DAMAGE TO BURIED UTILITY PIPES IN THE 1978 MIYAGIKEN-OKI EARTHQUAKE

by

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SUMMARY

The Tohoku districts in Japan was struck by a severe earthquake of magnitude 7.4 on June 12, 1978, which caused damage to various structures and systems. This paper describes the damage to buried utility pipes caused by the Miyagiken-oki earthquake. Damage statistics of city gas and water supply pipes are examined through cross tabulated tables and failure ratio matrix, and typical modes of failure are identified from damage analysis.

INTRODUCTION

Immediately following a foreshock of magnitude 5.8, the 1978 Miyagiken-oki earthquake of magnitude 7.4 hit the Tohoku districts of Honshu at 17:12 (JST), June 12, 1978. Although the epicenter was located in the Pacific Ocean, several cities in Miyagi Prefecture and the surrounding area were subjected to strong shaking. The shock took 28 lives, injured more than 1,300 and caused an estimated some 200 billion yen in property damage. Figure 1 shows the epicenter and the distribution of JMA intensity at various locations.

One of the particular features of the 1978 Miyagiken-oki earthquake was, however, the damage sustained by various lifeline utility systems especially in Sendai, the 14th largest city in Japan with a population of 617,000, and its effect on community or city life was of the greatest concern[1,2,3]. In the case of water supply and city gas systems, the damage was mostly restricted to the small diameter buried pipelines, although some damage was sustained by buildings, plants and transmission lines.

DAMAGE TO CITY GAS PIPES

The Sendai City Bureau of Gas supplies city gas to about 136,000 customers through a total of 1,741 km of buried pipes. Although the Bureau maintained 189.1 km of arc-welded steel pipes and 6.4 km of ductile cast-iron pipes as medium pressure transmission lines (1~10 kg/cm), only 4 minor failures were reported to have occurred in the joints between steel pipe and attached installation.

The minor distribution pipes were, however, extensively damaged and it took almost three weeks before the accumulated percentage restored became 90 % of the total number of customers. During its restoration process, a total of some 550 failures were identified and thier pertinent data recorded. The distribution of damage to low-pressure pipes in Sendai area is shown in Fig. 2. The ground conditions were roughly classified into the three groups A, B and C as shown in Fig. 2 and Table 1.

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Based on these data, a cross tabulation was made for the damage to low-pressure gas pipes with respect to various items and categories. The low-pressure buried pipes included distribution mains, branches, services and pipings on customers' premises. Damage to medium pressure transmission lines was not included. Six items selected are failure mode, pipe classification, pipe material, pipe size, type of joint and type of ground. Each item was divided into two to five categories. The results of cross tabulation are shown in Table 1. A number on the diagonal shows the simple sum of failures under each respective category. A total of 552 failures have been reported in the low-pressure pipings. From Table 1, it is possible to find the number of failures for every combinations of item-categories.

In order to generalize the extent of damage, it is necessary to normalize the number of failures in each element of cross tabulated matrix by its corresponding pipe length. The results of normalization are shown in Table 2 as the failure ratio matrix (number of failures per 100 km). It should be noted that, since the pipe length of mechanically-jointed steel pipes was not known, the failure ratios associated with mechanical joint in Table 2 are those of mechanically jointed cast-iron pipes. Table 3 shows the numbers of failures of mechanically-jointed cast-iron pipes with respect to all item-categories. Low-pressure , arc-welded steel pipes with a total length of 51.2 km were not damaged although almost 2/3 of them were installed in Type C ground where the pipeline damage was most extensive. The 49.7 km sections of cast-iron pipes with bell and spigot joints were also undamaged. However, these cast-iron pipes were mostly buried in Type A ground (terrace).

DAMAGE TO WATER DISTRIBUTION PIPES

Since the most part of the Miyagi Prefecture experienced the JMA V intensity, 64 out of 74 cities and towns suffuerd damage to their water supply systems. The sizes of these systems varied from about 200 to about 600,000 (Sendai) in population. Table 4 summarizes the total numbers of failures in water supply pipes and the failure ratios for different pipe materials in 29 water utilities in the Miyagi Prefecture. Figure 3 correlates the failure ratio with the pipe diameter. It is observed that the failure ratio of asbestos-cement pipe decreases with the increase of pipe diameter, while it is almost constant for cast-iron and ductile cast-iron pipe. Note that the types of joints for steel pipelines are different according to pipe diameters. Therefore, the mode of failure as well as the vulnerability to seismic effect should be distinguished according to the type of joint.

