STATE OF THE ARTS ON RESEARCH AND DEVELOPMENT IN EARTHQUAKE DISASTER PREVENTION OF LIFELINE FACILITIES IN JAPAN

by

Ken-ichi Tokida[1)], Keiichi Tamura[2)] and Osamu Matsuo[3)]

ABSTRACT

Presented are review results of research and development in earthquake disaster prevention and countermeasure technologies for lifeline facilities and current practice in Japan. We expect that this paper will promote mutual understanding of earthquake disaster prevention for lifeline facilities in both the United States and Japan, and enhance the activities of new Task Committee on lifeline engineering.

Key words: lifeline facilities, research and development, technology, future course

1. INTRODUCTION

Under the Panel on Wind and Seismic Effects, UJNR, the Task Committee "F" on Disaster Prevention Methods for Lifeline Systems has been in charge of information exchange and joint research on damage survey of lifeline facilities, their evaluation and countermeasures, however, the recent activity of this Task Committee has not always been efficient. This may attribute to the facts that there are a wide variety of lifeline facilities; the policy of Task Committee activities has not been clear; and so forth.

On the occasion of the 33rd Joint Panel Meeting, a new Task Committee will succeed the current Task Committee F under the mutual understanding that continuation of activity in this area is important. For this purpose, it is essential to have common recognition between the United States and Japan for the technical problem of lifeline facilities and future course of research and development, clarifying the current status of research and development and engineering practice.

We summarize review results on research and development of earthquake disaster prevention and countermeasure technologies for lifeline facilities and current practice in Japan. We expect that this paper will promote mutual understanding of earthquake disaster prevention for lifeline facilities in both the United States and Japan, and enhance the activities of new Task Committee on lifeline engineering.

2. LIFELINE FACILITIES

Lifeline facilities are most basic public infrastructures that support citizen's life and industry, and the highest priority should be given to secure safety of lifeline facilities against earthquakes.

In the present study, we focus on electric power, gas, telephone, water, sewage and common utility duct, which are given in Table 2.1, as major lifeline facilities.

1) Director, Earthquake Disaster Prevention Research Group, Public Works Research Institute, Tsukuba-shi, Ibaraki-ken 305-8516 Japan
2) Team Leader, Ground Vibration Research Team, ditto
3) Research Coordinator for Earthquake Disaster Prevention, National Institute for Land and Infrastructure Management

Since the common utility duct is to store other lifeline facilities, it is different from them, however, it is here included as a large-scale link facility. In Japan, local governments construct and maintain water and sewage facilities, road managers, i.e., either the central government or local governments are responsible for common utility ducts, and public corporations, which are private sectors, are in charge of electricity, gas and telephone facilities. Besides those, roads and railroads are also lifeline facilities in a broad sense, however, they are excluded in this paper, because another Task Committee on transportation systems discuss them.

This paper summarizes technical problems, and the current situation and future course of research and development regarding lifeline facilities, in cooperation with the members of Task Committee F.

3. TECHNICAL PROBLEMS IN EARTH-QUAKE DISASTER PREVENTION OF LIFELINE FACILITIES

Reviewed here are technical problems in earthquake disaster prevention of lifeline facilities, and we attempt to make clear the objectives of research and development in this area.

3.1 Seismic Design Standards

Current technical standards for earthquake disaster prevention or seismic design of lifeline facilities in Japan are given in Table 3.1. They have been revised after the 1995 Kobe Earthquake, except for common utility duct. They are categorized as earthquake disaster prevention manuals for overall system and design standards for individual facilities.

3.2 Earthquake Disaster Prevention

We here survey viewpoints of earthquake disaster prevention by referring to the earthquake countermeasures for sewage and water supply systems.

According to the "1997 Earthquake Disaster Countermeasure Manual for Sewage System", the following six items are to be basic policies for earthquake countermeasures.

1) Structural countermeasures

Secure enough seismic performance against Level 1 and Level 2 design ground motions.

2) Systematic countermeasures

For pipelines, secure redundancy and build a network. For wastewater treatment plants and pomp stations, secure reserve felicities, redundancy, backup power supply and emergency water supply, and build a network between pomp stations.

3) Lifeline (electric power and water supply) countermeasures

Countermeasures against the indirect damage due to shutoff of electricity or water.

4) Organized countermeasures

Drill of disaster prevention and restoration, mutual cooperation among local governments, etc.

5) Utilization of sewage facility as disaster prevention facility

Use sewage facilities as evacuation space and route, and fire prevention belt. Use wastewater for firefighting and other purposes.

6) Post-disaster response

Drill of emergency inspection, survey, restoration and reconstruction as a series of post-disaster response.

"1997 Seismic Planning Guideline for Water Supply System (Draft)" indicates the following:

1) Damage prediction

Seismic inspection, damage prediction for water supply system and damage prediction including damage to other lifeline facilities.

2) Target of seismic performance

Develop target indices, such as damage (area and population) prediction, restoration period, emergency water supply level, and portion of seismic upgraded major structures.

3) Seismic upgrading for individual facilities (menu)

Seismic upgrading of individual facilities (mitigate damage and minimize its influence) and emergency response (rapid restoration and fulfill emergency water supply).

Figure 3.1 shows classification of earthquake countermeasures for water supply system, and Figure 3.2 conceptually illustrates seismic upgrading of individual facilities.

4) Development of strategic plan

Selection of upgrading method corresponding to the level of seismic performance, prioritization of upgrading pipelines, and deployment of emergency water supply station.

5) Establishment of action plan

Cost-benefit evaluation and development of project plan.

As mentioned before, in both case of sewage and water supply facilities, earthquake countermeasures cover not only individual facilities but also system and emergency response. Of particular importance for sewage system is utilization of facility as disaster prevention facility.

3.3 Recent Revise of Seismic Design Standards

We here review the points of recent revise of design standards for lifeline facilities and structures, taking the case of sewage facility.

According to the "1997 Earthquake Disaster Countermeasure Guideline and Commentary for Sewage System", the major revised points are the following:

1) Establish Level 1 and Level 2 design ground motions.

Level 1 design ground motion represents the ground motion that is probable to occur once or twice during design service period. Level 2 design ground motion represents the ground motion that is less probable to occur during design service period, such as ground motion caused by large plate-boundary earthquakes or inland active faults.

2) Consider settlement of the ground and liquefaction-induced ground flow, in addition to uplift of structure by soil liquefaction.

3) Establish seismic performance level corresponding to design ground motions.

For important major pipelines, secure design flow capacity against both level 1 and level 2 design ground motions. For other pipelines, secure design flow capacity against level 1 design ground motion, when they are newly constructed.

For wastewater treatment plants and pomp stations, design against level 2 ground motion when newly constructed, and determine a target level based on the importance of facility for the time being.

4) Prescribe systematic countermeasures.

For pipelines, secure redundancy and build a network. For pomp stations, secure reserve felicities, redundancy, backup power supply and emergency water supply, and form a network by connecting a wastewater treatment plant and a pomp stations by major lines.

As stated above, recent revise of seismic design standards for lifeline facilities in Japan aims to improve seismic performance against destructive earthquakes, specify target performance level and quantitatively estimate effects of soil liquefaction, reflecting damage caused by the 1995 Kobe Earthquake.

Furthermore, it is characterized that the necessity of systematic response is prescribed. For example, "1997 Earthquake Disaster Countermeasure Manual for Sewage System" states building 1) network of pipelines, 2) network of pomp stations, 3) network of wastewater treatment plants, 4) network of information, and the necessity of establishing 5) comprehensive operating system.

