Paper No. 1902. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

SOME ASPECTS OF PRIORITIZATION FOR REHABILITATION OF BURIED LIFELINES

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ABSTRACT

Buried water, sewer and gas pipelines have been damaged heavily by recent earthquakes, including the Northridge Earthquake of January 17, 1994 in the United States and the most recent Hyogo-ken Nanbu (Kobe) earthquake of January 17, 1995 in Japan. Many existing water, sewer and gas pipelines have been built several decades ago without seismic considerations. They are unsafe even under moderate earthquakes. The improvement of earthquake resistance of buried pipelines is urgently needed in earthquake prone areas. With proper rehabilitation, sever earthquake damage to buried pipelines can be mitigated.

Seismic rehabilitation or retrofit is a cost-effective way to prevent pipeline damage caused by future earthquakes. In general, it is very difficult, if not impossible, to rehabilitate all buried pipelines at the same time because of limited funds and time available. The purpose of this study is to establish a priority strategy for rehabilitation of buried pipelines considering several important factors such as pipeline damage probability, rehabilitation cost, rehabilitation rate (e.g. km/day), pipeline importance and total funds available. The paper provides a rehabilitation scheme for rehabilitation of pipelines considering both technical and economical issues. In addition, the actions and steps taken to retrofit the lifeline systems in general and buried lifelines in specific will be discussed.

KEYWORDS

Buried pipelines; earthquake damage to buried pipelines; lifeline earthquake engineering; pipeline damage probability model; pipeline damage statistics; pipeline rehabilitation schemes; prioritization for rehabilitation of buried pipelines; water and sewer lifelines.

INTRODUCTION

Buried water, sewer and gas pipelines have been damaged heavily by recent earthquakes, including the Northridge earthquake of January 17, 1994 in the United States (Hall, 1994), and the most recent Hyogo-ken Nanbu (Kobe) earthquake of January 17, 1995 in Japan (Comartin et al., 1995). Because of the importance of buried lifelines to the health, supply and safety of the populace, mitigation of earthquake damage of buried lifelines becomes a worldwide concern. Many existing water, sewer and gas pipelines have been built several decades ago without seismic considerations. They are unsafe even under a moderate earthquakes. The improvement of earthquake resistance of buried pipelines is urgently needed in earthquake prone areas. With proper rehabilitation, sever earthquake damage to pipelines can be mitigated.

Pipeline rehabilitation is costly. It is impossible to rehabilitate all pipelines in a system within a short time for insufficient manpower, equipment, materials and funds. This paper provides a rehabilitation scheme and guidelines on the priority for rehabilitation of pipelines of any existing systems.

REHABILITATION SCHEME

A water, sewer or gas pipeline system in general can be divided into mains and branches as shown in Fig. 1. Pipelines in the main system are much more important than pipelines in the branch system. Before starting the rehabilitation of the branch system, pipelines in the main system must be rehabilitated completely. The rehabilitation of the main system is performed from pipelink to pipelink, while the branch system is performed from area to area. Once a pipelink or an area is rehabilitated, the performance of retrofitted pipelink or area should be monitored to evaluate the effectiveness of the actions taken.

The strategy to establish priorities for rehabilitating buried pipelines requires the following tasks: (1) evaluating the damage probability of buried pipe links using a probability-based Earthquake Damage Estimation Model (**EDEM**) (Li, 1994, Wang & Li, 1993) which will include such important parameters as pipe diameter, soil condition, pipe material, joint type, buried depth, buried age and earthquake intensity, etc.; (2) calculating the node weights of the system which will represent the importance of the network nodes; (3) calculating the pipe link weights of the network, either based on a cost or a time factor, which will show the significance of the pipe links; (4) generalizing the source expansion tree which will enable the ranking of the damage probability of all pipe links of the pipeline system; and (5) setting the priorities based on the generalized link weight which is defined as the summation of node weights for the nodes served by the pipe link. The pipe link which has the largest link weight is the one to be rehabilitated first, and so on.

To assist the development of pipeline rehabilitation strategy (Wang and Li, 1993), this paper reports the statistical analysis of the pipeline damage data from 7 past earthquakes occurred in China, Japan and the United States. Pipeline damage probabilities serve as a basis for determining rehabilitation priority.

