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Recent developments in lifeline earthquake engineering

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ABSTRACT: This paper summarizes the present state of Lifeline Earthquake Engineering (LEE) and points out what we have achieved in the last 20 years, where we are now, what the remaining problems are, and which direction we should take in the future. The beginnings of LEE are briefly reviewed. The importance of damage assessment in LEE is described with respect to physical damage, effects of soil, and network vulnerability analysis. It is emphasized that preparation is key to LEE and that ongoing/co-event response will become important for a large lifeline network. It is concluded that LEE is a highly interdisciplinary field and that lifelines should be understood as a catalyst which transforms many different problems in a large city into an integrated urban safety issue.

1 WHAT ARE THE LIFELINES?

When preparing this state-of-the-art report, I reviewed one of the pioneering papers on this subject by Duke and Moran (1975), which I had not read for many years. They wrote in 1975, "The lifelines of cities may be classified as: Energy (Electricity, Gas, Liquid Fuel), Water (Potable Flood, Sewage and Solid Waste), Transportation (Highway Railway, Airport, Harbor), and Communication (Telephone and Telegraph, Radio and Television, Mail and Press). In general, each of these is a network within which there are sources, major transmission lines, storage, and a distribution or collection system. They are public utilities. Each has a terminus outside the city and an extensive matrix of contact or distribution points inside."

In his recent state-of-the-art report, W.J. Hall (1991) states, "Within a broad definition lifelines can be defined as those utilities, facilities, structures and equipment that make up much, but not all, of the fabric of our infrastructure, whether it be in a rural or urban setting. The field of lifeline earthquake engineering can be subdivided generally into the subject areas listed in the following: Electric Power and Communications, Gas and Liquid Fuels, Transportation, Water and Sewage." Hall continues, "In addition there are other important aspects of study and concern surrounding the field of lifeline earthquake engineering, and in most respects these are of equal importance. A limited list of these topics includes the following: Seismic Risk; Political, Economic, and Social Issues; Legal and Regulatory Issues; Engineering and Medical Services; Education."

In examining the future of lifeline earthquake engineering in New Zealand, D.C. Hopkins (1991) asks himself, "Does it (=lifeline) include building services, and even buildings themselves? Does it (=lifeline earthquake engineering) include parts of disaster response planning? Is it purely a technical subject, or does it involve management?" Then, he answers himself, "I believe that physically it should be any engineered system which we rely on and which is of vital importance in sustaining the physical and economic life of a community. The subject must include consideration of all factors which can affect the performance of a life supporting service in the event of earthquake."

I am sure that Martin Duke did also foresee that the field of lifeline earthquake engineering would enormously expand from what was known at that time, as it has in the last 20 years. It is, therefore, impossible for me to treat all the aspects of what we call "Lifeline Earthquake Engineering" today. In this state-of-the-art report, I will try to summarize the problems, which I consider pivotal in the near future, based on my limited experiences in the said field. Many of the points I am going to discuss are taken from two of my recent papers published last year (Katayama 1991a; Katayama 1991b).

2 BEGINNINGS OF LIFELINE EARTHQUAKE ENGINEERING

To my best knowledge, we owe the name "Lifeline Earthquake Engineering" to the late Professor Martin Duke, who served as founding chairman of the ASCE's TCLEE (=Technical Council on Lifeline Earthquake Engineering) established in 1974.

Professor Martin Duke had written in summary papers that lifelines of various types are subjected to damage in the same manner as buildings. He was acutely aware of the vital importance of lifelines to the personal well-being of the public as well as to the sustenance of infrastructures required by modern society. The occurrence of the 1971 San Fernando earthquake in the Los Angeles area, however, provided him the final motivation to work in earnest in the field of lifeline earthquake engineering (Hall 1991).

Research needs for earthquake effects on some of the utility systems in a large city were also becoming recognized in the late 60's in Japan, following the considerable advancement in the earthquake resistance of conventional civil and building structures. We were asked in the early 70's by the Tokyo Metropolitan Government to assess the damage to the buried pipelines assuming a recurrence of the 1923 Kanto earthquake. Soon after having started the work, we found that basic data were appallingly lacking. Data on pipeline damage during past earthquakes had not been collected nor well summarized.

Therefore, the lessons from the San Fernando earthquake were seriously considered by the concerned people in Japan.

