Multicriteria Decision Analysis for Risk Mitigation: Case Study of Lifeline Infrastructures

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SUMMARY:
Risk mitigation of structure and infrastructure systems is an intrinsically complex, multi-dimensional process that must consider both scientific facts and reflect subjective values. In this study, we propose a multicriteria criteria analysis model to clarify the subjectivity implicit in appraising the facts and values. To deal with the imprecise judgments of decision makers, the proposed model employs a new fuzzy analytical hierarchy process as an evaluation tool for the decision-making model. The application of the model is illustrated through, a case study of pipeline replacement prioritization in a large-scale water distribution network. The real-world case study demonstrates that the developed model can be used as an effective tool for tackling the uncertainty associated with risk mitigation of infrastructures.

Keywords: Risk mitigation, multicriteria analysis, lifeline infrastructures

1. INTRODUCTION

Catastrophes may damage several infrastructures such as lifeline networks. Their loss of functionality has a considerable effect on post-earthquake emergency response. Investing in prevention actions, such as the application of mitigation measures and upgrading to current seismic design codes, aims at contributing to reduce the risk and extent of earthquake damages. However, the engineering processes for mitigation of lifelines are extremely costly and time consuming, whereas the authorities responsible for their restoration and repair are constrained by limited financial and human resources. Consequently, the availability of a model allowing a quick identification and prioritization of the lifeline components that need to be mitigated is extremely important.

Multicriteria decision analysis (MCA) for comparing and ranking different outcomes, even though a variety of criteria with different units are used. This is a very important advantage over traditional decision making methods where all criteria need to be converted to the same unit. Another significant advantage of most MCA techniques is that they have the capacity to analyze both quantitative and qualitative evaluation criteria together. Caterino et al. (2009) investigated the applicability and effectiveness of some of these analytical models for the seismic retrofit of structures. Javanbarg et al., (2012) developed a new MCA model based on fuzzy analytical hierarchy process (fuzzy AHP) and showed the effectiveness of the model comparing its performance with the existing ones. The method has the advantage of integrating the engineering knowledge of a system and environmental objectives into the decision process.

In this paper, we use the MCA model developed by Javanbarg et al. (2012). The effectiveness of the model is illustrated in its application to a case study of the prioritizing pipeline renewals in a water distribution network. Considering the importance rank of the pipelines as the main criteria and pipeline properties as the sub-criteria, we try to deal with uncertainty and imprecision in decision-making for priority evaluation of earthquake mitigation in a pipeline network.

2. MULTICRITERIA DECISION ANALYSIS FRAMEWORK

The multicriteria analysis model is constructed as a hierarchical process in which the overall goal of decision is located at the highest level, and m alternatives, $A_1, A_2, ..., A_m$, are at the lowest level. The n criteria, $C_1, C_2, ..., C_n$, (sub-criteria) form the internal layers of the hierarchy. Fig. 1, for instance, shows a hierarchical structure for risk management of a structure or a system. The structure of the decision hierarchy depends on the purpose of prioritization problem. For example, in terms of risk mitigation, alternatives could be considered either the components of the system that need to be prioritized or the seismic retrofitting methods which need to be decided as the most effective alternative for risk mitigation.

The preferences of decision makers are elicited in the form of ratios using pair-wise comparison matrices. The uncertain assessments of a decision maker's preference can be translated into corresponding triangular fuzzy numbers $\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$, in which the parameters, l, m, and u respectively denote the smallest possible value, the most promising value, and the largest possible value that describe a fuzzy event. Each set of comparisons for a level with n elements requires $n(n-1)/2$ judgments, which are further used to construct a positive reciprocal comparison matrix $\tilde{A} = \{\tilde{a}_{ij}\} \in \Re^{n \times n}$, where $\tilde{a}_{ji} = 1/\tilde{a}_{ij}$, and $\tilde{a}_{ij} > 0$, for $j = 1,2,...,n$, $i = 1,2,...,n$, and $\tilde{a}_{ij} = \tilde{a}_{ji} = (1,1,1)$ for $i = j$. In final step an exact priority vector can be derived from $\tilde{A}$ which indicates the priority of elements in pair-wise comparison matrix.

