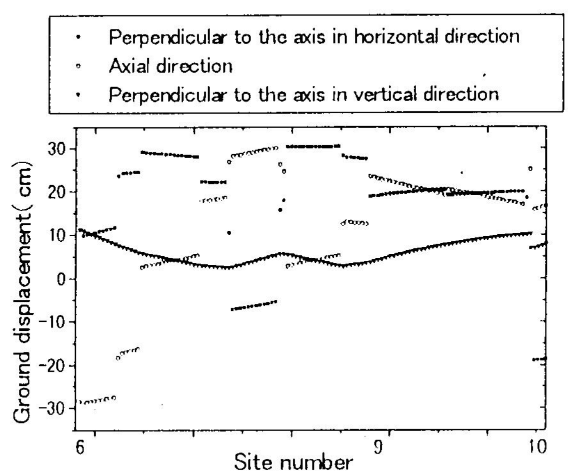

Fig. 6 Ground displacement along pipeline in Egeyama area.

A part of the water supply pipe network constructed in Fukaehama, northeast area where the pipe failures were concentrated, was analyzed. A rough sketch of pipelines analyzed here is displayed in Fig. 11. The sites of pipe failure are also shown in this figure. The type of pipes was a ductile cast iron with mechanical joint and their diameters

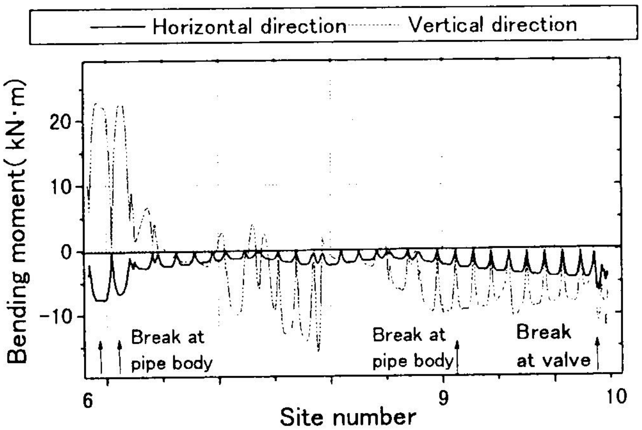

Fig. 7 Bending moment of pipeline in Egeyama area.

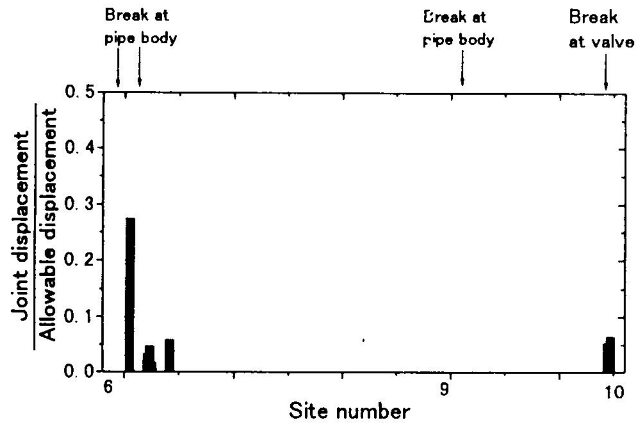

Fig. 8 Joint displacement divided by allowable value in Egeyama area.

were 100 mm and 200 mm. The response of the pipelines corresponded with point 4 to point 16 shown in Fig. 11 was investigated in this chapter. The length of pipelines was about 680 m. Fig. 12 indicates the distribution of permanent ground displacement along pipelines. The maximum magnitude of displacement was about 2 m in this area, much larger than that in Egeyama area.

<u>Results of analysis</u>

Fig. 13 illustrates the bending moment of the pipeline from point 4 to point 16 shown in Fig. 11. The bending moment was smaller than the allowable value. There was no failure of pipe body in these pipelines due to the earthquake according to Fig. 10. Fig. 14 illustrates the joint displacement divided by the allowable value. The sites where pull-out of pipe at joint occurred are also indicated on this figure. There was no damage at the bent part according to Fig. 11. This is because that the joints near the bent part have been strengthened before the earthquake. On the other hand, strengthening of joints at the bent part seems to affect the failure at straight part near the bent part. Fig. 14 suggests that there is a good agreement between the high value of ratio of joint displacement and sites of pull-out of pipe at joint.

