DAMAGE ASSESSMENT OF LIFELINE SYSTEMS IN JAPAN

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Abstract

This paper introduces the current status of damage assessment of lifeline facilities, including estimation of loss of function. The methods of estimating earthquake motion on bedrock as well as on ground surface were outlined, and a general flow for the evaluation of damage probability of lifeline facilities is shown.

Introduction

Large-scale development projects are now proceeding on waterfront areas of many major Japanese cities, including Tokyo and Osaka. These waterfront projects are often conducted on soft ground reclaimed from the sea or river. In the 1989 Loma Prieta earthquake, lifeline facilities were seriously damaged as a result of liquefaction of reclaimed land in the San Francisco Bay area. The Loma Prieta earthquake taught us the importance of earthquake resistant design of structures on and in reclaimed ground. Accordingly, local governments such as the Tokyo Metropolitan Government and the companies providing lifeline service, such as electricity and gas, are now conducting assessments of the potential damage from a strong future earthquake. Pre-earthquake measures to reinforce facilities and post-earthquake recovery strategies are also being investigated based on the results of the damage assessment. In these studies, the effects on lifeline facilities of liquefaction-induced ground displacement are also being examined. This paper describes the current status of damage estimation of lifeline facilities, including estimations of the loss of function and the research problems still to be solved in making these estimations in Japan.

Damage Assessment of Lifeline Facilities and System Function

The damage estimation of lifeline facilities, the loss of the function, and the recovery process follows the flow chart shown in Figure 1, on next page. Lifeline facilities are generally distributed over a wide area, so seismic activity is surveyed for the whole area. For cities on the Pacific Coast, such as Tokyo and Osaka, an undersea earthquake of magnitude 8 and an inland one of magnitude 7, with the hypocenter under the city, are sometimes assumed. If an earthquake under the ocean is assumed, the effects of a tsunami must be taken into consideration because some lifeline facilities, such as thermal power stations, are located on the coast.

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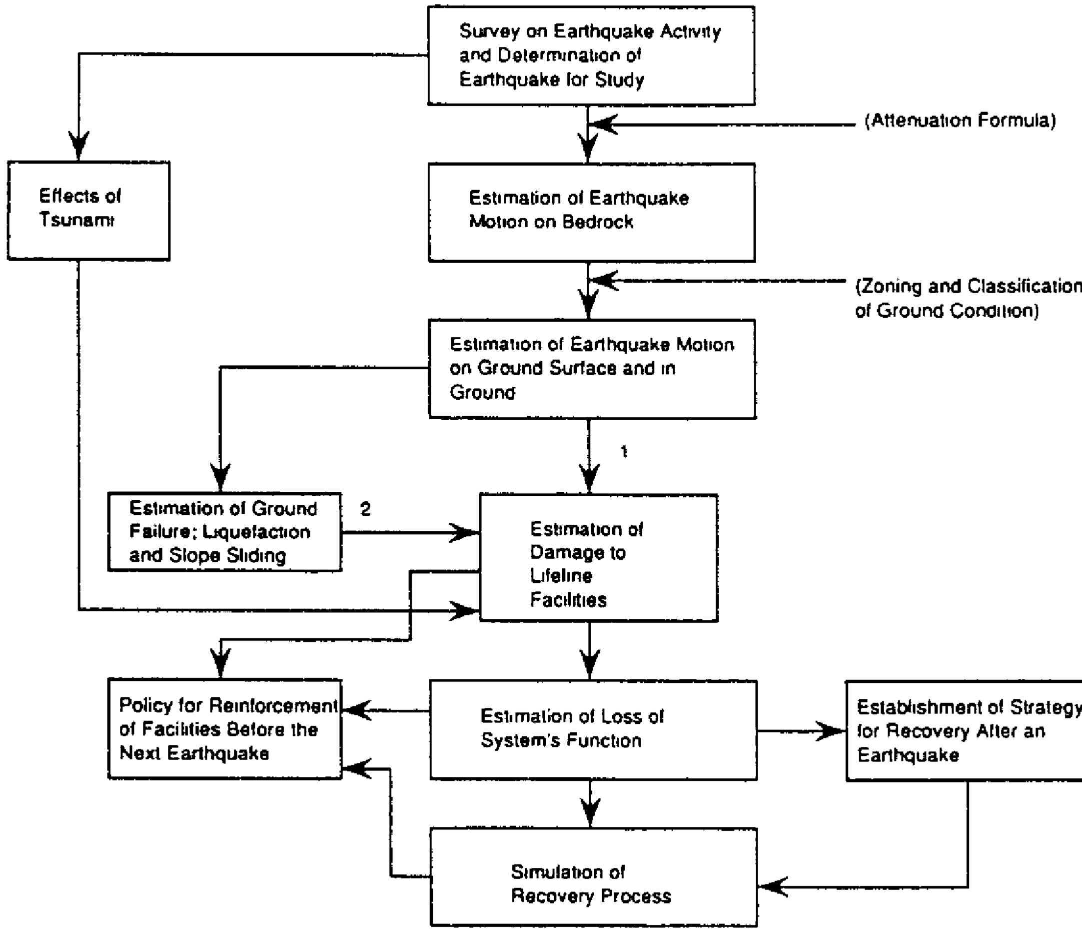

Figure 1 General Flow of Damage Estimation of Lifeline Systems.

