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SEISMIC DAMAGE BEHAVIOR OF BURIED LIFELINE SYSTEMS DURING RECENT SEVERE EARTHQUAKES IN U.S., CHINA AND OTHER COUNTRIES

by

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Under the US-PRC Cooperative Science Program, this report is jointly written by Dr. Leon R.L. Wang, Mr. Sun Shao-ping and Mr. Shen Shijie*** Senior Engineer of the Municipal Engineering Design Institute of Beijing.

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(1). PREFACE

This report is the product of a joint research effort under the United States (US) - People's Republic of China (PRC) Cooperative Science Program of the National Science Foundation. In the U.S. side, the project was first initiated at the University of Oklahoma (OU), Norman, Oklahoma in 1982, and later transferred to the Old Dominion University (ODU), Norfolk, Virginia, in 1985 when the Principal Investigator, Dr. Leon R.L. Wang moved from OU to ODU. In the China side, the project has been carried out at the Municipal Engineering Research Institute of Beijing (MERI) and the Principal Investigator is Mr. Sun, Shao-ping Director of MERI.

The object of this report is to study the damage behavior of buried lifeline systems, particularly water and sewer lifelines, during recent severe earthquake occurred in U.S., China and Japan by both sides. The damage behavior of buried lifelines from 1971 San Fernando, California Earthquake in the United States and the 1978 Miyagi-Ken-Oki Earthquake in Japan were studied by Dr. Wang and his students in the United States. The 1975 Hai-Cheng (海城) Earthquake and the 1976 Tangshan (唐山) Earthquake in China were studied by Mr. Sun and his colleagues in Beijing.

The discussions of results took place three times, once in the summer of 1982 and 1984 when Dr. Wang visited China, and once in the summer of 1983 when Mr. Sun and his colleagues visited the United States. The report represents the team effort from both sides.

(2). 1971 SAN FERNANDO USA EARTHQUAKE

2.1. Seismological and Geological Information

The San Fernando earthquake occurred at 6:01 AM on February 9, 1971 inflicting severe damage and major losses along the foot hills of San Gabriel Mountains and along a narrow east-west band of faulting on the valley floor. The map showing epicenters of the main shock and after shocks as having a magnitude 3.0 and greater for the first 3 weeks of activity, February 9 through March 1, 1971 is given in Fig. 2.1.

The earthquake's heaviest shaken region was located in the northern suburbs of the city of Los Angeles and the adjacent small communities. More specifically, the center of the earthquake's energy was near the northern boundary of San Fernando Valley as indicated in Fig. 2.2.

The main shock of the San Fernando earthquake has been assigned the following values:

Richter magnitude: 6.6
Origin time: 6.00:41. 6 AM, PST
Epicenter: 43°24.0'N., 118°23.7'W
Focal depth: 13.0 km (8 miles)

The actual fault movement which occurred during the earthquake was a left lateral thrust fault.

The relative movement of the San Gabriel Mountains, north of San Fernando Valley was up and over the San Fernando Valley on the slopping fault plane. However, the San Gabriel Mountains simultaneously moved westerly in terms of feet with respect to the San Fernando Valley.

Where the San Fernando fault reached the ground surface, lateral movements up to 3 feet apparently occurred. Vertical displacements of 3 feet were found, and ground shortening of almost 3 feet was noted across the fault zone.

An isoseismal map of the San Fernando Earthquake is shown in Figure 2.3.

2.1.1. Earthquake Forces:

The overall strong motion lasted about 12 seconds: the strongest shaking began about 1 to 2 seconds after the instruments started to record, and the strongest shaking lasted for about 8 seconds.

The earthquake's horizontal accelerations were the highest ever recorded, 104% of gravity for the greatest single pulse and a number of other peak accelerations in the 50 to 75% of gravity range. In addition, substantial vertical forces also existed. Over 1000 landslides, and more than 250 strong-motion instruments were triggered by the earthquake.

2.1.2. Soil Conditions:

Soil generally tends to be structurally poor throughout the San Fernando Valley. The valley floor, encompassing some 160 square miles, is relatively flat - having a gentle drainage gradient toward the southeast. The soils underlying the basin consist of alluvium derived from the present bedrocks making up the boundary mountain system. These soils range in composition and consistency from the very fine grained, highly expansive clays derived particularly from the marine shales (Modello and Topanga Formations) located within the Santa Monica Mountains in the south and southwest valley to the very coarse-grained sand, gravel, cobble and boulder type sediments derived from the granite bedrocks of the San Gabriel and Verdugo Mountains bounding the northwest side of the Valley. The alluvial deposits in the basin reach depths in excess of a thousand feet and range in consistency from soft, wet and highly compressible, as in areas to the northwest of the Sepulveda Flood

Control Basin, to the relatively dense sand, grave, and cobble deposits located in the north central valley area are along the old Tujunga Flood plain.

2.2. Damage to Water and Sewer Lifelines

2.2.1. Earthquake Damage to Water and Sewerage Facilities:

This damage ranged from numerous small service leaks to major trunk line breaks and extensive damage to two major earthfill storage reservoirs. Severity of the damage was largely caused by the nearness of the epicenter to the Van Norman Reservoir Complex and the surrounding concentration of water and sewerage facilities.

Damage to water distribution and supply facilities involved pipes of every type and description, values and fittings, water storage facilities of both steel and concrete construction, large conduits, tunnels, walls, pumps, and pump stations. In some areas distribution mains were damaged in as many as 8 to 10 locations per 100 feet of pipe.

Water and sewer systems and gas lines suffered numerable breaks. Table 2.1 shows the list of breaks and leaks of underground ultities. The water system had 363 breaks in mains and 513 leaks in service lines. There were 1155 breaks in sewer lines. The gas lines, had 189 breaks in mains and 191 breaks in services. Figure 2.4 shows the map of major sewer damage. Figures 2.5 and 2.6 show the water main and the gas main damages, respectively.

All the cast iron water mains with cement-caulked joints that crossed the fault in the area under consideration were damaged. Most of the mains were composed of 18 ft (5.5 m) lengths of gray, cast iron pipe joined at cement-caulked, bell-and-spigot couplings. Both northwest and northeast trending lines ruptures, but damage was most prominent along northeast trending lines where compressive ground deformations were largest. The most striking damage occurred along the norteast-trending line at Harding Street where 100 ft (30 m) of cast iron line were shattered.

In contrast to the lines with cement-caulked couplings, cast iron mains with rubber gasket joints showed no damage in the area under consideration. These pipelines were composed of 18 ft (5.5 m) lengths of gray, cast iron pipe joined by rubber gasket, or push-on, couplings.

2.2.1.1. Los Angeles City:

The water supplied from the Woens River is delivered by two aqueducts, extending 338 miles through conduit, open channel, and tunnel terminating in storage reservoirs at the northern edge of the San Fernando Valley. Both aqueducts were damaged: one had tunnel leakage by grouting; and the other experienced impairments including separated couplings, a protruding 6 inch compression wrinkle, and dislocated saddle supports.

There were 22 breaks in two major trunk lines (48 and 54 inch) serving areas west of the reservoirs. In addition, numerous breaks occurred in major trunk lines serving areas to the east. The majority of these lines were comprised of riveted or welded steel pipe, with the balance of largely unreinforced concrete. There was a total of 153 leaks in these major trunks ranging from 16-inch to 99-inch in size. About 23 square miles of area were without water while over 1400 individual repairs were performed. Almost 500 fire hydrants were out of service until the repair of 22,000 feet of 6, 8, and 10 inch diameter pipe could be made in Sylmar-Olive View area.

Los Angeles had over 6,000 miles of sanitary sewers. An assessment of the damage, as shown by the video tapes, indicated that 126,000 linear feet of mainline needed to be reconstructed. Data on the extent of sewer pipe damage is given in Table 2.2.

2.2.1.2. San Fernando City:

The city was served by a municipally-owned water system which was supplied by 7 wells in or adjacent to the northerly section of the city. The distribution system was primarily composed of a single service level. Earthquake effects on the system were severe, including damage to wells, broken pumps, reservoirs, and distribution mains.

With all the wells and storage facilities located in the same general areas north of a section which experienced extensive ground movement; the supply facilities were, in essence, severed from the distribution system by the multitude of breaks.

The types of pipe and joints used in water distribution pipelines in San Fernando consisted principally of cast-iron class 150 pipe with bell and spigot joints sealed with cement mortar or mineral lead. Other types of pipe included: 1) thin-walled longitudinally riveted steel pipe with either bell and spigot, stovepipe, or riveted joints: 2) pre-tensioned steel cylinder, concrete-encased and cement-lined pipe having bell and spigot joints and rubber gland seals; and 3) some standard 6 inch steel pipe. The pertinent data on the water pipe system in San Fernando is shown in Table 2.3.

During the process of locating and pressurizing sections, some gate valves were found to be inoperative. Earthquake damage to the water mains occurred principally in the northwestern corner of San Fernando where the intense surface rupturing occurred. There was ground shortening across the ruptures of as much as one foot and left-lateral movements of over three feet. There was also a general rise in the ground elevation of over 4 feet in the area.

2.2.1.3. California Aqueduct System:

Facilities of the California Aqueduct, within the area of significant influence of the San Fernando earthquake, included the Tehachapi Crossing, the West Branch, and portions of the Mojave Division. On the date of the earthquake, most of these facilities were in final stages of construction. These facilities did not contain water at the time, and inspections conducted immediately following the earthquake revealed that no structural damage had been sustained.

Criteria for establishing earthquake forces for all pumping and powerplants located within 12 miles of any major fault were based on a structural acceleration of 0.5g.

2.2.1.4. Los Angeles Owens River Aqueducts:

At the time of the earthquake, the 1st L.A. aqueduct was carrying a near-capacity flow of 485 cfs., and the 2nd aqueduct had been shut down for a scheduled maintenance.

Inspection of the first L.A. aqueduct revealed that the 9'8" x 10'6" tunnel suffered hundreds of new factures in the concrete lining. The fractures were primarily circumferential, but longitudinal and diagonal patterns were also quite prevelant.

There were several locations where the first aqueduct crosses canyons by means of riveted steel pipe spanning adjacent tunnels. In most instances leaks developed at transition points in the pier-supported pipelines.

2.2.1.5. Penstock:

The power penstock, which is a 46 inch riveted steel pipe, connects the southern terminus of the first L.A. aqueduct to the San Fernando powerplant. The penstock was subjected to heavy movement by the force of the earthquake which displaced the supporting piers both vertically and horizontally for up to 2 feet in many locations. Reinforced concrete anchor blocks were shattered as the pipe elongated at two expansion joints which were approximately one foot at each location.

Several dozen rivets were sheared off or loosened as stiffener rings were brought into contact with adjacent piers by the force of the axial movement. Moderate buckling of the steel plates took place at several pier contact points and at anchor points.

The First Los Angeles Cascades and Bypass Channels suffered heavy fracturing and displacement of the channel lining (reinforced concrete lining).

2.2.1.6. Second L.A. Aqueduct:

A massive slide movement was triggered by the earthquake on the north side of Terminal Hill, which serves as the foundation for the above ground 76 inch diameter welded steel pipeline. The pipe was pulled apart at both mechanical couplings on top of the hill and suffered a compression failure at midslope near the top of the slide. All of the support piers and anchor blocks were displaced along the slide area.

2.2.1.7. Major Distribution Facilities:

The Balboa Inlet Tunnel, San Fernando Tunnel and the Santa Monica Feeder suffered concrete damage that was chipped out to the hoop reinforcing steel, in addition, some joint separations were observed.

The Granada Trunkline is a steel pipe, 49 1/2 inches in outside diameter, with welded slip joints. The steel is ASTM A - 283, Grade C, 1/4 inch thick and design hoop stress on pipe is 11,760 psi. All failure in the Granada Trunkline occurred at joints, two at mechanical couplings and eight at the welded slip joints. Failure were predominantly compressive, but some tensile failures did occur.

2.2.2. Variable Factors Associated With Damage:

There are numerous variables which could conceivably be related to the extent of pipe damage. These include the following:

1. Kind of Pipe.
2. Buried depth of pipe.
3. Proximity of other substructures.
4. Type of soil.
5. Location with respect to fault zone and areas of vertial uplift.
6. Size of Pipe.
7. Type of joint.
8. Encasement of pipe.

However, there is not sufficient information available concerning all of these variables to be able to develop conclusions in respect to all eight items.

In summary, the information on pipeline damage along the San Fernando fault shows four significant features:

1. Pipelines with rubber gasket joints performed substantially better than those with cement-caulked joints. In the area under study there were no leaks on rubber gasket mains during or immediately after the earthquake, whereas there were several repairs at cement-caulked couplings on lines in the immediate vicinity of those with rubber gasket couplings.
2. Adjacent to the fault zone, northeast trending lines were compressed, and northwest trending lines were extended. The alternating modes of tension and compression were primarily a function of pipeline orientation relative to the left lateral slip along the fault. Nevertheless, within the zone of largest ground movement, all lines were placed under compression regardless of orientation.
3. Lines made of Mannesman steel were highly susceptible to internal

corrosion and were more heavily damaged than lines composed of cast iron or other types of steel.

4. Damage to water mains continued for several years after the earthquake, mainly in the form of rupture connetions between mains and service lines.

2.2.3. Recommendations:

In the design and construction of utilities, such as water systems in Southern California, consideration must be given to the strong possibility of the occurrence of earthquakes of major magnitudes and intensity, and unusually high ground surface accelerations may be experienced in earthquakes of only medium magnitude.

Significant structures settlement may result from the consolidation of compacted fills caused by ground shaking.

Cities and utilities should be ready to cooperate for effective emergency repairs after natural disaster by helping each other when necessary.

2.3. Earthquake Damage to Dams/Reservoirs

2.3.1. San Fernando Dam Complex:

The San Fernando Dam complex consists of 3 earth dams, impounding water and forming the Van Norman Reservoir Complex which provided about 80% of the city's water supply in 1970-71.

The lower San Fernando Dam experienced the worst damage of all dams in the complex. The embankment including the parapet wall, dam crest, most of the upstream slope, and a portion of the downstream slope for a length of approximately 1800 feet, slid into the reservoir. As much as 800,000 cubic yards of dam embankment may have been displaced into the reservoir, resulting in a loss of about 30 feet of dam height. The east outlet tower was cracked at the base and broken off about 20 feet above the base and came to rest in an upstream orientation.

2.3.2. Van Norman Reservoir Complex:

The complex consists of three reservoirs in the northern area of the San Fernando Valley for the purpose of storage for the domestic water supply.

An extensive soil investigation was initiated on both the Upper and Lower Dams. The investigation at the Lower Dam have led to the conclusion that the slide was caused by liquefaction of the loose, saturated sands in hydraulic fill. This is evidenced by the extent of lateral movements of slide mass, the pressence of sand boils within the slide debris and the disruption of the soil towards the bottom of the trench.

2.3.3. Pacoima Dam:

Pacoima Dam is a concrete arch dam, located in the Pacoima Canyon about four miles northeast of San Fernando. It was designed for the dual purpose of flood control and water conservation.

Observations were as follows:

1. Only minor damage occurred to the dam structure and to the right abutment.
2. Damage to the left abutment was generally confined to the upper 60 feet.
3. The magnitude of the load placed on the dam by seismic forces far exceeded the design criteria.
4. It is believed that the past remedial maintenance work of guniting, grouting, drainage, and rockbolting has been extremely beneficial in maintaining the structure during the earthquake. No rock movement was noted in the rockbolted area.

