PRIORITY EVALUATION OF SEISMIC MITIGATION IN PIPELINE NETWORKS USING MULTICRITERIA ANALYSIS FUZZY AHP

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ABSTRACT:

In general, the cost of seismic mitigation in a lifeline network is large but the budget is limited. Thus, a priority list of pipeline for mitigation is necessary. This paper develops a fuzzy analytic hierarchy process (FAHP) to support decision making for priority evaluation of the pipelines renewal applicable to metropolitan water distribution networks considering customers importance, pipeline properties, and hazard factors. To deal with the uncertain judgment of decision makers, a fuzzy modification of the AHP method is applied as an evaluation tool, where uncertain and imprecise judgments of decision makers are translated into fuzzy numbers. The proposed FAHP method is applied to a case study of Osaka City water distribution network. It demonstrates that the proposed prioritization method can be utilized as an effective tool for tackling the uncertainty and imprecision associated with priority evaluation of seismic mitigation and renewal programs in a pipeline network which can be applicable to mitigation prioritization modeling in other lifeline networks.

KEYWORDS: Prioritization, Seismic Mitigation, Pipeline Network, Lifeline Network, Multicriteria Analysis, Fuzzy AHP

1. INTRODUCTION

The financial resource for seismic mitigation plan in a lifeline network is limited. Thus, it is necessary to prepare a priority list of important components of network for upgrading. Typically, there are several available methods to prioritization of decision making and policy analysis namely: cost-benefit analysis (CBA); cost-effectiveness analysis (CEA); multi-criteria analysis (MCA); and other methods such as expert judgments, Delphi technique, sensitivity analysis, and Monte Carlo analysis. CBA has been the most popular method for making comparisons between different alternatives. In CBA, costs and benefits are monetized whereas in CEA, benefits can be expressed in units of effectiveness. One of the advantages of CEA is that it compares a series of mutually exclusive alternative projects. MCA, on the other hand, describes any structured approach used to determine overall preferences among alternative options, where the options accomplish several objectives. In MCA, desirable objectives are specified and corresponding attributes or indicators are identified. The actual measurement of indicators need not be in monetary terms, but are often based on the quantitative analysis (through scoring, ranking and weighting) of a wide range of qualitative impact categories and criteria. Different environmental and social indicators may be developed side by side with economic costs and benefits. Explicit recognition is given to the fact that a variety of both monetary and non-monetary objectives may influence policy decisions. MCA provides techniques for comparing and ranking different outcomes, even though a variety of indictors are used. Multicriteria analysis methods have the advantage that they can assess a variety of options according to a variety of criteria that have different units. This is a very important advantage over traditional decision aiding methods (e.g. CBA) where all criteria need to be converted to the same unit. Another significant advantage of most MCA models is that they have the capacity to analyze both quantitative and qualitative evaluation criteria together.

TOPSIS, outranking, and AHP are three of the most frequently used MCA techniques. TOPSIS views a MCA problem with m alternatives as a geometric system with m points in the n-dimensional space. It was developed by Hwang and Yoon (1981). The method is based on the concept that the chosen alternative should have the shortest distance from the positive-ideal solution and the longest distance from the negative-ideal solution. TOPSIS defines an index called similarity (or relative closeness) to the positive-ideal solution and the remoteness from the negative-ideal solution. Then the method chooses an alternative with the maximum similarity to the positive-ideal solution.

The outranking decision aid methods compare all couples of actions. Instead of building complex utility functions, they determine which actions are being preferred to the others by systematically comparing them on each criterion. The comparisons between the actions lead to numerical results that show the concordance and/or the discordance between the actions, and then allow to select or to sort the actions that can be compared.

In literature, analytic hierarchy process (AHP) is the most popular method to perform a MCA. This method developed by Saaty (1980), divides a complicated system under study into a hierarchical system of elements. Pairwise comparisons are made of the elements of each hierarchy by means of a nominal scale. Then, comparisons are quantified to establish a comparison matrix, after which the eigenvector of the matrix is derived, signifying the comparative weights among various elements of a certain hierarchy. Finally, the eigenvalue is used to assess the strength of the consistency ratio of the comparative matrix and determine whether to accept the information.