Earthquake motion on bedrock throughout the area on which lifeline facilities are distributed is estimated by using attenuation formulae. In this case, correct estimation of the earthquake motion in the neighborhood of earthquake faults will be one of the most important subjects, for reasons described later.

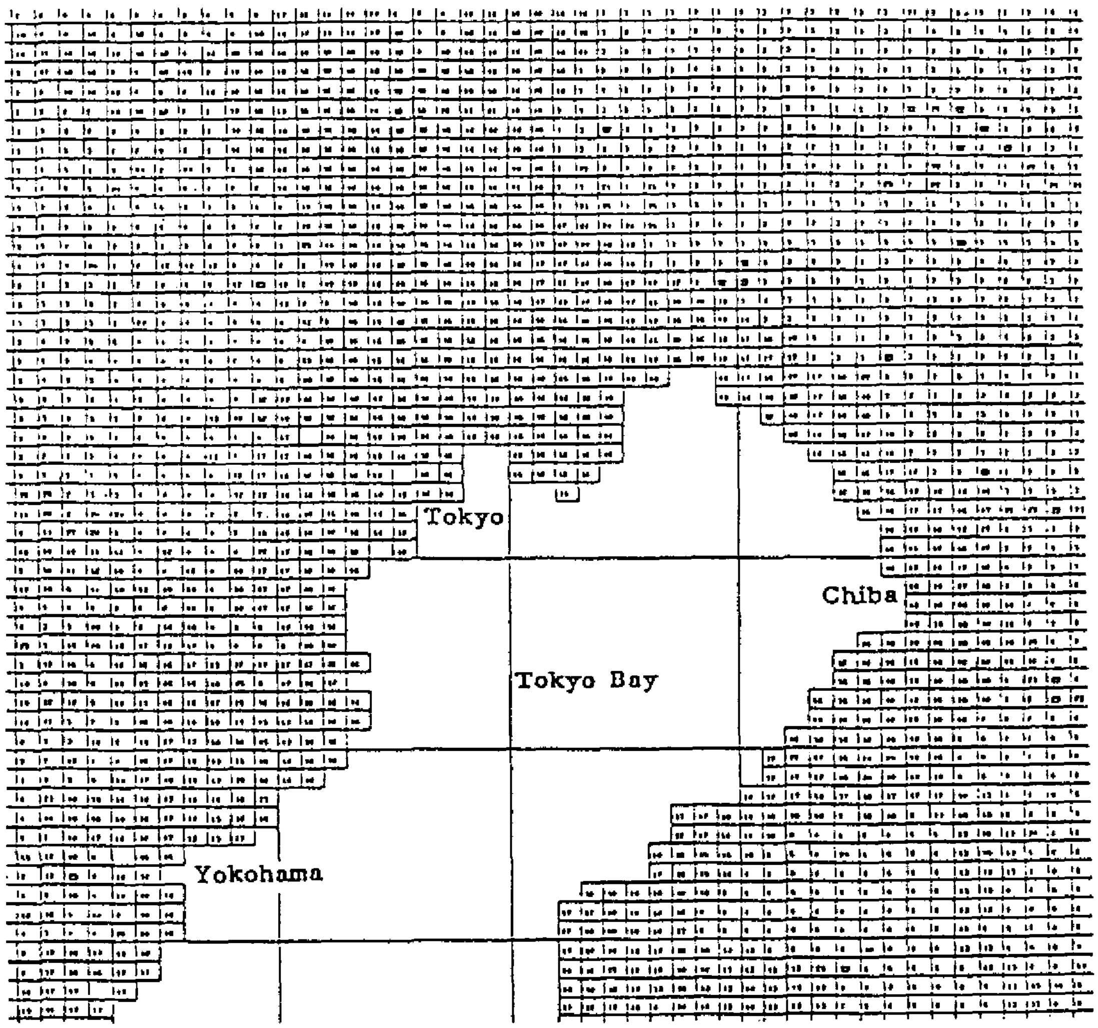

Figure 2 Example of Mashes for Calculation of Ground Response in Tokyo Metropolitan Area (1Km Kesh).

The next step is to estimate, by dynamic response analysis, the earthquake motion on the ground surface as well as in the ground. The input for this is the earthquake motion on the bedrock. Besides acceleration, velocity, and displacement, the relative displacement and strain must be determined in order to estimate the damage to buried lifeline facilities. Since lifeline facilities are distributed over a wide area, the area of interest is generally divided into meshes with a size of 1 kilometer to 500 meters, and the earthquake motion for each mesh, where the ground conditions are considered to be uniform, is calculated. For example, Tokyo is divided into about 10,000 meshes, as shown in Figure 2, with 150 kinds of ground conditions.

Based on calculated earthquake motions on the surface and in the ground, the probability of liquefaction and land sliding are examined. Since many areas of large Japanese coastal cities are constructed on reclaimed land, the exact estimation of liquefaction potential is one of the key subjects for damage assessment of lifeline facilities. The damage to lifeline facilities is estimated based on the calculated earthquake motion by taking into consideration the effects of ground failure, such as liquefaction.

The damage degree to facilities is generally represented as a probabilistic value. For example, the damage degree of buried pipes is given as the average number of failures per unit length of pipe or as the damage probability at the connection point with other structures such as the manhole.