Some liquefaction-related experiments dealing with the equivalent soil spring constant have been conducted (Miyajima et al. 1991). Since the equivalent soil spring constant depended on the degree of liquefaction, the initial coefficient was assumed here to be 0.3 of the stiffness of the non-liquefied soil. As a result, the bending moment and axial force were reduced and the joint displacement was almost same as the above results. There was a good agreement with the actual damage in this case.

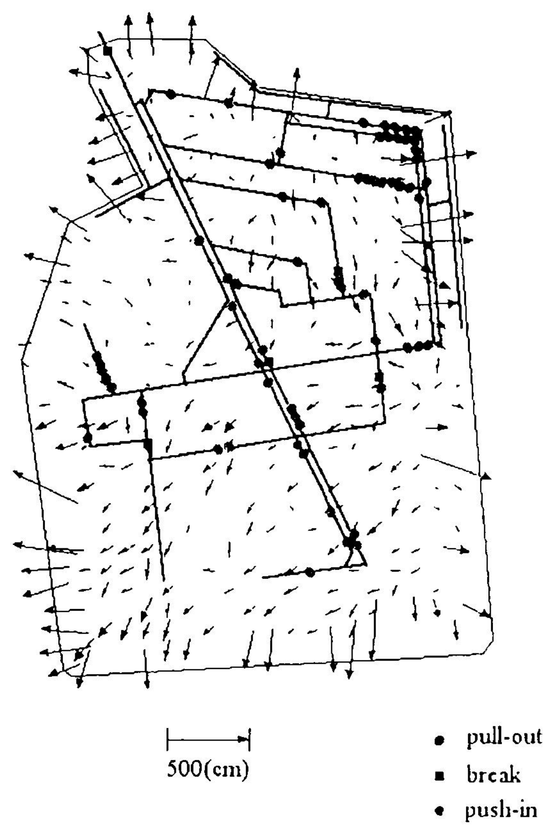

Fig. 9 Site of pipe failures and permanent ground displacement in Fukaehama.

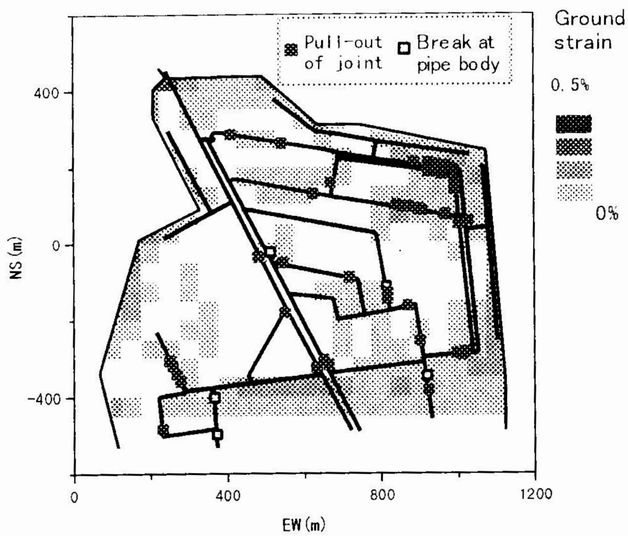

Fig. 10 Distribution of principal ground strain in Fukaehama.

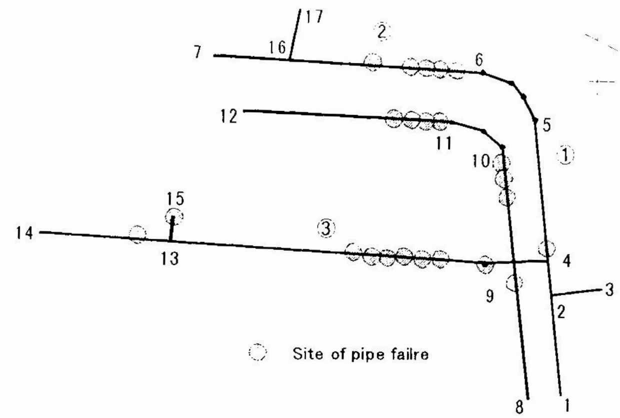

Fig. 11 Rough sketch of pipeline analyzed in Fukaehama.