The fuzzy versions of all aforementioned techniques were developed to deal with situations, which are ambiguous or not well defined. In this study, fuzzy AHP is preferred in the prioritization of pipeline mitigation since this method is the only one using a hierarchical structure among goal, criteria, and sub-criteria. Usage of pairwise comparisons is another asset of this method that lets the generation of more precise information about the preferences of decision makers. By using pairwise comparisons, judges are not required to explicitly define a measurement scale for each attribute.

2. MITIGATION PRIORITIZATION METHODOLOGY

In this paper, we develop a fuzzy prioritization model to support the decision-making for seismic mitigation plan in a large scale lifeline network. As an example of performing the analysis, the method is utilized to priority evaluation of pipelines replacement program in a water distribution network considering customers importance, pipeline properties, and hazard factors. Fig.1 shows the flow chart of the proposed prioritization method of water supply systems. The method can be applied to other lifeline systems considering characteristics of each system. The method includes five steps: (1) GIS database preparation; (2) classifying important customers due to their importance in terms of contribution to disaster risk reduction; (3) path tracing between sources and important customers; (4) recursive rank assignment to the pipelines; and (5) performing a MCA prioritization method by FAHP. In the following, each step is explained in more detail by applying the methodology to a case study of Osaka City water distribution network.

A comprehensive GIS database should be constructed including, spatial distribution of important customers, pipeline properties, network topology, flow analysis results and seismic hazards, etc. Javanbarg et al. (2006) and Javanbarg (2008) performed an extensive seismic reliability analysis of Osaka City water distribution network subject to five scenario earthquakes based on a comprehensive GIS database. We have utilized the same database in which the total number of 25 routes, 46 routes and 197 routes have been assigned to trunk, main and branch lines, respectively. These routes include 1505 links made of different type of pipe materials ranged between diameters 300 to 2000 mm with an approximate total length of 727 km.

The classification of important customers may vary through the different systems due to their level of importance in corporation with their degree of contribution to disaster risk reduction. Accordingly, the target performance of each component in a lifeline system under seismic condition is related to its intended function and importance. For instance, the importance of a pipeline route within a water network is in conformance with the assigned importance rank to type of customers which are supplied by the route. As such, the pipelines provide water for emergency health care facilities or fire suppression serve a more important function for post-earthquake response than those that provide common customers, e.g. residential customers, regardless of the size and capacity. JWWA (1997) guideline classifies the importance rank related to each facility into two ranks: Rank A, facilities with high level of importance; and Rank B, other facilities. Water supply systems must rank their own facilities based on the facility location with respect to other social and economical facilities. Among the American guidelines, ALA (2005) guidelines, define a pipe function class and categorized it into four classes which is an analogy with the current building code definitions for Occupancy Category and Seismic Use Group with additional definitions based on how critical the pipelines are and consequences of failure, with considering of: importance of the customers they serve; importance to community in terms of fire fighting, health care, and emergency response and recovery; potential for secondary disasters resulting from pipe damage, difficulty in making repairs; and effects on community. In this study, we have classified the importance rank of customers into three ranks; very important, important, and others (Table 1) based on the contribution degree of each customer to post-earthquake response as a part of emergency preparedness plans. For instance, Fig. 2 shows the classification of important customer entire the Osaka City.

Table 1 Rank assignment to important customers

Rank (importance)	**Type of Customer**
Rank A (very important)	Large emergency evacuation positions Main emergency health care facilities Emergency preparedness and response facilities Essential communication centers and control towers Fire departments, fire stations and fire suppression tanks Major economic and marketing centers
Rank B (important)	Secondary emergency evacuation positions (shelters) Secondary emergency health care facilities
Rank C (others)	All demand nodes not classified as Rank A and Rank B

