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# LONG-TERM EFFECTS OF EARTHQUAKE DAMAGE ON WATER SUPPLY PIPELINES

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## SUMMARY

Damage data from five cities in Japan, U.S.A. and Mexico subjected to similar levels of seismic motion are analyzed to clarify the long-term effects of earthquake damage to underground water supply pipes. Discussion is focused on the period needed for each system to recover its normal level of pipe break rate, leak rate, etc. It is made clear that the long-term recovery period, which lasts after functional restoration, ranges from ten months to two years, depending on the mode of ground failure, pipe materials, etc.

## INTRODUCTION

Studies of earthquake damage to water supply systems have been focused on their problems arising in the periods immediately following the earthquakes (Refs. 1-4). It has been experienced, however, that earthquake damage of underground pipes in many cases can not be recovered completely in repair works exercised for functional restoration, as minor pipe breaks are difficult to find out and their damage extends progressively to cause pipe breaks after a considerable long period of time. Such a long-term effect should be regarded as seismic damage in a wide sense, and should be implemented in the comprehensive damage evaluation and restoration planning.

With this notion of the problem, this study is devoted to data analysis for water supply systems through which long-term variation of the system states for periods extending before and after the attack of earthquakes is made clear. Three Japanese cities, Sendai, Noshiro and Oga, one American city, Coalinga, California, and Mexico City are compared. It is believed that comparative studies for these cities will provide useful information for a new aspect of understanding pipeline earthquake damage.

## DAMAGE DATA ANALYSIS

Monthly variation of leak rate and pipe repair rate are treated as major damage indices. Leak rate is defined as the amount of water lost through leakage, whereas the pipe break rate is defined as the number of repairs. The leak rate is regarded as a "real time" damage indicator, and the repair rate as an indicator of management response.

The cities dealt with herein are Sendai, Noshiro and Oga of Japan, Coalinga of the U.S.A. and Mexico City of Mexico. The earthquakes that these cities were attacked, statistics of their water supply systems and general damage descriptions are shown in Table 1.

The levels of information obtained for these cities are not uniform due to different activities of documentation. Data analysis has been performed to maximize the possibility of comparative observation of these cities. It can be said that the damage data dealt with herein are from earthquakes causing roughly the same level of ground shaking as Table 1 ② indicates. In order to make objective comparisons between these cities, the damage indices are normalized with the served population or the total length of distribution pipes; i.,e., water amount is represented in terms of $m^3$ pcpd (pcpd = per capita per day), leak rate, in terms of (lost water amount / delivered water amount), and pipe break rate, in terms of (breaks / km).

A certain level of leak rate and pipe break rate are observed even under normal conditions. They can be figured out from their trends in pre-earthquake normal levels. It is judged that the system have got rid of the earthquake effects when these damage indices have recovered their normal levels. The "long-term effects of earthquake damage" is discussed in terms of the water leak and pipe breaks integrated over the period.

## DESCRIPTION OF DAMAGE DATA FOR INDIVIDUAL CITIES

Sendai (Miyagi, Japan) Fig.1 shows the variation of the system state in Sendai City water supply system. The pipe repair rate, Fig.1(a), has many peaks during the winter times before the year, of the earthquake(1978). These peaks are due to breaks of asbestos-cement pipes (ACP) freezing. Replacement of ACP by higher grade cast iron pipes (CIP) was exercised extensively before 1978. For this reason, the number of pipe breaks caused by the earthquake in June 1978 was relatively small, but ten months were needed for the monthly break rate to recover the normal level.

Fig.1(b) and (c), on the other hand, shows that these are no clear long-term effects of the earthquake on the leak rate, leak ratio, or other data of delivered water. This can be explained from the fact that the severely damaged areas with poor soil conditions were limited to a part of the whole system so that these local effects were not reflected in the total system data, that high grade pipes had replaced old ACP in a large proportion of the system, and that intensive survey works were done to find out undetected leaks after functional restoration was finished.

From this observation, it may be pointed out that despite the inconvenience caused by the earthquake, the case of Sendai City water supply system was an example of reasonable system performance, emergency operation and recovery works.