2.3.4. Recommendations:

Attention must be paid to the structure of alluvial foundations, as a loose soil structure is subject to significant reduction in shear strength under seismic vibrations. Also, it must be recognized that differences in seismic response between the foundation and embankment, or between high earthfills in a valley and low earthfills or adjacent terraces, may lead to significant overstress, causing cracks to develop in the embankments.

More attention should be given to achieving the maximum densification possible in outer portions of the dam embankment where surface cracking sloughing, and slides are likely to occur from the sudden settlements which accompany strong seismic vibrations.

2.4. Earthquake Damage to Gas Lifelines:

The San Fernando-Sylmar area is supplied with natural gas by the Southern California Gas Company. This company provides natural gas to approximately 3,100,000 customers within 530 cities and towns.

2.4.1. Transmission System:

A portion of the transmission system handling the deliveries to California gas from San Joaquine Valley southward to the Los Angeles basin was damaged to the extent that four lines had to be shut down in the San Fernando area. Damage to the four lines, which range from 12 - 25 inches in diameter and are of welded steel construction, occurred between Newhall and San Fernando which resulted in the loss of gas supply to the distribution system.

The greatest damage was sustained by a 16 inch transmission line on Foothill Boulevard, about one mile north of San Fernando, where an approximately six mile length of pipeline had 52 separate breaks. The damage ratio is

8.7 breaks/mile. The 16 inch line buckled under the compressive forces generated by the earthquake.

Five miles of twelve inch trasmission lines had been abandoned between Sylmar and San Fernando because of numerous breaks. It is believed that a significant portion of the transmission system consisting of 22 and 30 inch diameter pipes, located slighly west of Sylmar San Fernando area, suffered no apparent damage. While there was evidence of soil slippage along a portion of the route of these pipelines, there was no faulting. The 22 and 30 inch pipelines are of welded steel construction.

2.4.2. Distribution System:

An area of four miles square suffered the greatest distribution system damage. The distribution system in the hard-hit area consists principally of 2, 3 and 4-inch welded steel mains and 3/4 inch welded steel services. The violent earth movement pulled, compressed, and twisted the piping system which resulted in broken mains, valves, and service risers. There were approximately 181 breaks in mains, mostly at welds but some occurred in the pipe and others in values and fittings. There were 137 breaks in service and 62 breaks at service-to-main connections.

Gas transmission line damage and distribution system drainage were clearly related to ground movement, i.e. faulting, landslide, lurching, and similar effects.

- upward direction with an angle of 52° at top of fault plane
- fault trace on ground crack showing 115 cm of relative displacement

Obviously, pipeline layout and mains of sectionalizing can greatly minimize these geologic hazards: valves can be located adjacent to faults, and line laid parallel to faults when possible.

Table 2.1 gives the summary of water, sewer and gas breaks.

2.4.3. Conclusions and Recommendations:

In general, the gas system sustained the stresses of the earthquake remarkably well. This was borne out by the fact that in many areas where appreciable damage occurred to buildings, the gas system remained intact. This was the result of improvement in welding techniques over the years, earthquake pipe breaks, of the type that formerly occurred at welds, now occurred in the pipe.

2.5 Damage to Power Facilities

2.5.1. Electric Lifeline Systems:

The earthquake disrupted power service and blacked out large portions of the city of Los Angeles. The immediate impact on the city's power system was as follows:

1. The interruption of 700 mega watts of load;
2. The loss of northwest power supply for the high voltage direct current intertie;
3. The interruption of power output from four steam plants generated units and three hydroelectric plants;
4. The interruption of power flow at ten transmission substations and numerous other points in the distribution system.

Of the 18 major substations, 7 were put out of service by the earthquake, with all restored to complete or partial service within 1 1/2 hours.

Of the 1400 distribution system radial feeders, about 200 tripped and locked out by action of circuit breakers or fuses.

In addition to damaged poles, many wires and poles were knocked down, insultors cross-over broken, cables sheared off in underground ducts and about 70 pole transformers were damaged or downed.

2.5.2. San Fernando Powerplant:

The plant consists of two 300-kw hydroelectric generating units. They are enclosed in a small reinforced concrete power house built in 1921. This plant suffered severe structural damage from intense shaking and settlement. Damage to the powerplant included diagonal cracking and crushing of reinforced concrete walls and columns, a break in the penstock and resultant flooding, rupture of sanitary sewers, slumping and slides in the trail race, and buckling and settlement of the peristock sections upstream.

Two major factors contributed to the damage:

1. power house structure designed 50 years ago with no seismic forces accounted for in the design.
2. there was no articulation joint where the peristock entered the power house to accommodate differential settlement. Settlement combined with intense shaking caused the break in the peristock.

Other generating plants suffered minor damage, usually units tripping off the line and were restored quickly.

2.5.3 Sylmar Converter Station:

The station sustained severe damage. Intense shaking caused the greatest amount of damage, although permanent ground movement contributed to damage in certain instances (station was 40% destroyed).

The building was designed for 0.20 g seismic loading. Major damage was concentrated in the location where the service area joined the valve hall. The area (140' x 210' x 36') and valve hall (130' x 33' x 50') are separate steel frame structures above the first floor levels. Extensive damage was concentrated in the basement and foundations along a column line that separated these two areas. Other damage, primarily to plaster partitions, light fixtures, manholes, and underground conduits where they entered the manholes, was noted.

All 42 mercury gas valves suffered major damage to their current divider and a node structures. The primary cause of failure was the very complex swinging and bouncing motion of the current divider during the earthquake. The movement of the current divider resulted in a combination of dynamic loading of the suspension insulator strings and relative displacement between the node structure and the current divider.

2.5.4. Recommendations:

1. Replace the suspension insulators with insulators of ultimte strength of at least 30,000 lbs.
2. Incorporate type of energy dissipation device in the suspension insulator string assembly to ease the impact loading and increase damping capability.
3. Incorporate long, flexible leads between dividers and nodes to allow for relative movement between them.

Radio interference screen structures are light weight steel frames supported by pier-type foundation with x-bracings. Permanent groud movements stretched these frames from 7 to 9 inches in the east-west direction.

Table 2.1

UNDERGROUND UTILITY BREAKS AND LEAKS

Tract	Los Angeles Water System		Sewer breaks	Gas Line breaks	
	Breaks in mains	Service leaks		Mains	Services
01	7	49	96	4	7
02	6	32	53	15	24
03	13	49	38	3	11
04	13	33	57	4	5
05	9	18	29	4	1
06	21	20	44	10	14
07	2	6	20		
08	27	3			
09	8	3			
10			1		
11	15	6	4	9	2
12	3	6		8	11
13	19	38		1	5
14	9	3	5		
15	4	9	29		
16	14		9	1	1
17		7	8	3	8
18	5	5	3		4
19	3	3	3		
20					
21	9	42	94	9	10
22	4	13	35	6	7
23	32	37	71	4	3
24	6	3	32		1
25	34	2	29	9	
26	22	36	58	5	3
27			34	17	10
28	8	6	16	14	11
29		7	38	3	5
30			17		
31	6	1	18		
32	1	1	16		
33	2		20	2	2
34	2	1	6	1	1
35	3	4	6	5	4
36			46	17	10
37			45	5	4
38	22	17	38	19	16
39			5		2
40			16	2	1
41			25	6	4
42			25		
43			18		
44			1		
45				1	
46			3		
47			6		
48				1	2
49			3	1	1
50			3		
51					
52	17	17			
53	2	5			
54	8	16			
55	3	1	32		
56	2	13			
57	2	1			
Totals	363	513	1,155	189	191

Table 2.2 - Extent of sewer pipe damage

Pipe Size and type of joint	Length of existing pre-earthquake	Length to be reconstructed	Percent to be reconstructed
	Lineal feet	Lineal feet	
8-in. flex.............	363,600	58,400	16.1
8-in. rigid............	90,600	30,900	34.1
8-in. encased..........	1,200	260	21.6
10-in. flex............	23,800	4,000	16.8
10-in. rigid...........	5,300	1,000	18.9
10-in. encased.........	270	40	14.8
12-in. flex............	24,900	3,900	15.7
12-in. rigid...........	9,700	2,800	28.8
12-in. encased.........	3,400	1,800	53.0
15-in. flex............	13,900	3,500	25.2
15-in. rigid...........	3,500	1,800	51.5
15-in. encased.........	3,600	1,000	27.8
18-in. flex............	17,800	4,900	27.5
18-in. rigid...........	8,000	6,100	76.3
18-in. encased.........	7,300	5,600	76.8

Table 2.3-Pertinent data on water pipe in San Fernando water system

Type of pipe	Diameter	Total linear feet of pipe in system	Linear feet of pipe replaced	Percent of type replaced	Stove-pipe joint	Bell and spigot joint	Mineral lead joint	Cement joint	Rubber gland joint	Screw joint coupling	Riveted joint
	Inches										
Cast iron	4	10,450		7		X					
	6	145,789	12,037			X	X	X	X		
	8	48,620	2,265			X	X	X			
	10	18,619	2,705			X		X	X		
	14	4,431				X					
Thin-walled riveted steel.	6	4,870	2,235	47	X						
	8	7,530	720		X						
	10	6,779	1,320		X						
	12		1,460			X Field					X Shop.
	14		4,555			X Field					X Shop (see text).
Concrete-steel cylinder (SSP 381).	18	5,493	1,200	22		X			X		
Standard steel casing	2 to 4	17,790		2							
	6	25,115	856							X	
	8	8,260									
	10	2,600									

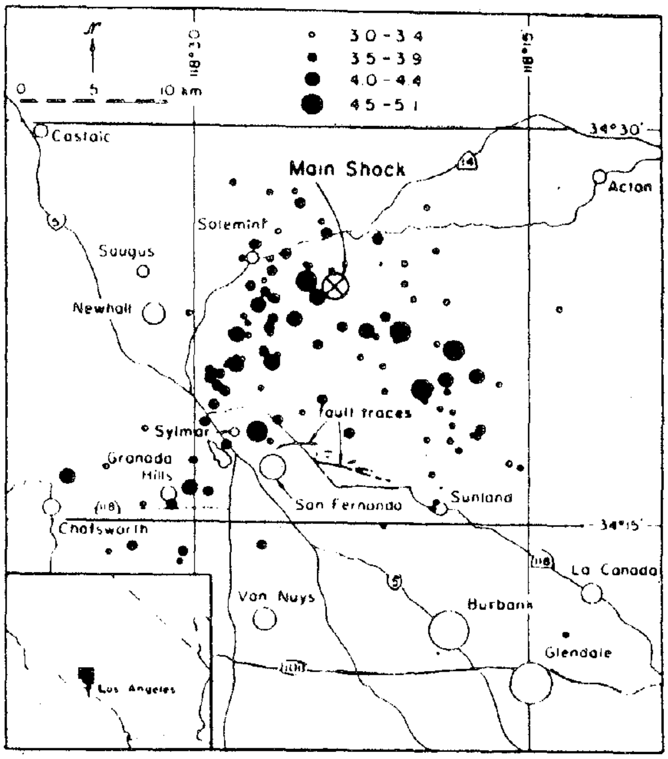

Figure 2.1 Map showing epicenters of the main shock and after-shocks having magnitude 3.0 and greater for first 3 weeks of activity, February 9 through March 1, 1971.

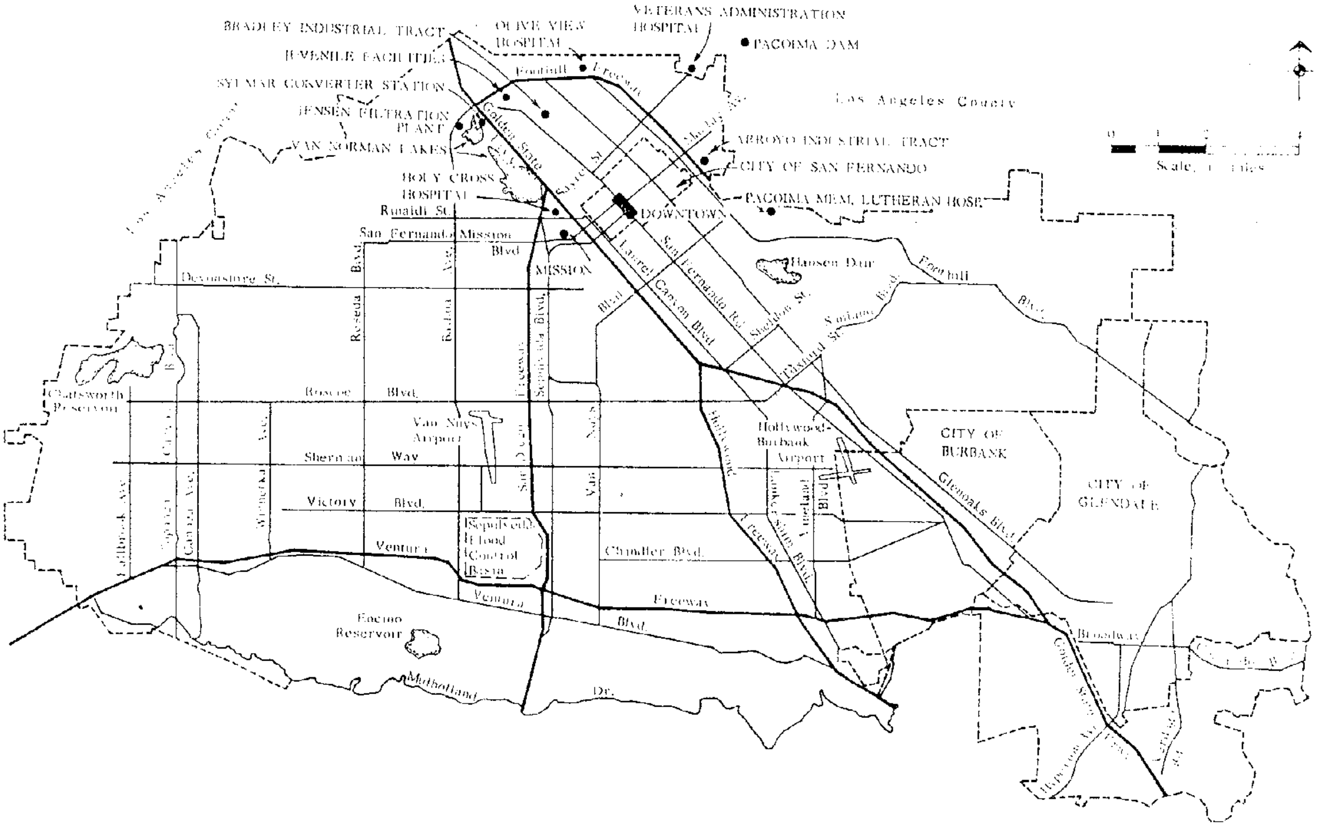

Figure 2.2 Heavily shaken area of San Fernando valley.