The developed multicriteria analysis model uses a fuzzy nonlinear optimization model as the prioritization method to deal with uncertainties in decision making process. An improved particle swarm optimization (PSO) method is applied to solve the fuzzy optimization model as a system of nonlinear equations (Javanbarg et al. 2012). The prioritization method can derive exact priorities from consistent and inconsistent fuzzy comparison matrices.

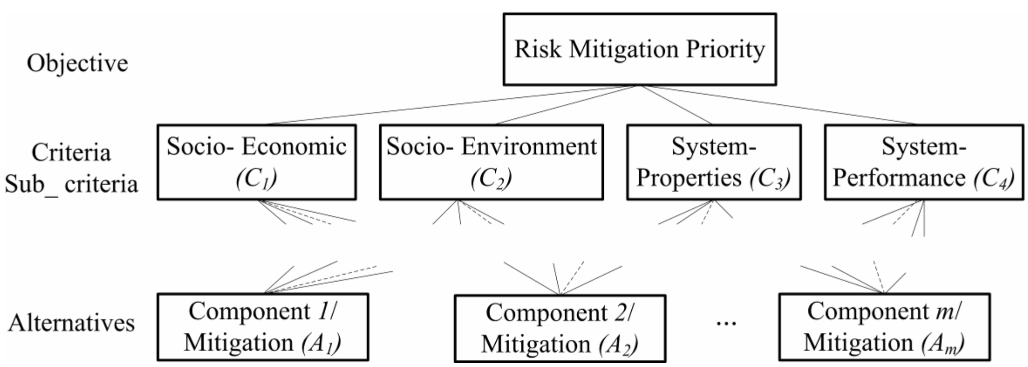

Figure 1. Hierarchy structure of the multicriteria analysis for risk mitigation

3. CASE STUDY OF A LIFELINE SYSTEM

To demonstrate the application of the model, a case study analysis was conducted for a mitigation prioritization of a water pipeline network located in a region of high seismicity. In the next section, the water distribution network is reviewed and the criteria and sub-criteria for replacement prioritization are discussed. This will be followed by a step-by-step procedure on applying the developed model to evaluate the priority of pipeline replacement.

The hierarchy structure used for earthquake risk ranking and priority evaluation of pipeline replacement throughout the water network is represented in Fig. 2. This hierarchy structure is constructed by the authors based on the information available from Osaka Municipal Waterworks Bureau (2006). The hierarchy structure includes five levels. It should be noted that other appropriate hierarchy structures may also be adopted depending on the available data and the requirements for seismic mitigation. Based on the classification in this model, the total number of 63 pipe groups (3× [3+4+4+3+3+4]) is considered as the pipeline alternatives for mitigation.

The classification of important customers may vary through the different systems due to their degree of contribution to risk reduction. Accordingly, the seismic performance of each component in a lifeline system 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. Criticality and consequences of failures include consideration of: importance of the customers served; 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; Rank A, very important; Rank B, important; and Rank C, others based on the degree of contribution of each customer to post-earthquake response as a part of emergency preparedness plans. Accordingly, an importance rank was then assigned to each pipeline across the network as shown in Fig. 3.