3.4 Structural Characteristics and Management System

We take an overview of the structural characteristics of lifeline facilities and their management system, taking the case of gas and telephone and telecommunication facilities.

Tokyo Gas supplies gas to the area shown in Figure 3.3. Their network consists of 500km high-pressure main routes that connect gas-manufacturing factories, 2,000km medium-pressure A lines and 3,500km B lines in their service area, and 40,000km low-pressure lines. The gas lines are 46,000km in total and managed by Total Gas Control System (TGCS).

Figure 3.4 presents the emergency shutoff system for earthquakes. High and medium-pressure gas lines are always remote-monitored, and shutoff by the Control Center, while low-pressure gas lines are automatically shutoff when an earthquake occurs. For gas supply system, shutoff is emergency treatment to prevent the secondary disaster, and it is performed at each stage as follows:

1) Shutoff by microcomputer at each consumer
2) Shutoff by SI sensor at regional governor where gas pressure is reduced from medium to low pressure
3) Remote shutoff by regional block valve
4) Remote shutoff dividing medium-pressure line network into 15 blocks
5) Shutoff at a manufacturing factory

Shutoff by regional governor has been controlled by the Seismic Information Gathering and Network Alert (SIGNAL) since June 1994. SIGNAL, gathering strong motion information from 332 SI sensors, can suspend gas supply for individual regional blocks by remote control of regional block valves.

Figure 3.5 shows an overview of outside telecommunication facilities by the Nippon Telegraph and Telephone Corporation (NTT). Their civil infrastructures are categorized as conduit facilities and pipelines. They employ underground cables in urban areas and aerial cables in residential areas. The conduit facilities are tunnel structures for telephone lines with diameter 3-5 m, and are buried 20-40 m below the ground surface.

Pipelines are classified as medium-size pipes and 75mm-diameter pipes by pipe diameter. The former are iron pipes with diameter 300-600 mm and are buried by micro-tunneling method. The latter are buried 1-2m below the ground surface. Besides them, pipes with diameter 25mm and 50mm are used for underground pipelines.

As mentioned above, lifeline facilities are characterized as follows:

1) Spread widely as a network system.
2) There are large amount of facilities.
3) Performance and importance are not uniform.
4) Most of facilities are constructed

underground.

5) Network management is important.

3.5 Technical Problems for Individual Facilities

We review the technical problems for individual lifeline facilities based on questionnaires to the Members of Task Committee F. Note that those related to water supply and sewage systems have already been mentioned in 3.2.

Electric Power

1) Risk management
   - Optimization of large-scale complicated system
   - Social agreement for risk expose
   - Deployment of element technologies to comprehensive problem
2) Ground motions in specified areas
   - Zonation by dense instrument array monitoring
   - 3-D ground motion simulation
3) Improvement of evaluation system for seismic performance of electric power facilities and cost benefit analysis
   - Evaluation of facility importance based on network function
   - Estimation of seismic performance of important facilities and disaster prevention bases
   - Strategy of seismic inspection, retrofit and upgrade for power transmission facilities
   - Seismic inspection and retrofit of underground structures, such as conduits, pipelines and pile foundations
   - Evaluation of earthquake influence on consumers
4) Emergency response after an earthquake
   - Disaster information system
   - Emergency information transmitting system
   - Restoration support system
   - Emergency drill simulator

Gas Supply

1) Seismic improvement of individual facilities
   - Renewal of existing facilities
   - Seismic retrofit of existing facilities
   - Seismic design of pipelines against liquefaction-induced ground flow
2) Prevention of the secondary disaster and emergency countermeasures for minimizing supply suspended area
   - Spread of microcomputer-aided valve
   - Formulation of emergency block
   - Deployment of accelerometers
   - Damage information gathering and transmission
   - Damage prediction system for pipelines
   - Supply suspension criteria; immediate shutoff when 60(cm/s)$\leq$SI, emergency shutoff when 30(cm/s)$\leq$SI$<$60(cm/s)
3) Quick restoration for service
   - Development of small and light restoration equipments
   - Acquisition and transport of restoration equipments

Telephone and Telecommunications

1) Gathering damage information
   - Application of GPS, GIS and wireless communication
2) Cable damage prediction and reliability assessment
   - Prediction of pipeline damage due to seismic ground motion and ground failure
   - Prediction of cable damage
3) Seismic design against level 2 design ground motion
4) Monitoring and non-destructive inspection for concrete structures
   - Optical fiber sensoring technology
   - Electromagnetic wave prospecting

technology

Common Utility Duct

1) Revise design guideline
   - Introduction of level 2 design ground motion
   - Improvement of seismic design against uplift caused by soil liquefaction
2) Economical countermeasures against soil liquefaction

4. CURRENT SITUATION OF RESEARCH AND DEVELOPMENT

Corresponding to the technical problems that were described previously, we mention current situation of research and development, and example of practice, based on the questionnaires.

Electric Power

- Rational seismic performance level of electric power supply system by multi-risk assessment

Gas Supply

- Real-time earthquake disaster prevention system

SIGNAL, which was mentioned in 3.4, has been integrating to the Super High-dense Real-time Disaster Mitigation System (SUPREME). It will come into operation from summer of 2001. New accelerometers called "New SI sensor" (Photo 4.1) will be deployed at regional governors in service area of Tokyo Gas. Monitored data such as SI values and peak ground accelerations will be gathered in real-time, and applied for damage estimation and system control. Figure 4.1 compares accelerometer locations of SIGNAL and SUPREME.

Surface ground motion at each 50m $\times$ 50m mesh will be computed from the measured data, and it will be applied for prediction of liquefaction and its induced ground flow, and buried pipeline damage, as shown in Figure 4.2. Figure 4.3 indicates an example of SI value distribution by a scenario earthquake occurring 30km below Tokyo Metropolitan area with magnitude 7.0.

Telephone and Telecommunications

- Seismic upgrade of connection parts

Since connection parts between different structures are weak against earthquakes, installation of flexible joints between conduits and between a pipe and a building, and retrofit of manhole ducts are promoted. Figure 4.4 schematically illustrates those countermeasures.

- Damage detection system for metallic access facilities

This system immediately detects damage to metallic access facilities by macro facility test using test lines, and micro test. An outline of the system is given in Figure 4.5.

- Cable tunnel management system

This system monitors deformation or deterioration of a conduit using optical fiber as a strain sensor, as illustrated in Figure 4.6. The alarm is transmitted when strain exceeds a threshold level.

- Free space medium pipeline
- Seismic performance evaluation system for access underground route
- Geographic information system for shared spatial database
- Damage survey support system
- Structure of medium-size pipe in the liquefiable ground

Water Supply

- Seismic upgrade of reservoir

After the 1995 Kobe Earthquake, Tokyo Metropolitan Government investigated seismic stability of their reservoir in detail, and upgraded the embankment of reservoir based on the results. Figure 4.7 shows a cross section of Yamaguchi Reservoir. Although no functional damage was detected to this reservoir, 1 m settlement of the embankment was predicted at the crest level, and they upgraded the existing embankment.

- Damage detection system for water pipelines

<u>Sewage</u>

- Network of wastewater treatment plants

As one of sewage network systems, network of wastewater treatment plants are being planned. Figure 4.8 shows a conceptual view of network of wastewater treatment plants planned in Kobe City. They aim to establish strong sewage system against earthquakes, connecting treatment plants by deep main pipelines.