The first academic meeting on lifeline earthquake engineering seems to be the Japan-US Seminar held in Tokyo in November, 1976. It may be interesting to note that the coeditors of the Proceedings (Kubo & Jennings 1976) mentioned in its Foreword, "Although the area of research is relatively new, the subject is very broad in its technical content as implied by the somewhat unusual title of lifeline earthquake engineering."

On June 12, 1978, a magnitude 7.4 earthquake occurred in the northern part of the main island of Japan, at a point about 100 km east of Sendai with some 640,000 population. About 1,400 houses, or 0.6% of the houses in Sendai, were destroyed. The damage was far from devastating. However, it became the first occasion in which lifeline behaviors during and after an earthquake were studied in depth. We investigated how the system was being operated before the earthquake, how its components were damaged during the earthquake, what kind of impairment took place and how the system was restored after the earthquake (Katayama 1980).

More than 20 years have passed since the San Fernando earthquake. Martin Duke wrote in 1975, "The present state-of-the-art of earthquake engineering for buildings has taken 40 years since the Long Beach earthquake to evolve. It may be evaluated today as fair to good. A comparable state-of-the-art for lifelines should be accomplished for the United States within 20 years after the San Fernando earthquake, and within 10 years for the more seismic states." Of course, I am quoting this not only for the U.S. people but also for all the scientists and engineers involved with lifeline earthquake engineering.

Have we achieved the goal?

The answer is mixed. Yes, we have better lifelines being built in these days. Yes, we have much more academicians and engineers who are working for the advancement of earthquake resistance of lifeline systems. No, remember the damages to the Bay Bridge and the elevated highway in Oakland during the 1989 Loma Prieta earthquake. No, utilities in large cities in Japan are not at all confident of their systems if they were to be subjected to strong and widespread tremors.

Even 20 years ago, large cities were dependent upon complex systems of lifelines for their day-to-day activities. The only thing Martin Duke underestimated was the huge amount of then existing lifelines whose upgrading is a formidable task. (Probably he did not want to discourage people at the starting point.)

Where are we now? What are the remaining problems?

3 DAMAGE ASSESSMENT

After Niigata was badly damaged in 1964 without almost any preparedness, many jurisdictions in Japan began to perform damage assessment studies. The most comprehensive of such earlier assessments was made for metropolitan Tokyo by assuming a recurrence of the 1923 Kanto earthquake. The report published in 1978, however, did not contain much about lifeline damage. The Tokyo Metropolitan Government has redone the assessment, as a 5-year project beginning in 1986, by taking into account recent methodologies and data. The project was carried out under nine subcommittees; ground motion & soil, buildings, transportation facilities, lifelines, hazardous materials, fire, casualties, socioeconomic problems, and damage on the islands.

The Lifeline Subcommittee dealt with the assessments of physical damage, associated impairment, and restoration of the five lifeline systems; water supply, city gas, power, telecommunications, and sewage disposal systems.

3.1 *Physical damage*

A lifeline is laid out in a network over a large area and the major component of the network in many cases is buried pipes. Hence, pipe failures play an important role in systemic impairment. However, knowledge on physical seismic vulnerability of buried pipes is insufficient at present. There are a great variety of types of pipes and their seismic damage is strongly affected by subsoil conditions which are also extremely variable.

Situations differ in different countries. Even in one country, qualities of buried pipes are different in different cities or in different utilities. Let us take Japan as an example. Japan experienced rapid and large-scale urbanization during the 60's and a huge number of pipelines were laid. Therefore, generally speaking, Japanese pipelines are not very old. Because Japan often experiences damaging earthquakes, existing key facilities have been retrofitted or replaced in many cases. At the same time, however, in order to catch up with the speed of urbanization, some substandard materials were used particularly for pipelines. For example, about 20% of existing water pipes, mostly in small to medium jurisdictions, are asbestos-cement pipes which are known to be vulnerable to seismic damage.

Lessons have been learned from past earthquakes. We now know that arc-welded steel pipes perform well during an earthquake. The screw joints in small-sized steel pipes are extremely vulnerable to seismic-induced cracks and breaks and cast iron fittings often show brittle-type failures under earthquake disturbance.

A lifeline does not consist of buried pipelines alone. It is an integrated system of many different types of structures, facilities and equipment. Assessment of their seismic strength, especially that of existing ones, is difficult. The lack of reliable quantitative information on component failures results in the lack of reliability of the systemic analysis of a lifeline network.