A total of 237 failures in steel pipes were reported in 29 utilities, but most of the damage was sustained by small diameter (less than 100 mm) pipes with screw joints. Only 18 failures occurred in greater than 400 mm diameter steel pipes, of which 14 were associated with loosenings of flange joints.

Most of the damage was again restricted to minor distribution pipings, and the distribution of pipe failures in Sendai was very similar to that of city gas pipes (Fig. 2). For the total of 401 failures which occurred in the distribution mains and branches having diameters equal to or greater than 50 mm, a cross tabulation was made as shown in Table 5. The upper and the lower figure in each element indicate the number of damage to distribution mains (diameter $\geq$ 75 mm) and the distribution branches (diameter = 50 mm), respectively. Table 6 gives a more detailed description of the relation between number of damage and diameter for the waterlines with diameter greater than 75 mm in Sendai.

In order to see the effect of sub-soil conditions objectively, the pipe length of the mains in each ground condition was roughly estimated. The failure ratio (per km) of water mains was obtained as 0.02 for Type A, 0.27 for Type B and 0.12 for Type C. Even though these values are very rough, the tendency is similar to that observed in gas pipes.

CLASSIFICATION OF DAMAGE

In the preceeding sections, the damage statistics of gas and water pipes were examined by using the cross tabulated tables and the failure ratio matrix. In order to more clearly understand the general features of pipeline damage, the tabulated data were analyzed by using a statistical technique called the Quantification Theory III.

Statistical data are, in general, scattered in a multi-dimensional space. By the transformation of axes, the Quantification Theory III aims to classify these data in terms of the set of axes that most clearly show the structure of data. In other word, axes are transformed in order to see the structure of data in a less dimensional space. This theory , although very similar to the principal component analysis, permits data to be qualitative in items, for example, steel pipe and cast-iron pipe.

The damage to low-pressure gas pipes and water distribution mains was analyzed by the Quantification Theory III based on the data shown in Tables 1 and 5. Figure 4 shows the scattergram of categories for gas pipe with respect to the transformed principal axes I and II. Axis I may be considered to represent a certain quantity which reflects the combined effect of the kind of pipe and its strength property, but the meaning of axis II is not clear. The points which are close each other in Fig. 4 form a group of categories closely related among them. According to this, two primary groups seem to exist in Fig. 4. One includes Breaks, Cracks, Screw, SP (Steel Pipe), D_1 , Services, Branches, etc., and another includes Mains, CIP (Cast-Iron Pipe), D_3 and D_4 . These two groups seem to roughly correspond to the steel pipe group and the cast-iron pipe group. Not so clear as these, there is an additional group with respect to axis I consisting of Mechanical, Slip Out, Loosening, D_2, and Others. Although loosening and slip-out are modes of failure commonly encountered in mechanical and screw joints, this third group is located between the primary two groups because a substantial number of failures of mechanical joints were associated with steel pipes (Table 1).

From the foregoing discussions and the examination of the failure ratio matrix, the damage to low-pressure gas pipes in Sendai may be summarized as follows.

(a) Damage were severe on the small diameter screw jointed steel pipe which were used as branches, services and domestics, and their predominant mode of failure were mostly breaks and cracks.

(b) The second mode of failure was the loosenings and slip out of mechanical jointed cast-iron and ductile cast-iron pipes, however, these modes were small as shown in Table 2.

The Quantification Theory III was also applied to the damage to water distribution mains. The results are shown in Fig. 5. Two groups are also recognized, although the separation is not clear as compared with the case of gas pipes. One is the group associated with cast-iron pipe, corresponding to (a) for gas pipes, and another corresponds to (b). It is noted that the category of asbestos-cement pipe is located at a position which neither corresponds to (a) or (b).

DAMAGE IN THE NEWLY DEVELOPED CUT-AND-FILL AREA

One of the most important points of argument in the 1978 Miyagiken-oki earthquake has been the various damage in the newly developed residential area (Type C ground), where large scale cut and fill has extensively altered the original ground profile. A large number of pipe failures were found to have occurred near the cut and fill boundary in these districts. Because of inherent instability of artificial slopes, insufficient densification of fills, and abrupt change in subsoil properties between cut and fill, strong seismic shaking easily produced fissures , local settlement, slippage, and relative displacement over short horizontal distance.

Figure 6 correlates the number of failures of gas and water distribution pipes with the distance from the cut and fill boundary to the location of pipe failure in several newly developed residential areas. Very high correlation is found to exist between damage and distance from cut and fill boundary.