- Countermeasures against liquefaction

A series of dynamic centrifugal model tests was conducted at the Public Works Research Institute in order to investigate the effects of characteristics of backfill soil on the stability of sewer pipes against liquefaction-induced uplift (Photo 4.2). Test results show that the uplift displacements of pipes can be reduced by densification of backfill soil even though the backfill soil liquefies. Compaction of the backfill soil is an efficient countermeasure against liquefaction.

<u>Common Utility Duct</u>

- Assessment of uplift due to liquefaction

As a quantitative index to estimate the stability of underground structures against uplift caused by soil liquefaction, the minimum safety factor against uplift was proposed by the Public Works Research Institute. This factor is defined as a ratio of the total weight to the total uplifting force acting on structure. Figure 4.9 presents relationship between the minimum safety factor and uplift displacement, which was obtained by centrifugal model tests. Although further studies are necessary, the minimum safety factor gives an appropriate threshold level regarding uplift phenomena.

- Countermeasures against liquefaction

Among preventive measures against liquefaction including densification, deep soil mixing, gravel drain and sheet pile driving, sheet-piling method is often used especially in urban areas where workspace is limited. Photo 4.3 shows a dynamic centrifugal model test at the Public Works Research Institute to investigate behavior of a common utility duct and sheet piles installed vertically at the sides of duct. Test results indicate that sheet piles reduce uplift displacement of underground structure by suppressing lateral deformation of liquefied soil.

- Seismic isolation

As one of the technology to improve the seismic performance of the underground structures, the seismic isolation technology has been developed. The seismic isolation for underground structures is the system in which a tunnel body is covered by a thin isolation layer consisting of elastic materials with low shear modulus as shown in Figure 4.10. The isolation layer absorbs the strain transmitted from the surrounding soils during large earthquakes so that the seismic performance of underground structures be improved. The Public Works Research Institute has developed this new seismic isolation technology in 1998 and this technology has been applied for a practical construction at the connection of vertical shaft and tunnel of common utility ducts first in the world in 1999.

5. FUTURE COURSE OF RESEARCH AND DEVELOPMENT

We here describe future course of research and development on earthquake disaster prevention for lifeline facilities, in view of their characteristics.

5.1 Characteristics of Lifeline Facilities

Systematic, structural and social characteristics of lifeline facilities are summarized below.

1) Since lifeline facilities form linear or areal network that spreads widely, the amount of facilities is large and the influence of earthquake damage extends to a wide area.
2) Seismic performance of network system is important, in addition to that of individual facility.
3) Most part of lifeline network is constructed underground, and they are affected by soil condition, seismic motion in the ground and ground failure.
4) For the underground facilities, it is difficult to find out earthquake damage and repair it.
5) Network facilities are composed of nodes and links, and their connection parts behave specially during an earthquake.
6) Structure and importance of network are not uniform, but are different by importance and influence to other parts.
7) Lifeline facilities are interdependent.
8) Cost benefit of earthquake countermeasures is to be agreed by consumers.

5.2 Objective of Research and Development, and Technical Problems

Based on the characteristics of lifeline facilities, the following three viewpoints may by deduced, when we establish technical problems on earthquake disaster prevention. We expect these different viewpoints will help to make objective of research and development, and important technical problems clear.

1) Time axis

Earthquake countermeasures are divided into two groups, when an earthquake occurrence is set up as a standard point of time, i.e., pre-earthquake and post-earthquake countermeasures. Seismic design, retrofit and damage prediction belong to the former, and emergency response and restoration belong to the latter. We establish technical problems that correspond to objectives of each stage.

2) Soft- and hard-technology countermeasure

Soft-technology countermeasures include seismic damage prediction system, supply shutoff system, while hard-technology countermeasures include upgrading of structure. We establish technical problems, considering role and mutual complement of these two technologies.

3) Individual function and network function

Gas shutoff by microcomputer and installation of a flexible joint to the connection part of conduits are examples of earthquake countermeasures to secure individual function, and minimizing supply suspension area and damage prediction system are examples to secure network function. We establish technical problems, considering role and mutual complement of these two functions.

5.3 Future Course of Research and Development

The following viewpoints may be important as future course of research and development in earthquake disaster countermeasures for lifeline facilities.

1) Classification of soft- and hard-technologies and cooperation
2) Improvement and development of individual technologies
3) System integration and efficient operation
4) Seismic inspection, retrofit and renewal of existing facilities
5) Cost reduction

6) Invest standard and evaluation of standard
7) Multi-purpose use of lifeline facilities and improvement of their seismic performance
8) Coordination of seismic performance level among various lifeline facilities

6. CONCLUSION

We reviewed in this paper technical problems, current situation and future course of research and development on earthquake disaster countermeasures for lifeline facilities. We regard it is necessary to stand out the objectives of Task Committee activities and develop the ideas presented in the paper into practice.

ACKNOWLEDGMENTS

Valuable information was provided by the members of Task Committee F of the Japan-side Panel on Wind and Seismic Effects, UJNR. The authors would like to express sincere thanks to their cooperation.

Table 2.1 Lifeline Facilities

	Owner	Member of Task Committee
Electric power	Public corporation	Research and Development Center, Tokyo Electric Power Co. Central Research Institute of Electric Power Industry
Gas	Public corporation	Tokyo Gas Co., Ltd.
Telephone	Public corporation	Access Network Service Systems Laboratories, Nippon Telegraph and Telephone Corporation
Water	Local government	Bureau of Water Works, Tokyo Metropolitan Government
Sewage	Local government	Water Quality Control Department National Institute for Land and Infrastructure Management
Common utility duct	Central / Local government Public corporation	Earthquake Disaster Prevention Research Group Public Works Research Institute

Table 3.1 Seismic Design Standards of Lifeline Facilities in Japan

	Standards	Publisher	Issued year
Electric power	Earthquake Disaster Countermeasure Guidelines for Electronic System at Transformer Substation	Japan Electric Association	1999
	Seismic Design Guidelines for Thermal Power Station	Japan Electric Association	1999
Gas	Guidelines for Earthquake Disaster Prevention Countermeasure	Japan Gas Association	1998
	Design Guidelines for Main and Sub Pipes	Japan Gas Association	1999
	Seismic Design Guidelines for High Pressure Gas Pipeline	Japan Gas Association	2000
	Seismic Design Guidelines for High Pressure Gas Pipeline against Liquefaction	Japan Gas Association	to be issued
Telephone	Seismic Design Guidelines for Underground Pipeline Facilities (Draft)	Access Network Service Systems Laboratories, NTT	1999
Water	Seismic Planning Guidelines for Water Supply System (Draft)	Water Supply and Environmental Sanitation Department, Ministry of Health and Welfare	1997
	Seismic Design and Construction Guidelines for Water Supply Facilities	Japan Water Works Association	1997
Sewage	Earthquake Disaster Countermeasure Guidelines and Commentary for Sewage System	Japan Sewage Works Association	1997
	Earthquake Disaster Countermeasure Manual for Sewage System	Japan Sewage Works Association	1997
Common utility duct	Design Guidelines for Common Utility Duct	Japan Road Association	1986 (to be revised)