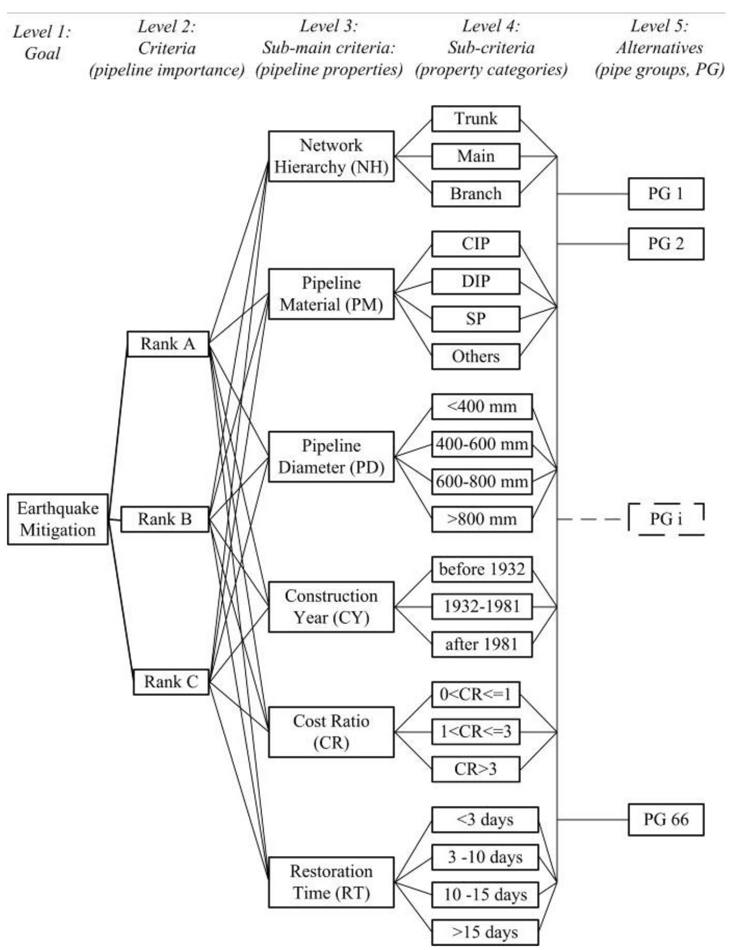

Figure 2. Hierarchy structure for replacement prioritization of the pipeline network