DATABASE

To accomplish the rehabilitation task effectively, a comprehensive database information on various aspects of the pipeline system should be available. The following items are some important parameters for a typical pipelink: (1) pipe diameter; (2) pipe material; (3) joint type; (4) pipe length; (5) soil conditions; (6) buried depth; (7) buried age; (8) number of customers served; (9) rehabilitation cost; (10) rehabilitation speed (km/day); (11) rehabilitation methods; (12) pipeline use (emergency, hospital, school, factory or resident); and (13) expected earthquake intensity (MMI-Modified Mercalli Intensity).

PARAMETERS AND ASSUMPTIONS

Previous studies (Isoyama & Katayama, 1981; Wang et al., 1985) revealed that pipeline damage are strongly correlated with: (1) Pipe diameter; (2) Soil condition (including soil liquefaction effects); (3) Pipe types (the combination of pipe material and joint type); (4) Earthquake intensity; (5) Buried age (including corrosion effects); (6) Buried depth. In this paper, other factors such as internal pressure, fault movement, and landslide are not considered due to limited damage data obtained from past earthquakes. Although more parameters can be included in the analysis model if sufficient data are available, only six parameters indicated above are used in the demonstration analysis in this study.

For simplicity reasons, the assumptions used for the probability damage model are: (1) Pipeline system information is already in database; (2) The influential parameters are considered statistically independent (Freund, 1971); (3) Pipe link damage along the length follows the Poisson's Law (Crovelli, 1973; Shinozuka et al., 1991) along the length.

PIPELINE DAMAGE PROBABILITY

Based on the above assumptions, the damage probability of a pipe link is the combined damage probabilities of all statistically independent parameters. Thus, the damage probability model for the pipeline can be written as:

$$P_j = 1 - [1 - P_j^d(i)] \cdot [1 - P_j^s(k)] \cdot [1 - P_j^m(y)] \cdot [1 - P_j^e(x)] \cdot [1 - P_j^a(l)] \cdot [1 - P_j^b(e)] \tag{1}$$

where P_j is the damage probability of pipeline j. P_j^d, P_j^s, P_j^m, P_j^{ei}, P_j^a, and P_j^b are damage probabilities with respect to pipe diameter, soil condition, pipe type, earthquake intensity, buried age and buried depth, respectively. i, k, y, x, l, and g are indices for parameter domains of pipe diameter, soil condition, pipe type, earthquake intensity, buried age and buried depth, respectively.

By the assumption that pipeline damage follows **Poisson's Law** along the pipe length, the damage probability with respect to each variable can be expressed as:

$$P_j^c(z) = \frac{[R_j(z)\ L_j]^c}{c!} e^{-R_j(z)\ L_j} \tag{2}$$

where z is an index correlated to i, k, x, y, i or g. c is a random number, it can be 0, 1, 2, and so on. When c equals zero, P_j^0 means reliability. L_j is the pipeline length (km). R_j is the damage rate which is determined by the analysis of damaged data collected from past earthquakes worldwide. The Eq. 2 can also be expressed as:

$$P_j(z) = 1.0 - e^{-R_j(z)\ L_j} \tag{3}$$

PRIORITIZATION PARAMETERS FOR REHABILITATION OF BURIED PIPELINES

Node Weight: Node weight which is denoted by NW_i represents the importance and the reliability of the node i. It is defined as:

$$NW_i = \frac{1}{2} \sum_{j=1}^{N_i} \alpha_j P_j \tag{4}$$

where N_i is the number of pipelines directly connected to node i. α_j is the importance factor of pipe j. The node which has the largest node weight in the system is the most important node.

Importance Factor: The importance factor α_j of pipelink j is determined by:

$$\alpha_j = \alpha_j^1\ \alpha_j^2\ \alpha_j^3 \tag{5}$$

where α_j^1 is the pipeline usage factor. According to the pipeline usage, pipelines used for emergencies, hospitals, schools and residents are much more importance than those for factories. The more important the pipeline is, the larger value the pipeline usage factor should be. α_j^2 is the system factor. It is known that pipelines in the main system are more important than in the branch system. The system factor for pipeline in the main system should be larger than in the branch system. α_j^3 is the population factor according to the population served by pipelines. The more population the pipeline serves, the more important the pipeline is.