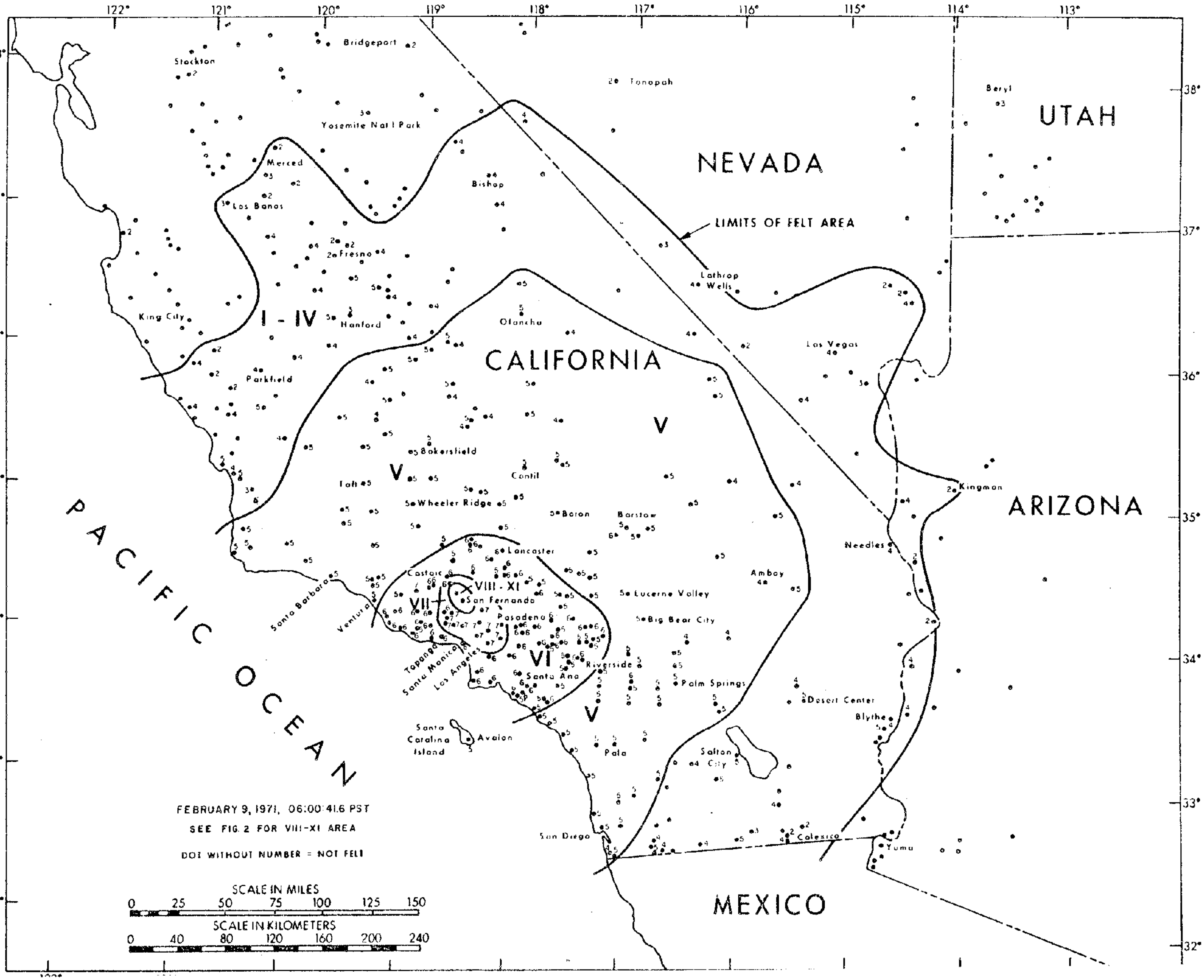

Figure 2.3 - Isoseismal map of the San Fernando Earthquake

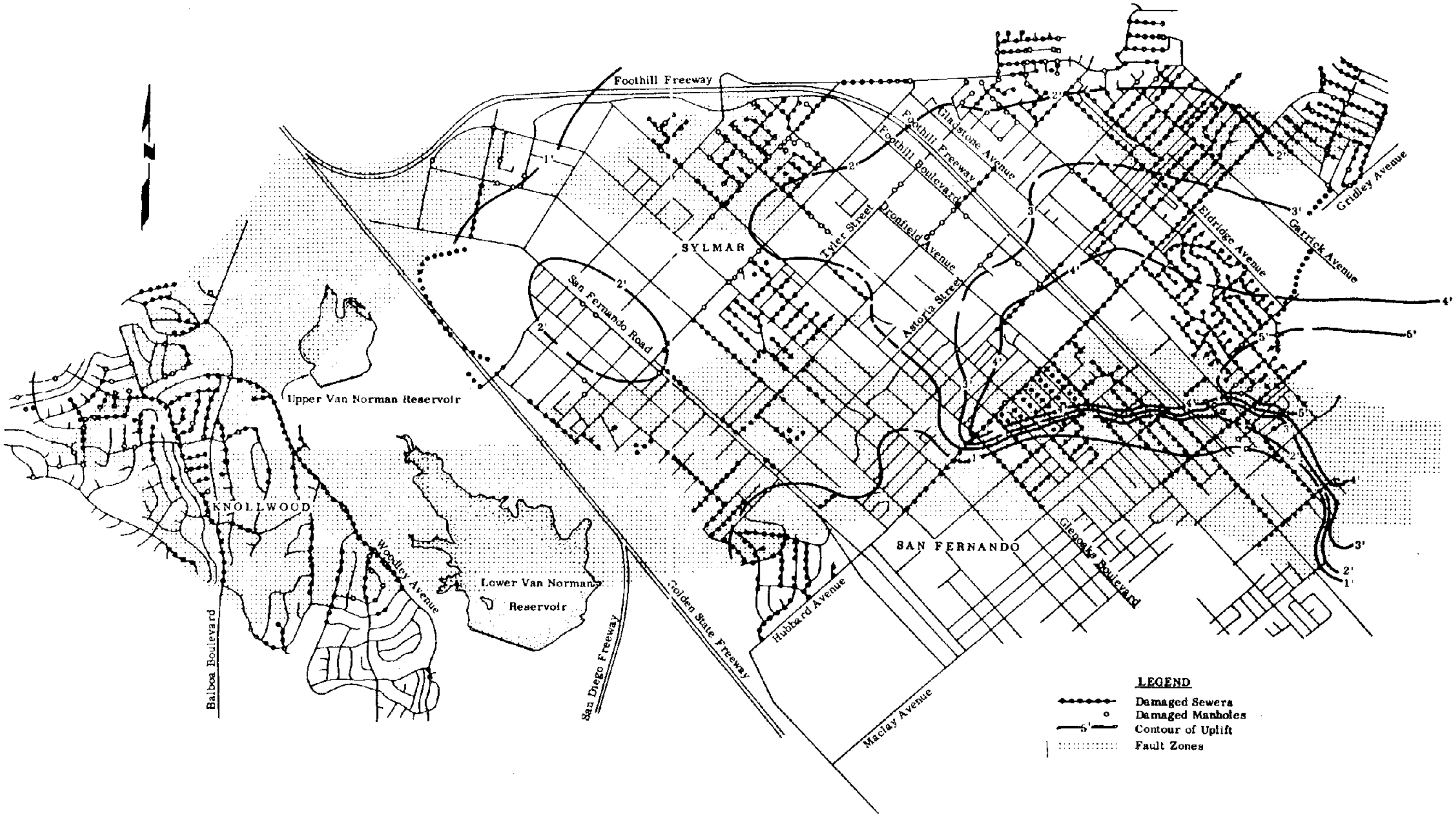

Figure 2.4 - Map showing major sewer damage in San Fernando Area

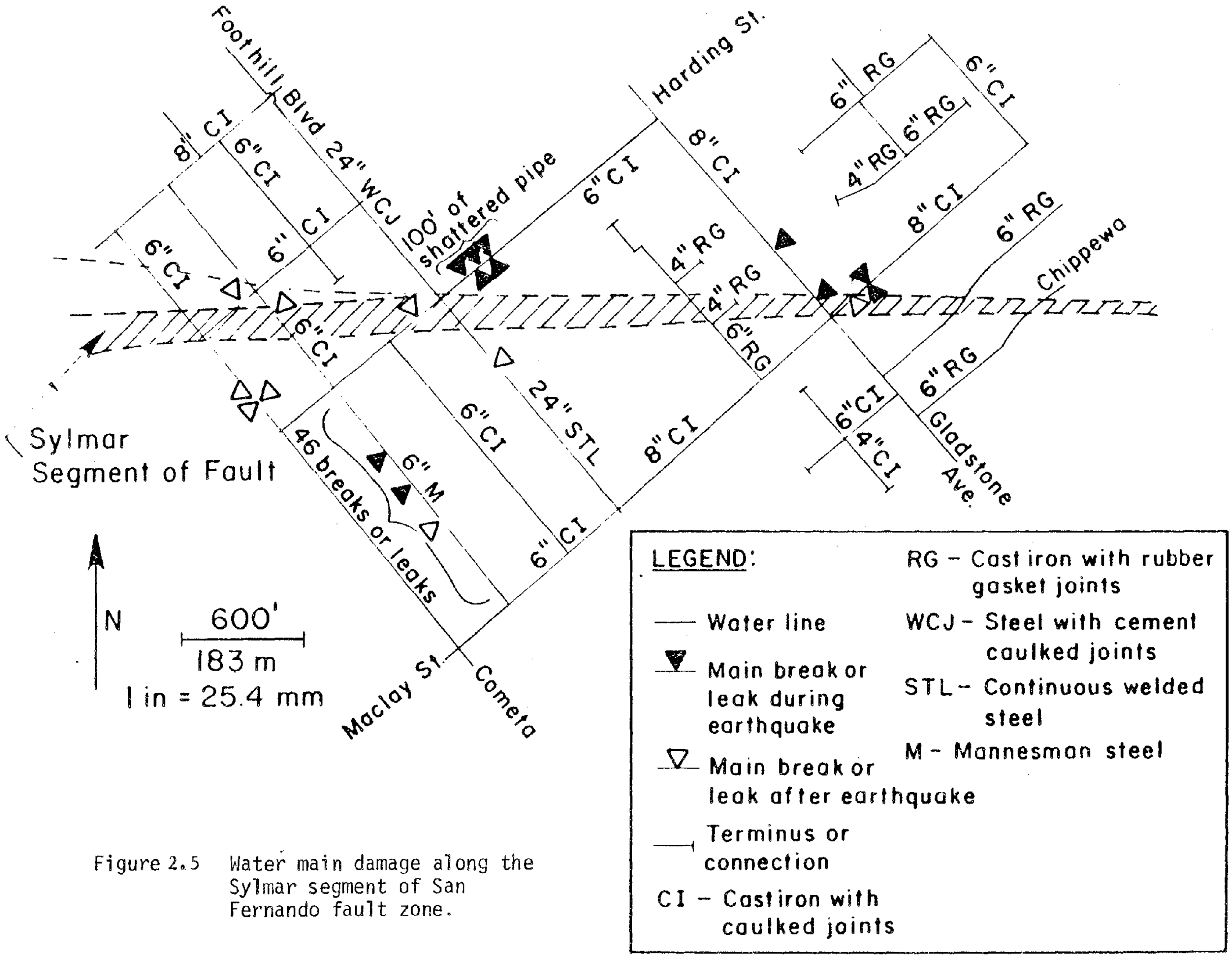

Figure 2.5 Water main damage along the Sylmar segment of San Fernando fault zone.

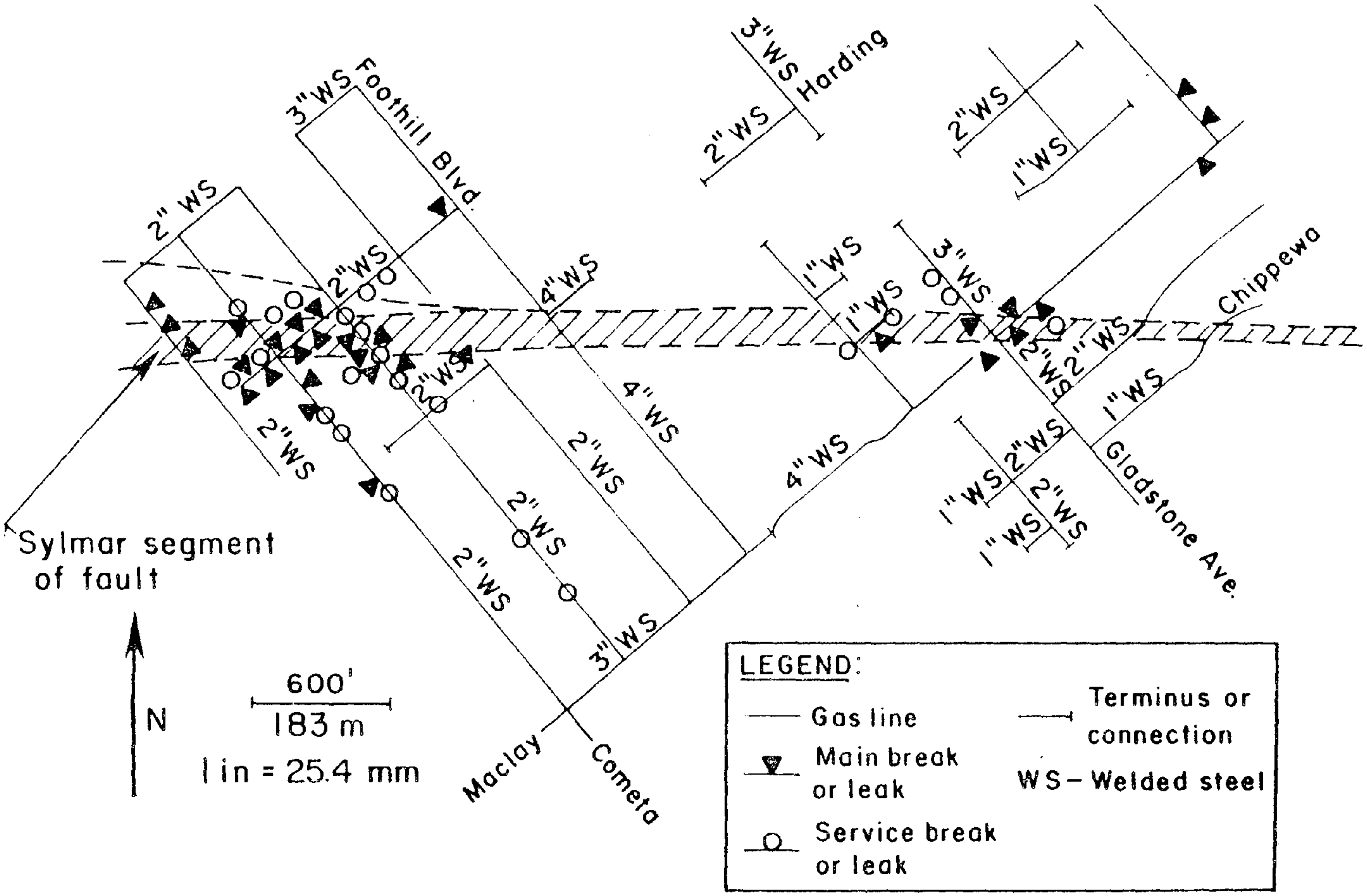

Figure 2.6 Gas main damage along the Sylmar segment of San Fernando fault zone.

(3). 1975 HAICHENG, (海城)CHINA, EARTHQUAKE

3.1. Seismologial Condition:

3.1.1 Parameters of the Earthquake:

(Beijing) time of commencement of the shock:

7:36 P.M., on the 4th of February 1975

Magnitude: M 7.3.

Epicenter: 40°39' N, 122°48' E.