CLOSING REMARKS

The extent of damage to various kinds of buried pipes caused by the 1978 Miyagiken-oki earthquake was in general not so severe as those by the Kanto, the Fukui, the Niigata or the San Fernando earthquake. However, it was again recognized that the lifeline or buried pipe was very susceptible to earthquake effects in comparison with other structures, and that the effect produced by the functional deterioration of lifelines can be serious, especially in a modern urban area like Sendai.

ACKNOWLEDGEMENTS

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Table 1. Cross Tabulation of Gas Pipe Failures in the Sendai Area.

		Mode of Failure					Classification of Pipe				Material		Size of Pipe				Type of Joint					Site Geological Condition		
		B	C	S	L	O	M	B	S	D	S	C	D_1	D_2	D_3	D_4	W	M	S	B	O	A	B	C
Mode of Failure	Breaks	409	0	0	0	0	3	127	129	150	409	0	399	9	1	0	0	4	404	0	1	45	73	291
	Cracks		43	0	0	0	1	14	8	20	43	0	42	1	0	0	0	0	43	0	0	2	18	23
	Slip Out			60	0	0	11	46	2	1	49	11	47	5	3	5	0	42	17	0	1	0	2	58
	Loosening				13	0	4	5	2	2	11	2	9	4	0	0	0	5	6	0	2	5	2	6
	Others					27	1	6	7	13	26	1	25	1	1	0	0	0	24	0	3	4	4	19
Classification of Pipe	Mains						20	0	0	0	6	14	0	11	4	5	0	13	4	0	3	2	6	12
	Branches							198	0	0	198	0	198	0	0	0	0	36	160	0	2	3	14	181
	Services								148	0	148	0	144	4	0	0	0	1	146	0	1	18	32	98
	Domestics									186	186	0	179	6	1	0	0	1	184	0	1	33	47	106
Material	Steel										538	0	522	16	0	0	0	38	494	0	6	55	98	385
	Cast Iron											14	0	5	4	5	0	13	0	0	1	1	1	12
Size of Pipe	D_1	$D_1 \leq 50$ mm											522	0	0	0	0	38	480	0	4	52	89	381
	D_2	$75 \leq D_2 \leq 100$ mm												20	0	0	0	5	13	0	2	4	8	8
	D_3	$125 \leq D_3 \leq 150$ mm													5	0	0	3	1	0	1	0	1	4
	D_4	$200 \leq D_4$														5	0	5	0	0	0	0	1	4
Type of Joint	Welded																0	0	0	0	0	0	0	0
	Mechanical																	51	0	0	0	2	3	46*
	Screw																		494	0	0	51	95	348
	Bell & Spigot																			0	0	0	0	0
	Others																				7	3	1	3
Site Geological Condition	A	Terrace (Old City Area)																				56	0	0
	B	Alluvial Plain																					99	0
	C	Cut and Fill																						397

Table 2. Failure Ratio Matrix (No. of Failures per 100 km) of City Gas Pipe in the Sendai Area.

			Classification of Pipe		Material		Size of Pipe				Type of Joint				Site Geological Condition		
		Total	M&B	S&D	SP	CIP	D_1	D_2	D_3	D_4	W	M	S	B	A	B	C
Mode of Failure	Breaks	26.5	10.6	87.2	42.4	0	43.8	4.2	0.5	0	0	0	44.7	0	9.7	36.3	33.1
	Cracks	2.8	1.2	8.8	4.5	0	4.6	0.5	0	0	0	0	4.7	0	0.4	9.0	2.6
	Slip Out	3.9	4.7	0.9	5.1	1.9	5.2	2.3	1.5	2.3	0	2.1	1.9	0	0	1.0	6.6
	Loosenimg	0.8	0.7	1.3	1.1	0.3	1.0	1.8	0	0	0	0.4	0.7	0	1.1	1.0	0.7
	Others	1.7	0.6	6.3	2.7	0.2	2.7	0.5	0.5	0	0	0	2.6	0	0.9	2.0	2.2
Class. of Pipe	M & B*		17.8	-	31.6	2.4	33.5	5.1	2.0	2.3	0	2.5	27.6	0	1.5	12.5	26.0
	S & D**			104.4	104.4	-	... (104.4)...				0	-	103.1	0	35.5	192.7	150.8
Material	Steel				55.8	-	60.5	45.3	0	0	0	-	54.1	-	20.4	87.5	66.0
	Cast Iron					2.4	-	2.8	2.2	2.3	-	2.5	-	0	0.5	1.1	4.1
Size of Pipe	D_1		$D_1 \leq 50$ mm				57.2	-	-	-	0	-	52.6	0	20.2	84.0	69.4
	D_2		$75 \leq D_2 \leq 100$ mm					9.2	-	-	0	3.8	722.2	0	5.9	25.0	6.8
	D_3		$125 \leq D_3 \leq 150$ mm						2.5	-	0	1.6	-	-	0	3.3	4.0
	D_4		$200 \leq D_4$							2.3	0	2.3	-	-	0	3.0	3.6
Type of Joint	Welded										0	-	-	-	0	0	0
	Mechanical											2.5	-	-	0.7	1.1	3.7
	Screw												54.1	-	19.8	89.6	63.2
	Bell & Joint														0	-	-
Site Geolog. Condition	A		Terrace (Old City Area)												12.0	-	-
	B		Alluvial Plain													49.3	-
	C		Cut & Fill														45.2