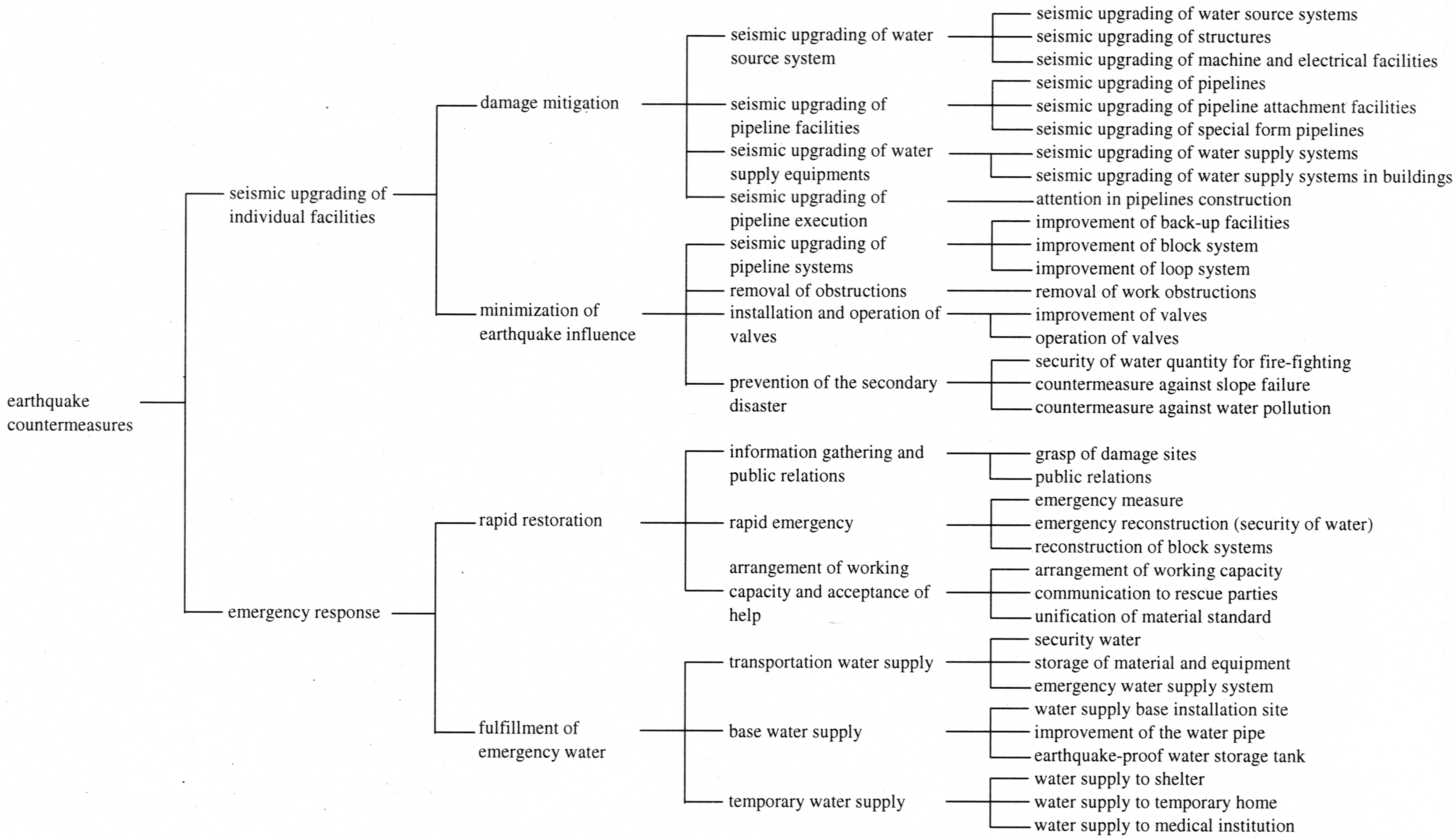


Figure 3.1 Structure of Earthquake Countermeasures for Water Supply System

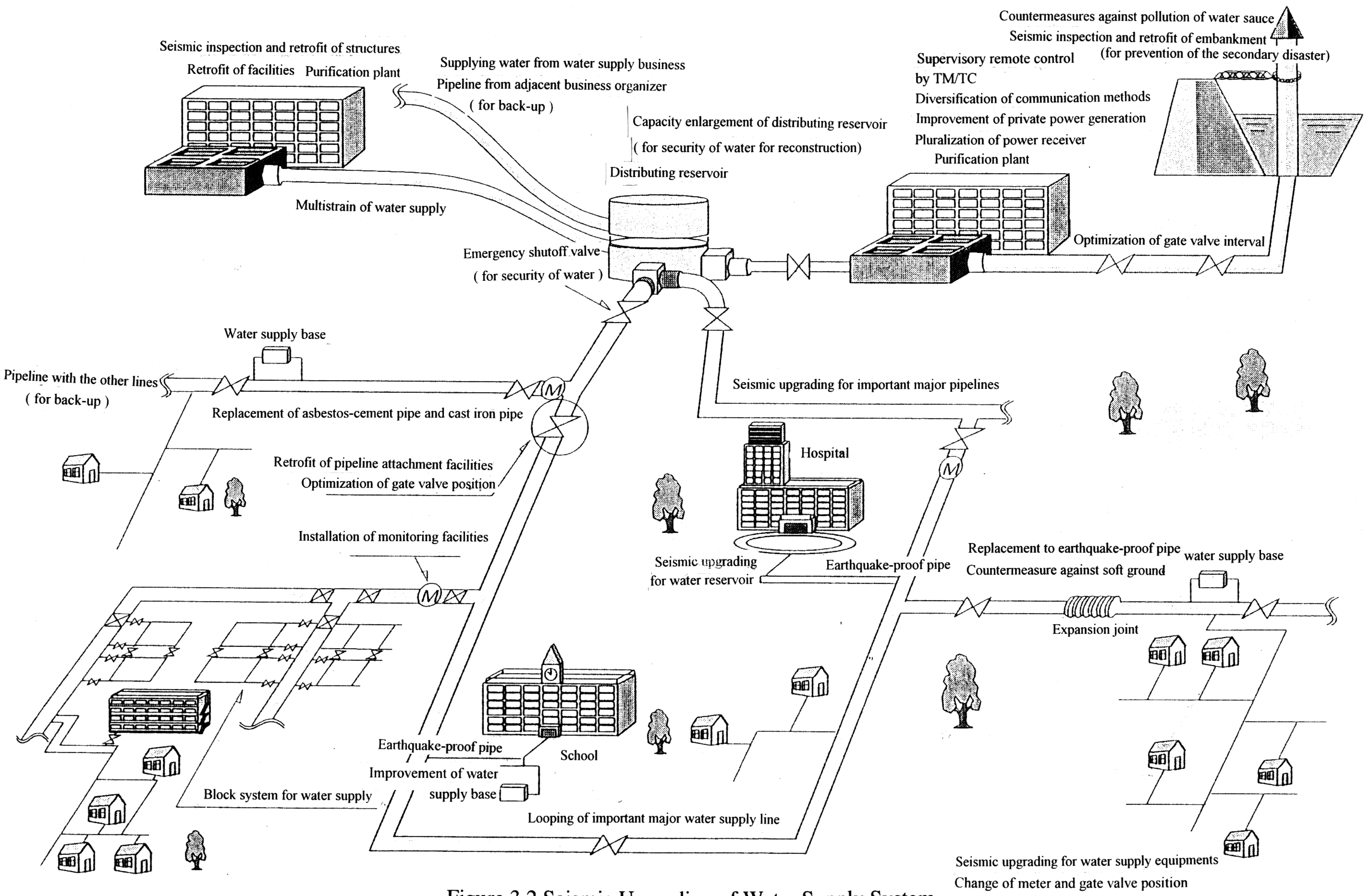


Figure 3.2 Seismic Upgrading of Water Supply System

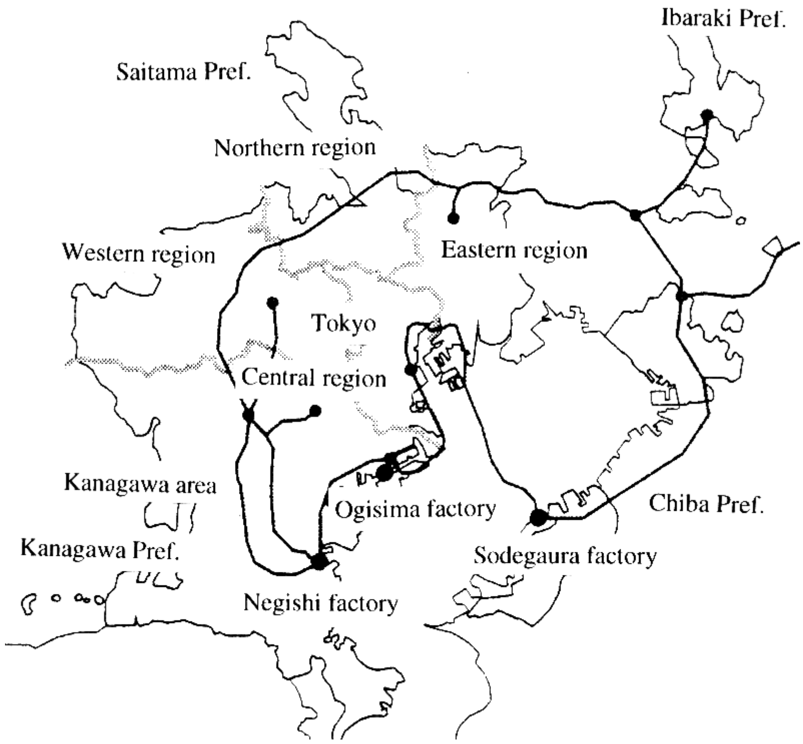