Near Zhaojiabao (趙家堡) Village, Haicheng.

Focal depth: Approx. 12 km.

3.1.2. Geological Structure of the Haicheng and Yingkou (营口) Regions:

In Fig. 3.1 the Shenyang(瀋陽)--Dalian (大連) railway can be seen. On the east of the railway is the mountainous land of eastern Liaoning which is an upwarped district of paleometamorphic and eruptive rocks. On the west of the railway is an alluvial plain at the lower end of the Liao River, (遼河) which is a part of meso-neopalaeo fault basin. In the region there are three structural zones striking W--E, N--W, and N--E. Rock formation of the region is cut into many blocks of different sizes and depths of grating structures by faults of different strikings.

3.1.3. Distribution of the Seismic Intensity:

In this paper the intensity is adopted to describe the observed effect of ground shaking at a particular site, it is divided into 12 degrees. The macroscopical distribution of the intensity of Haicheng Earthquake is shown in Fig. 3.1.

Here the soils at the site are divided into three types (classes):

Type I. Readily and moderately slackened solid rock;

Type II. Ordinary soil in steady state except I and III;

Type III. Saturated loose sand, silt and silty soil, alluvial soil and other impurities.

Distribution of the seismic intensity, as shown in Fig. 3.1, is not only relevant with the geological structure but evidently affected by the soil conditions. On the rolling country with an intermontane basin of paleometamorphic and eruptive rocks is covered by a thin layer of the soil types I and II. On the alluvial plain of the Liao River, the sedimentary layers of diluvium, old river channel, march, etc. belong to the soil types II and III.

As shown in Fig. 3.1, there are some abnormal posts and regions in each intense zone; for example, the 9° intensity occurred in the 8° intense zone in Haicheng; the 8° intensity occured in the 7° intense zone in Yingkou. The 9° intensity occurring in Haicheng may be possibly due to its being an intersection point of the three N--E, N--W, W--E striking faulting belts. The 8° intensity occurring in Yingkou may be in connection with the conditions of the field and the different properties of the foundation soil there. As the epi-strata contain sand layers of transgression phase, valley flat phase and bayou lake phase, the disaster of the earthquake was intensified through liquefaction of the sand.

3.2. Seismic Damage of Water Supply Pipeline:

The Haicheng earthquake brought serious damage to the water supply pipelines buried in Haicheng (海城), Yingkou (营口), Panshan (盘山), Anshan (鞍山) and other cities. Most of the pipelines (about 90%) are of cast iron, and the rest are of steel, prestressed reinforced concrete, asbestos cement and ordinary concrete. Among them the larger diameter steel pipe is mainly used for transmission or river crossing of supply water; the steel pipe with the diameter less than 75 mm mainly for water distribution to house holds.

3.2.1. Haicheng City:

The city is located in the south of Liaoning (遼寧) Province on the juncture of a river terrace and piedmont diluvium. There the ground water level is rather high. In the depth of 5 m of the ground surface is mostly epigenetic soil in which most pipelines are buried.

Before the shock some of the pipes had been used for over 60 years, and their surface was seriously corroded long ago. The total length of the pipelines in the city is about 21.35 km, the damaged places during the shock were up to 216, the damaged ratio being 10 breaks/km. Among them a 1.14 km long, 50 mm diameter distribution pipeline was damaged in 18 places, the damaged ratio being 15.7/km. The length of cast iron pipelines with diameter 75--200 mm was totally 16.7 km; with lead gasket joint pipeline was about 15.2 km long, 19 places were damaged; the damaged ratio of the cast iron pipes was up to 9.8/km. On a 3.5 km long, diameter 50--100 mm asbestos cement pipeline, the damaged places were up to 35 and the damaged ratio was about 9.0/km.

3.2.2. Yingkou (营口) Dashiqiao (大石桥) Region:

In the region the overlying stratum is not very deep, mostly belonging to the type II site soil. In the eastern part of the region there are mountain lands nearby and are sea crops of rock that belong to the type I site soil. There the ground water level is rather deep.

After the shock, 26 seismic damaged places were found for pipe with Ø > 75 mm, along 26.10 km long water supply network; the damage ratio averaging 10/km; and on pipes with Ø < 80 mm, along 31 km long distribution lines, 65 damaged places were found, the damaged ratio being 2.1/km.

3.2.3. Yingkou City: (营口市)

The city which is located in the north-eastern coast of the Gulf of Liaotung (遼東) and southern bank of Liao River (遼河) debouch is on a regression alluvial plain. There the overlying strata of the Quaternary is over 300 m in thickness. The ground surface layer is about 3--5 m thick, most of them belong to the silty clay or silty loam. In the western part of the

the city, most soils are slag and impurities, down to a depth of about 15 m where hard layer could be found. There the ground water level is higher, about 0.5--1.0 m deep from the ground surface. At this site soils belong to the type III class. When this region was attacked by the 8° intensity shock, liquefaction of subsurface sand layer occurred with gushing sand and water. In these conditions the pipelines suffered serious damages.

After the shock, 372 seismic damaged places were found on a Ø > 50 mm, along 158.5 km long water supply network, the damaged ratio being 2.35/km. Among them the damaged ratio of 4 km long, Ø 75--189 mm asbestos pipelines was 3/km. The main pipelines including a 17 km long, Ø=700 mm cast iron line and a 23 km long, Ø = 500--600 mm prestressed reinforced concrete lines are still in good condition after the stock, except a Ø = 600 mm cast iron pipeline with asbestos cement gasketed joint and buried in a back fill foundation of a railway was damaged in 5 places.

3.2.4. Panshan Town(盘山鎮):

The town located on the bank of the Shungtaizi (双台子) River on the west side of the Liao River is a region of regression alluvial plain. Under the ground surface 3--4 m deep most soil is silty clay and silty loam; below them is drift sand stratum with a thickness of over 100 m. There the site soil is of type III class. The region is lower with an elevation of +2.5-- 4.0 m; the ground water could be easily found under the surface of 0.5 m. During the earthquake, the liquefaction of sandy soil was quite serious with gushing sand and water. As the pipe bedding was seriously deformed and destroyed by the ground motion; therefore, the damage of the pipe is correspondingly increased.

In this town a 25.9 km long, Ø > 100 mm water supply pipeline was damaged 35 places by the earthquake, the seismic damaged ratio being 1.60/km.

3.2.5. Anshan (鞍山) City:

The ground water level in Anshan (鞍山) City is rather low, the site soil is of type III class. Geological conditions are favorable, so the pipe is only lightly damaged during the shock.

On a 500 km long, Ø = 78--100 mm buried water supply pipeline only three damaged places were found after the shock. First, at one place a Ø = 350 mm pipe was cracked longitudinally 1.2 m by a water hammer resulted from the sudden stopping of the pump due to the shock; the second, a Ø = 200 mm pipe was cracked longitudinally 1.3 m; and the third, a Ø = 200 mm pipe was pulled out from a watergage due to a ground fissure that is nearby.

3.3. Damage of Sewer Pipeline:

In the disaster region of the Haicheng earthquake, only in Yingkou City and Panshan Town, there were relatively integrated sewer systems. In the Panshan Town's sewer system, the length of masonry sewers is about 5.5 km, reinforced concrete pipelines is about 5.4 km. In the 7° intensity zone, twenty-one damaged places were found, and the damage ratio was around 1.9/km.

East of Yingkou City, on a diameter 600 mm, 36 km long concrete pipeline with mortar joints, three damaged places were found. The damage ratio was 0.08/km. In the west and the center of the city, buried diameter 600--1000 mm, 6 km long reinforced concrete pipelines with mortar joints and concrete bedding, no serious damage have been found after the shock.

3.4. Features of Seismic Damages of Pipe

3.4.1. Influence of Ground Condition and Intensity:

The various damage ratios of water supply pipelines in the disaster regions are listed in Table 3.1.

From Table 3.1 it can be seen that the soil of the site plays an important role in damage of pipes during an earthquake. It can be seen that the Dashiqiao (大石桥) and Haicheng regions both suffered 9° shock, but the ratio of the damaged pipes in Haicheng is much higher than that in Dashiqiao due to the unfavorable soil condition in Haicheng. Similarly, as liquefaction of sand and failure of bedding efficacy in Panshan, so the ratio is also much higher than that in Anshan, though both regions suffered the same intensity shock.

The intensity usually represents the displacements and amplitudes of ground movement, and it also plays an important role in damaging of buried pipelines. For example, though the site soils in the three regions are all of the type III class and the intensities in Panshan, Yingkou and Haicheng were 7°, 8°, and 9° respectively. Table 3.1 shows that the ratio of damaged pipe is mainly dependent on the intensity. However, one must remember that the ratios in Panshan and Yingkou were higher than that in the Dashiqiao region, which proved the fact that the intensity comes next to the site soil characteristics in its influence in damaging of pipe during earthquake.

3.4.2. Influence of Geography and Terrain:

Geography and terrain also have great influences on seismic damaging of pipes. In Yingkou City all pipes buried in the bank and bottom of Liao River were seriously damaged during the shock, see Fig. 3.2. Such as a diameter 200 mm submarine cast iron pipe was pulled out from its rigid joint on the bank; another Ø = 200 mm cast iron pipeline buried in back fill was also pulled out from a watergage in the shock.

The seismic influence of topgraphy on the pipelines was mainly reflected on the damages caused by the evident sliding of slope and obvious downwarping difference between back fill and original soil where the ground fissure could be readily found in this shock.

3.4.3. Influences of Pipe Material and Joint:

The different pipes buried in different intense zones and different sites have different seismic damaged ratios, as shown in Table 3.2.

From this table, one can see that the ratio of steel pipes buried in the 9° intensity zone is higher, which is mainly due to the serious corrosion in its long-term burying. Two Ø = 50 mm, water distribution steel pipelines in Yingkou and Haicheng had been buried about 40--60 years. During the shock, both lines were damaged especially on their threaded joints which had been seriously corroded.

Even if corrosion is not considered, the joint is still a weak part as compared with the pipe body; therefore, the structure or type of joint is also one of the important keys of pipe shock-resistance. For example, if the joint permits the pipe to have a displacement in a certain range, then stress distribution of the pipe might be improved to suit the ground movement. If the range is too small, the joint would be damaged easily. In Table 3.3 the relation of different joints and the seismic damaged ratios is listed, from which it can be seen that the damaged ratios of the flexible joint pipe were much smaller than those of rigid ones.

3.4.4. Pipeline Diameter and Damage Ratio:

According to the analysis of data on seismic damaged pipes, it can be seen that the damaged ratio of various diameter pipes are different. In general, the bigger the diameter is, the smaller the ratio will be. For example, in Yingkou City the sewer pipe is of cement mortar or reinforced concrete, and the water supply pipe of cast iron. Though the strength of the former is much lower than that of the later, the diameter of the former is bigger than that of the later. As a result, the damaged ratio (only 0--0.08/km) of the former is much smaller than the latter. In the city, the water supply network includes various diameter cast iron pipes with asbestos cement gasket joints. Table 3.4 shows the conclusion that the damaged ratio is lessened with the enlargement of the pipe diameter.

Table 3.1: Ratios of Seismic Damage Water Supply Pipes in the disaster Zones of Different Intensities

Region	Intensity	Site Soil	Diameter of pipeline (mm)	Length of pipeline (km)	Number of damage places	Average ratios of the damaged pipes/km	Notes
Anshan City	7°	II	≥ 100	537.40	3	0.006	
Panshan Town	7°	III	≥ 100	25.90	35	1.60	
Yingkou City	8°	III	≥ 50	158.50	372	2.35	
Yingkou (Dashiqiao)	9°	I,II	≥ 75	26.10	26	1.00	
Haicheng	9°	III	≥ 50	21.35	216	10.00	

Table 3.2 The Ratios of Seismic Damaged Pipes
of Different Materials

Intensity	9°		8°	7°
Location / Pipe Material	Haicheng	Yingkou	Yingkou City	Panshan Town
Steel	15.70	2.10	11.40	0.7
Cast Iron	9.80	0.92	1.06	1.60
Prestressed concrete	-	—	0	-
Asbestos	9.00	3.00	3.00	1.30

Table 3.3: The Ratios of the Seismic Damaged Pipes of Different Materials

Material of Pipe	Steel		Cast Iron		Asbestos		Prestressed concrete
Kind of joint	Welded	Threaded	Lead	Asbestos & cement	Self-stressed cement	Rubber ring	Rubber ring
Haicheng	-----	15.70	9.50	12.70	-----	9.0	-----
Yingkou	-----	2.10	0.89	0.94	5.0	2.0	-----
Yingkou City	0	11.40	0.85	1.28	4.5	1.5	0
Panshyan Town	-----	0.70	----	1.60	1.3	-----	-----

Table 3.4: Ratio of Seismic Damaged Cast Iron Pipe with Asbestos Cement Gasket Joint in Yingkou City

Diameter (mm)	75	100	150	200	250	300	350	400--700
The ratio	3.03	2.65	0.60	0.68	0.48	0.43	0.39	0.30

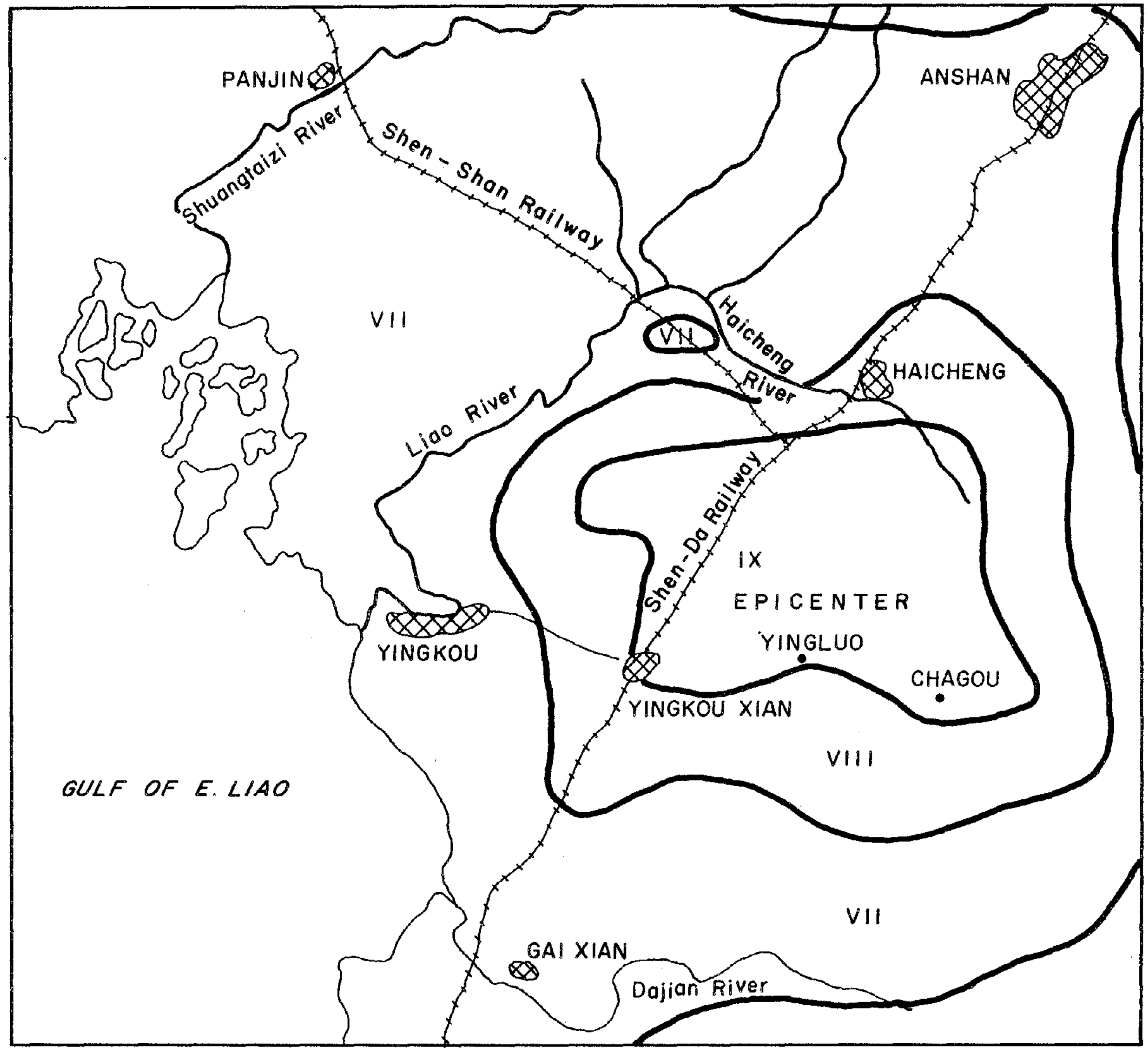

Figure 3.1 Isoseismal Map of Haicheng Earthquake

Figure 3.2 A Pipe Broken in Yingkou City From Haicheng Earthquake

(4). 1976 TANGSHAN (唐山) CHINA EARTHQUAKE

4.1. Seismogeological Condition

4.1.1. Parameters of the Earthquake

(Beijing) time of commencement of the shock:

3:42 AM, 28th, July, 1976

Magnitude: M 7.8

Epicenter: 30°24' N, 118°06' E. In Tangshan

Focal depth: : 12--16 km.