3.2 *Effects of soil on seismic damage of lifelines*

A number of past earthquakes have clearly indicated that seismic vulnerability of lifeline systems is highly dependent on ground failure hazards. The characteristics of subsoils are more important for most of the lineal lifelines than for buildings. The lineal nature of lifelines makes it important to take into account the differences in ground deformation over a short distance produced by permanent soil displacement or traveling seismic waves.

Many researchers have pointed out, based either on damage observation or analytical study, that the local inhomogeneity of subsoil conditions may be of importance for the seismic response of buried pipelines. Such inhomogeneity arises in the transition zone between firm and soft soils or in the area where the depth of the soft surficial soil layer abruptly changes over a short distance.

From the study on the damage to water pipes in Tokyo during the 1923 Kanto earthquake, Okamoto (1984) concluded that, although damage was generally greater in the lower (eastern) areas than in the higher (western) areas, the heaviest damage to buried pipelines seems to have taken place in the transition zone between the western highland and the eastern lowland. The transition zone is characterized by extremely intricate distribution of soil conditions, which resulted in uneven ground motions.

The utility pipe damage during the 1978 Miyagi-ken-oki earthquake has been well documented. The damage rates of gas pipes in Sendai were compared in different geological conditions. Most of the small-sized pipe failures occurred in the newly developed residential areas. In these cut-and-fill areas and on the alluvial plain, the damage rate was 3 to 4 times greater than that in the terrace area. Because of the instability of artificial slopes, insufficient densification of fills, and abrupt change in subsurface soil properties between cut and fill, strong motion easily produces fissures, local settlement, slippage and relative displacement over short distances. The resulting permanent deformation within the soil near the ground surface caused the high damage rate near the cut-and-fill boundary.

However, the severest hazard for a buried pipeline occurs when underlying soils liquefy causing large permanent horizontal movement in surficial materials. This phenomenon is called "Lateral Spreading." The seismic-induced liquefaction became the object of close scrutiny only after the Niigata and the Alaska earthquakes, both of which occurred in 1964.

The devastating effect of liquefaction on buried pipelines was first recognized in Japan after the 1964 Niigata earthquake. Widespread liquefaction caused extremely heavy damage to minor distribution pipes, both water and gas, in Niigata. Liquefaction-induced permanent displacement was also the major cause of the damage sustained by transmission pipelines of natural gas during the 1971 San Fernando earthquake.

Evoked by the Niigata and the San Fernando experiences, the relationship between pipeline damage in San Francisco during the 1906 earthquake and the subsurface conditions was studied (O'Rourke et al. 1985). Water main breaks were superimposed on previous marshes, estuaries, and bay areas. The close relationship between pipeline breaks and previous topography was evident. Many of the pipeline breaks were found to have occurred in the zones where differential soil displacements are likely to be severest. It was found that 52% of all water main breaks in the city took place in the zones of lateral spreading, which accounted for only 5% of the built-up area affected by strong ground shaking.

Then, the Nihon-kai-chubu (Central Part of the Japan Sea) earthquake occurred in 1983, which gave a rare opportunity to quantitatively investigate the amount of lateral spreading associated with liquefaction. Aerial photographs taken before and after the earthquake were used and permanent displacement of as much as 5 m was found to have taken place along the gentle slopes of sand dunes with gradients less than 5% (Hamada 1989).

Damage observed for the 1989 Loma Prieta earthquake was also strongly influenced by local soil conditions (Earthquake Engineering Research Institute 1990). A majority of shaking-induced structural damage in the San Francisco and Oakland areas occurred on the deep clay sites, where ground motion amplification was great. In the Marina district, where loose, sandy hydraulic-fill soils are underlain by deep clay deposits, this amplification is believed to have contributed to the liquefaction. Liquefaction is considered to have contributed to the generation of lateral ground deformations. In this small area, there were more than four times the number of repairs in the entire water system outside of it.

It should be noted that liquefaction becomes a serious problem only when it leads to some form of permanent ground movement or ground failure. As far as buried pipeline damage is concerned, the single most common cause is lateral spreading. Unfortunately, estimation of the amount of movement associated with lateral spreading, which generally takes place even on the gentlest of slopes, is extremely difficult.