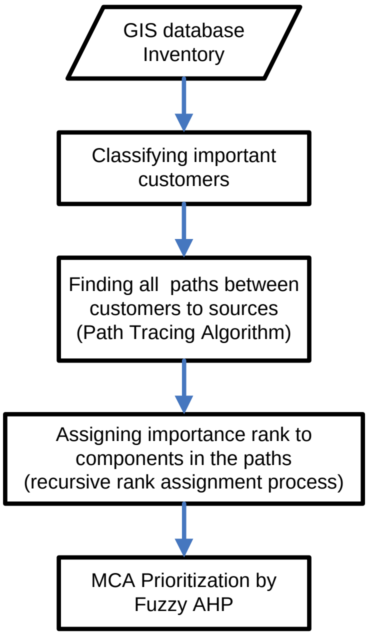

Figure 1 Methodology of seismic mitigation prioritization in pipeline networks

Because of limited mitigation budget the pipeline could not immediately incorporate all of projects identified during the initial development of the mitigation program. Thus, it is vital to identify the main pipeline paths to important customers that are most likely to remain operational after the scenario earthquakes. Javanbarg and Takada (2007) presented a path tracing algorithm to identify the main path between sources and desired demand nodes entire the network based on constructing a path matrix and various path selection factors. Herein, we have applied their method to find all main paths between sources and demand nodes in Osaka City water distribution network.

Once the importance rank was assignment to customers and main paths between sources and customers were found, an engineering analysis is needed to assign the importance rank to each individual pipeline in a route entire the network. Initially the trunk lines, which are considered as the backbone of the distribution network and are sub-transmission pipelines between distribution plants/pump stations, are assigned as Rank B assuming that there is some amount of reserve capacity for a limit time at each plant/station. With respect to the rank assigned to the main pipelines served by each trunk line, it is then possible to upgrade the rank of trunk lines, recursively. In the meantime, an importance rank is assigned to each branch pipe in conformance with the higher rank among the importance rank of its customers. Similarly, the importance rank can be assigned to each main pipe as the highest rank of its branch pipes. An engineering analysis can be performed to adjust the rank assignment to main and branch lines considering installed isolation valves, multiple uses of lines and redundancy issue which is out of this paper scope. Finally, the importance rank to each trunk line can be adjusted to the highest rank of its main pipes. If at least one main pipe has been assigned as the Rank A, the trunk line is considered as Rank A. The similar engineering analyses in previous steps can be recursively repeated till all trunks, mains and branches assigned with Rank A or B are rechecked. The rest of pipelines can be considered as the Rank C. Fig. 3 shows the importance rank assignment to distribution pipelines .in Osaka City distribution network.

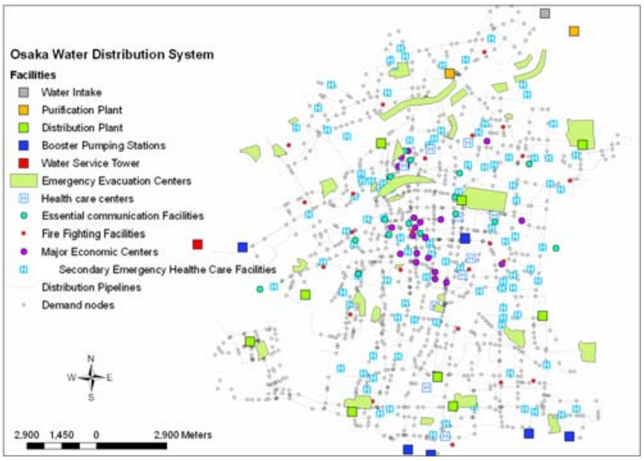

Figure 2 Classification of important customers

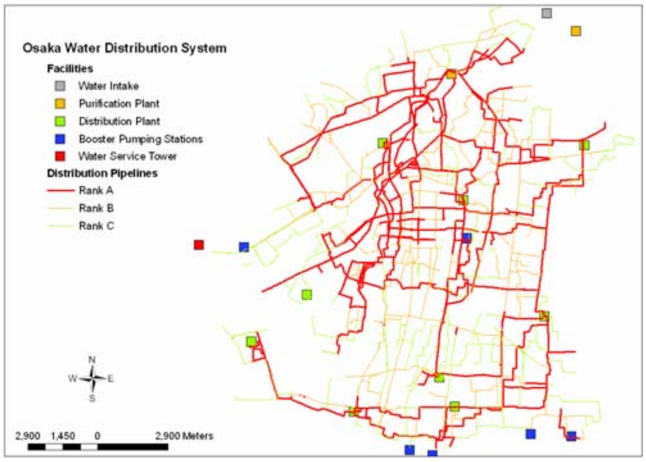

Figure 3 Importance rank assignment to pipelines

In the remainder of the prioritization steps; to deal with the uncertain judgment of decision makers, a fuzzy AHP method can be applied as an evaluation tool, where uncertain and imprecise judgments of decision makers are translated into fuzzy numbers, to make a prioritization list of components. To do so, first a comprehensive list of criterions affecting the pipeline mitigation plan should be established. Then, considering the pipe segments groups as the alternatives for mitigation, a hierarchy structure of the prioritization model should be implemented. Finally, the priority evaluation process can be done by applying an efficient fuzzy prioritization model. More specifically, the process is explained in the sequel.