* Mains and Branches
** Services and Domestics

Table 3. Number of Failures of Mechanically-jointed Cast-iron Gas Pipe in the Sendai Area.

	Mode of Failure					Classification of Pipe				Mate-rial		Size of Pipe				Type of Joint					Site Geological Condition		
	B	C	S	L	O	M	B	S	D	S	C	D_1	D_2	D_3	D_4	W	M	S	B	O	A	B	C
Number of Failures	0	0	11	2	0	13	0	0	0	0	13	0	5	3	5	0	13	0	0	0	1	1	11

Table 4. Number of Failures and Failure Ratio per km of Water Supply Pipe in 29 Utilities in Miyagi Prefecture.

	Material						Total
	Asbestos Cement	Polyvinyl Chloride	Cast Iron	Ductile Cast Iron	Steel	Others	
Number of Failures	724	335	109	36	237		1,481
Length (km)	1,509.1	1,228.3	646.1	880.1	190.8	20.3	4,474.6
Failure Ratio per km	0.48	0.27	0.17	0.04	1.24	0.0	0.33

Table 5. Cross Tabulation of Water Distribution Pipe Failures in Sendai.

			Damaged Part				Mode of Failure					Material							Size of Pipe					Site Geological Condition		
			S	B	J	O	B	S	C	SO	O	C	D	S	A	V	L	O	D_1	D_2	D_3	D_4	D_5	A	B	C
Damaged Part	Straight		68 148	0 -	0 0	0 0	18 33	24 74	21 31	0 0	5 10	13 -	2 -	0 24	32 22	21 57	- 45	0 0	- 148	59 -	7 -	2 -	0 -	6 11	12 37	50 100
	Bent			5 -	0 -	0 -	1 -	3 -	0 -	1 -	0 -	0 -	1 -	0 -	2 -	2 -	- -	0 -	- -	5 -	0 -	0 -	0 -	0 -	2 -	3 -
	Joint				37 111	0 0	22 93	0 3	1 0	14 15	0 0	6 -	7 -	1 22	4 11	19 55	- 23	0 0	- 111	29 -	7 -	1 -	0 -	1 14	17 25	19 72
	Others					18 14	16 14	1 0	0 0	1 0	0 0	0 -	0 -	0 0	0 0	0 0	- 0	18 14	- 14	16 -	2 -	0 -	0 -	0 1	9 3	9 10
Mode of Failure	Breaks						57 140	0 0	0 0	0 0	0 0	3 -	3 -	1 27	8 14	26 69	- 16	16 14	- 140	49 -	6 -	2 -	0 -	1 15	21 29	35 96
	Snaps							28 77	0 0	0 0	0 0	4 -	0 -	0 13	20 4	3 29	- 31	1 0	- 77	24 -	4 -	0 -	0 -	3 5	4 23	21 49
	Cracks								22 31	0 0	0 0	7 -	0 -	0 6	5 6	10 12	- 7	0 0	- 31	21 -	1 -	0 -	0 -	2 2	7 8	13 21
	Slip Out									16 15	0 0	5 -	7 -	0 0	0 0	3 1	- 14	1 0	- 15	10 -	5 -	1 -	0 -	1 4	8 5	7 6
	Others										5 10	0 -	0 -	0 0	5 9	0 1	- 0	0 0	- 10	5 -	0 -	0 -	0 -	0 0	0 0	5 10
Material	CIP	Cast Iron										19 -	0 -	0 -	0 -	0 -	- -	0 -	- -	11 -	7 -	1 -	0 -	6 -	5 -	8 -
	DCIP	Ductile Cast Iron											10 -	0 -	0 -	0 -	- -	0 -	- -	3 -	5 -	2 -	0 -	1 -	7 -	2 -
	SP	Steel												1 46	0 0	0 0	- 0	0 0	- 46	1 -	0 -	0 -	0 -	0 5	0 12	1 29
	ACP	Asbestos-Cement													38 33	0 0	- 0	0 0	- 33	36 -	2 -	- -	- -	0 0	1 1	37 32
	VP	Polyvinyl Chloride														42 112	- 0	0 0	- 112	42 -	- -	- -	- -	0 9	18 24	24 79
	LP	Lead															- 68	- 0	- 68	- -	- -	- -	- -	- 11	- 25	- 32
	Others																	18 14	- 14	16 -	2 -	0 -	0 -	0 1	9 3	9 10
Size of Pipe	D_1	D = 50 mm																	- 273	- -	- -	- -	- -	- 26	- 65	- 182
	D_2	75 ≤ D ≤ 125 mm																		109 -	0 -	0 -	0 -	2 -	32 -	75 -
	D_3	150 ≤ D ≤ 300 mm																			16 -	0 -	0 -	5 -	6 -	5 -
	D_4	350 ≤ D ≤ 600 mm																				3 -	0 -	0 -	2 -	1 -
	D_5	700 ≤ D																					0 -	0 -	0 -	0 -
Site Geolog-ical Condition	A	Terrace (Old City Area)																						7 26	0 0	0 0
	B	Alluvial Plain																							40 65	0 0
	C	Cut & Fill																								81 182