Noshiro (Akita, Japan) Fig.2 shows the data for Noshiro City water supply system. The pipe repair rate, Fig.1(a) has an extremely high peak immediately after the earthquake, May 1983. Repair rate peaks relatively higher than the normal level are observed in a subsequent year, implying that long-term effects of the earthquake damage did exist.

The long-term effects are clearly observed in the water supply and leak data in Fig.2(b) and (c). It is noted in Fig.2(b) that effective water supply recovers its normal seasonal variation when functional restoration was finished two weeks after the earthquake, whereas the total amount of delivered water continues to maintain much higher levels than in the pre-earthquake period.

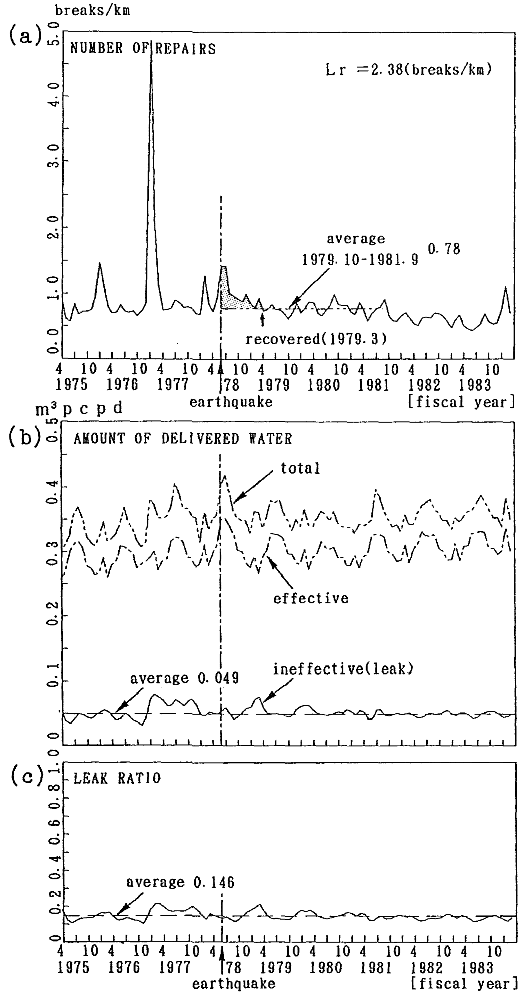


Fig.1 Monthly variation of the system state in Sendai City

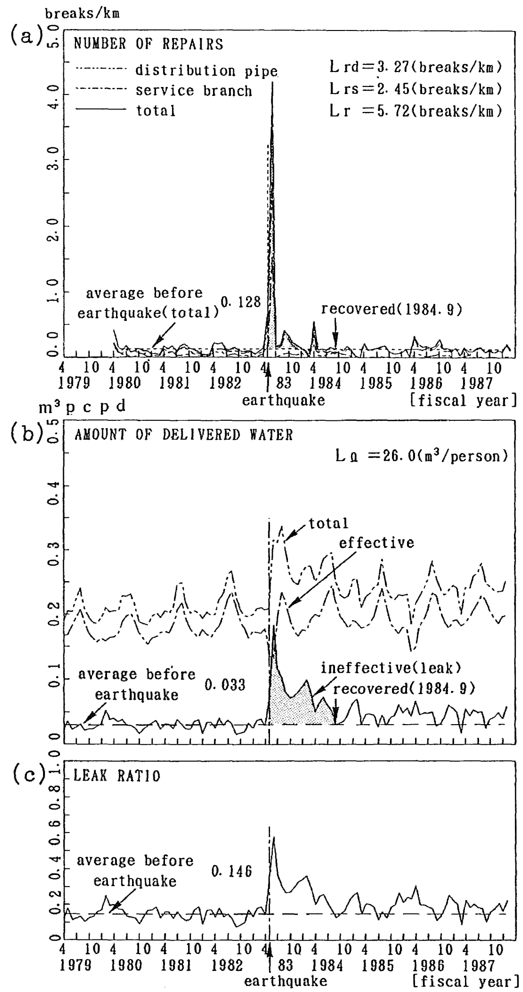


Fig.2 Monthly variation of the system state in Noshiro City

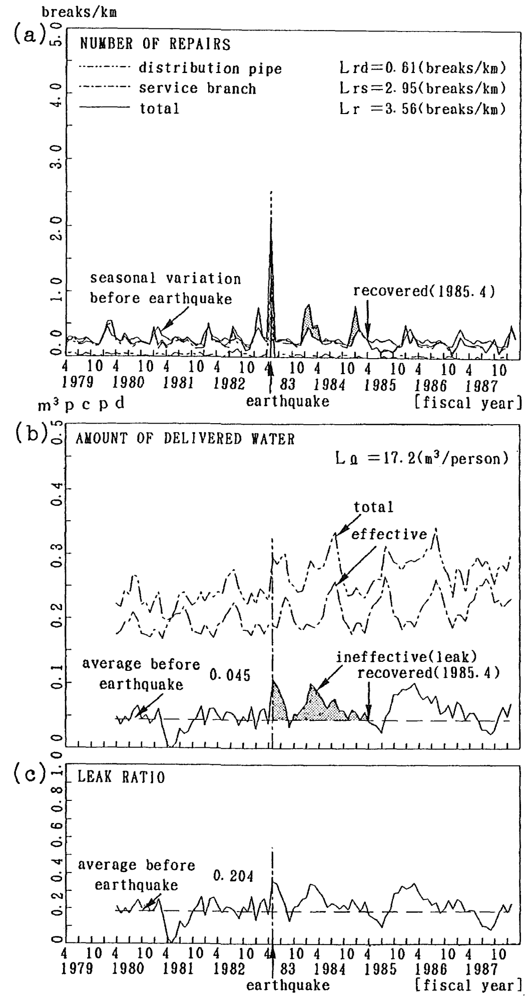


Fig.3 Monthly variation of the system state in Oga City

This is directly reflected in the high leak rate. Also in the high level of the leak ratio, Fig.2(c). Two years were needed for the leak rate to recover its normal level.

The damage to the Noshiro City water supply system was caused by extensive liquefaction of sandy grounds that badly affected more than half of the system. The data in Fig.2 typically demonstrates the long-term effects of earthquake damage in water supply systems.