3. FUZZY AHP PRIORITIZATION MODEL

The proposed structural hierarchy for fuzzy prioritization of pipeline mitigation process in a network is presented in Fig. 4. In general, the fuzzy comparison judgment matrices are decided according to suggestions of group decision-making process made by senior experts in a water authority. The imprecise and uncertain assessments of them can then be translated into corresponding triangular fuzzy numbers. Table 2 presents definition of the uncertain judgment as the fuzzy scores used in this analysis. With respect to pipeline importance as the main criteria in FAHP model, the fuzzy comparison judgment of three criteria namely: Rank A; Rank B; and Rank C are presented in Table 3. As seen, Rank A was considered as the most important criteria, evaluated as being between two to four times more important than Rank B, about four to six times more important than Rank C. Accordingly, the Rank B was considered between one to three times more important than Rank C.
Among the most recent fuzzy AHP methods, in this study we applied an efficient fuzzy prioritization method presented by Wang et al. (2004), and the exact weights of main criteria were obtained and presented under the column w in Table 3. Moreover, the consistency index γ was calculated and presented in Table 3. In the Wang's fuzzy prioritization method, the results of analysis has a good consistency when the consistency index γ is greater than $e^{-1} = 0.3679$. It is evident that the prioritization model in Table 3 has a good consistency since $0.8326 > 03679$. Similarly, the fuzzy comparison judgment matrices for other levels in hierarchical structure were implemented as shown through Tables 4 to 10 and the local weights were calculated by the same prioritization method performed in level 2. The consistency index, shown in Tables 4 to 10, shows an acceptable consistency in the analysis.

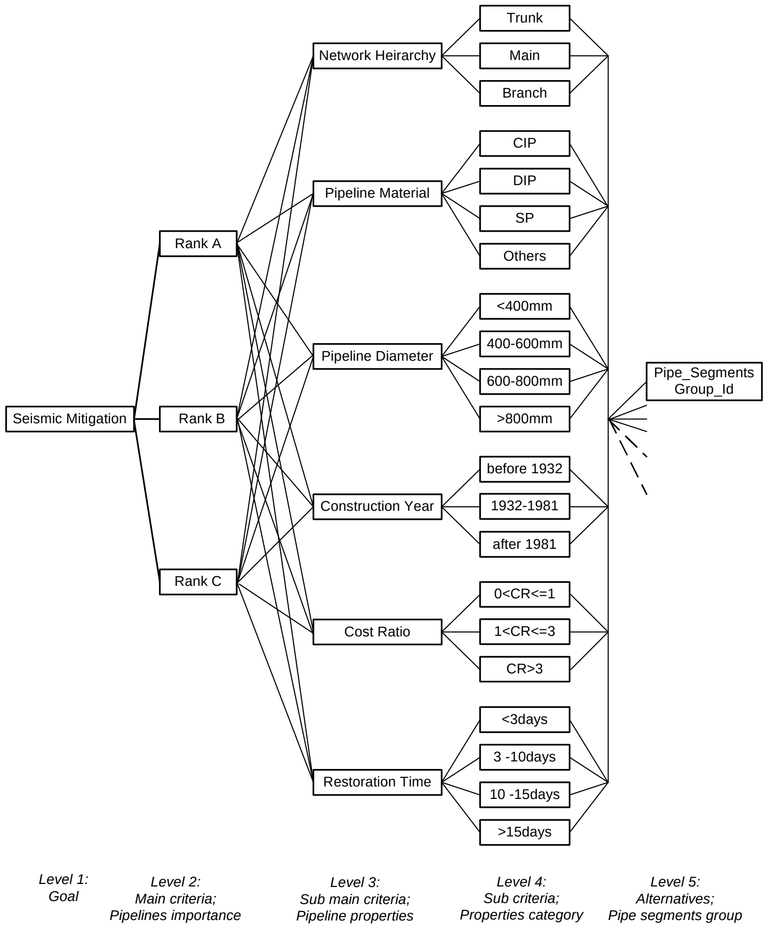

Figure 4 Hierarchy structure of the FAHP prioritization for seismic mitigation of pipeline networks