At present, empirical evidences from previous earthquakes and well documented case histories seem to provide the soundest basis for estimating the movements likely to occur during liquefaction failures. Significant data can be gained from a careful review of past earthquake records of soil and structural behavior interpreted in the light of current geotechnical engineering knowledge. In recent years, a great deal of effort has been made mostly by the earthquake and soils engineers in Japan and USA, to collect and analyze, in depth and quantitatively, case histories of liquefaction and liquefaction-related lifeline damage (Hamada & O'Rourke 1992).

Information such as those described above is undoubtedly useful to understand how and where the ground movements are likely to occur. As of today, however, there is only a very limited amount of quantitative and practical knowledge which can be used for the estimation of damage by future earthquakes.

We should not be too pessimistic. Maps showing previous topography and subsurface structure help to identify the factors that control ground movements. Mapping in this fashion can locate zones of lateral spreading and help characterize the relative severity of permanent ground deformations (O'Rourke et al. 1985).

Let us summarize some of the practical knowhow. Although they are qualitative, they may be helpful.

The following are several lessons learned from the 1971 San Fernando earthquake (O'Rourke & Tawfik 1983):

(1) Pipelines crossing alluvial fans, especially near the margins of water bodies, are vulnerable to lateral spreading.
(2) To the extent possible, pipelines in the area of potential lateral spreading should be constructed without bends, elbows, tie-ins, and slip joints that promote eccentricity and increase the risk of buckling and plastic wrinkling.
(3) Pipelines should be oriented to avoid large compressive movements. Pipelines crossing the toe area of slopes are particularly vulnerable to compression.

If seismic risk zoning were to be made for buried pipes with special emphasis on liquefaction-induced lateral spreading, at least the following five site conditions should be considered:

(1) Are the soils liquefiable?
(2) How thick are the liquefiable soils?
(3) Is the ground surface (mildly) sloped?
(4) Is the surface of the layer underlying the liquefiable soils sloped?
(5) Is the slope open-ended?

3.3 *Network vulnerability*

Lifelines are laid in a large area and usually form networks consisting of a large number of different components. Being a network can be both an advantage and a disadvantage for lifelines.

The seismic vulnerability of an isolated or geographically localized facility like a building is dependent on the seismic hazard at the site where the facility is located. Therefore, the structural strength should be increased if the site has unfavorable conditions. Risk analysis for a lifeline, on the other hand, is characterized by its redundancy. At least theoretically, a more robust lifeline system can be constructed by incorporating sufficient network redundancy.

In the case of buildings, collapse of one building does not usually affect the behaviors of surrounding buildings. Seldom does a lifeline fail in the sense that a building collapses and becomes a total loss. However, even a single break of pipe may affect the overall behavior of a lifeline system. Lifeline failure is the inability or impairment or the loss of operation effectiveness, at some level of probability, to provide some minimum level of service deemed essential to the welfare of the community (Whitman & Hein 1977).

Individual assessment of the earthquake vulnerability of a facility at a particular site is also necessary for lifeline systems. Take a water system as an example. Individual vulnerability assessment is needed for dams, pumping stations, and treatment facilities. At least, the principles of risk analysis for isolated facilities are well established.

When we were asked to do the seismic damage assessment study of the water system in Tokyo in the early 70's, we had to rely heavily upon the pipe failure data of the 1923 Kanto earthquake (Katayama et al. 1975). By considering soil condition, pipe material and size, and buried depth, and by using the lengths of different kinds of pipes, the number of pipe failures in each of the 1km x 1km cells was estimated, the numbers were added up for a ward ("ku" in Japanese) and then for the whole metropolitan Tokyo. The study seems to have been one of the earliest of this kind and gave some impact to the more concerned jurisdictions and utilities in Japan.

The water utility people of Tokyo were not satisfied with the results. They wanted to know where the failures would occur. We persuaded them that this kind of problem is necessarily probabilistic, but at the same time, we knew that if we were to approach the problem probabilistically, we have to take into account the network redundancy and analyze the inability of operations caused by the physical pipe failures.

Occurrence of an earthquake is uncertain, if not probabilistic. Its size and location are uncertain, and a unique damage state cannot be determined for a network even if a seismic hazard environment is defined. The effects of the damage to network performance are necessarily probabilistic. Hence, simulation studies have often been performed for network vulnerability analysis.