4.1.2. Geological Structure of the Tangshan Region

This region is located in the junction zone of Hebei(河北)--Shandong (山東) downwarp and the Yanshan (燕山) fault, which was known for earthquakes in history. From Fig. 4.1, it can be seen that the region is surrounded by different striking neoand-palaeo-faults. Such as Hanjiazhong (韓家莊)--Shaheyi (沙河驛), Linghe (寧河)--Changli (昌黎) fault ruptures in W--S striking; Luanxian (滦縣) --Leting (樂亭), Jiyunhe (薊运河) fault ruptures in N--W striking; Tangshan (唐山) fault rupture in N--NE striking. The Tangshan fault rupture is located in the south-east of Tangshan upwarped district, which is a principal shock belt in the earthquake.

4.1.3 Distribution of Intensity:

In this earthquake the induced shock fault was located in the boundary between Tangshan (唐山) and Fengnan (丰南). The 7° and 8° main shock intense zones are located in the pediment. In propagating of seismic wave, the intensity was gradually weakened under different geological conditions. Thus, the geological conditions could be partly reflected by distribution of intensity. The epicenter was located in the urban district of Tangshan where the intensity was up 11°. For the rest of the city the intensity was up to 10° and in the surburbs up to 9°. In Tianjin (天津) the intensity was abnormally up to 8° in a 7° intensity region. In most areas of Beijing, the intensity was 6°, although in some places it was abnormally up to 7° and 8°. The detailed distribution is shown in Fig. 4.2.

4.2. Seismic Damage of Water Supply Pipelines

4.2.1 Tangshan City (唐山市):

The city is located in the Eastern Hebei Plain. The geological structure of the region can be briefly described by dividing it into the following three kinds.

4.2.1.1. Sedimentary System in Xingkezhung (荆各莊):

The sedimentary deposit is about 300--400 m thick. This region can be divided into two parts. In one part the upper layer is plastic silty clay, and the lower layer is fine silt, belonging to the class III site soil. In another part the upper layer is plastic and hard plastic silty clay, while the lower layer is uniform and dense sand of medium size, belonging to the class type II site soil.

4.2.1.2. Upwarped District of Tangshan:

The district is an epibatholite zone of hillocks overlaid by dense silty clay with a thickness of 0--20 m, the site soil belonging to the class type I.

4.2.1.3. Sedimentary System in Kaiping (開平):

This region is at the south-eastern surburbs of Tangshan City where the Tangshan fault descends the most. The sedimentary deposit is about 150 m thick with silty loam and silty clay of a thickness of 3--5 m on the surface, the site soil being of the class type III.

The length of the Tangshan City water supply network is about 220 km. In this earthquake it suffered serious damages. Before the shock most of the pipes were of cast iron, partly of steel, self-stressed concrete and prestressed concrete. The joints were mostly of spigot-bell type, some were of flange; the gasket materials were mostly of asbestos cement, some were of lead and rubber rings. By the end of Oct. 1976, 444 seismic damaged pipes were found in the Ø = 75--600 mm cast iron pipelines with the length of 111 km of the network. The average damaged ratio was 4/km. However, in a 5 km^2 intense zone, the ratio was up to 10/km. Meanwhile 17 damaged pipes were found on a 9 km long self-stressed concrete pipeline and 10 damaged pipes on a 0.9 km long small diameter steel pipeline.

4.2.2. Tianjin City (天津市):

The city is located on a lateral plain at the debouch of the Hai River, (海河), a flat region with many marshes and lacunas. Before the shock, about 40--50 big pools with a depth of 2--4 m and a few of 10 m had been filled up. The municipality at the south of the Hai River (海河) is a region of 5--6 m thick back fill on the terrene, belonging to silty loam with a plastic index of 10--11, the site soil being class type I. In this region liquefaction was serious in this earthquake. In other places of the city, the earth layer could be divided into three layers in 20 m depth of the ground surface. The upper layer is 2--5 m thick back fill of slag and wastes. The middle one is yellow brown silty clay or clay of a thickness about 5.0 m, and some puddly sandwiched in some parts of the layer, being of mid-compressibility. The bottom is about 10 m thick layer of gray silty clay in which silty clay, silt and some puddly lenticles are sandwiched with black organic laminnae widely deposited in the bottom. In the city there are four old Hai River courses which have been filled up by sand and gravel, where liquefaction occurred with serious downwarping of ground during this earthquake.

Tang-gu (塘沽) and Hangu (汉沽), two outer suburbs districts of Tianjin (天津), located at the debouch of the Hai River, are in a region of regression plain covered with a 1.0--1.5 m thick layer of back fill, where the ground water level is only 0.5--1.0 m deep, the site soil being of the class type III. In this earthquake, some large-area settlement occured in this region.

In the water supply network of the Tianjin City, most pipes are made of cast iron: the joints are gasketed with asbestos cement. From an investigation of 870 km long, Ø = 75--1000 mm pipelines, the seismic damaged pipes were found to be 161, the damaged ratio being 0.18/km. Meanwhile, 815 seismic damaged places were found from Ø = 50 mm, steel pipels with thread joints in a total of 772 km of pipeline, the damaged ratio being 1.13/km.

Due to the serious effects of seismic liquefaction movement and downpunching, the water supply networks in Tang-gu (溏沽) and Hangu (汉沽) were damaged more seriously than in the Tianjin City (天津市) during the earthquake. In Tang-gu (溏沽) on a 79 km long, Ø = 75--600 mm cast iron pipelines, the damaged pipes were found to be 332, and the damaged ratio was 4.18 breaks/km. On a 3.4 km long, 100--200 mm asbestos pipelines with rigid joints of sleeve and asbestos cement gasket 120 damaged places were found, and the ratio was up to 30 breaks/km. In Hangu (汉沽) Ø = 75--150 mm cast iron pipeline were out of commission after the earthquake, and the damaged ratio was more than 10 breaks/km.

4.3. Damages of Sewer Pipeline

4.3.1. Tangshan City:

Before the shock, the length of the masonry sewer conduits and reinforced concrete pipelines was about 176 km in this city. From an investigation after the shock, aggregating about 8.5 km length of the pipelines were investigated. Among them, parts in 1.9 km must be repaired, accounting for 14% of that length. The lightly damaged parts were about 0.8 km, being 9% of the length.

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4.3.2. Tianjing City:

Before the earthquake the total length of sewer main lines in the city was about 931 km, most of the lines were of reinforced concrete pipe. Some large ones were of masonry construction with box or semi-elliptical sections, and a few of them were of arch pipes. After the shock the length of damaged lines was found to be 5.0 km, which accounted for approximately 1% of the total length. The damages were mostly sheared off or pulled out on the joints of the reinforced concrete pipelines. Some arch pipes manufactured in the 30's suffered fissures and cracks, but on arch or box pipelines no damages were found.

4.4. Features of Seismic Damages of Pipe:

4.4.1. Influence of Tectonic Ground Fracture:

Although in this shock no penetations were found between the tectonic ground fracture and the deep focus, yet the forms of the fracture were evidently effected by the striking of major faulting belts, thus reflecting a very strong directivity and regularity.

In Tangshan, under the Fuxing Road (復兴路, there were two cast iron pipelines of diameter 100 mm and 200 mm running parallel with a fault rupture. After the strong shock, no major damage has been found. Another pipeline, buried in the southern section of Jixang Road (吉祥路), is also parallel with a fault rupture. Because its bedding foundation was of puddy soil with a higher water level, a pipe of this line was pulled out 15 cm and sheared off 10 cm from its joint.

Contrarily in Hanjia Street (韓家街) a buried cast iron pipeline with a diameter of 150 mm across had a fault rupture where the ground fracture was up to 60--70 cm, a pipe of this line was pulled off 1.2 m in S--N striking, and sheared off 0.3 m. In faulting belt most pipelines were cross-cut, and very often the damage part is its joint. In Shengli Road (勝利路), a cast iron pipeline with a diameter of 100 mm and a length of 1070 m was damaged and the damages were almost concrentrated on joints under the shear actions.

In fact, any buried pipelines can not withstand the tremendous ground shear action brought on by the fault rupture disregarding to the diameter or the type of joints of the line. In the southern zone of Xiaoshandong Street (小山東街) and west of the Fuxing Road, all pipelines suffered damage. In the Xiaoshandong (小山東), Hayuan (花園), and Shengli (勝利) Streets, all pipelines which were of cast iron and with diameter 100 mm were cross-cut by ground fractures. In Jixang Road (吉祥路, one secton with three big trees beside it was displaced southernly 1.5 m and downwarped 40 cm caused by the ground movement. All pipelines in this section were also correspondingly displaced, and all the joints broke. In front of a gate of textile-printing works, a ground fracture caused a tee with diameter 150 mm broken with displacements 3 cm in horizontal and 8 cm in vertical directions. In summary, all the pipelines which crossed with fault rupture zone suffered serious damages. Figures 4.3 and 4.4 show the pipeline damage.

4.4.2. Influence of Bank Sliding:

In Tangshan and Tianjin many pipelines were buried in or near the river bank. In this shock earthquake-induced bank sliding brought serious damages to the pipelines, especially in and near the epicenter zone. In some place, the sliding exceeded 20 m in width, all buildings and buried pipelines in this range suffered serious destructions and damages. In Tangshan, the Shengli Bridge (勝利桥) and the pipeline beside it suffered serious damages by bank sliding, and the width of this section of the river was reduced 2.6 m, as shown in Fig. 4.5. Nearby, a spanning river pipeline was broken by both sides sliding, as shown in Fig. 4.6.

4.4.3. Influence of Ground Downwarping:

In the Tangshan region, the ground downwarping was a vertical deformation of ground induced by the strong earthquake. Its geological conditions can be divided into three kinds:

1) Regional downpuching in connection with young downwarping zone;
2) Regional downpuching caused by sand layer densifying and soft soil drafting; and
3) Collapsing of cave.

Most of the collapses occurred in mining areas with mined caves. For example, in a coal mining area, the earthquake-induced ground collapse formed a pool with an area up to 83 acres and a depth of 1.0--1.5 m respectively. In these regions all buried pipelines suffered serious damages, and some of them were sheared off up to 60 cm in length. In the collapse district of the Kailuan (開滦) coal mining area, most cast iron pipelines with a diameter of 100 mm and with cement gasket joints were sheared and broken.

4.4.4. Influence of Soil at Site:

The condition of site soil is an important factor in seismic damage of buried pipeline. In the Tianjin region, site soil is of class III with a higher ground water level, and the liquefaction movement of sand stratum is easily induced by an earthquake. In this shock, therefore, a considerable seismic energy released was absorbed by this soft soil region and the period was increased, thus the pipelines buried there were greatly stressed. In the regions with different intensities and site soils, the ratios of seismic damaged pipelines were different as indicated in Table 4.1.

In Tangshan city there are two regions of somewhat different geologial structures. These two regions are of coal measures stratum of Periods of Carboniferous and Permian which are covered with gravel and intercalations of clay and sand in two different thicknesses. In one region the layer is over 100 m thick, while in the other it is a bit thinnner as 5 6 m, or the lime stone was exposed. In this earthquake, the seismic damaged pipes mostly occurred in the former region.

In general the seismic damages of buried pipes appear to have a certain regularity. For analyzing the relationship between the forms of damaged pipes and ground movements macrocosmically, the site sesimic strain must be taken into account. Let the epicenter be a center in a drawing of triangular microzonation analysis. From the strain values found in each microzoned triangle zone, equivalent lines of these site strains could be plotted, as shown in Fig. 4.7. From the figure, it can be seen that

a) In the epicenter region the seismic stress was the strongest, the stress compressing northerly and deflecting to the right.

b) In the W--E direction the seismic strain was compressive, and in the N-S direction tensive.

In fact the distribution of seismic damaged pipes tallies with the two seismic conditions.

4.4.5. Influence of Pipe Material and Type of Joint:

The Tangshan water supply network consists mainly of cast iron pipes, and next is the steel pipes and concrete pipes. Seismic damaged types of the pipe bodies are as follows:

- Crack at the weak part of pipe body;
- Break of the body;
- Longitudinal fissure;
- Circumferential fissure;

° Shear fissure;

° Explosion of pipe bodies.

The types of seismic damaged joints are as follow:

° Pulling off;

° Loosening and leakage;

° Shear break;

° Bell crack.

Among these pipelines, the self-stressed concrete pipeline with rubber flexible joints appeared to be shock-resistance in this earthquake. For example, along a pipeline with a diameter of 300 mm and 500 mm, and a length of 1000 m, there were only 6 places that were damaged by lateral spreading. The damages were the squeezing out of the rubber rings and the cracking of the bell. During this earthquake, the prestressed concrete pipeline joined by socket with rubber ring appeared to be satisfactorily shock-resistance.

In Tianjian city, the prestressed concrete pipelines with rubber flexible joints were still remaining in good condition in an 8 intensity zone, while asbestos cement pipelines with rigid joints suffered serious damages (see Table 4.2). The serious seismic damages of cast iron pipelines were evidently concerned with corrosion, (see Tables 4.3 and 4.4).

4.4.6. Influence of Pipe Diameter:

From the statistical data of Tables 4.2 to 4.4, and 4.5 it can be seen that the ratios of smaller diameter pipes are worse than those of larger ones. This is because the larger diameter pipe has higher rigidity. This is very much like the situation in the famous earthquakes in Japan and other countries. This should be, therefore, taken into account in the analysis of a rational substructural mode.