Oga (Akita, Japan) Fig.3 shows the data for Oga City water supply system. A remarkable aspect for this case is observed in the high peaks of the pipe repair rate during the two winter seasons following the earthquake. This is interpreted as a remarkable example of combined effect of potential earthquake damage and pipe freezing.

In the case of Oga City, liquefaction of sandy ground did not occur so extensively as in Noshiro City. This explains the relatively low leak ratio (35% max) after the functional restoration compared to the case of Noshiro (60% max). However, the long term effect on the leak ratio lingers on with the pipe repair rate.

Coalinga (California, U.S.A.) Fig.4 shows the data for Coalinga City water supply system compiled by Isenberg (Ref.5). The data represents the variation annual pipe repair rate on the water distribution network. As no intensive repair works were exercised after the earthquake, the pipe breaks continued to take place, taking two years before recovering a normal break rate.

Mexico City (Mexico) Fig.5 shows the variation of monthly average for the total intake flow rate at the Mexico City water supply system. Seasonal variation in the pre-earthquake period is disturbed after the earthquake, keeping high levels with a temporary drop at the time of the earthquake. Although thorough interpretation of the data will need more detailed analysis of the system performance, they at least demonstrate the long-term effect of the earthquake.

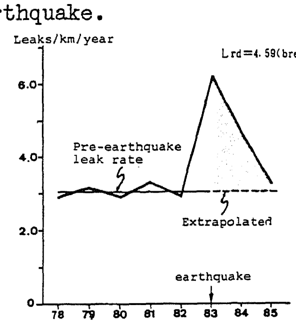


Fig.4 Annual number of leaks in water distribution system, Coalinga City (Ref.5)