As for the effects of liquefaction. we must also consider the effect of the permanent ground displacements, subsidence, heaving and floating of manhole covers. In places where lifelines cross a river, the effects of subsidence of the embankment behind bridge abutments must also be taken into consideration.

The following two methods can be used to obtain a damage probability. The first method is by empirical formulae obtained by statistically analyzing the damage caused to lifeline facilities in past earthquakes. For example, the following empirical formula is proposed for the buried pipes.

$$R_f = C_G \cdot C_L \cdot C_P \cdot C_E \cdot R_S$$

R_f: Damage probability of buried pipes
R_S: Standard damage probability
C_G: Factor by ground condition
C_L: Factor by liquefaction
C_P: Factor by pipe's material and diameter
C_E: Factor by strength of earthquake motion

Figure 3 shows damage rate of buried pipes (mean number of the failure points per 1 km) obtained from 1971 San Fernando and 1978 Miyagiken-Oki earthquakes. From these data the standard damage probability R_S can be determined. However, most of the damage resulting from these earthquakes was caused to pipes with a relatively small diameter and low strength, so it is necessary to make a correction to the standard damage probability according to strength and ductility when it is applied to strong, large-diameter pipes. Recently, large-diameter steel pipes or ductile iron pipes with flexible joints have come into wide use for lifeline system mains. It is one of the most difficult tasks to determine a correction factor suitable for these pipes, since almost no actual damage data are available.

The second method of the evaluation of the damage probability of facilities is to compare stress, strain and deformation based on the predicted earthquake compared to the ultimate strength of the facilities. Figure 4 shows the process of calculating the damage probability for buried pipes. In addition to relative ground displacement and ground strain resulting from earthquake motion, permanent ground displacement due to liquefaction is taken into consideration in calculating the stress, strain and deformation of buried pipes.

The functionality of lifeline systems after an earthquake is evaluated based on damage assessment of the facilities. Several numerical methods of network analysis have been proposed. However, practical networks of lifeline facilities consist of an enormous number of elements and such an analysis covering all elements is actually impossible. Thus, to achieve the objectives, some simplifications are made by taking into account the characteristics of the network. An electricity supply substation, for example, consists of many transformers, circuit breakers, and other components, but it is substituted by a simple system with fewer elements, based upon the judgment of experts.

The post-earthquake recovery strategy is developed on the basis of estimated damage to facilities and functions. The recovery process is simulated in accordance with several probable recovery strategies, and, based on the simulation, the best strategy is selected using expert opinion. The pre-earthquake policy for the reinforcing facilities is also determined by damage estimation and by simulating the recovery process.

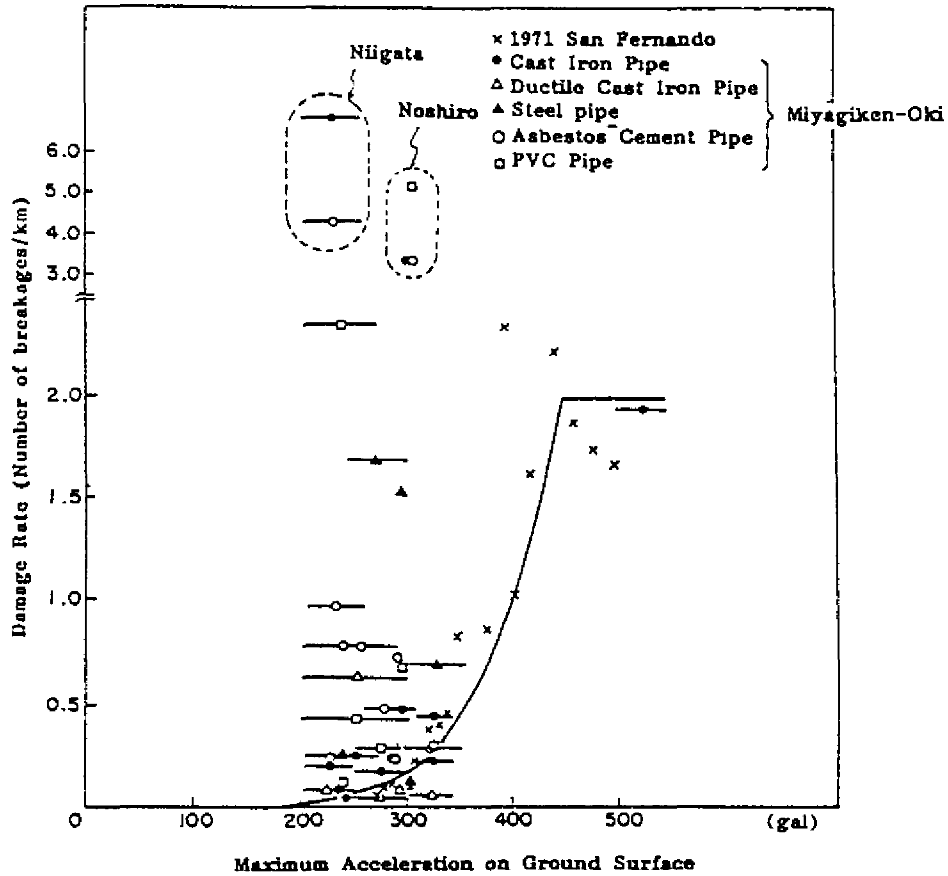

Figure 3 Water Pipe Damage Rate in 1971 San Fernando and 1978 Miygiken-Oki Earthquake.