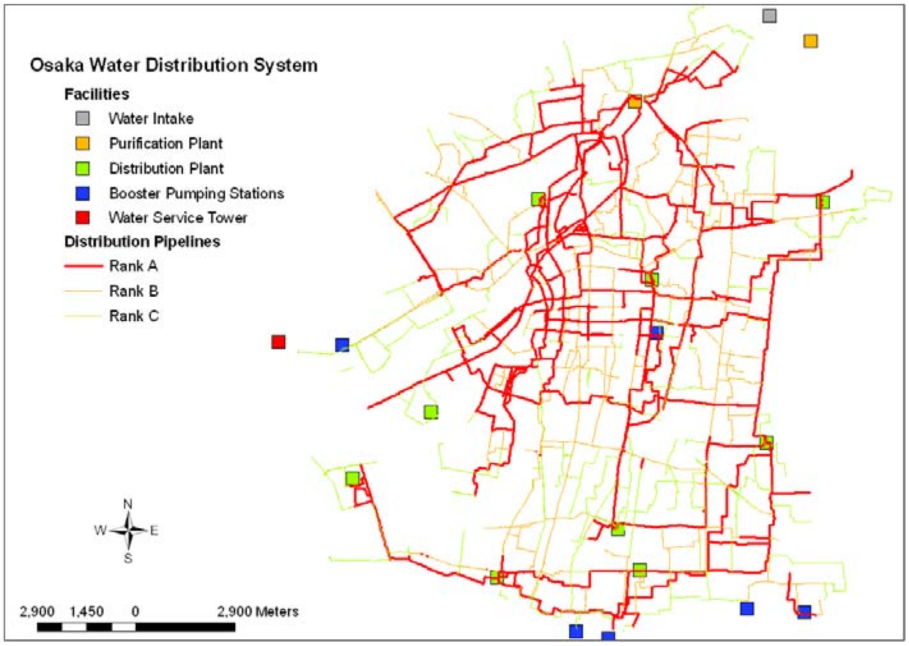

Figure 3. Classification of pipeline importance

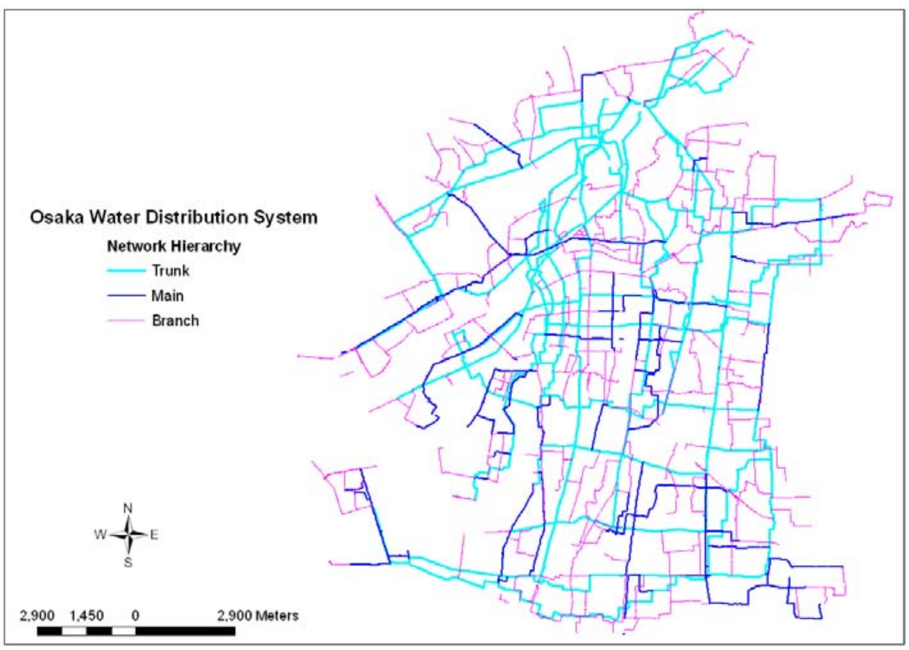

Figure 4. Classification of network hierarchy

The network hierarchy of the water pipeline network can be classified into trunk, main, branch and service pipes. Since we have considered pipelines with diameters more than 300 mm, the service pipes are not included in this case study. Fig.4 shows the network hierarchy classification in the water pipeline network.

Pipeline materials were classified as cast iron pipe (CIP), ductile iron pipe (DIP), steel pipe (SP) (Fig. 5). The CIP has a higher priority level in pipeline replacement compared to other types of pipe material because of higher CIP damage observed in past earthquakes. The DIP without the aseismic joint has the next priority level. The SP pipe is in third level of priority and “Others” refers to plastic pipelines such as vinyl pipes and polyethylene pipes have the last priority.

Pipeline diameter was classified into four classes as shown in Fig.6. This classification was mainly selected in conformance with the detailed cost analysis in cost ratio calculation. In other words, in list of repair cost of pipelines received from the waterworks bureau, the cost for repairing each damage location has been categorized with respect to classification of pipe diameter. It is evident that pipes with larger diameters should be put in higher priority in a pipeline replacement program since they serve more customers and are considered as the backbone of the network supplying water to other pipelines with medium and smaller diameters.

The water supply system was established in 1895. The basic pipe material used in the network was gray CIP and later CIP pipelines of higher quality were installed in 1932. In 1955, the DIP was used as the new material for better performance of the network with lower leakage. After 1981, Waterworks Bureau employed seismic joints to make earthquake-proof some parts of DIP lines. Assuming a useful lifetime of 75 years for water pipelines, we classified the construction year of the pipelines into three categories: pipelines installed before 1931, with an age of more than the pipe lifetime; between 1932 and 1981; and after 1981. The construction year classification for pipeline network is represented in Fig.7.

Earthquake economic losses are usually classified into two categories: direct loss, somewhat easier to evaluate, and indirect loss. The direct loss includes post-earthquake emergency response activities such as emergency and permanent repairs of the seismic damage sustained by the system, emergency water delivery, and loss of revenue, etc. The indirect loss, on the other hand, consists of inconveniences suffered by residential users, damage due to post-earthquake fires, industrial loss, business interruption, etc., pertaining to the ‘unserviceability’ of the system. Hence, the indirect loss is much more difficult to assess. In this study, while we have considered the repair cost as the direct loss, the indirect loss has not been included for the sake of simplicity. To involve the economical analysis in seismic mitigation prioritization, a cost ratio was defined in equation 9. It is equal to the annual repair cost of pipe seismic damage divided by the annual cost of pipe replacement as a part of the current improvement program.

$$CR = EC_{repai} / EC_{replacement} \tag{3.1}$$

in which EC_{repair} and $EC_{replacement}$ are annual expected cost of repair of damaged pipes once earthquake occurs, and the annual cost of regular replacement which are explained in the following.