Figure 3.3 Service Area of Tokyo Gas

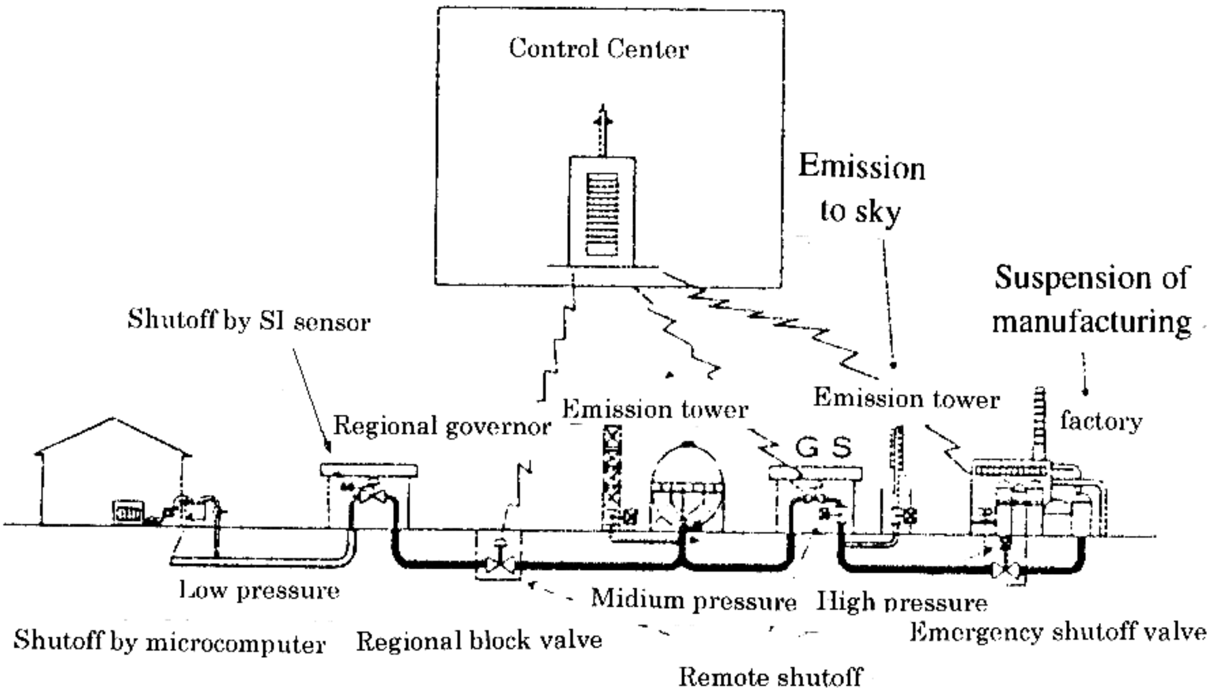


Figure 3.4 Emergency Gas Shutoff System

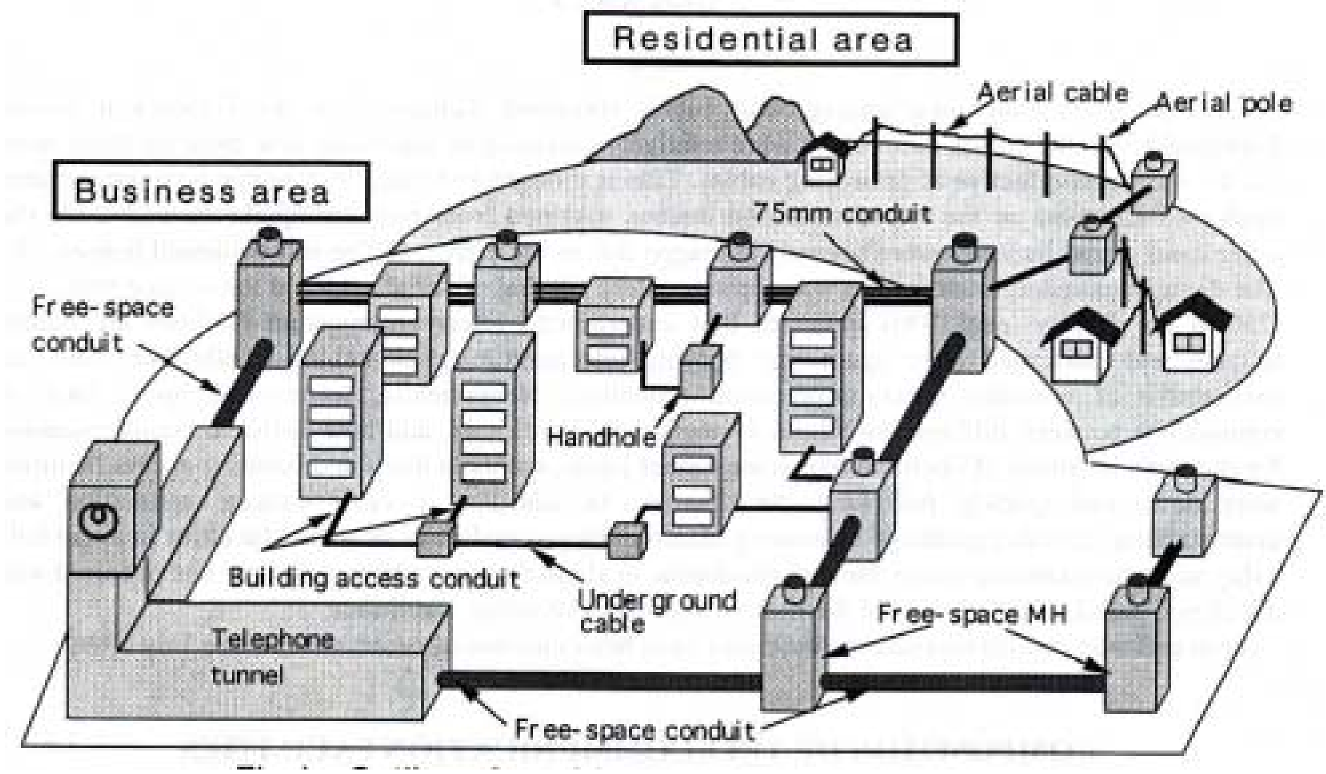


Figure 3.5 Overview of Outside Telecommunication Facilities

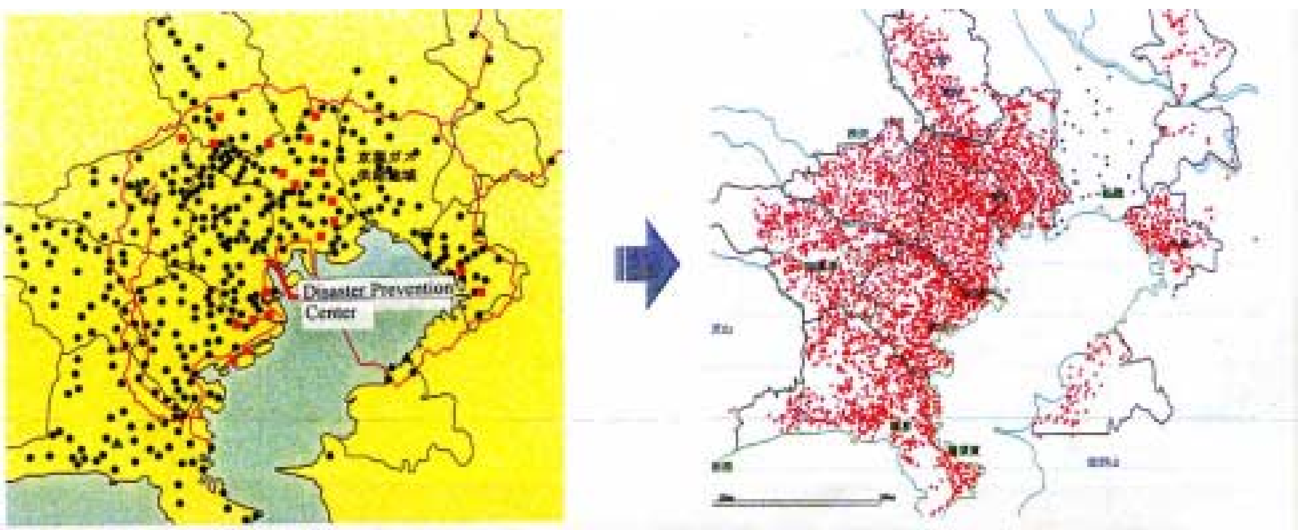