Table 6. Damage to Water Distribution Mains in Sendai.

Diameter of Pipe (mm)	Material of Pipe								Total	
	Cast Iron		Steel		Asbestos Cement		Polyvinyl Chloride			
	Length (km)	Breaks	Length (km)	Breaks	Length (km)	Breaks	Length (km)	Breaks	Length (km)	Breaks
75	18.4	2	1.1	1	7.0	32	114.4	24	140.9	59
100	183.6	12	1.7	0	29.1	4	207.2	18	421.5	34
125	-	-	-	-	0.05	0	-	-	0.05	0
150	205.0	5	1.4	0	7.0	0	-	-	213.4	5
200	118,9	2	1.4	0	1.5	1	-	-	121.8	3
250	39.9	3	0.7	0	1.3	0	-	-	41.9	3
300	70.0	2	3.7	0	2.1	1	-	-	75.8	3
350	2.0	0	0.07	0	-	-	-	-	2.1	0
400	27.6	2	3.5	0	-	-	-	-	31.1	2
450	1.7	0	0.1	0	-	-	-	-	1.8	0
500	20.0	1	6.6	0	-	-	-	-	26.6	1
550	1.5	0	-	-	-	-	-	-	1.5	0
600	8.7	0	5.6	0	-	-	-	-	14.3	0
700~	6.1	0	44.6	0	-	-	-	-	50.7	0
Total	703.4	29	70.5	1	48.1	38	321.6	42	1,143.6	110

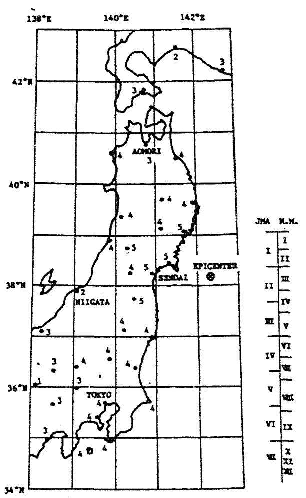

Fig. 1. Location of Epicenter and JMA Intensities at Various Places.

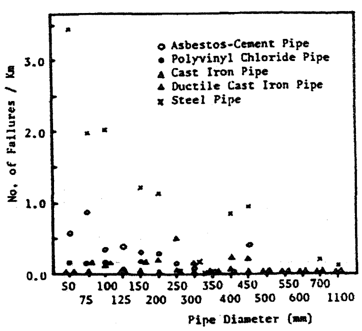

Fig. 3 Failure Ratio per km of Water Supply Pipe and Diameter (29 Utilities in Miyagi Prefecture).