Tan and Shinozuka (1982) considered a probabilistic calculation of the expected repair cost performing a life cycle cost analysis of pipeline systems. The expected repair cost for a period of $T = 50$ years can be written as:

$$EC_{repair} = C_j \times T \sum_{i=1}^{N=5} \upsilon_i \times p_{ij} \times \frac{(1+r)^T - 1}{Tr(1+r)^T} \tag{3.2}$$

where C_j is cost of repair for each damage location, N is number of scenario earthquakes (five scenarios due to the existing scenario faults), υ_i is the annual probability of occurrence for scenario earthquake i, p_{ij} is the probability of damage for pipe j under earthquake i, and r is a discount rate of 4 % as considered in JWWA (2002).

In general, the pipeline replacement cost is deterministically estimated as $EC_{replacement} = C'_j \times L_j \times DC$, which C'_j is replacement cost of one meter of pipelines based on the pipe diameter, L_j is the length of pipe in meter, and DC is a discount factor can be considered in the first year of project or estimated as an annual rate during the T years. However, since the expected repair cost of a pipeline is calculated probabilistically, a probabilistic estimation of the annual cost of pipeline replacement is also considered. To do so, the probability distribution of the age of a pipeline can be included in the estimation. Alternatively, the annual rate of pipe replacement corresponding to annual replacement budget limitation can be included in the calculation to cope with the probabilistic calculation of pipeline replacement. In this regard, the annual pipe replacement rate for different types of pipe material during the past 15 years could be included in deterministic equation of replacement cost to make it probabilistic:

$$EC_{replacement} = C'_j \times L_j \times q_j \times \frac{(1+r)^T - 1}{r(1+r)^T} \tag{3.2}$$

where, q_j is the estimated annual rate of pipe replacement considering the annual budget limitation. For CIP, DIP and SP pipes, the annual rate of pipeline replacement by the waterworks bureau was considered 3.7%, 0.5% and 0.9%, respectively. Fig. 8 represents the cost ratio classification for pipeline network. To illustrate the validity of cost ratio calculation, the layer of estimated cost ratio of pipelines were overlaid with the most causative scenario earthquake of Uemachi fault which is able to produce the highest seismic activities in the study area. It is found that the pipelines located in the areas with higher peak ground velocity (PGV) show higher cost ratio.