Obviously, the values of three factors should be decided by expert experience. The recommended values are $\alpha_j^1 = 1$ for normal daily use; $\alpha_j^1 > 1$ for emergency and hospital use; $\alpha_j^2 = 1$ for branch pipeline; $\alpha_j^2 > 1$ for main pipeline; α_j^3 can be determined by:

$$\alpha_j^3 = e^{\frac{M_j}{\sum_{k=1}^{N} M_k}} \tag{6}$$

where M_j is the population served by pipelink j.

Link Weight: Link weight which is denoted by LW_j represents the importance of pipelink j. It is defined as:

$$LW_j = NW_i + NW_k \tag{7}$$

where i and k are two nodes of pipelink j. The more link weight the pipelink has, the more important the pipeline is.

Rehabilitation Time of Each Pipelink: Rehabilitation time T_j of a pipelink j is defined as:

$$T_j = \frac{L_j}{\gamma_j} \tag{8}$$

where γ_j is the evaluated rehabilitation rate factor (km/day) of pipelink j. Note that the rehabilitation rate factor represents the suitability and the efficiency of rehabilitation of the pipelink j. Some pipelinks may be difficult or impossible to be rehabilitated from the standpoint of present technology or funds available. From this viewpoint of rehabilitation rate, rehabilitation should start from pipelinks which have less rehabilitation difficulty and less expense.

In general, the rate factor of rehabilitation has relations with rehabilitation method, equipment, surrounding environment and manpower used for carrying out the rehabilitation work, etc. Before carrying out the prioritization scheme, the rehabilitation plan which includes rehabilitation method, rehabilitation rate, and cost required for each pipelink in the system is supposed to be stored in the database.

Link Weight Efficiency: Theoretically, a pipelink which has the largest link weight is the most important pipelink that needs to be rehabilitated first. But the pipelink may have very low rehabilitation rate. Link weight efficiency denoted by LWE_j represents the link weight furnished by rehabilitation per unit time, which is defined as:

$$LWE_j = \frac{LW_j}{T_j} \tag{9}$$

Sub-system: Sub-system (denoted by $S_{(a,b,c,...)}$, a, b, c are node numbers) is defined as a system that all nodes in the sub-system are connected by pipelinks which need not be rehabilitated. If a node is connected by pipelinks that need not be rehabilitated, the node is also called a sub-system. In a sub-system, if there are more than two nodes, any node will be connected at least by one pipelink which needs not be rehabilitated. For example, Figure 2(a) shows a simple pipeline system. It is assumed that pipelinks a, b, c and g will be rehabilitated. The system can be expressed by sub-systems as in Fig. 2(b). In sub-system $S_{(1)}$, there is only one node. In sub-system $S_{(2,3,4,5)}$, there are four nodes and five pipelines. Any node in this sub-system is connected by a pipelink which needs not be rehabilitated.

PRIORITIZATION SCHEME FOR MAIN SYSTEM

To decide the priorities of pipeline rehabilitation in a system with the objective of minimizing the rehabilitation time, there are four items to be considered: (1) total funds available; (2) damage probability of each pipeline; (3) rehabilitation time of each pipeline; and (4) rehabilitation cost of each pipelink. The procedure of prioritization for pipelink rehabilitation includes the following steps:

Step one is to make a list of all pipelinks in the main system according to damage probabilities from the largest one to the smallest one. **Step two** is to sum the rehabilitation costs required according to the list in step one to be equal or within the total funds available:

$$C = \sum_{k=1}^{N1} C_k \leq C^T \tag{10}$$

$$\sum_{k=1}^{N1+1} C_k > C^T \tag{11}$$

where C_k is the cost required for the rehabilitation of pipelink k, C^T is the total funds available and N1 is the number of pipelinks under the summation of C. P^c is the damage probability of pipelink No. N1.

