Post-earthquake Recovery Strategy of Old Urban District Water Supply Network Based on Segmentation

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Abstract. Abstract. China's small and medium-sized cities are experiencing problems such as the old urban pipe networks, the chaotic zoning of functions, the incomplete files, the backward disaster prevention planning and the low level of information management causing sluggishness and chaos in the recovery of their cities after earthquake. These problems have posed serious risks to Chinese people's lives and properties. In this context, the author proposed the segmentation strategy which is an economical, effective and low-cost strategic analysis method aiming to maximize the functional recovery of water supply for old urban district after the earthquake. Based on the reliability analysis of network connectivity and the calculation of pipeline's importance degree, the segmentation strategy helps to analyze the coordination relationship between the restoration of physical structure of the network and the water supply function from the perspective of space, and to discuss the mitigation plan including the function restoration target, the recovery steps and the project performance evaluation. With the application of the segmentation strategy, the author discovered the key node and pipeline routes of the water supply in the old urban area of Tieling City of China and obtained the solution of disaster prevention and mitigation of the urban water network. The research findings indicate that the post-earthquake recovery based on the segmentation strategy for the old urban pipe network provides a low-cost, practical and feasible alternatives.

1. Introduction

With the new policies of reform and opening up, China's urbanization peaked from 1978 to 1995, with the number of cities and towns rapidly increasing, the number of cities increased from 193 to 622 during that period [1]. However, in the construction of many cities and towns during this period, problems such as the backward infrastructure planning and the lack of archives management emerged. Nowadays, the issue of inadequate disaster prevention ability of the old underground pipe network constructed during this period is particularly outstanding. Sichuan Wenchuan Earthquake in 2008 (magnitude 8.0) [2], because of confusion in the planning of water supply function, missing of pipe network file in many old urban areas, which resulting in post-earthquake water supply restoration cannot be carried out orderly. According to statistics, the economic loss of urban and rural water
supply system caused by Wenchuan earthquake is about 5.8 billion yuan, some cities and counties still
cannot fully restore the water supply function for 2 months after the earthquake.

Water supply network covers a large area with a systematic, the impact of earthquake damage has a
large rage and long time. For the government disaster prevention and mitigation work, the restoration
of the urban water supply network after the earthquake is crucial for the post-quake fire prevention,
health and epidemic prevention, and the resettlement of the victims.

In 2000, at the 12th International Conference on Earthquake Engineering, a series of research and
practical results were published by scholars. Urban lifeline system in earthquake engineering research
has entered a new stage. Scholars of various countries have begun to use the system risk theory and
system engineering theory to study the urban lifeline system, earthquake prevention and post-
earthquake recovery theory research [3] [4].

Su Youpo [5] comprehensively summarized the research system of earthquake damage system of
lifeline system, mainly including: physical damage analysis, loss of function analysis, impact analysis
of seismic waves and the interaction between them. Study on recovery process of urban water supply
system after earthquake includes research contents of recovery prediction model, recovery strategy,
reliability evaluation and analysis.

In the next years, systematic dynamics, dynamic programming, genetic algorithms, and neural
networks have had a significant impact on the study of post-earthquake safe recovery of water supply
systems [6]-[9]. The results discussed the optimization problems including the prediction theory of
sequential recovery and simultaneous recovery, the prediction of recovery process and results, the
characteristics of post-earthquake recovery process, the structural damage and function recovery
model, the impact of recovery strategy on recovery process and the post-earthquake recovery.

It is considered as the basic work of urban disaster prevention and mitigation planning to formulate
a feasible water supply recovery strategy. Despite, a number of water supply network restoration
optimization information model was established, and relatively little progress has had been made in
those small and medium-sized old urban areas for pipeline network system of disaster recovery
planning and recovery strategy. There are practical problems such as unknown pipe network
information, unclear pipe network functions and inadequate detection staff after the earthquake. These
factors will have a significant impact on investment in disaster prevention, restoration steps and
recovery effects.