Table 2 Fuzzy judgment scores in FAHP

Uncertain judgment	*Fuzzy score*
About equal	(1/2,1,2)
About x times more important	(x-1,x,x+1)
About x times less important	(1/(x+1),1/x,1/(x-1))
Between y and z times more important	(y,(y+z)/2,z)
Between y and z times less important	(1/z,2/(y+z),1/y)

$x = 2,3,...,9$, $y, z = 1,2,...,9$, $y < z$

While network hierarchy was proposed as the most important factor affecting prioritization procedure in level 3, pipe material and pipe diameter were considered to have the same effect. It was also assumed that both of the pipeline construction year and cost ratio have similar effect on prioritization of pipelines mitigation (Table 4).
High vulnerability of the cast iron pipes (CIP) observed in past earthquakes leads to be assigned with a higher priority level in pipeline mitigation compare to other types of pipe material. Ductile iron pipes (DIP) without the aseismic joint takes the next priority level. It should be noted that the steel pipes, listed in Table 6 as SP, are the welded steel pipes and not included the carbon steel SGP pipes or screwed steel pipes. In Table 6, the “Others” refers to plastic pipelines such as vinyl pipes and polyethylene pipes (6).
Osaka City water supply system was implemented in 1895. The basic pipe material used in network was gray CIP and later in 1932, CIP pipelines with more quality were installed in 1932. In 1955, the DIP was utilized as the new material for better performance of the network with lower leakage. After 1981, Osaka City Waterworks Bureau employed seismic joints to make earthquake-proofed some parts of DIP (Osaka Municipal Waterworks Bureau, 2006). A useful lifetime of 75 years can be considered for water pipelines. Hence, we classified the

construction year of the pipelines into three categories: pipelines installed before 1931; with age of more than 75 years; between 1932 and 1981; and after 1981 (Table 8).

An annual expected cost ratio, equal to ratio of cost of pipeline damage repair to replacement cost as a part of improvement program, is defined to involve the economical analysis in prioritization process. The expected repair cost for a period of 50 years was calculated based on the method presented by Tan and Shinozuka (1982). For calculation of annual expected cost of replacement, the presented method in JWWA (2002) was applied (Table 9).

The restoration/repair time for pipe segment may not be considered as a proper indicator since each link is included several pipe segments and a link is considered to be restored when all segments are repaired. Hence, the restoration time of each link was estimated based on the compound damage ratio calculation presented in HAZUS (1999) and assigned to its pipe segments (Table 10).

Table 3 Fuzzy comparison matrix at the level 2

Pipeline Mitigation	*Rank A*	*Rank B*	*Rank C*	w	γ
Rank A	(1,1,1)	(2,3,4)	(4,5,6)	0.6458	0.8326
Rank B	(1/4,1/3,1/2)	(1,1,1)	(1,2,3)	0.2285	
Rank C	(1/6,1/5,1/4)	(1/3,1/2,1)	(1,1,1)	0.1258	

Table 4 Fuzzy comparison matrix at the level 3

Rank A, B, or C	**NH**	**PM**	**PD**	**CY**	**CR**	**RT**	w	γ
NH	(1,1,1)	(2,3,4)	(2,3,4)	(3,4,5)	(3,4,5)	(5,6,7)	0.5281	0.4188
PM	(1/4,1/3,1/2)	(1,1,1)	(1/2,1,2)	(1,2,3)	(1,2,3)	(3,4,5)	0.2480	
PD	(1/4,1/3,1/2)	(1/2,1,2)	(1,1,1)	(1,2,3)	(1,2,3)	(3,4,5)	0.2480	
CY	(1/5,1/4,1/3)	(1/3,1/2,1)	(1/3,1/2,1)	(1,1,1)	(1/2,1,2)	(1,2,3)	0.1457	
CR	(1/5,1/4,1/3)	(1/3,1/2,1)	(1/3,1/2,1)	(1/2,1,2)	(1,1,1)	(1,2,3)	0.1457	
RT	(1/7,1/6,1/5)	(1/5,1/4,1/3)	(1/5,1/4,1/3)	(1/3,1/2,1)	(1/3,1/2,1)	(1,1,1)	0.0783	