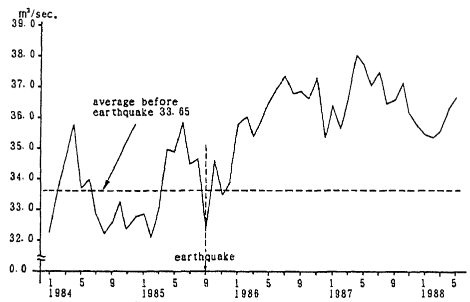


Fig.5 Variation of in-take amount from source wells (Mexico City)

**LONG-TERM DAMAGE MEASURE**

The long-term effects of earthquake damage is represented by the index of long-term damage measure L whose general definition is given by

$$L = \int_{t_0}^{t_r} \{ d(t) - d_n \} \, dt \qquad (1)$$

in which $d(t)$ = any quantity representing damage level, $d_n$ = normal level of $d(t)$ during the pre-earthquake period, $t_0$ = time of earthquake occurrence, and $t_r$ = termination of the long-term effect. Depending on the kind of quantity represented by $d(t)$, the long-term damage is classified as

$L_\ell$ : per-capita total leak loss ($m^3$/person)

$L_{rd}$ : total number of breaks of distribution pipes per their total length (breaks/km)

$L_{rs}$ : total number of breaks of service branches per total length of the distribution pipes (breaks/km)

$L_r$ : total number of breaks of distribution pipes and service branches per total length of the distribution pipes ($L_{rd}+L_{rs}$: breaks/km)

$L_v$ : per capita total intake flow ($m^3$/person)

All quantities appearing in Eq.1 and the above classification are shown in Figs. 1-5, and also summarized in Table 1. Although the populations of the cities dealt with herein vary from 6,600 to 18 million, consequently having water supply systems with very different network sizes, the long-term damage measures as defined above in normalized forms have common features among the cities thus enabling one to make comparative discussion.

On the basis of general experiences that asbestos-cement pipes (ACP) and polyvinyl pipes (PVC) are more vulnerable to earthquakes than cast-iron pipes (CIP) and ductile cast-iron pipes (DCIP), the pipe break rates found out immediately after the earthquakes, Table 1 ⑧ are plotted against the proportion of ACP+PVC to the whole water distribution networks. There is roughly a trend in the data for Sendai, Oga and Mexico that the pipe break rate increases with the

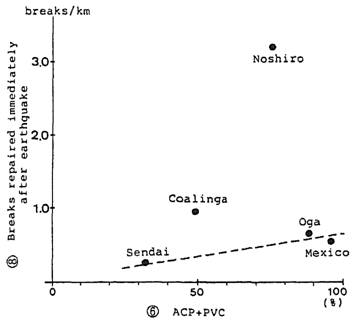


Fig.6
Break rate immediately after E.Q. vs. pipe material proportion

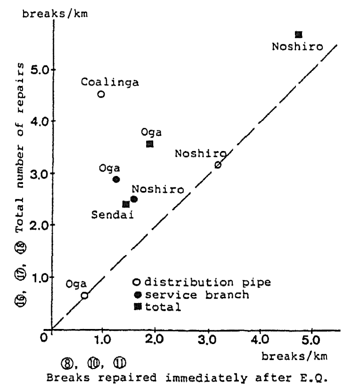


Fig.7
Total number of breaks versus break rate immediately after E.Q.