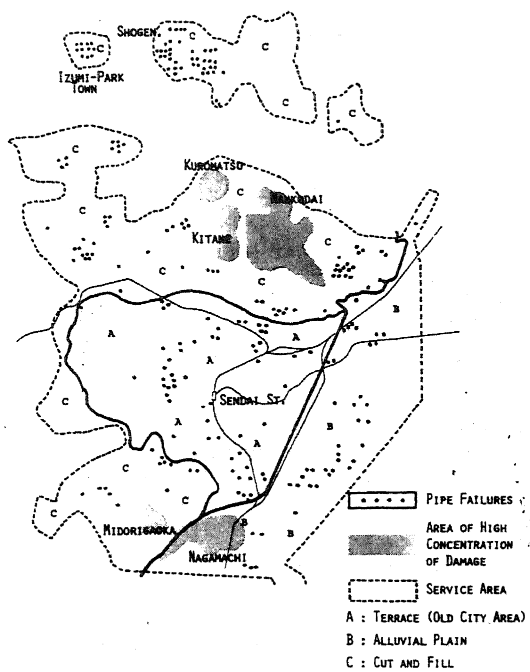

Fig. 2 Distribution of Gas Pipe Failures in the Sendai Area.

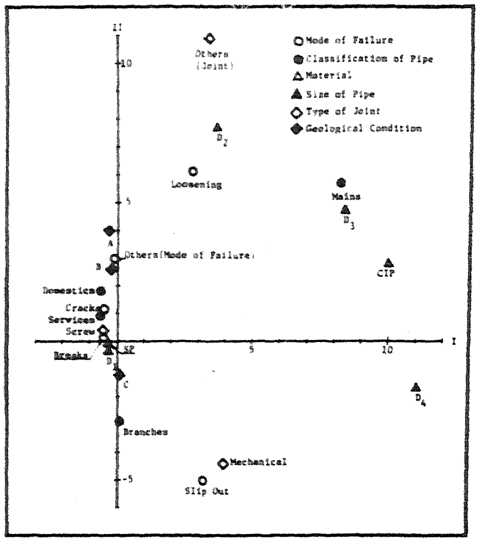

Fig. 4 Sccatergram of Categories for Gas Pipe.

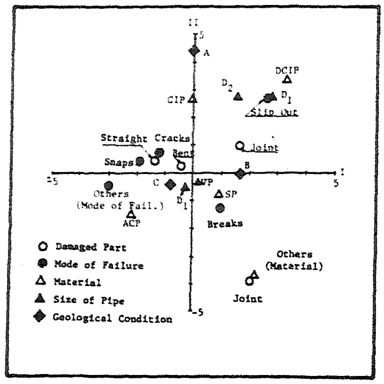

Fig. 5 Sccatergram of Categories for Water Distribution Mains.

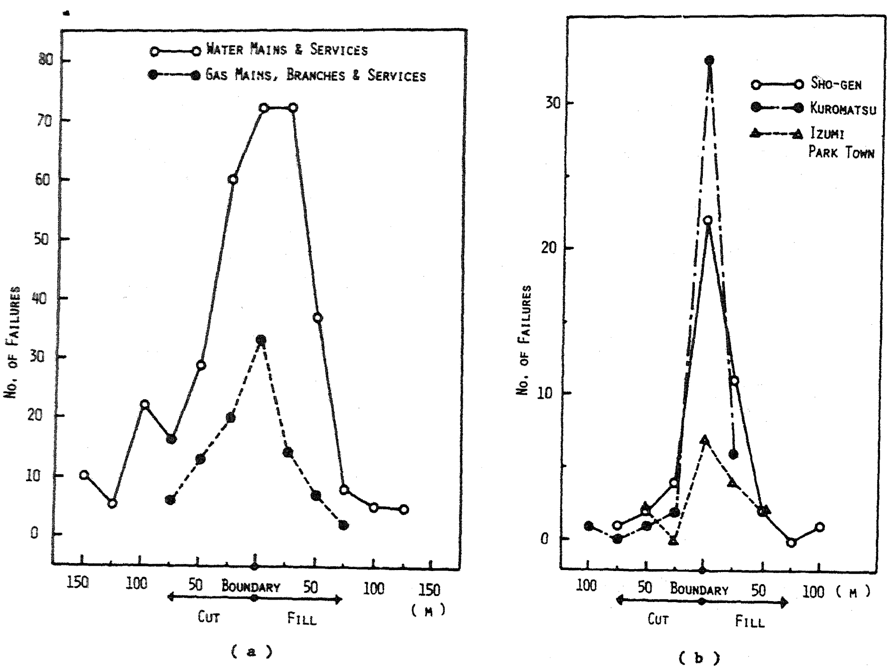

Fig. 6 Number of Failures and Distance from Cut and Fill Boundary.