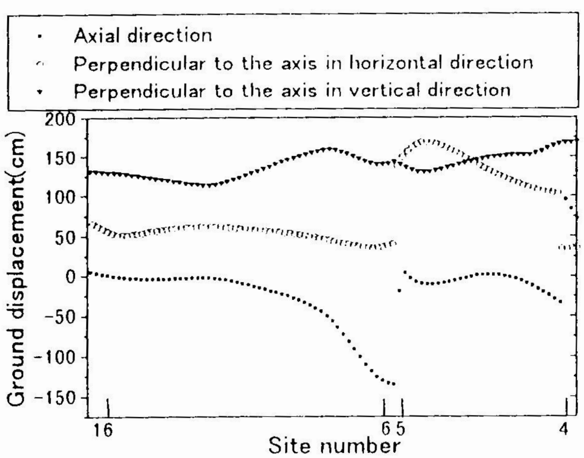

Fig. 12 Ground displacement along pipeline in Fukaehama.

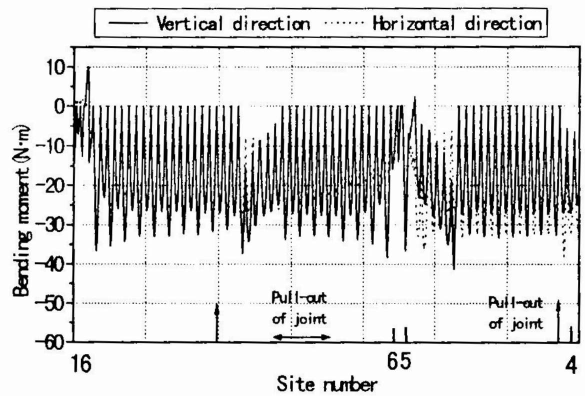

Fig. 13 Bending moment of pipeline in Fukaehama.

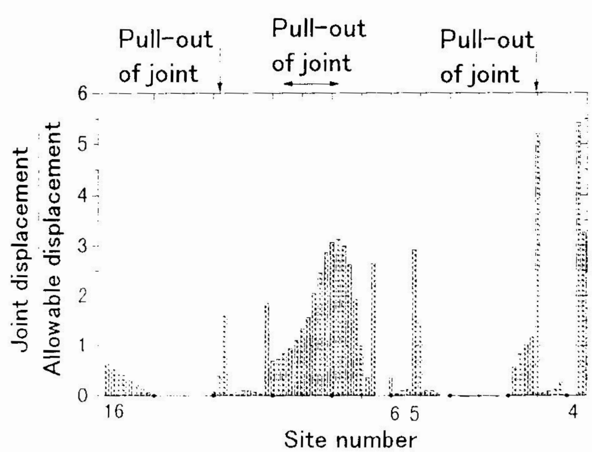

Fig. 14 Joint displacement divided by allowable value in Fukaehama.

CONCLUSIONS

The seismic response analysis of water supply pipelines which were damaged by the 1995 Hyogoken Nambu earthquake was conducted and the analytical results was compared with the actual pipeline damage. The following conclusions may be drawn from the present study.

(1) The distributions of ground strain at Egeyama area and Fukaehama were clarified. The ground strains at Egeyama area that was fault topographical lands were greater than those at Fukaehama that was liquefied ground flow areas. The ground displacements at Fukaehama were, however, greater about ten times than those at Egeyama area. Many pipe failures occurred at the locations of large ground strain.

(2) The results obtained by the response analysis suggest that the pipe damages were influenced not only by ground strains but also by combination of several kinds of pipes and joints, and shape of pipeline network.

(3) The method of analysis in this study was verified because the results of analysis coincided with the actual failures of pipelines.

Not only the permanent ground displacements induced by fault movement and liquefied ground flow but also that due to ground vibration have to be predicted if the method proposed in this study is used in seismic diagnosis for a scenario earthquake.

ACKNOWLEDGMENTS

The present paper is based on data collected through a detailed investigation. Many individuals and organizations generously helped with this investigation. In particular, we deeply indebted to the staffs of the Kobe Municipal Waterworks Bureau and KUBOTA Ltd. for their help. We would like to thank Mr. Y. Tsuda for preparing figures.

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