Table 1 Earthquake damage statistics of water supply systems

| | | Sendai | Noshiro | Oga | Coalinga | Mexico City |
|---|---|---|---|---|---|---|
| | ①Earthquake | 1978 Miyagiken-oki (1978.6.12) $M_J$=7.4 | 1983Nihonkai-Chubu (1983.5.26) $M_J$=7.7 | | 1983 Coalinga (1983.5.2) $M_L$=6.5 | 1985 Mexico (1985.9.19) Ms=8.1 |
| | ②Intensity | V (JMA) | V (JMA) | V (JMA) | VIII (MM) | VIII (MM) |
| System condition | ③Served population | 624,000 | 48,000 | 28,000 | 6,600 | 18,000,000 |
| | ④Water consumption immediately before earthquake | $21.8\times10^4 m^3$/day (delivered) $0.36m^3$pcpd* | $1.0\times10^4 m^3$/day (delivered) $0.21m^3$pcpd | $0.68\times10^4 m^3$/day (delivered) $0.24m^3$pcpd | | $300\times10^4 m^3$/day (intake) $0.17m^3$pcpd |
| | ⑤Total length of distribution pipes | 1,144km | 145km | 173km | 42.8km | 12,500km |
| | ⑥Proportion of pipe material | ACP 4%<br>PVC 28%<br>CIP, DCIP 62%<br>SP 6% | ACP 48%<br>PVC 28%<br>CIP 5%<br>DCIP 16%<br>SP 1%<br>PP 2% | ACP 59%<br>PVC 29%<br>CIP, DCIP 6%<br>SP 6% | ACP 48%<br>PVC 1%<br>CIP 32%<br>WIP 12%<br>RC 7% | ACP 96%<br>RC, PC 4% |
| Basic damage statistics | ⑦Number of distribution pipe breaks (those found out immediately after earthquake) | 215(259**) | 461 | 108 | 130 | 7,400 |
| | ⑧Break occurrence rate (⑦/⑤) (breaks/km) | 0.19(0.23**) | 3.2 | 0.62 | 1.0 | 0.59 |
| | ⑨Number of service pipe breaks (those found out immediately after earthquake) | 1,391 | 231 | 219 | | |
| | ⑩Break occurrence rate (⑨/⑤) (breaks/km) | 1.24 | 1.59 | 1.27 | | |
| | ⑪Total break occurrence rate(⑧+⑩) (breaks/km) | 1.43(1.47**) | 4.79 | 1.89 | | |
| | ⑫Type of major ground failure | Block failure and dislocation in cut-fill land developed for residental areas | Extensive liquefaction | Local liquefaction | | Settlement and large deformation of soft ground |
| | ⑬Period needed for functional restoration | 8days | 19days | 6days | | 40days |
| Long term effect | ⑭Duration of long-term effect (recovered month) | 10months (1979.3) | 2years (1984.9) | 2years (1985.4) | 2years (1985) | |
| | ⑮ LΩ ($m^3$/person) | 0.93 | 26.0 | 17.2 | | |
| | ⑯ Lrd (breaks/km) | | 3.27 | 0.61 | 4.59 | |
| | ⑰ Lrs (breaks/km) | | 2.45 | 2.95 | | |
| | ⑱ Lr (Lrd+Lrs) (breaks/km) | 2.38 | 5.72 | 3.56 | | |
| | ⑲ Lv ($m^3$/person) | | | | | |

* $m^3$ pcpd=$m^3$per capita per day

** Total including by the leaks-detecting team proportion of ACP+PVC. The extremely large pipe break rate for Noshiro is obviously attributed to extensive occurrence of sand liquefaction observed throughout the service area. The large value of the pipe break rate for Coalinga is not clear. One possible reason may be high electric conductivity of the ground in this area which is situated in an oil-production zone, affecting the corrosion of CIP rather than ACP or PVC.

In Fig.7, the long-term damage measures regarding the pipe break rate, Table 1 ⑧, ⑩, ⑪ are plotted against the break rate for the period immediately after the earthquakes, Table 1 ⑯, ⑰, ⑱ , respectively. The vertical distance of each data point from the diagonal dashed line relative to its elevation stands for the proportion of the long-term effects to the total damage. Observe that the two data points for the distribution pipe lie on the dashed line, whereas those for service branches and those for distribution and service total lie necessarily above the dashed line. These results indicate that the distribution pipes recover their strength through the restoration works immediately after the earthquakes, whereas breaks of service branches continue to take place as a major part of the long-term effects. The number of service branch breaks occurring as long-term effects are some 0.4-1.4 times those detected immediately after the earthquake.

## CONCLUSIONS

From the present study on the earthquake damage of water supply networks, conclusions may be summarized as follows.

(1) Dependence of the pipe break rate on the pipe material and presence of sand liquefaction has been demonstrated.
(2) The long-term effects of earthquake damage up to two years were observed.
(3) The long-term effects in cold regions are remarkably observed during winter seasons, combined with freezing effect.
(4) The long-term effects are observed mainly at service branches rather than at distribution pipes.

## ACKNOWLEDGMENT

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