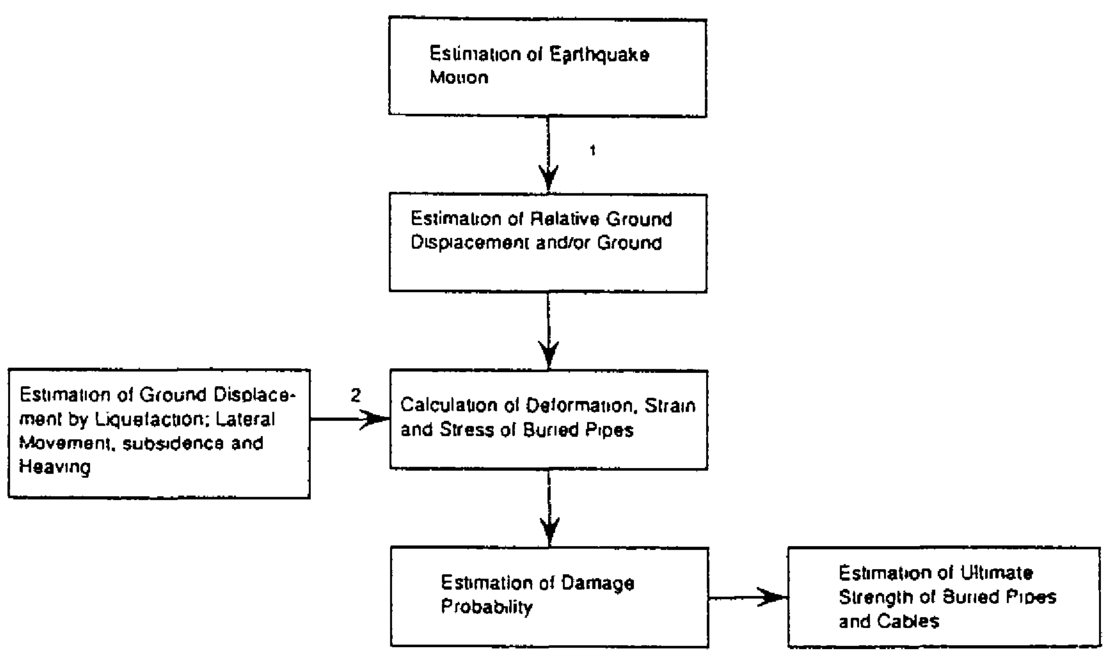

Figure 4 General Flow for Estimating Damage Probability for Buried Pipes.

Further Subjects on Earthquake Resistance of Lifeline Systems

To enable more accurate damage estimation of lifeline facilities and their functions, further study in the following areas is needed.

Earthquake Motion Near the Fault

Many attenuation formulae, which take earthquake magnitude and epicentral or hypocentral distance as functions for estimating earthquake motion, have been proposed. Some examples are shown in Figure 5. Most of the earthquake records which were used to develop these attenuation formulae were collected relatively far from the earthquake fault, during large- or medium-magnitude earthquakes, or were measured during small-magnitude earthquakes. Earthquake motions which are recorded near faults are currently insufficient to establish reliable attenuation formulae. Thus, ground motions within an epicentral distance of 0-20 km due to earthquakes with a magnitude of 7-8 are estimated by extrapolation.