Table 4.1: Average Ratios (amount of damaged places/km) of Seismic Damages on Pipelines under Different Conditions in the Tangshan Earthquake

Location	Seismic intensity	Site Soil	Damage Ratio	Note
Tianjin	7--8	III	0.18	
Tang-gu	8	III	4.18	The site soil worse than that in Tianjin
Hangu	9	III	10.00	The site soil worse than that in Tang-gu
Tangshan	10--11	II	4.00	

Table 4.2: Statistics of the Seismic Damaged Concrete and Asbestos Cement Pipes Buried in Tianjin City

Pipe	Joint	Ø (mm)	Length (km)	Results of investigation
Prestressed concrete pipe	rubber	600	3.6	still in good condition
Asbestos cement pipe buried in Tang-gu District	asbestos cement	100-200	3.4	damaged places up to 102
	rubber	100-200	3.0	still in good condition
Reinforced concrete pipe buried in Tang-gu District	steel bell and spigot rings gasketed with cement	1800	0.4	two joints leaked
Same above	rubber	1400	0.4	still in good condition
Reinforced concrete pipe casted-in-site	rubber band	2200	9.5	three joints leaked

Table 4.3: Statistics of the Seismic Damages of Water Supply Cast Iron Pipes in Tianjin City

Kinds of the damages	Diameter (mm) / Number of the damaged places	75	100	150	200	250	300	400	500	600	700	800	Number of seismic damaged places	Ratio of seismic damaged pipes (%) Single ratio	Ratio of seismic damaged pipes (%) ratio
Joint	Pull off		16	10	8		2	1	7	5		1	50	31	39
	sleve break		1	1						1			3	2	
	bell break or fisure	1	1	2	1		2		1	2			10	6	
Pipe body	break	1	21	10	3		6	1					42	26	32
	break longitudinally		4	3	2								9	6	
Fitting	elbow, tee or yee and cross			4		1	2		1	1			9	6	29
	Valve		6	2	2		1	2					13	8	
	others	4	10	6	2			2		1			25	15	
Number of Seismic damaged places		6	59	38	18	1	13	4	11	9		2	161	100	
Length of pipeline, km		302.7		379.9				146.3			41.1		870		
Ratio of seismic damaged places per km		0.21		0.18				0.16			0.07		0.18		

Table 4.4: Statistics of the Seismic Dasmaged Cast Iron Pipes Buried in Tianjin City

Ø (mm) Amount of damaged places Kinds of damage	75-100	150-200	250-200	500	600	Total amount	Ratio of pipes damaged
Pulled out from joint	56	42	23	11	3	135	40.7
Broken	91	29	15	1		136	40.9
Damaged fittings	15	45		1		61	18.4
Total amount	162	116	38	13	3	332	
Length of pipeling (km)	35.51	27.36	12.28	2.31	1.85	79.31	
Damaged places	4.55	4.25	3.10	5.61	1.62	4.18	

Table 4.5: Statistics of the Seismic Damaged Pipes and Joints in Tangshan City

Diameter (mm)	the length of investigation (m)	Damages rate (No/km)		
		Pipe	Joint	Total
600	6,770	-	1.89	1.89
400	10,680	0.56	4.31	4.87
300	19,420	0.41	4.22	4.63
200	17,430	1.03	3.38	4.41
100	12,610	1.35	3.88	5.23