NH: Network Hierarchy, **PM**: Pipe Material, **PD**: Pipe Diameter, **CY**: Construction Year, **CR**: Cost Ratio, **RT**: Restoration/Repair Time

Table 5 Fuzzy comparison matrix for network hierarchy criteria at the level 4

NH	**Trunk**	**Main**	**Branch**	w	γ
Trunk	(1,1,1)	(2,3,4)	(5,6,7)	0.6995	0.7262
Main	(1/4,1/3,1/2)	(1,1,1)	(1,2,3)	0.1884	
Branch	(1/7,1/6,1/5)	(1/3,1/2,1)	(1,1,1)	0.1121	

Table 6 Fuzzy comparison matrix for pipe material criteria at the level 4

PM	**CIP**	**DIP**	**SP**	**Others**	w	γ
CIP	(1,1,1)	(4,5,6)	(5,6,7)	(8,9,10)	0.6332	0.6110
DIP	(1/6,1/5,1/4)	(1,1,1)	(3,4,5)	(5,6,7)	0.2151	
SP	(1/7,1/6,1/5)	(1/5,1/4,1/3)	(1,1,1)	(1,2,3)	0.0967	
Others	(1/10,1/9,1/8)	(1/7,1/6,1/5)	(1/3,1/2,1)	(1,1,1)	0.0550	

Table 7 Fuzzy comparison matrix for pipe diameter criteria at the level 4

PD	**<400 mm**	**400- 600 mm**	**600- 800 mm**	**>800 mm**	w	γ
<400 mm	(1,1,1)	(1/3,1/2,1)	(1/5,1/4,1/3)	(1/9,1/8,1/7)	0.0667	0.9992
400-600 mm	(1,2,3)	(1,1,1)	(1/3,1/2,1)	(1/5,1/4,1/3)	0.1334	
600-800 mm	(3,4,5)	(1,2,3)	(1,1,1)	(1/3,1/2,1)	0.2666	
>800 mm	(7,8,9)	(3,4,5)	(1,2,3)	(1,1,1)	0.5333	

Table 8 Fuzzy comparison matrix for construction year criteria at the level 4

CY	<1932	1932-1981	>1981	*w*	*γ*
<1932	(1,1,1)	(2,5/2,3)	(3,4,5)	0.5944	0.4499
1932-1981	(1/3,2/5,1/2)	(1,1,1)	(2,3,4)	0.2789	
>1981	(1/5,1/4,1/3	(1/4,1/3,1/2)	(1,1,1)	0.1267	

Table 9 Fuzzy comparison matrix for cost ratio criteria at the level 4

CR	CR<=1	1<CR<=3	CR >3	*w*	*γ*
CR<=1	(1,1,1)	(1/4,1/3,1/2)	(1/7,1/6,1/5)	0.1013	0.4188
1<CR<=3	(2,3,4)	(1,1,1)	(1/5,1/4,1/3)	0.2157	
CR >3	(5,6,7)	(3,4,5)	(1,1,1)	0.683	

Table 10 Fuzzy comparison matrix for restoration time criteria at the level 4

RT	<3days	3-10days	10-15days	>15days	*w*	*γ*
<3days	(1,1,1)	(1,2,3)	(3,4,5)	(8,9,10)	0.4849	0.4169
3-10days	(1/3,1/2,1)	(1,1,1)	(2,3,4)	(4,5,6)	0.3348	
10-15days	(1/5,1/4,1/3)	(1/4,1/3,1/2)	(1,1,1)	(2,3,4)	0.1226	
>15days	(1/10,1/9,1/8)	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(1,1,1)	0.0577	