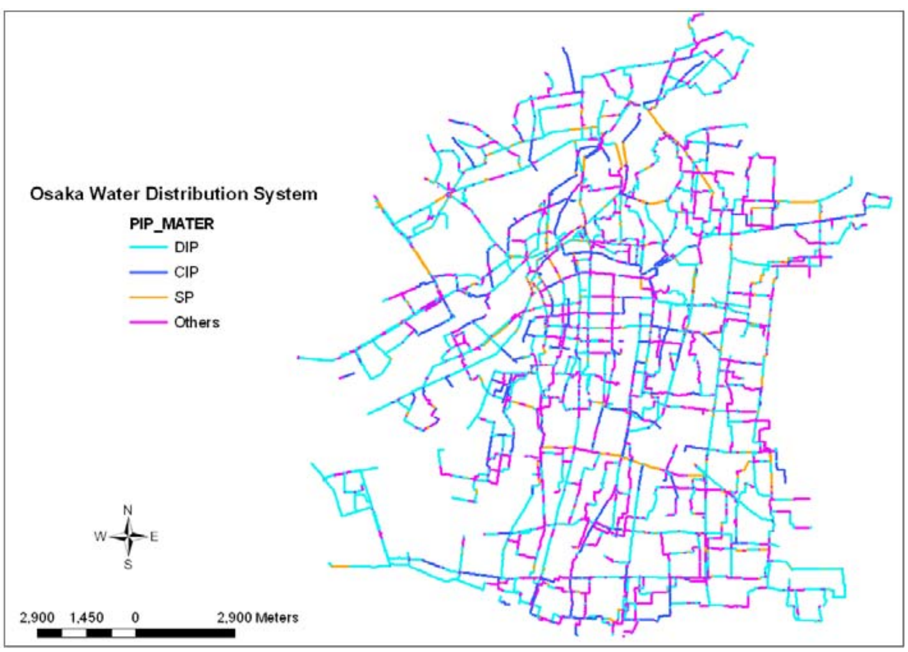

Figure 5. Classification of pipeline material

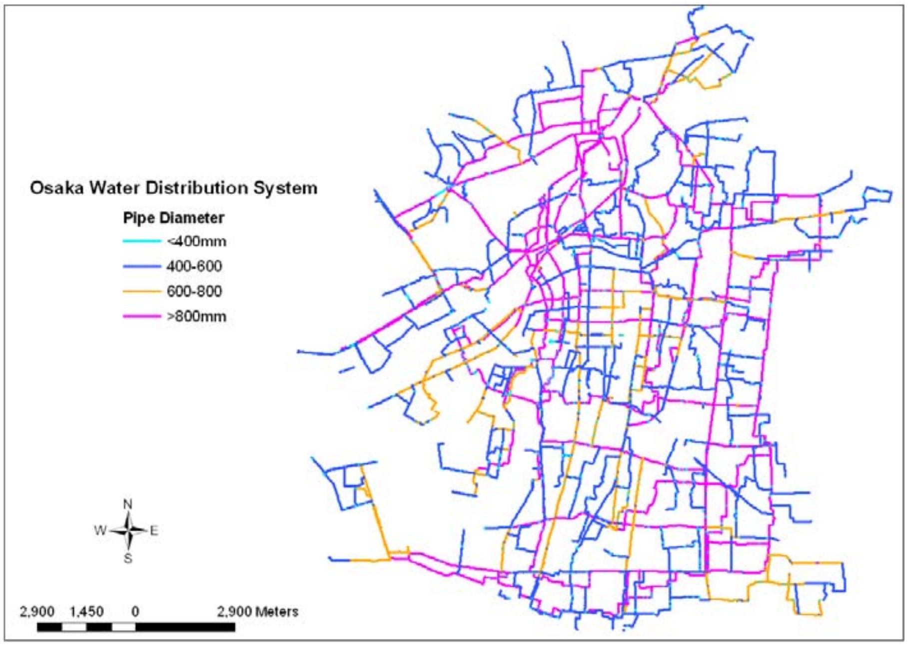

Figure 6. Classification of pipeline diameter

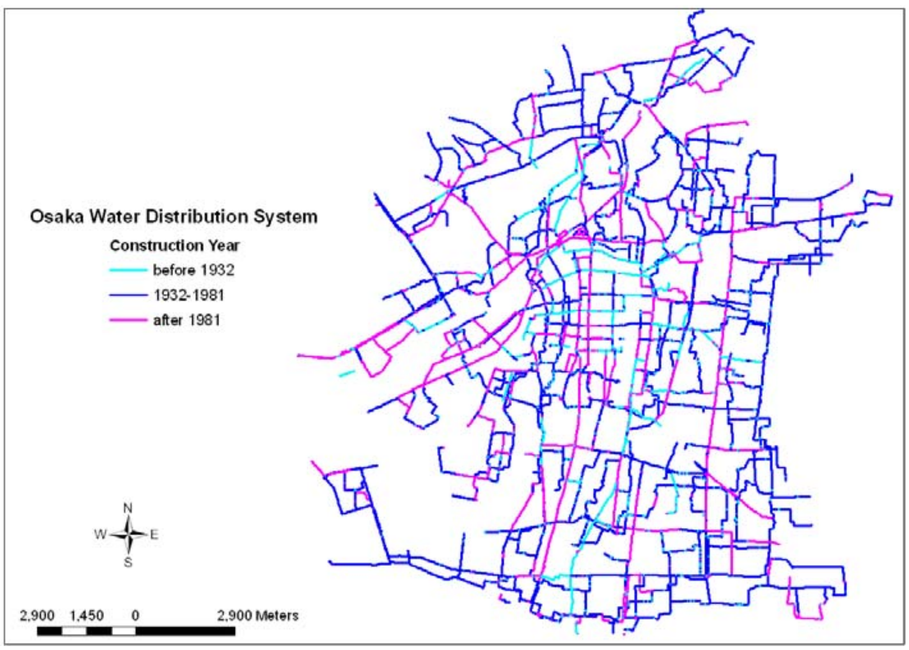

Figure 7. Classification of pipeline construction year

To estimate the pipelines restoration time, the compound damage ratio was computed as the probabilistic combination of damage rate (HAZUS, 1999) as follows:

$$DR_c = \sum_{i=2}^{3} DR_i \times P(ds_i) \tag{3.3}$$

where DR_c is compound damage rate of pipeline, DR_i is damage rate for each damage state, and $P(ds_i)$ is the probability of a pipe being in damage state $i = 1,2,3$, associated with damage state none, breakage and leakage. Due to the pipeline damage database of the 1995 Kobe Earthquake, Javanbarg (2008) reports 20% breakage rate and 80% leakage rate for CIP and 0% breakage rate and 100% leakage rate for DIP and SP pipelines. We have considered the same assumptions to calculate the compound damage rate of pipeline. Considering this compound damage rate, length of the pipelines and required time for repair of each damage location assumed from the experience of Hanshin-Awaji Earthquake, the restoration time for each pipe could be estimated. Moreover, the restoration time for one pipe on a route may not be considered as a proper indicator for required time of repair because each route includes several pipes and a route is considered to be restored when all pipes on that route are repaired. Hence, the restoration time of each route was estimated and assigned to its corresponding pipes (Fig. 9).

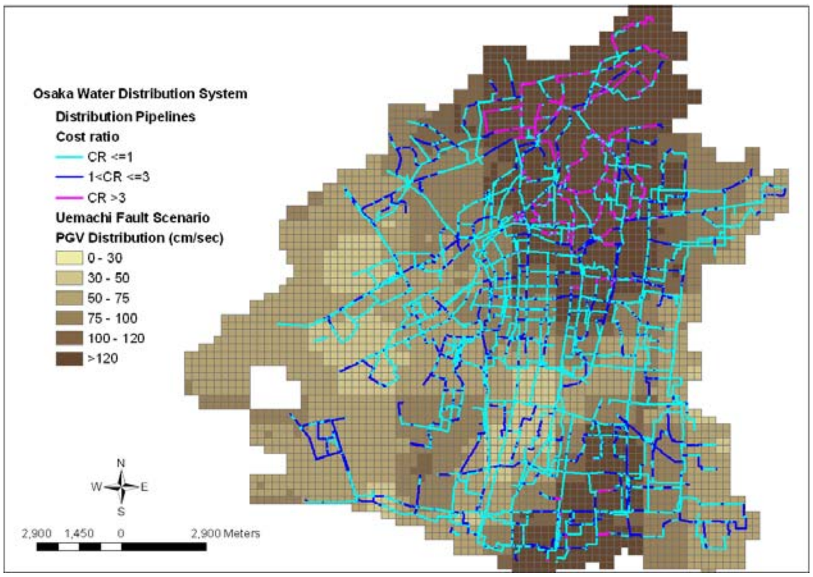

Figure 8. Classification of pipeline cost ratio

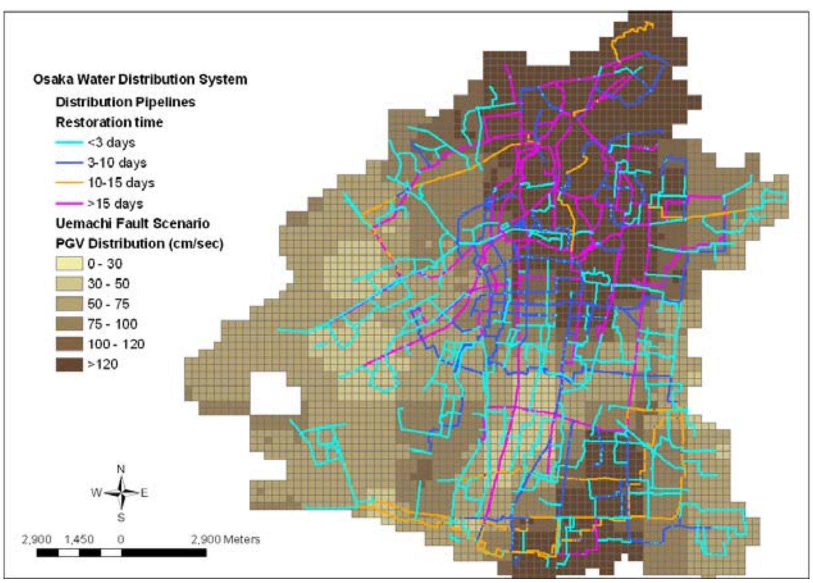

Figure 9. Classification of pipeline restoration time

4. RESULTS

After calculating the local priorities for criteria in terms of pipeline importance (level 2), pipeline properties (level 3), and properties categories (level 4) in Fig. 2, the global priorities of the alternatives (63 pipe groups) were then determined