Pioneering studies on the seismic vulnerability of lifeline networks were initiated by a group of MIT researchers (Whitman & Hein 1977) and by Shinozuka and his colleagues (Shinozuka et al. 1981). We did the earliest of such studies in Japan for the water network in the Tokyo metropolitan area (Isoyama & Katayama 1981; Isoyama & Katayama 1982). We incorporated in the Monte Carlo simulation study as much empirical data on pipe failures and soil effects as we could collect from past earthquakes in Japan. The network performance was evaluated for each of the 500 simulated patterns of pipeline failures. Areas with different degrees of serviceability were identified and plotted on a map.

Since then, there have been a great number of seismic impairment analyses on lifelines. A variety of analytical methods were employed, including some refined and sophisticated ones. However, there seems to be no significant differences as far as their purposes and results are concerned.

This kind of probabilistic output, however, does not seem to be very appealing to the practicing engineers, who usually want the locations of physical failures pinpointed. I believe it is essential for the people in the research sector to direct the attention of utility people to the importance of reliability-based vulnerability analysis of a spatially distributed network. At the same time, however, we have to face the hard fact that the numbers we get from such network analyses today do not have much importance. All that is meaningful is the relative levels of the vulnerabilities in the area covered by the network.

4 PREPAREDNESS - A KEY IN LIFELINE EARTHQUAKE ENGINEERING

The 1964 Niigata earthquake attacked the citizens as well as the lifelines of Niigata which had almost no predisaster planning nor preparedness. There had not been any damage assessment. At the time of the 1978 Miyagi-ken-oki earthquake, the city gas utility of Sendai Municipality did not have any established strategies for service shutoff, damage survey, and efficient recovery. It was strongly realized that shutoff of a city gas system in a large service area entails extremely tedious and time-consuming restoration work even when the general damage level is moderate.

In short, "Assess (damage beforehand), be prepared (for disaster), and restore (the system as soon as possible)" may be a guiding principle of lifeline earthquake engineering. This is quite different from that of building earthquake engineering, which may be summarized as "Analyze, design, and build" according to the best knowledge available today. It is implicitly understood in lifeline earthquake engineering that a system will be impaired even under a moderate level of ground motions.

One can be prepared by improving components and systems. Earthquake-resistive capabilities of components can be upgraded. Electric power and telecommunication lines to critical facilities may be supplied via two independent routes, or standby generators may be installed.

We cannot perform efficient restoration unless we know the system during ordinary times. Things we should know are, for example:

(1) Subsoil conditions of the service area, including where we have vulnerable soils,
(2) The kinds of pipes and other facilities in the service area, i.e., where we have older or substandard pipes,
(3) Where we have chronic problems of corrosion,
(4) Which pipes show higher rates of leaks and incidents.

If the service area of a lifeline is zoned according to the liquefaction potential and the geomorphological setting including the inhomogeneity in subsoil conditions, the utility may be prepared for most possible locations of failures during strong earthquakes. If this kind of information is mapped over a large region covering the essential network, the planning of various preparedness measures can be greatly facilitated. Appropriate form of such mapping will also allow rapid scenario analysis, which should become crucial during the period immediately following a damaging earthquake.

Construction of databases and maps, and their integrated use for systematized maintenance and renewal program, and disaster preparedness seem to be essential. In this respect, Geographical Information System (=GIS) will become a strong tool for damage assessment and preparedness activities in the near future. Large utilities can do these things by developing computerized mapping systems and facilities/customers databases. However, such a modern method is not available everywhere. I would like to emphasize, however, that a map of a service area showing several subzones according to descriptive land patterns alone is extremely informative for experienced engineers.

The importance of human and organizational factors in preparedness must be emphasized.

Although there are many reports on the structural damage caused by previous earthquakes, until recently very little study had been made on the emergency responses and the restoration processes following damaging earthquakes (Katayama 1983). Human and organizational behaviors during a disaster can be obtained only from real experiences. Based on the results of in-depth analyses of what happened during previous disasters, it is possible to make human resources prepared for what they will have to expect in a coming disaster. The importance of the studies on nonstructural aspects of lifelines during the disaster period has to be more widely recognized. I believe that this kind of information will make non-engineers in utilities more interested in the earthquake problems of lifelines.