Step three is to separate the main system into M sub-systems by pipelinks which have damage probability larger than or equal to P^c. If there are more than two sources, all sources in the system are assumed to be one sub-system. **Step four** is to establish the optimization objective. The objective is to minimize the rehabilitation time T of the system to provide water, sewer or gas to all nodes in the system. As it is known that in a system with M sub-systems, the minimum requirement of pipelinks to connect M sub-systems is M-1. The objective can be shown:

$$T = \sum_{k=1}^{M-1} T_k \tag{12}$$

provided that all M sub-systems are connected by M-1 pipelines.

Step five is to search for a **Generalized Source Expansion Tree**. The method is called **Generalized Source Expansion Method**. The expansion starts from a sub-system with source along a connected pipelink with the smallest rehabilitation time to a node, then continues to expand to other sub-systems until all sub-system are covered. Every expansion covers one sub-system and one pipelink. This method which looks like source expansion is called **Generalized Source Expansion Method**. The final system which includes M sub-systems and M-1 pipelinks is called generalized source expansion tree. When an earthquake occurs, the pipeline system should be in operation if these M-1 pipelinks are properly rehabilitated.

Step six is to calculate the sub-system weight. The sub-system weight SSW_i of the sub-system i is defined as:

$$SSW_i = \sum_{k=1}^{N_i} NW_k \tag{13}$$

where N_i is the number of nodes in the sub-system i. **Step seven** is to calculate the generalized link weight. The generalized link weight GLW_j of pipelink j is defined as the summation of all sub-system weights associated with pipelinks served by the pipelink j, which is:

$$GLW_j = \sum_{k=1}^{N_s} SSW_k \tag{14}$$

where N_s is the number of sub-systems which will be served by the pipelink j.

Step eight is to calculate the link weight efficiency of other pipelinks in the system which have damage probability larger than or equal to P^c and are not covered by generalized source expansion tree according to Eq. 10. **Step nine** is to establish the priorities for pipelink rehabilitation. Pipelinks covered in the generalized source expansion tree are listed according to generalized link weight from the largest one to the smallest one followed by other pipelinks according to the link weight efficiency also from the largest one to the smallest one. No.1 in the list is the one for which the rehabilitation work should be carried out first. No.2 is the second and so on.

PRIORITIZATION SCHEME FOR BRANCH SYSTEM

According to the rehabilitation scheme, the rehabilitation work of branch system is assumed to be performed from area to area. The procedure of pipeline prioritization for rehabilitation in branch system is as follows: **Step one and step two** are the same above by changing main system to branch system. **Step three** is to calculate average link weight efficiency which is defined as:

$$ALWE_i = \frac{\sum_{k=1}^{M_i} LW_k}{\sum_{k=1}^{M_i} T_k} \tag{15}$$

where $ALWE_i$ is the average link weight efficiency of area i and M_i is the number of pipelinks with damage probability larger than or equal to P^c. **Step four** is to make a list of all areas according to the average link weight efficiencies from the largest one to the smallest one. Number one is the area that should be rehabilitated first.

REHABILITATION PRIORITIZATION EXAMPLE

Examples to test the developed prioritization scheme using 1971 San Fernando earthquake data were studied and discussed in Li's dissertation (Li, 1994). Due to the limited space, readers are referred to Li's dissertation (Li, 1994) for details.

REHABILITATION OF VULNERABLE PIPELINES

The replacement of all existing lines is very expensive, if not impossible. Also, there are other important factors involved in a retrofitting project. Therefore, the replacement of all existing buried pipelines is not recommended by most experts in the lifeline earthquake engineering field. Old pipelines made-up of cast iron, clay, asbestos or plain concrete material with cement- or lead-caulk joints are very brittle and corrosive. They are most vulnerable to seismic hazards. The low-cost retrofitting strategy at the present time is to upgrade the existing system during routine maintenance or disaster repair works. Following options should be considered.

- Replace current brittle pipes with more ductile material pipes;
- Replace current rigid joints with more flexible and/or restrained joints;
- Replace current pipes that have been weakened by corrosion;
- Repair cracks with strong epoxy;
- Provide new linings.