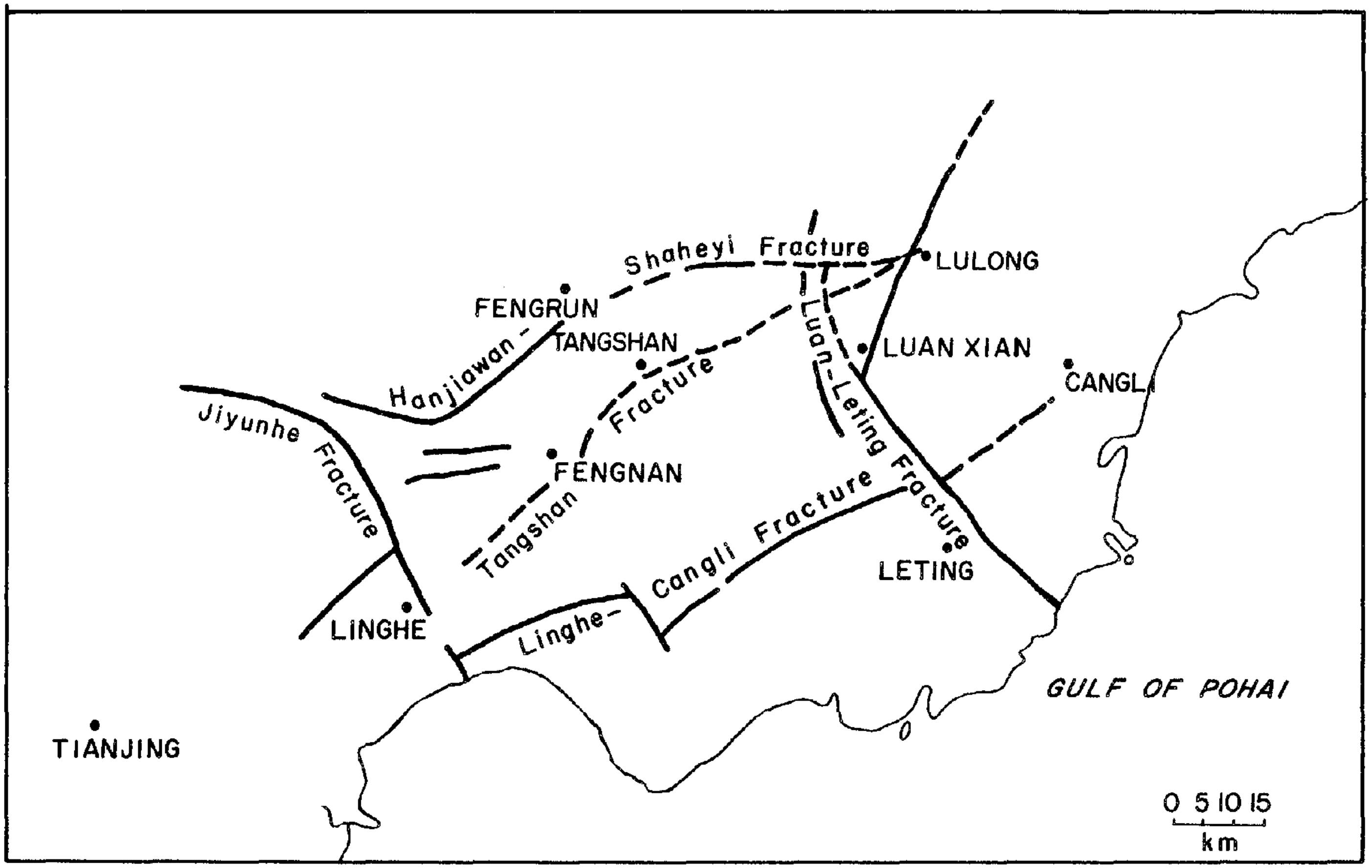


Fig. 4.1 The Distribution of the Fracture in Tangshan Area

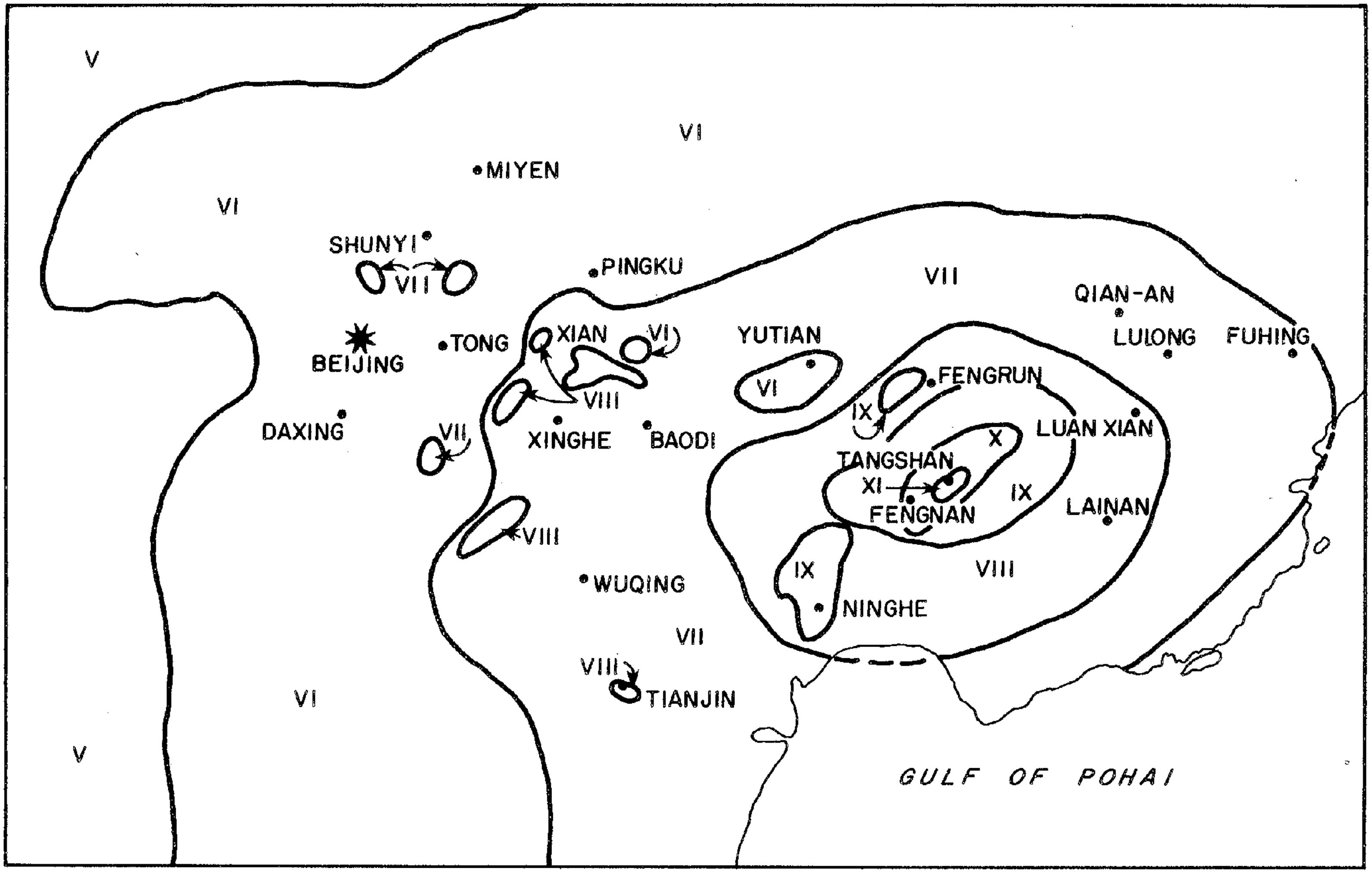


Figure 4.2 Isoseismal Map of Tangshan Earthquake

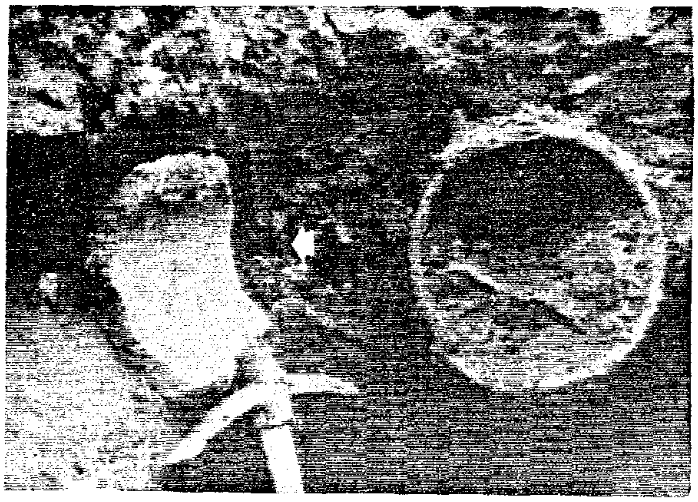


Figure 4.3 Concrete Pipe Damage in Jixang Road

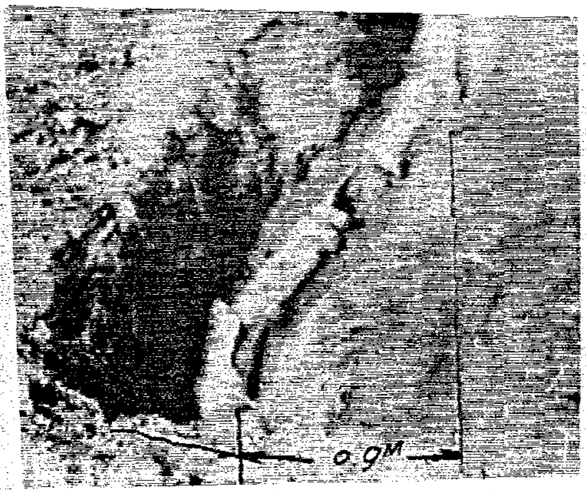


Figure 4.4 Damage of a Pipe Due to Ground Failure

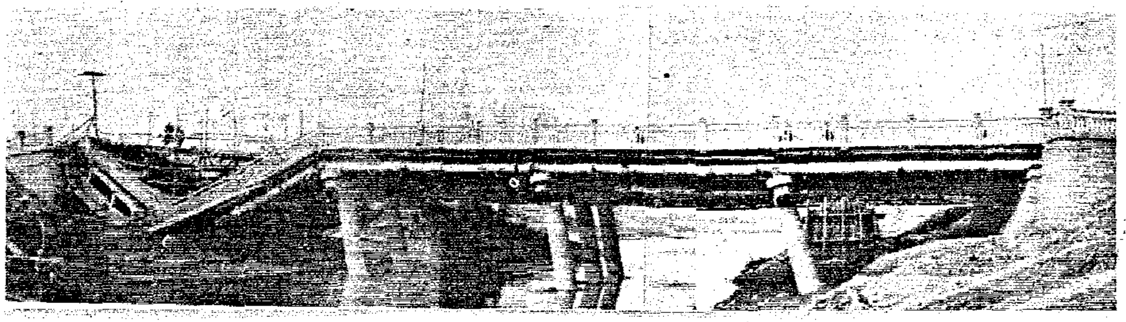


Figure 4.5 Failure of Shengli Bridge and Pipeline

Figure 4.6 Breakage of a River Spanning Pipe

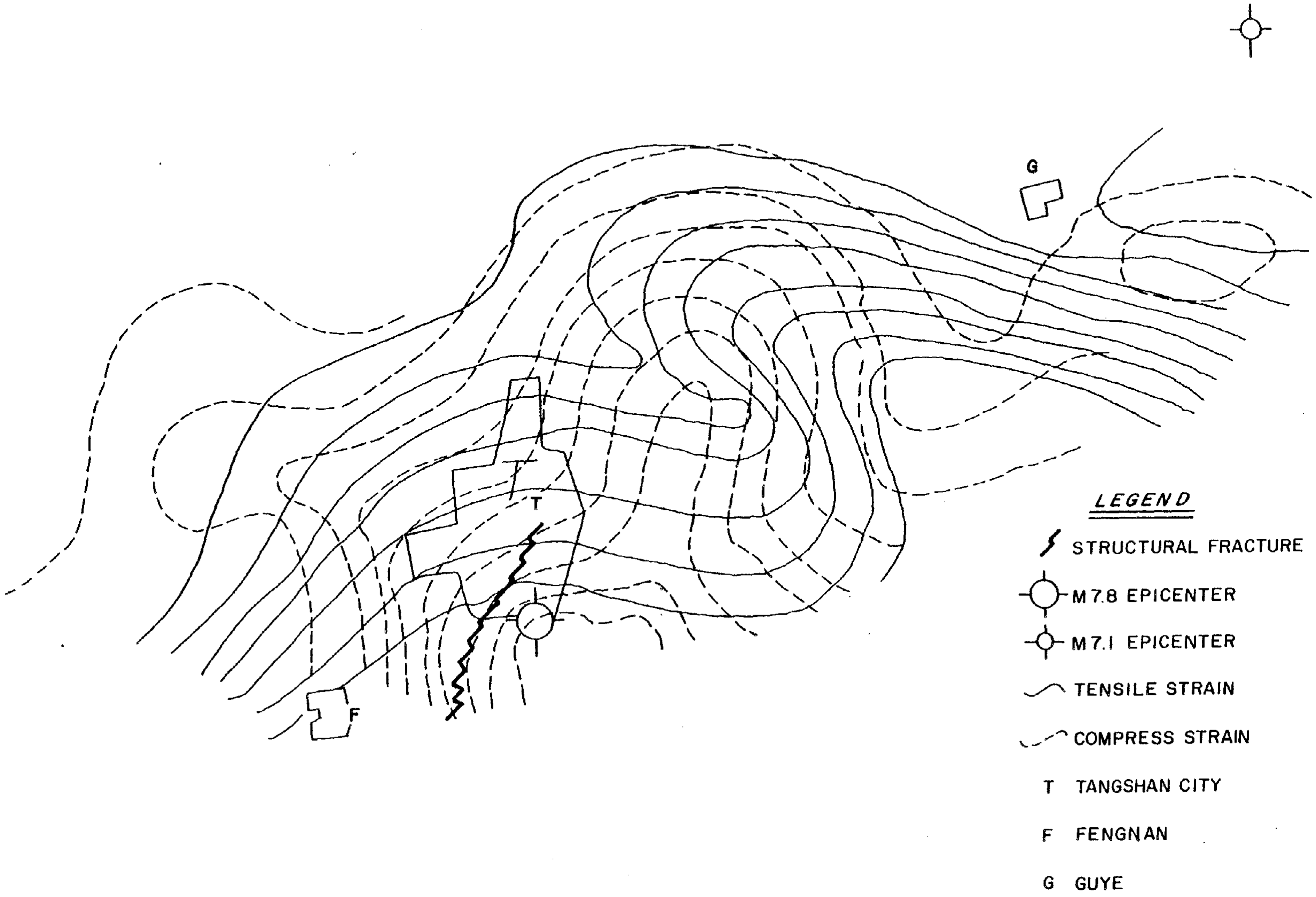


Figure 4.7 Strain Counters from Tangshan Earthquake

(5). 1978 MIYAGE-KEN-OKI, JAPAN EARTHQUAKE

5.1. Seismo-Geological Condition

5.1.1. Parameters of the Earthquake:

The earthquake data from U.S. Geological Survey (USGS) sources are:

Time: 08:14:27 GMT (17.14 local), June 12, 1978

Magnitude: 7.4

Epicenter: 38.2° N, 142.2° E, approximate 100 km from City of Sendai

Focal depth: 30 km

The peak horizontal accelerations recorded on the ground level and on buildings are shown in Table 5.1 and the seismic intensities are shown in Fig. 5.1.

5.1.2 Geology of the Damaged Region:

Figure 5.2 shows the general geological setting of the Sendai area. The broader the NE-SW line passing near the center of the map is the tectonic line, and the alluvial plain is developing on the depression which occurred in the east of this line. This alluvial plain consists mostly of sand, silt and gravels and partly of peat deposits. Its depth to the Tertiary basement rocks varies abruptly near the tectonic line, and the mean depth is about 40m. The general topography of the area to the west of the tectonic line is characterized by several levels of terraces.

Most of the damage resulting from the June 12, 1978 earthquake occurred within the Miyagi region which consisted of a broad central lowland bounded east and west by low mountains (Fig. 5.2). The broad central lowland consists of low bedrock hills and extensive alluvial plains. Bedrock in the region consists of grantitic and low grade metamorphic basement, exposed almost exclusively in the southern Kitakami block and the northern tip of the Abukuma block. The alluvial plains of the central lowland represent the newest deposits in the region, formed during recovery of sea level from the last glacial age which occurred about 18,000 years ago.

The old part of Sendai City was built on the complex Sendai terrace, which consisted largely of sand and gravel 5 to 7 meters thick overlying Neogeno bedrock. Recent growth of the city led to expansion into the adjacent hills.

The alluvial sediments of the Sendai coastal plain and the other plains of the central lowland bury a late pleistocene topography that consists of river valleys, flanking terraces and divides. The uppermost part of the alluvial section consists of an intricate assemblage of sediment types produced as the rivers migrated about the aggrading plain. Broad ribbons of channel sand and gravel were left as the rivers changed their position. Finer sand and silt were deposited in flanking natural levees. The sediment is soft and water-saturated.

The surface of the alluvial deposits is quite flat, and is crossed by several rivers responsible for depositing the sediment. Surface geologic mapping distinguishes the four facils described; active and abandoned river channels, levees, interenIry backmarsh peats and silts, and coastal beach sands.

5.2. Liquefaction of Soil:

The June 12, 1978 Miyagi-Ken-Oki earthquake caused soils to liquefy at several sites on the coastal flood plain boardering the Bay of Sendai. The engineering structures most extensively damaged by liquefaction were flood control dikes that were composed of earth fill. The damage consisted primarily of cracking, settlement and minor lateral spreading and slumping.

Most sites of damage were on the coastal plain where the sediments were unconsolidated Holocene gravels, sands, silts and clays primarily deposited by rivers. The river deposits were of three main types: channel, natural levees and back marsh deposits. Liquefaction occurred most commonly in channel deposits.

In the Port of Ishinomaki, a fine sand fill liquefied and caused severe damage to the anchored steel-sheet-pile bulk heads. The fill material had been dredged from the sea floor and placed hydraulically with no compaction.

5.3. Damage to Water Supply System

Water supply facilities were damaged at 54 cities, towns and villages in Miyagi Prefecture. In Sendai City, water supply was suspended at about 7,000 houses after the earthquake. The number of houses suspended in water supply decreased to 2,000 on June 14, and that decreased to 700 on June 15. As for other small cities, by the severance of water pipes, water supply was suspended at all houses (16,000 houses) in Shiogama City and at 10,500 houses in Izumi City. By the damage to industrial water supply facilities, more than 20 factories were obliged to be suspended without water supply for 24 ~ 79 hours.

The Sendai City Bureau of Water Supply has prepared portable water to some 200,000 customers (the total population is 620,000) in the event of an earthquake. The three treatment facilities which had a maximum daily capacity of 320,000 m^3 were built on firm ground. The few damages to water facilities were at the intake to the purification plant and minor distribution lines. A total of 215 breaks were reported to have occurred in the water distribution mains with diameters equal to or greater than 50 mm. The total of damage to the distribution pipes with diameters equal to or greater than 75 mm is shown in Table 5.2. Among the many kinds of water pipes, the steel pipe with turnbuckle joint showed the highest damage ratio, and its value was higher than that of asbestos cement pipes which is considered to be the most vulnerable against earthquake ground motions. The ductile cast-iron pipes showed the best performance.

Fig. 5.3 shows the distribution of seismic damage to water pipes. The damage was generally slight in the central part of the city located on geologically stable terrace, and pipe failures west of the tectonic line concentrated to the newly developed residential districts mentioned above. On the alluvial plain the damage features were very similiar to those of housing. In the areas where large-scaled cut and fill altered the original ground profile, there were, as an inevitable consequence, inherent instability of the artificial slopes, insufficient densification of fills and abrupt change in subsoil properties between cut and fill. These were the causes of local settlement, and relative displacement over short horizontal distance, which broke or bent the buried water pipes as well as gas pipes.

The city of Ishinomaki, located 45 km from Sendai, was shaken more severely than Sendai. There was slight damage to the purification plant, in which the hanging device of inclined parallel plates was collapsed, and the foundation of turbine house of steel frame was broken by differential settlement due to liquefaction of sandy soil.

In several newly developed residential districts, water supply stopped because there was danger of further slippage of the slope by leakage of water from the buried pipes.

5.4. Damage to Sewer System:

There were three sewer systems in Miyagi Prefecture, Japan in 1978. The construction of public sewerage facilities has been advancing in 16 cities and towns. At the outset of the earthquake on June 12, 1978, only two systems were operating to provide the service of sewer drainage. The third sewer system was under construction. After the Earthquake, sewerage plants and pump yards in Sendai City and some other cities around Sendai could not work because of electricity failures and structural damage. Under such situations, it was necessary to discharge sewage into a river without full treatment. As a result of temporary restoration, the function of these damaged facilities was recovered within a few days except for Kooriyama Pump Yard (recovered at 4:25 pm on June 23) in Sendai City.

In general, it was determined that the damage on the sewer systems was small in comparison with the total damages, and the citys' residents did not suffer too much inconvenience because the damaged sewer systems were still able to keep up normal functions.

With regard to the wastewater treatment condition of Sendai City (380 thousand population) in 1977, the percentage of families using flush toilets in the service area was only up to 60%. In sewer pipes, both types of separate-flow (30%) and combined-flow (70%) were employed to drain the sewer out to wastewater treatment plant. The buried pipes used for sewer systems were Hume concrete pipes and earthenware pipes with diameters of 250 -- 2200 mm.

After the earthquake, most of the pumping stations terminated their operations due to the power failure. From the second day after the occurrance of the earthquake, the operation of pumping stations were gradually back to normal when the electrical power was re-connected again. Usually, the water flow in buried pipes was fairly easy to be blocked off by invasion of sands inside the pipes through the breaks of the pipes. Fortunately, such damage was not found this time.

5.4.1. Damage to buried pipelines

Based upon the examination of damages, the reports showed that about 98% of the damages to the sewer system had occurred to buried pipelines and manholes (Fig. 5.4). The damages most commonly observed in these structures as previously mentioned, can be classified in the following items:

1) cracks on the pipe walls

2) breaks on the pipe couplings
3) cracks and breaks on the vertical walls of the manholes and the bottom connection boxes
4) cracks, breaks and slippage at joints.

In addition, several other pipe and box-type culvert damages such as subsidence, breakage and buckling, etc. were caused by landslides and settlement of soil layers within the buried zones of pipes/culverts. An obvious example was observed when a pipeline buried under a highway at Sendai City suffered many subsidences and upheavals along the pipeline. Both subsidence and upheaval of the pipe were estimated about 40 cm. The length of the pipeline damaged under examination was extended about 1.5 km. Note that in order to examine the seismic damages to buried pipelines, two inspection methods were utilized during the investigation, i.e., eye-view inspection and T.V. camera detection.

In addition to securing for the health of residents near the buried areas of sewer pipes, it was necessary to investigate the possible contamination of soil which might have been caused by the leakage of sewer pipes during the earthquake. The underground water had been sampling and analyzing at 25 locations adjacent to the surrounding regions of the buried pipes. The test zone was extended about 4 km long. Fortunately, no indication from test results showed that the surrounding soil layers of sewer pipes were contaminated by the possible leakage of sewer water. It was thus concluded that no sewer leakage along the pipes had occurred.

5.4.2. Damage to Pumping Station

Right after the earthquake struck, only two pumping stations were able to keep up normal operation. The rest of the pumping stations were damaged and could not manage the conveyance of sewer water. Under such circumstances it was inevitable for sewer drainage to discharge the wastewater into the rivers, streams and swamps nearby. It was observed that the operation of the pumping station failed mostly by the shutdown of electrical power and engine trouble of mechanical systems. Four of the pumping stations were forced to shut down their self-regulating dynamos for lack of cooling water and lubricating water which was provided by the water supply system. Some other damages to discharge pipes and suction pipes were also found at several pumping stations in Sendai City. Such pipes with diameter 35 -- 1000 mm were made of cast iron, and cracked transversely during the earthquake. Further investigation showed that the connection portions between the pumping room and the connected pipes were also damaged.

In summary, the observed damages to pumping stations are listed below:

(a) Shutdown of electrical power
(b) Disconnection of water supply
(c) Engine trouble of generator (dynamic) at pumping station
(d) Breakdown of electrical and mechanical system
(e) Breaks of discharge (press out) pipes
(f) Breaks of suction (flow in) pipes
(g) Damage of building

5.4.3. Damage to Wastewater Treatment Plant:

The treatment plants did not suffer much damage. A brief description was presented as follows:

(a) Settlement of water supply pipe at the outskirts of the treatment plant.
(b) Breakage of discharge (press out) and suction (flow in) pipes.
(c) Engine trouble of dynamo at treatment plant.
(d) Operation failure of sludge pump due to inundation.

5.4.4. Conclusion:

According to the description of damages to the sewer systems in Miyagi Prefecture, it can be concluded that the sewer systems were only slightly damaged in comparison with the other public works such as gas and water supply system, etc.

5.5. Damage to Gas Lifelines

The city of Sendai and parts of several surrounding cities were supplied with city gas by the Sendai City Bureau of Gas. There were two gas factories of the Bureau, one of which produced more than 90 percent of the total supply and was located adjacent to the Tohoku Oil Co. The old water-sealed gas holder at the smaller factory suffered structural damage due to instability of guide frame work and was eventually destroyed by the ensuing fire.

It is reported that there were only four minor failures of arc-welded steel pipes whose total length was about 240 km. All of the failures occurred in concrete boxes, and associated with loosenings of flange joints caused by the settlement of surrounding soil. It is especially noticed that arc-welded steel pipes performed well outside the concrete boxes, although major portions of these pipes were buried in soft alluvial soil, and estimated to be able to sustain high stresses due to severe ground motion.

Table 5.3 and Figure 5.5 shows the damage ratio of buried gas pipes of various kinds of materials as well as damage ratio of housings and water pipes. In this table, the damage ratio is classified by ground conditions where gas and water pipes were buried and Japanese wooden houses were standing. The damage ratio was the highest for structures in the newly developed residential districts which were made by cutting and filling the slopes, and it was the lowest for the terrace terrane, that is, central part of the city.

In order to elucidate the damage characteristics, damage ratio of gas pipes in the central part of the city was compared with that in the other alluvial soil, and for reference, damage ratios of housings as well as cast-iron water pipes in both areas were checked. It is concluded that damage characteristics of gas mains was similar to that of cast-iron water pipes, and damages to gas service pipes and housings revealed the similar feature. From the geographical point of view, this area has developed as an alluvial fan of the Hirose-river and therefore the soil condition is complicated near the ground surface, that is soil bands of soft deposit and gravel are setting one after the other. That is why gas mains buried deeper than service pipes showed better performance during the earthqake than service pipes and housing which affected more severely by shallow soil condition.

5.6. Lesson Learned From the Earthquake

Through the Miyagi-Oki earthquake, it becomes very clear that more civilized life requires more study in lifeline earthquake engineering. Formerly people in a city area could get drinking water from wells, and had some kinds of heat-source other than city gas. But now there are a few wells which are not sufficient for water-supply to citizens in modern cities, and people who have not special heat-source can not cook their foods, if city gas service stops, as it happened in Sendai.