The composite priority ranking of the alternatives (pipe segments groups) was determined by aggregating the local weights throughout the hierarchical structure presented in Fig. 4. By normalizing these composite priority rankings of pipe segments groups, a global priority ranking for each pipe segments group was then calculated. Considering the available annual fund of pipe replacement (predetermined annual budget for pipeline replacement) and having the length of pipelines, it is then possible to calculate the total length of pipelines could be replaced every year based on the pipe segments groups global priority ranking.
The results of priority evaluation of CIP and DIP segments replacement for Osaka City water distribution network are presented in Figs. 5 and 6, respectively. To illustrate the relation between spatial distribution of pipeline replacement and seismic hazard pattern, the layer of prioritized pipe replacement was overlaid with the peak ground velocity (PGV) distribution of Uemachi scenario fault (the most causative scenario) as depicted in Figs. 5 and 6. It is found that though most of pipelines located in higher PGV values are in priority for replacement, but other criterions such as pipeline importance as well as pipeline properties affect the prioritization procedure. To perform sensitivity analysis, the weights of the important criteria are separately altered and the relative nature of the weights, consistency degree, and overall priority ranking were observed. Because of lack of space, herein, the specified results of sensitivity analysis are not included; however, the findings of the analysis are presented in the conclusion section.

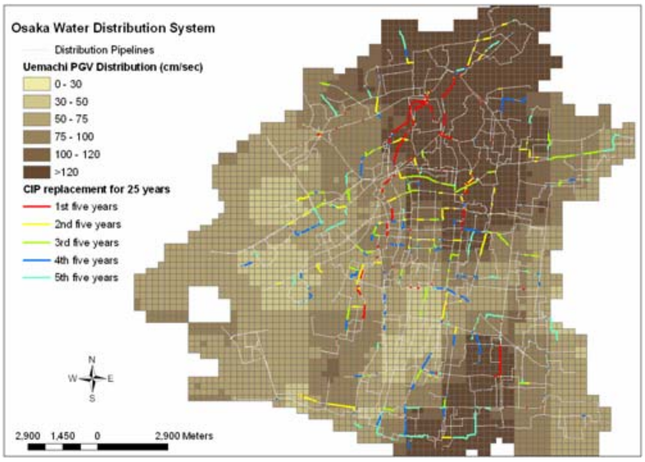

Figure 5 Prioritized CIP segments for mitigation in next 25 years

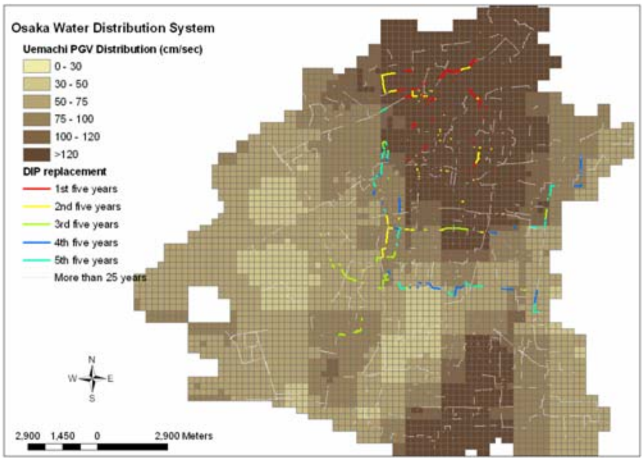

Figure 6 Prioritized DIP segments for mitigation in next 25 years

6. CONCLUSIONS

In this study, a MCA prioritization model of decision-making for seismic mitigation of lifeline systems has been developed. Validity of the model has been examined by applying to priority evaluation of pipeline replacement in a large scale water supply system. The concluding remarks are as follows.

1. To deal with the uncertain judgment of decision makers, an optimized fuzzy method of analytic hierarchy process can be applied as an evaluation tool, where uncertain and imprecise judgments of decision makers are translated into fuzzy numbers. Applying the proposed FAHP model to pipeline mitigation prioritization in Osaka City water distribution network demonstrates that the proposed priority evaluation method can be utilized as an effective tool for tackling the uncertainty and imprecision associated with prioritization of seismic mitigation and renewal programs in lifeline systems.
2. Due to the results of the sensitivity analysis of the FAHP model, it can be concluded that changing in the rate of the fuzzy ratio of the pairwise comparisons for higher level in the hierarchy tree, may affectively change the overall priority result and sometimes is increased inconsistency of the analysis. Therefore, the importance rank assignment to pipelines may extremely affect the priority evaluation process. Particularly, identification between the very important and important pipelines in the network hierarchy is an important issue. Furthermore, network hierarchy can be considered as the most important factor affecting the prioritization results. Accordingly, trunk pipeline priority has a meaningful effect on priority evaluation.

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