Figure 4.1 Sensor Locations of SIGNAL and SUPREME

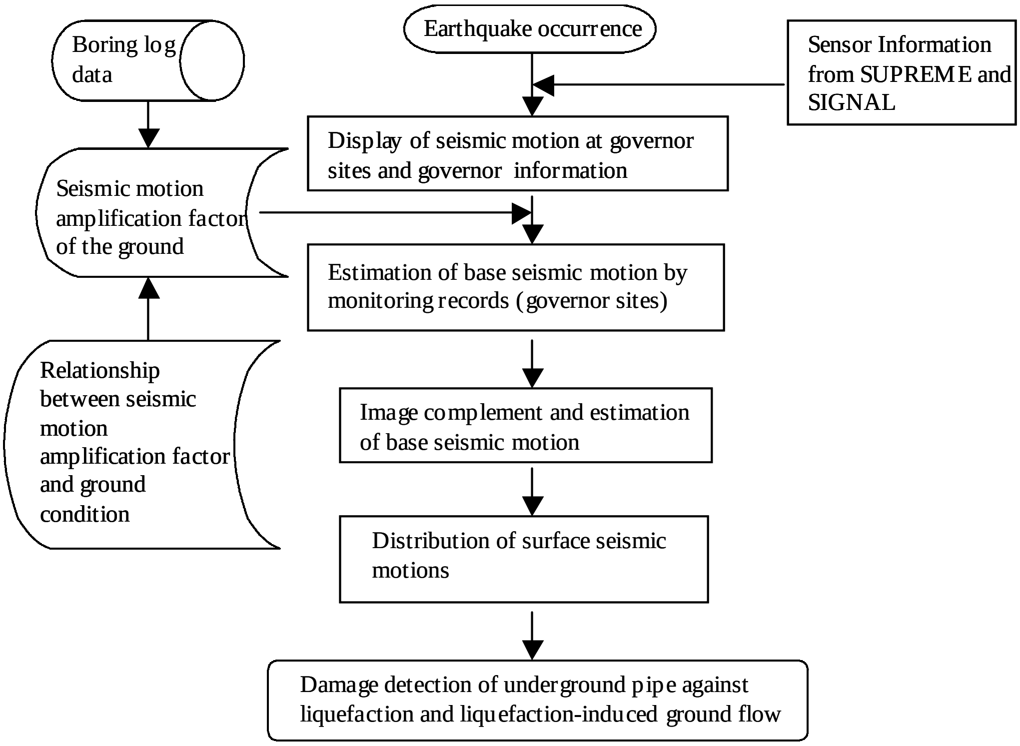


Figure 4.2 Flow of Damage Detection

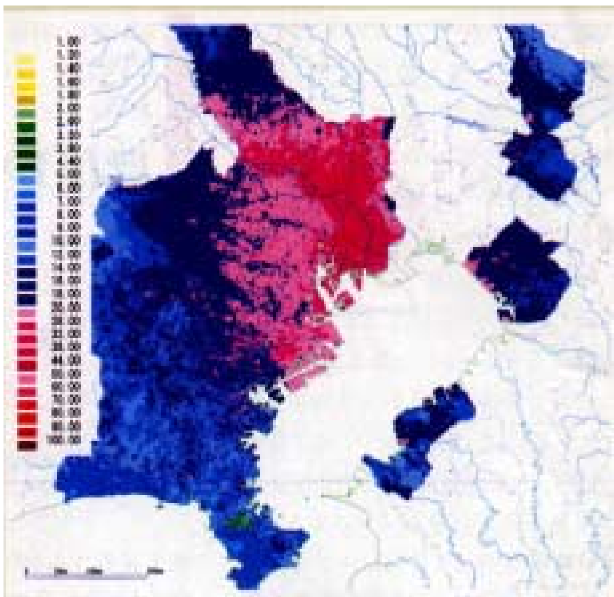


Figure 4.3 Distribution of SI Values by a Scenario Earthquake occurring below Tokyo Metropolitan Area with Magnitude 7.0