by aggregating the local priorities throughout the hierarchical structure. Based on these global priorities, the pipe groups can be prioritized for mitigation. The higher global priority, the higher the rank of pipe groups for mitigation could be. Considering the available annual budget of pipeline replacement for next 25 years, and knowing the length of pipelines, it is therefore possible to calculate the total annual length of pipelines with higher priority for mitigation based on the pipe groups' rank. The results are represented in Fig. 10. In this figure, 6 categories of pipeline replacement prioritization are presented in different colors. The dark color presents those pipes classified in one of the following three classes: 1) already replaced; 2) recently constructed, or 3) pipelines with aseismic joints. Other five colors show the pipelines prioritized for replacement in each 5 years time interval. To illustrate the relation between spatial distribution of pipeline replacement and seismic hazard pattern, the layer of prioritized pipe replacement was overlaid with the PGV distribution of Uemachi scenario earthquake (the most causative scenario) as depicted in Fig. 10. It is found that although most of pipelines located in higher PGV values have higher priority for replacement, other criteria such as pipeline importance as well as pipeline properties affect the prioritization procedure significantly.

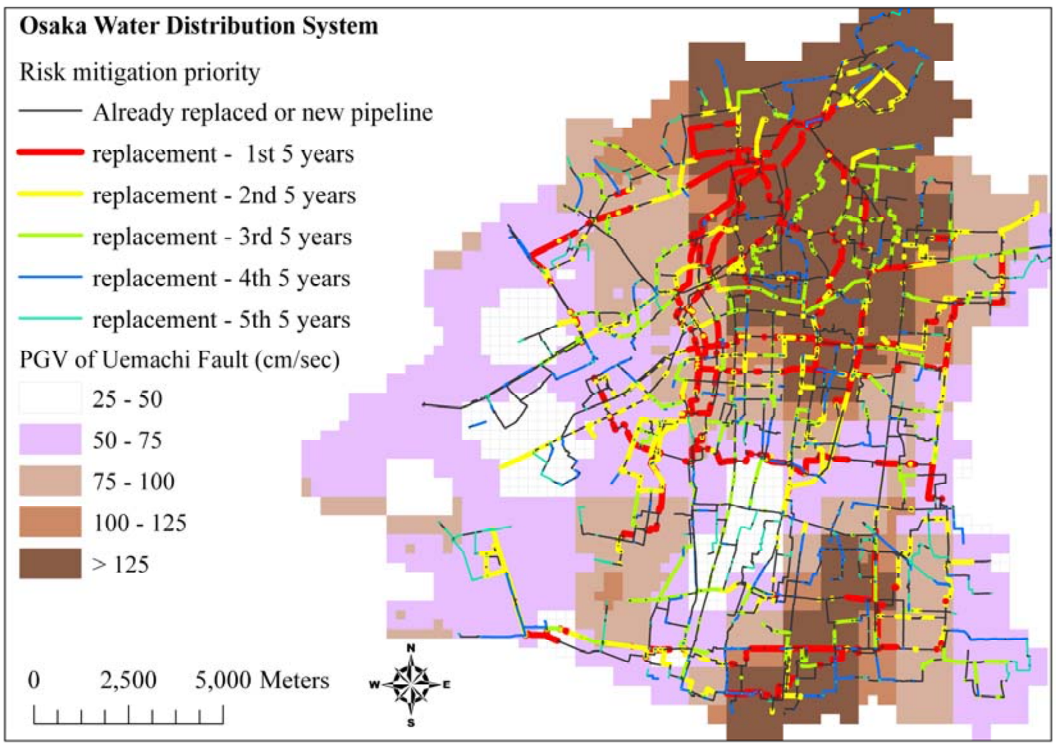

Figure 10. Risk mitigation priority of pipelines for a replacement plan in next 25 years

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