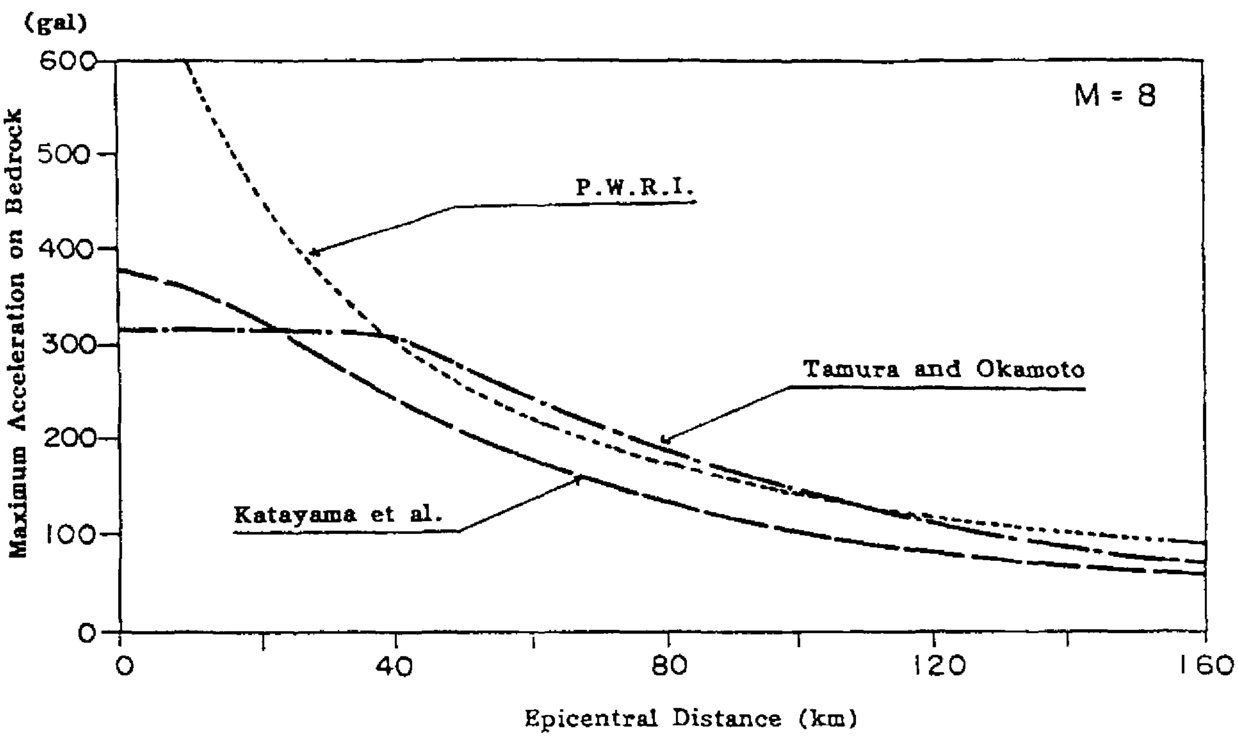

Figure 5 Attenuation Formula for Estimation of Ground Motion.

When an inland earthquake occurs, some lifeline facilities are inevitably located in the fault zone. The damage probability for facilities in the fault zone is high, and the degree of damage to those facilities has a great influence on the overall functioning of the system. Therefore, one of the most important tasks is to estimate correctly the earthquake motion in a fault zone for the damage estimation of lifeline facilities.

Figure 6 shows an example of a maximum acceleration map for the ground surface. This map was used to estimate the damage to lifeline systems resulting from a future earthquake in the metropolitan area. The maximum acceleration was calculated by non-linear dynamic analysis. According to this map, the maximum acceleration in Shinjuku Ward, on the diluvial plateau, is greater than that in Koto Ward along the Sumida River on alluvial low land. This map shows that the acceleration on soft ground is less than that on firm ground.

Dynamic Response of Soft Ground

In the Loma Prieta earthquake, the acceleration on reclaimed land around San Francisco Bay was two to three times greater than that on firm ground. And in the 1985 Mexico City earthquake, too, acceleration was amplified significantly on land reclaimed from the lake in the city and many tall buildings were seriously damaged.