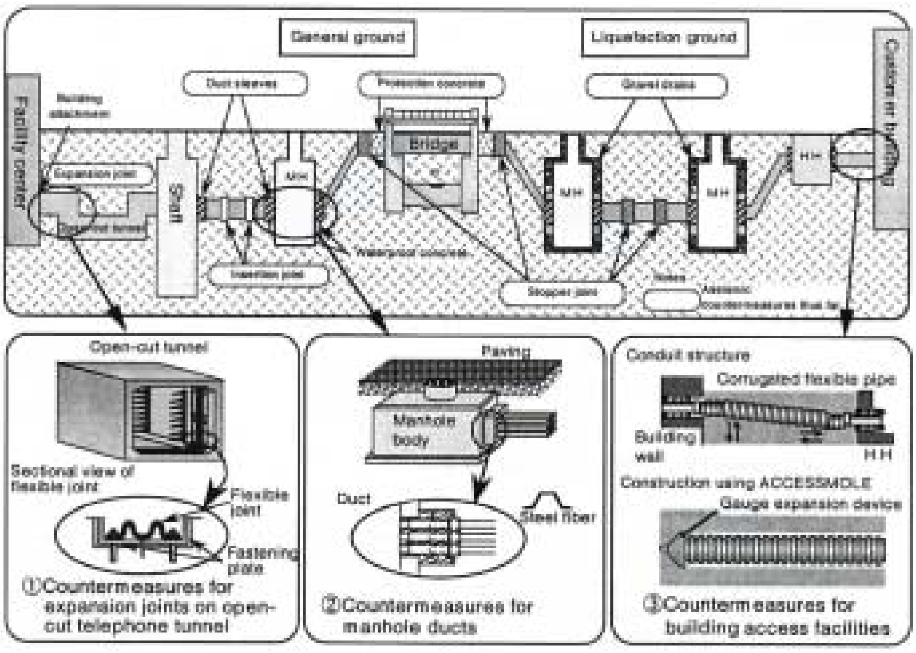


Figure 4.4 Earthquake Countermeasures for Telecommunication Facilities

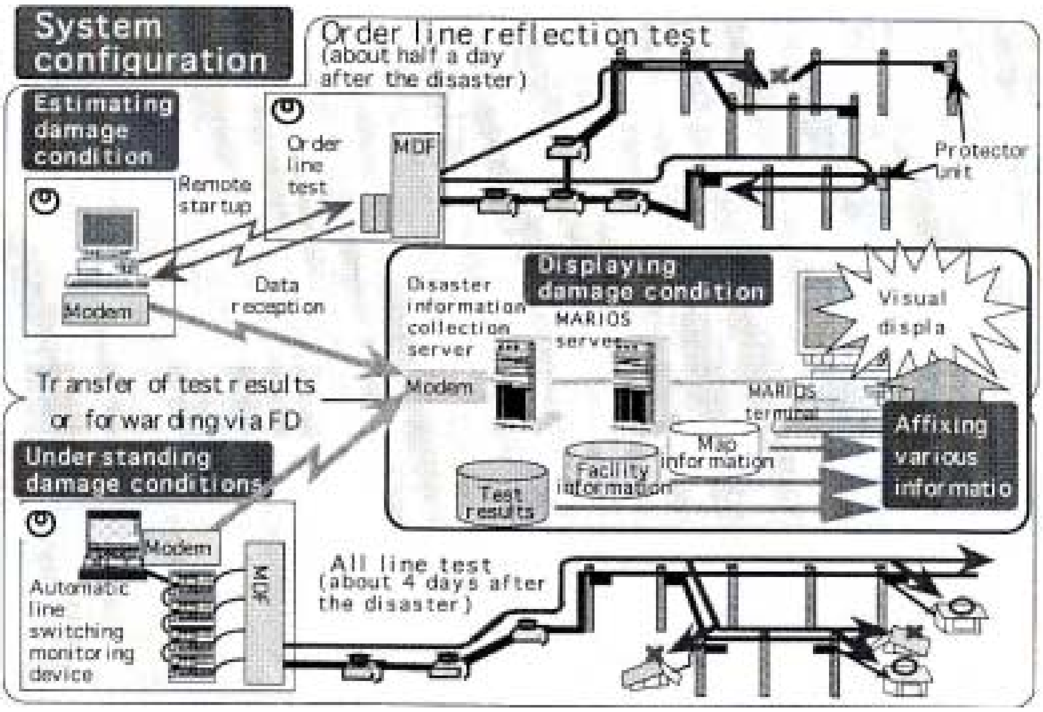


Figure 4.5 Cable Damage Detection System

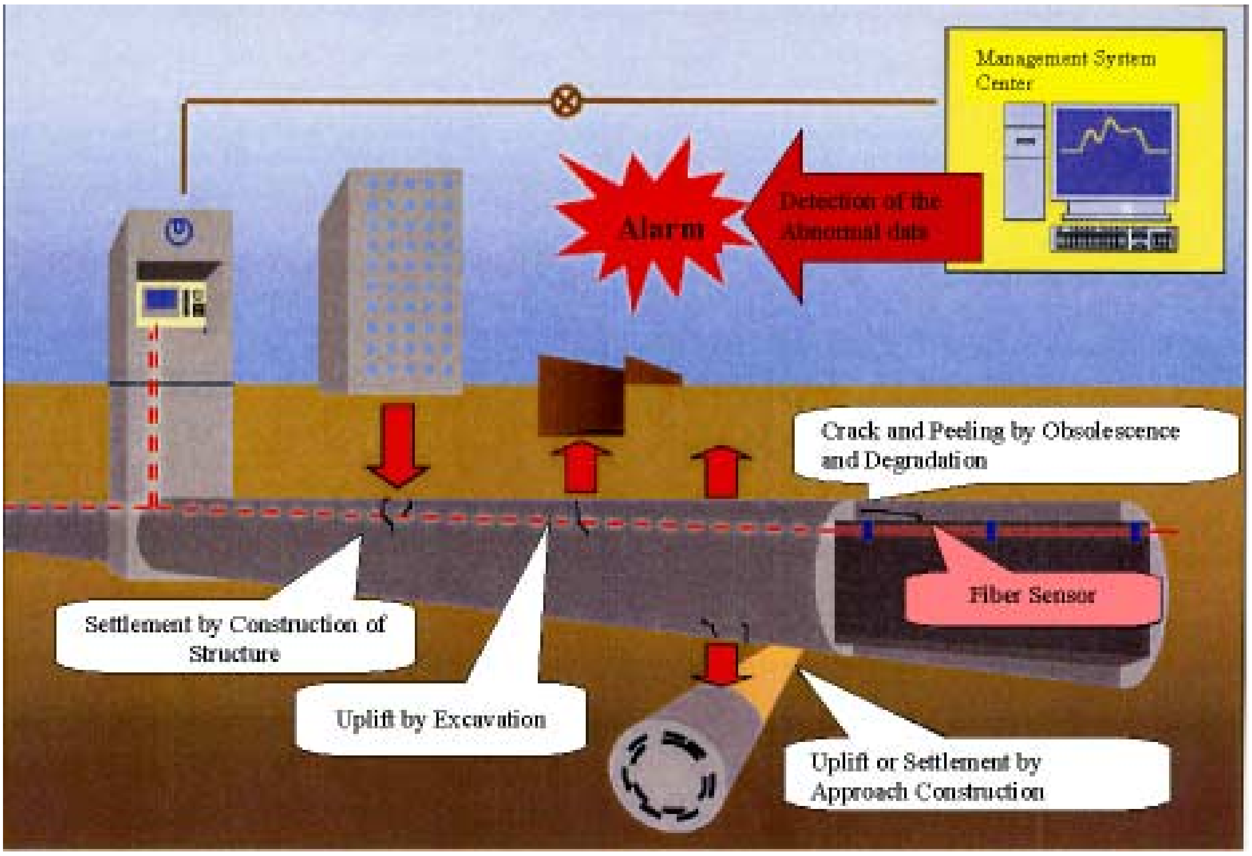


Figure 4.6 Cable Tunnel Management System

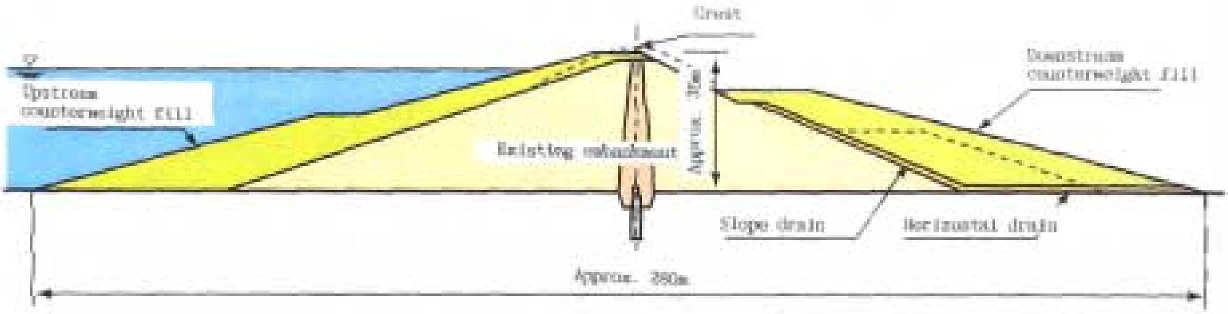


Figure 4.7 Seismic Upgrade of Embankment

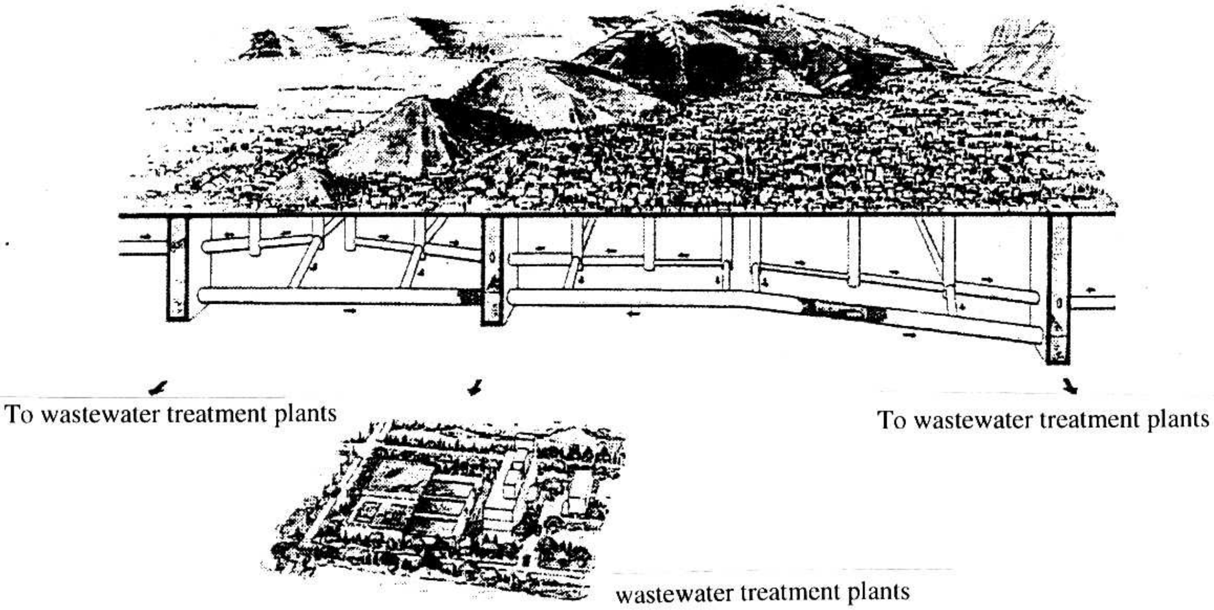