5 ONGOING RESPONSE/CO-EVENT RESPONSE

As often mentioned, many lifeline systems have become extremely large and complex as a result of urbanization. The modern society has become much more strongly and sensitively dependent on lifeline systems, and their disruptions will produce greater and more widespread impacts on the personal and industrial activities in the affected area. Supply interruptions, even on the ground of safety or for precautionary purposes, must be minimized, and the systems must be restored in the shortest possible time.

On the other hand, recent advances in technologies of ground-motion measurement, signal transmission, micro-computers and system control are really remarkable. Low-cost, high-performance and compact seismographs are becoming available. They may be placed in large numbers in the service area of a large lifeline system. If buildings can become intelligent, so can an area.

The conventional zoning has been a pre-event zoning and the conventional disaster response has been a post-event response. However, the recent technological advances have made it possible to incorporate co-event or ongoing disaster mitigation measures in a large lifeline system.

Such a high-tech based system is being developed by a Japanese gas company (Katayama et al. 1991). Micro-computer aided automatic shutoff valves are being installed at all the customers' premises. These valves automatically close the gas supply to each household when leak or strong seismic motion is detected. However, this alone is not sufficient. Areas with heavy and widespread damages should be identified, because these areas must be isolated to prevent secondary disasters including fires and explosions.

Decisions on the conservative side are not always optimal, because such an isolation causes inconveniences to many customers and it often takes a long time before the system is restored once a large service area is isolated. Therefore, well-founded damage estimation is essential.

For this purpose, a total of 330 ground-motion sensors are being installed in the service area of 2,600 square kilometers. Ground-motion severity indices will be telemetered to a control center. Observed ground-motion properties will be used, together with damage data of previous earthquakes and information on subsoil and facilities stored in a computer as databases, to identify area(s) to which supply should be discontinued.

Since lifeline earthquake engineering assumes occurrences of damages and system impairment, the estimate of the duration of supply interruption is as important as the estimate of damage and impairment. In the recent damage estimate of the lifelines in Tokyo metropolitan area, such restoration estimate was obtained by taking into account the number of physical failures of pipes, the amount of manpower available, the priority for restoration among districts, and the restoration efficiency, the last of which was determined from previous earthquake experiences. The output of such studies can be integrated into the socioeconomic scenarios of the events during the disaster period.

6 LIFELINES AS A CATALYST FOR URBAN SAFETY

As urbanization is taking place in many of the earthquake-prone countries and as day-to-day activities in cities are becoming more and more heavily dependent on large and complex systems of utilities, it is becoming increasingly important for a city to be equipped with robust lifeline networks which do not fail during strong ground motion.

A lifeline is a lifeline in ordinary times. In a metropolitan area there are many lifeline facilities and thousands of kilometers of pipelines which have been in use for more than several tens of years. As long as they function, people take it for granted. But as soon as they are laid, they begin to decay and cause troubles, often a big one, to our daily activities. We should realize that the safety during disaster is on the direct extension of the reliability during everyday use. The daily reliability itself is the best countermeasure in emergencies including earthquake disasters.

However, most users of lifelines pay little attention to how much reliability margin there is behind the apparently normal operation of a lifeline system. For a user of a telephone, it does not make any difference whether his call is connected with ample reliability or not, as far as his call is successfully connected.

In addition, it is extremely difficult in most of the real cases to take effective measures to improve the present state of lifelines which have already been in operation. What utilities can only do is to replace seismically weak facilities or to improve network redundancy according to planned maintenance programs.

The earthquake research and practice for lifeline systems require a broad effort from many different sectors existing in a city. They may be practicing engineers, people from jurisdictions and utilities, city planners, lawyers, economists, social scientists, and so on. Their mutual understanding is extremely important. In such a situation, the role of academicians seems catalytic in nature - to bring in needed ingredients and direct their apparently diversified interests to the best practical solution.

In short, the emphasis in earthquake engineering is shifting from the problems of each individual structure to those of lifelines, which require a broader areal scope of urban seismic disaster mitigation measures. However, earthquake engineering in the past had been dominated by structural engineers, who were hesitant about taking this responsibility. Urban planners also hesitated to take it because they do not have enough knowledge on the hardwares of lifeline systems.

Lifeline earthquake engineering today is, in essence, a highly interdisciplinary field, which may be defined as an integrated field of social safety sciences. It is difficult to isolate the problem of seismic safety as such from the daily reliability of lifeline systems. Rather, lifelines should be understood as a catalyst which transforms many different problems in a large city into an integrated urban safety issue.

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