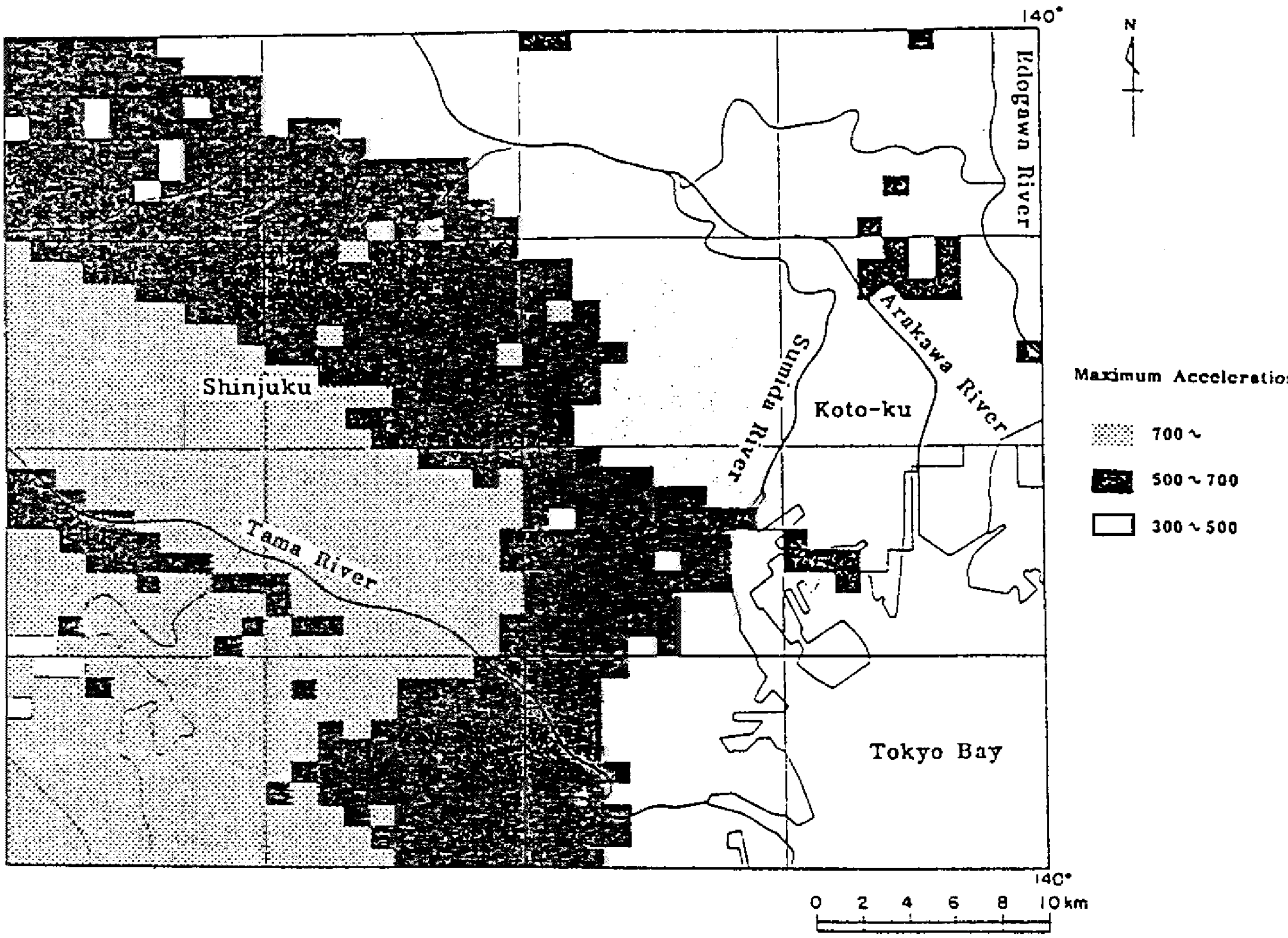

Figure 6 Maximum Acceleration Map of Tokyo Metropolitan Area.

Figure 7 shows maximum accelerations on the ground surface and on the bedrock as measured on reclaimed land around Tokyo Bay. The maximum acceleration on reclaimed land is two to three times greater than that on the bedrock. It seems that the maximum acceleration given in Figure 6 somewhat contradicts the actually measured accelerations in Figure 7.

The results of a dynamic analysis of reclaimed land in Tokyo, shown in Figures 8 and 9, illustrate this contradiction. Figure 8 shows the ground conditions and the numerical model while Figure 9 shows the acceleration on the surface calculated by non-linear response analysis using the R.O. model. The calculated maximum acceleration on the surface is 121 Gal, assuming the maximum acceleration on the bedrock to be 100 Gal. Some amplification of earthquake motion from the bedrock to the ground surface can be seen. However, the surface acceleration becomes 156 Gal, if the maximum acceleration on the bedrock is 200 Gal, so the amplification factor is less than 1.0. The reason for this is that, for a larger acceleration on the bedrock, the natural period of the ground increases and the damping effect is enhanced by the more significant influence of non-linear soil characteristics. Consequently, the accelerations on soft ground are estimated to be less than those on firm ground, as shown in Figure 6.

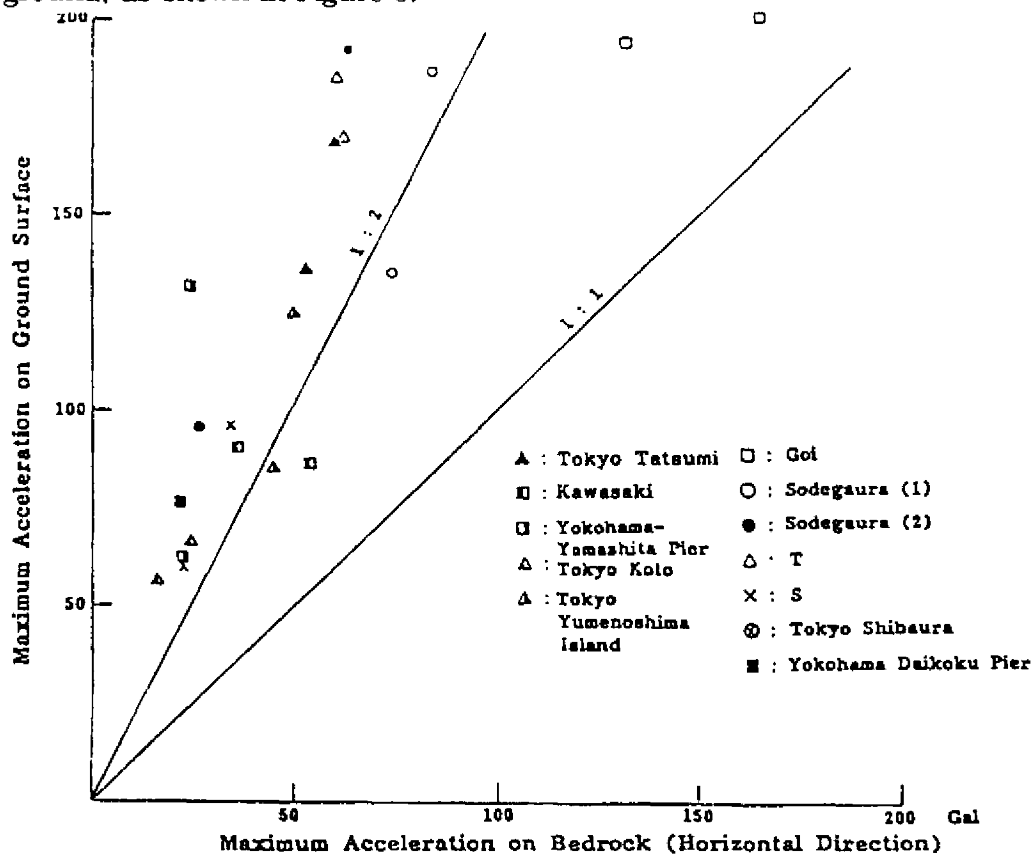

Figure 7 Maximum Acceleration on the Ground Surface and Bedrock Recorded on Reclaimed Land in Tokyo Bay Area.

The probable reasons for the lower acceleration on the soft ground are as follows.

1. Evaluation of soil properties for the analysis is not adequate. In particular, there may be problems in evaluating the damping coefficient.