Figure 4.8 Schematic Plan of Network of Wastewater Treatment Pants

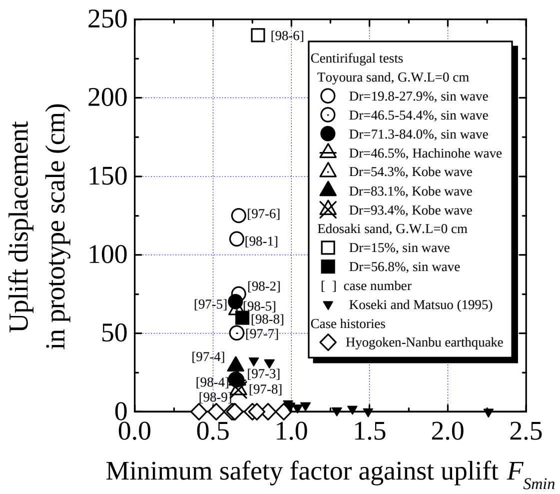
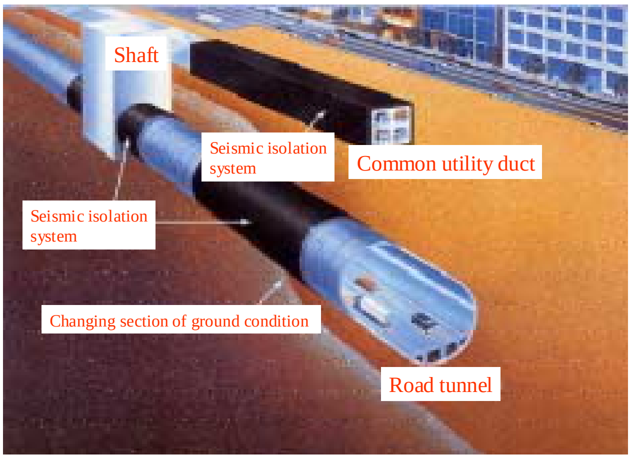


Figure 4.9 Relationship between Minimum Safety Factor and Uplift Displacement



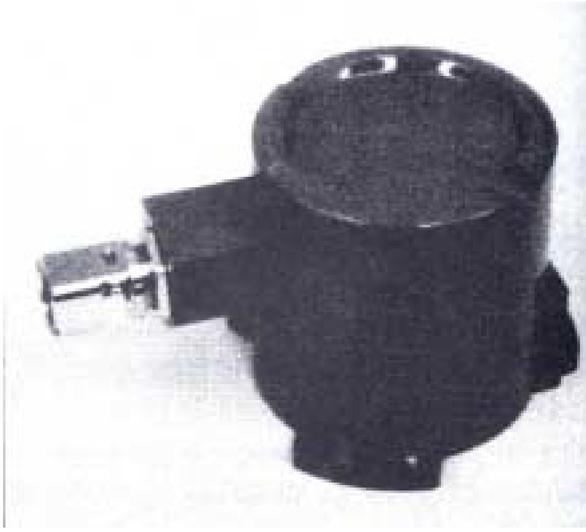


Photo 4.1 New SI Sensor

Photo 4.2 Deformation of a Pipe and Backfill by Dynamic Centrifugal Test

Photo 4.3 Effects of Sheet Piles Reducing Uplift Displacement of Underground Structure