Table 5.1 Acceleration at various places from Miyaki-Ken Oki Earthquake (From Ref. 2)

Epicentral Distance (km)	Structure	Location	Max. Acceleration (gal)		
			N-S	E-W	Vertical
115	Univ. of Tohoku	1st Floor	240	190	150
		9th Floor	980	480	300
115	S-Insurance co. Building	B-2 Floor	253	227	120
		9th Floor	393	520	207
		18th Floor	487	553	227
115	JNR-Building	B-1 Floor	438	238	100
100	ShiOgama-Port Construction Office	Ground level (GL)	266	288	166
80	Kaihoku-Bridge	GL	200	294	113
		Top of the Pier	>500	338	188

Table 5.2 Damage to Water Distribution Pipes in Sendai (From Ref. 2)

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	3	1.1	1	7.0	32	114.4	21	140.9	57
100	183.6	15	1.7	0	29.1	5	207.2	22	421.6	43**
150	205.0	4	1.4	0	7.0	0	-	-	213.4	4
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	4***
350	2.0	0	0.1	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
550-1100	16.3	0	50.2	0	-	-	-	-	66.5	0
Total	703.4	32	70.5	1	48.0	39	321.6	43	1143.5	117

* Including ductile cast iron pipes.
** Including one break of isolating valve.
*** Including one break of hydrant.

Table 5.3 Damage of Gao pipes and other structures related to ground conditions

Subject	Item	Ground Condition		
		Terrace	Alluvium	Cut & fill
Cast Iron Pipe	Total length (km)	168.13	75.55	251.32
	No. of damages	2	3	9
	Damage ratio	0.01	0.04	0.035
Turnbuckled Steel Pipe	Total length (km)	99.71	56.82	365.42
	No. of damages	5	18	177
	Damage ratio	0.05	0.32	0.48
Service Pipe	No. of customers	59714	17038	56226
	No. of damages	46	60	215
	Percentage of damage	0.077	0.352	0.382
Housing	Percentage of fully damaged houses	0.035	0.170	0.292
Water Pipe	Damaged ratio	0.03	0.22	0.87

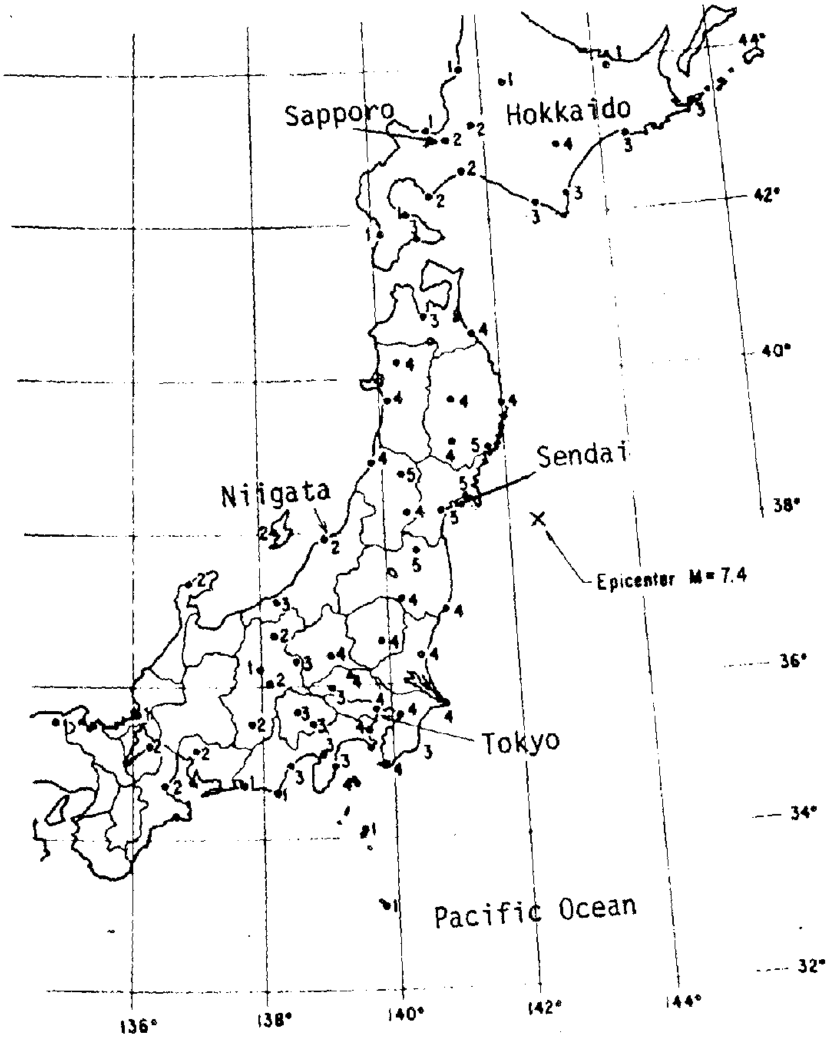


Fig. 5.1 Distribution map of seismic intensities during Miyagi-Ken-Oki Earthquake.

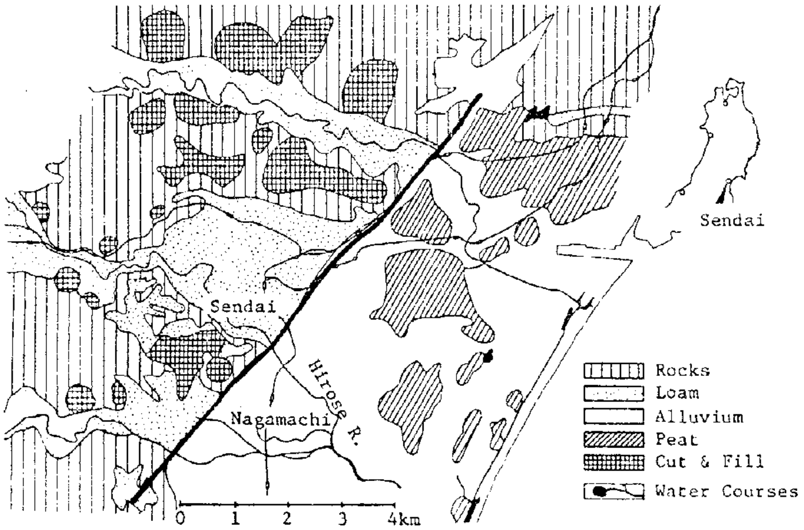
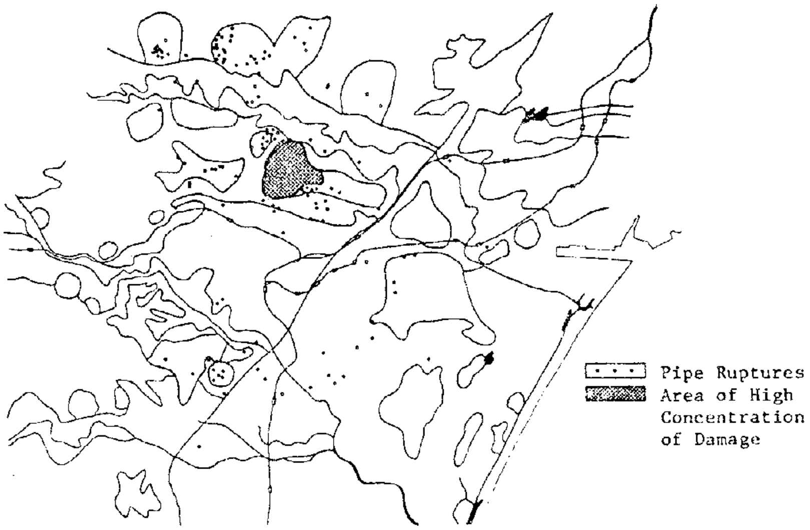


Figure 5.2 Geologic Setting of Sendai Area (Ref. 2)



5.3 Location of Ruptures in Water Distribution Mains (Ref. 2)

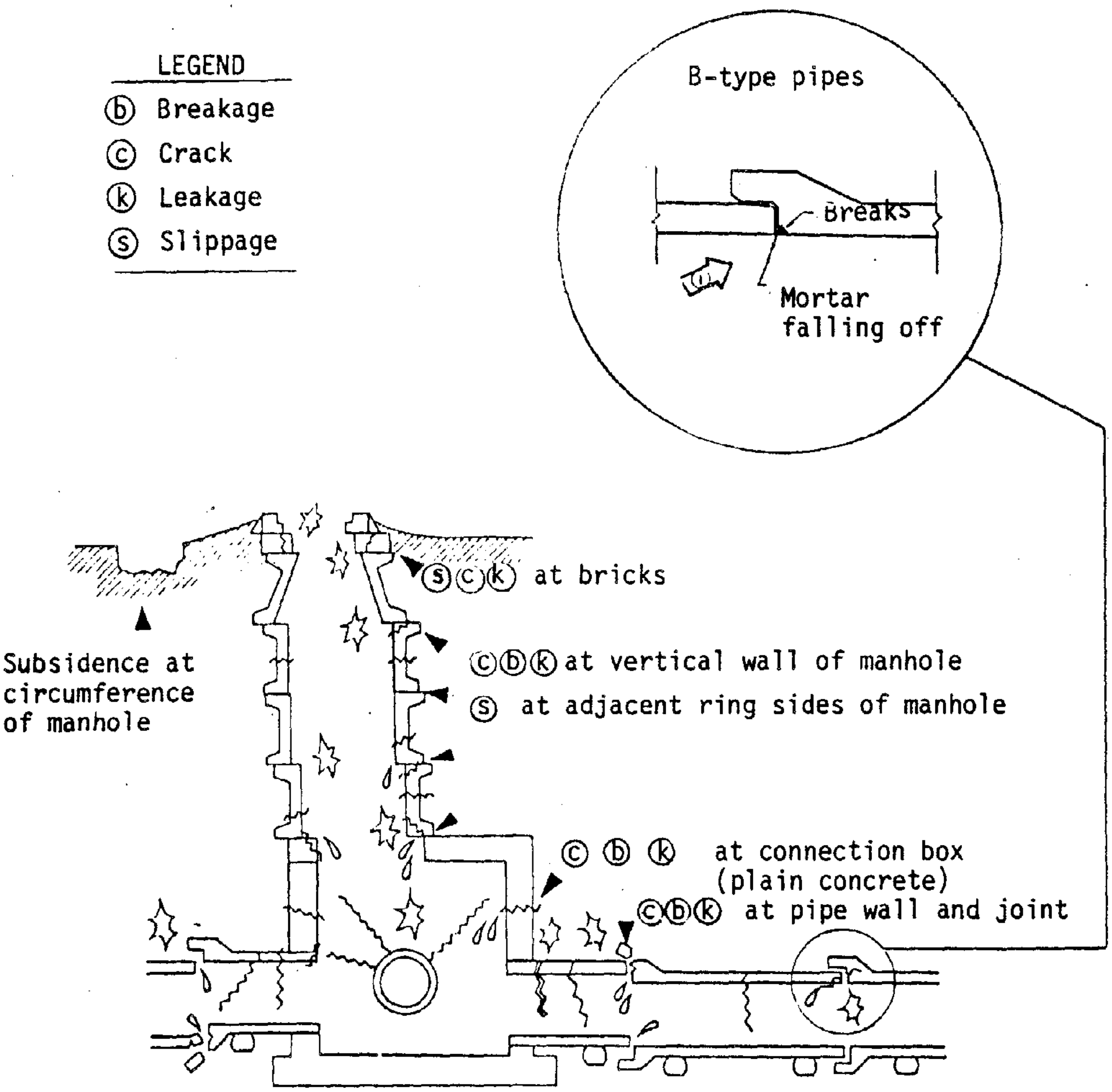
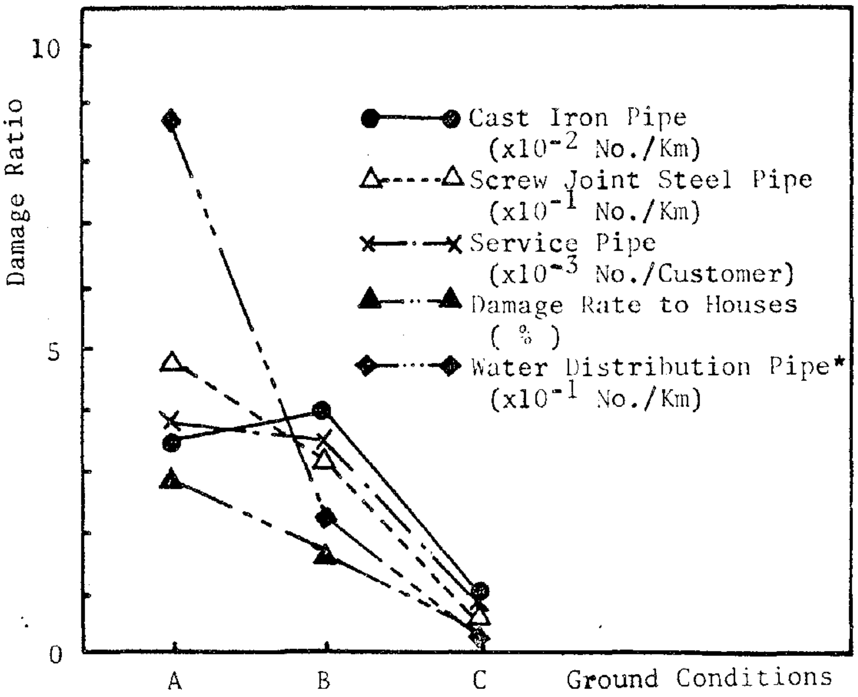


Fig.5.4 Damages to buried pipes and manholes



A :Newly Developed Residential Area (Cut & Fill)
B :Alluvial Plain, C :Terrace
* Except for Joint Loosening

Figure 5.5 Damage Ratio VS Ground Conditions

(6) SUMMARY

Based on the experience from recent severe earthquakes which occurred in the United States (1971 San Frernando Earthquake), China (1975 Haicheng Earthquake and 1976 Tangshan Earthquake), and in Japan (1978 Miyaki-ken-Oki Earthquake) common damage behavior of buried lifeline systems, particularly water and sewer lifelines, and their influential parameters are found and confirmed. They are reiterated in this summary.

The common damage behavior and mechanisms of buried pipeline are:

- cracks or breaks at weak points
- pull-out of joints
- breaks of pipe coupling
- longitudinal and circumferential fissures
- crack by water hammer
- buckling
- loosening of mechanical points
- leakage
- bell crack
- shear failure

The damage mechanisms are influenced by the following parameters

- Type of pipe material
- Type of pipe joint
- Type of surrounding soil
- Location relative to fault zone
- Proximity of other substructures
- Buried depth
- Topography
- Water table

The general damage behavior can be summarized below:

1. Pipeline with rubber gasket joints performed substantially better than those with cement-caulked joints.
2. More failures occur at junctions, such as between manhole and pipe, between building and pipe or even between main and service lines.
3. Corrosion which creates weak points is responsible for many pipeline failures.
4. More failures occur under weak ground.
5. Ground failures such as liquefaction, ground subsidence or uplift, lateral spreading and slides are responsible for many pipeline failures.
6. There were more brittle material (cast iron) pipe failures than ductile materials (ductile iron or steel) failures.
7. There seemed to be that larger pipes performed better because of their rigidities, while smaller pipes performed better in Tangshan.

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