2. The numerical model is not adequate. A one-dimensional model such as SHAKE is generally used for the calculation of the ground acceleration. In these numerical models, the effect of seismic waves propagating in a horizontal direction, which are caused by variations in ground conditions, are not taken into consideration.

In order to carry out accurate damage estimation of lifeline facilities, it is critical that earthquake motion of soft ground such as reclaimed land be evaluated. Research activity on this subject should be promoted by utilizing the observed earthquake motions on soft ground, such as those recorded during the Loma Prieta earthquake.

Liquefaction-Induced Permanent Ground Displacement

The author and his research team reported that liquefied ground was displaced as much as several meters in the horizontal direction, depending on topographical conditions, at the time of the 1983 Nihonkai-Chubu earthquake.[1] Since then research case studies of liquefaction-induced ground displacements caused by eight earthquakes in Japan and the U.S. have been conducted by the Japan-U.S. joint research team.[2),3),4)] The mechanism of liquefaction-induced ground displacement has been investigated by shake table test. However, no mechanism that gains a consensus of researchers has been found so far.

Depth (m)	Soil	Thickness (m)	Shear Wave Velocity (m/s)	Density
	Fine Sand	3.8	170	1.65
	Silt	2.0	170	1.50
-10	Sandy Silt	4.5	130	1.50
	Sandy Clay	2.0	200	1.50
	Sand	6.3	330	1.80
-20	Fine Sand	1.5	330	1.90
-30	Hard Clay	11.1	380	2.00
-40	Tertiary Layer	10.8	440	2.00
-50, -60	Tertiary Layer	——	530	2.00

Numerical Model

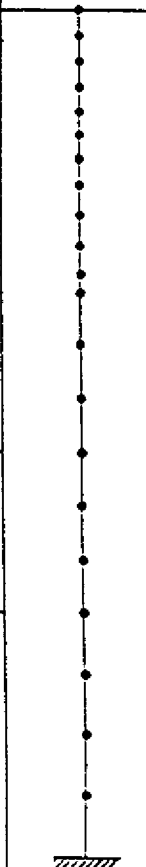

Figure 8 Ground Conditions and Numerical Model for Dynamic Response Analysis (Alluvial land in Tokyo).

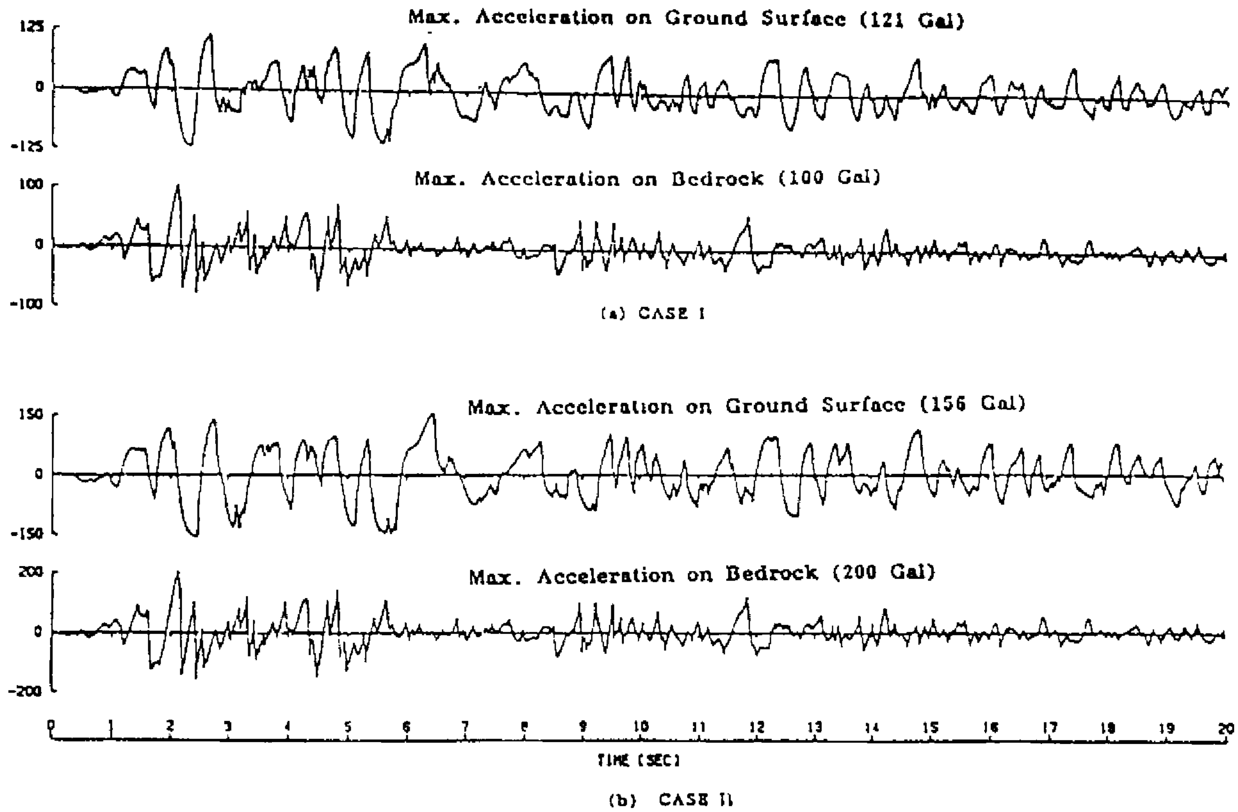

Figure 9 Response Acceleration on Ground Surface.