For an important project such as a single large pipeline at a critical fault zone, retrofitting and/or replacement of pipelines is necessary. Some suggested methods of strengthening the environment are as follows:

- Add drainage around existing pipes or add anchorage to pipeline;
- Inject chemical (or epoxy) or cement into potential soil liquefaction region;
- Drive piles at junction between pipeline and interconnected structures;
- Density soils surrounding the pipeline;

. Install flexible joints/junctions at strategic locations.

Methods of Strengthening Pipeline Itself

. Insertion of new pipe inside old pipe;
. Replacement of rigid joint with flexible joint;
. Replacement of old pipe with new pipe;
. Seismic isolation by cushion material;
. Epoxy lining;
. Bitumen lining;
. Cement mortal lining or concrete lining;
. Hose lining;
. Slip lining;
. Replacement of easily liquefiable soil with not easily liquefiable soil;
. Adding concrete block under the pipe in potentially liquefied areas;
. Adding piles along the pipe in the areas of liquefaction;
. Injection of epoxy or grouting materials before earthquake;
. Lower water level to avoid liquefaction;
. Others.

CONCLUSIONS

The prioritization scheme for rehabilitation of buried pipelines provides a rehabilitation planning. Pipelines no matter in main or branch system are classified according to damage probability evaluation. The rehabilitation work starts from pipeline with higher damage probability, more important and higher rehabilitation rate. The scheme can minimize the earthquake damage to pipelines if earthquake occurs during process or after the rehabilitation work.

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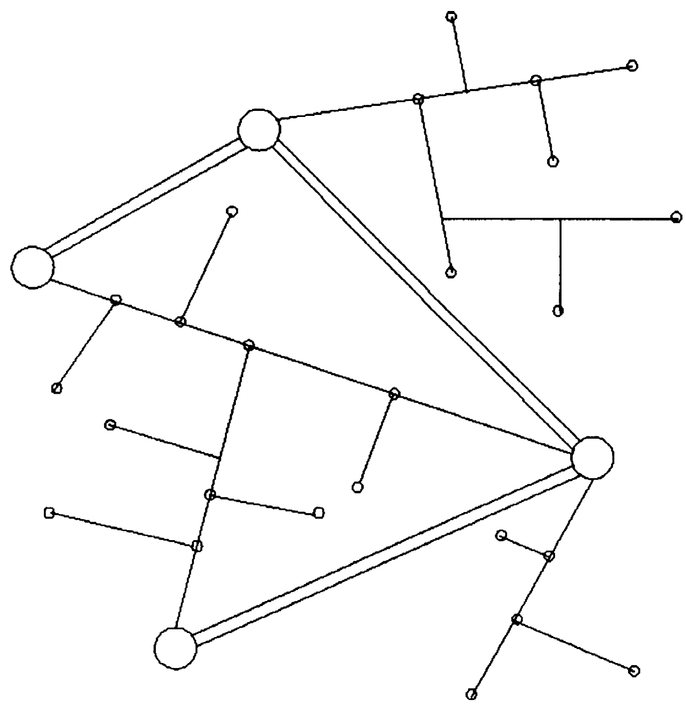

Fig. 1 Main and Branch of a Pipeline System

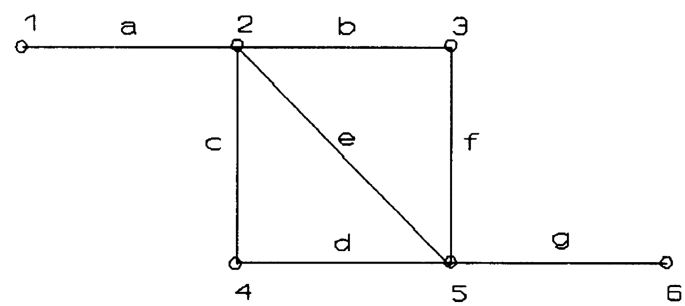

Fig.2(a) Pipeline System

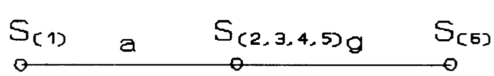

Fig.2(b) Sub-system Expression

Fig. 2 An Example of Pipeline System