Only the following empirical formula has been proposed:

$$D=0.75\sqrt{H}\,\sqrt[3]{\varnothing}$$

D: Liquefaction-induced ground displacement (m)
H: Thickness of liquefied soil layer
ø: Gradient of ground surface or of liquefied soil layer (%)

Estimating the effects of liquefaction-induced displacements on lifeline facilities, especially on buried pipes, requires accurate estimates of the displacement magnitude, its direction and pattern. To make this information available, the mechanism of ground displacement needs to be fully clarified. Model tests, using shake tables, are now being undertaken by several institutes in Japan, while work on numerical models to calculate the permanent ground displacement is proceeding.

Effects of Permanent Ground Displacement on Lifeline Facilities

Many buried pipes and foundation piles were damaged by liquefaction-induced ground displacement during the 1964 Niigata and 1983 Nihonkai-Chubu earthquakes. The effects of liquefaction on lifeline facilities are as follows:

1. Settlement and inclination of structures due to reduction of the ground's bearing capacity.

2. Floating of underground structures, such as manholes, due to buoyancy in the liquefied soil.

3. Liquefaction-induced permanent ground displacement.

Effects 1 and 2 are already taken into consideration in the earthquake-resistant design of facilities, but effects of permanent ground displacement 3 are at present not considered.

When large permanent ground displacements, with a magnitude of several meters, are considered in the earthquake-resistant design of buried pipes two matters become a problem. One is whether "the seismic response displacement method," which has conventionally been used for the design of underground structures, is applicable or not. And if it is applicable, there is also the problem of how to evaluate the coefficient of the subgrade reaction of partially liquefied ground.

The other is the evaluation of the ultimate strength of facilities. It is impossible to design the facilities using the conventional allowable-stress method when the permanent displacement is several meters, and information on the ultimate strength of lifeline facilities such as buried pipes is insufficient at present.

The former problem has been studied in an experiment on a pile foundation model in liquefied soil, and it was reported that the force acting on the pile during lateral movement of liquefied soil is similar to the drag force in a liquid. The second problem is now being studied by laboratory tests on piles and pipes.

Conclusions

In this paper, the current status of damage estimation of lifeline facilities in Japan and problems needing solution in the future are described. As stated in the introduction, large-scale waterfront projects have already progressed greatly in major cities. To create an earthquake-safe urban society, the study of damage to lifeline facilities must proceed much more quickly.

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EMERGENCY ASSESSMENT OF DAMAGED BUILDINGS IN JAPAN

Yujiro Ogawa

In 1986 the Japanese Ministry of Construction issued the engineering criteria concerning Emergency Assessment of Damaged Buildings. Prefectures started investigations to develop their Emergency Assessment System, e.g., the practical method to apply the criteria in the field, to educate volunteer engineers, etc. The news of emergency assessment in the Loma Prieta earthquake in 1989 accelerated these investigations.

In June 1991, the Ministry of Construction issued the guidelines of the Emergency Assessment System. Shizuoka Prefecture started a training course for Certified Architects. Ten thousand Certified Architects are expected to take the training course in five years. In fact, 2,000 architects have taken the course in the first four months. They are then required to register as volunteer engineers.

Kanagawa Prefecture also made an Investigation Report of the Emergency Assessment System after two years of research. The training course will start in 1992 with plans to educate 6,000 Certified Architects in five years. Tokyo, with many huge high-rise buildings, has not yet developed an Emergency Assessment System. While most prefectures did not recognize the necessity of Emergency Assessment after earthquakes, strong leadership of the Ministry of Construction required the development of the Emergency Assessment System nationwide.

The following problems are becoming clear and will need to be settled in practice.

The first point is the legal force of the Japanese Building Code in case of an emergency like an earthquake. In the Japanese Building Code, no description of regulation is found on how to evaluate disaster-damaged buildings. For example, no legal force exists to inspect the insides of residences or to keep residents out of damaged buildings. Unless local government officials take action based on the Disaster Countermeasures Basic Act, even the posting of tags according to the assessment cannot have legal force to secure buildings. Furthermore, this Act is not adequate to treat individual damaged buildings.

The second point is insurance for volunteer engineers. As "volunteer" is not common in Japan, the system and understanding of insurance has not matured. As far as the Emergency Assessment System is constructed on the basis of a volunteer system, an insurance system for Volunteer Engineers should be developed as soon as possible.

The third point concerns customers services of construction companies or other sectors most volunteer engineers belong to. In Shizuoka Prefecture, the Tokai Earthquake is supposed to occur soon and the number of damaged buildings estimated to be quite large. Therefore, each municipality has to ask for cooperation from architects living or working in that city. According to interviews with administrative persons in various sectors, these sectors may be too busy to respond to their customers' claims following an earthquake. Accordingly, it will be necessary to develop the Emergency Assessment System to ensure enough volunteer engineers in the post-event period.

There are many problems to be solved to organize an Emergency Assessment System before the Big One. The experience of Loma Prieta may show the solution for the problems described above. It is earnestly desired to widen exchange of information of Emergency Assessment Systems between Japan and the United States.

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