In this study, based on the reality of a large number of small and medium-sized old pipe networks
in China, we take the pre-earthquake urban water supply network, engineering conditions and existing
materials as the basic factors for research, analyze the failure mode of the target node of water supply
network which is the important object of disaster prevention and sets up the pre-earthquake planning
and post-earthquake recovery strategy with the risk theory so as to achieve the goal of reconciling the
cost of pipeline network restoration with the project investment. Referring to the application in
practice, pipe network stratified segmentation strategy proposed in this study is to be decided by
disaster prevention target level and disaster prevention input.

2. Methods

Step 1: Determine the analysis network. The target nodes include four types of key infrastructure
locations such as disaster prevention command center sites, emergency medical treatment and fixed
evacuation sites, large-scale secondary disaster hazard areas, secondary fire hazard sources and fire
water supply points. When determining the important categories of urban water pipelines, there is no
need to be too limited to the number of service nodes, which is the average number requirement for
each city. It should be specifically considered to set appropriate quantitative targets for specific cities.
The starting node determines the scope of pipe network analysis for the water supply node of the
waterworks.

Step 2: Calculate the importance degree [10]. Establish the reliability model of the pipe network,
input the working parameters of the pipeline, calculate the reliability of the network connection of the
target node of the water supply network to the starting node, and calculate the probability importance degree and critical path importance degree of each pipe segment according to the earthquake grade.

Step 3: Pipeline stratified segmentation. Take the urban area of about 1000km water supply line as a unit, according to the calculation results in step 2, roughly 1% to 5% of the pipelines are rated as Grade I, 10% to 20% of pipelines are rated as Grade II, and 75% to 85% of pipelines are identified as Grade III, about 5% or less of the pipeline identified as grade IV. Refer to Table 1 for the grading of the importance of pipeline.

Table 1. Classification of the importance of water supply pipeline disaster prevention.

| Grading | Classification of Importance | Destructive consequences | Description of Importance |
|---------|------------------------------|--------------------------|---------------------------|
| 1       | Extremely Important          | Extremely Serious        | Disaster and post-disaster functions cannot be interrupted, the city emergency relief and safety necessary to restore the important pipeline. |
| 2       | Very Important               | Very Serious             | Pipelines that supply a large number of users, once the damage to the urban area has a significant economic impact or the occurrence of secondary disasters that affect the safety of life |
| 3       | Important                    | Serious                  | Ordinary pipelines that does not belong to the level of I, II, IV in water supply system |
| 4       | General                      | Not Serious              | Once the damage has little impact on public life and safety, no adverse effects on the water system protection function and emergency response and recovery after the disaster, large-scale destruction will lead to long-term recovery (a few weeks or longer) without significantly damaging the city disaster life or recovery of the normal activities conduct. |

Step 4: Failure mode analysis and strategy analysis. The failure state refers to the recovery of urban water supply network system according to the corresponding procedures and methods, failed to achieve the desired recovery effect. Failure mode analysis is generally based on the study of urban earthquake probability, carried out from the different seismic levels. Strategic analysis includes:

1) Regional functional analysis. Which areas are the key water supply areas after the disaster protection function and which pipelines are responsible for supplying water.

2) Redundant analysis of pipeline network. Which pipelines need to be added to ensure the reliability of the post-earthquake network system.

3) Analysis of key pipeline reinforcement. Which pipelines in the pipe network need to be reinforced to ensure supply reliability.

Restoration sequence analysis: Which network parts need to be detected for the first time after the disaster and which pipes need to be temporarily isolated to stop water supply.

Step 5: Write a recovery strategy analysis report. Summarize the design problems that cannot be corrected and describe the necessary measures to prevent failure or to control the risk of failure.

3. Analysis of water supply recovery strategy in Tieling

Taking Tieling city as an example, this paper illustrates the application of stratified segmentation strategy. The distribution of water works and main pipelines in Tieling city is shown in FIG. 1. Most of the main water distribution pipelines in the urban water supply system have been connected into a ring. Some of the sub-arterial roads or urban-rural pipelines are still branched, and some of the branch pipe networks are not shown in the figure.
Figure 1. Main water supply pipelines and model in Tieling city

Step 1: Determine the analysis network. The location of node 21 in the figure is the post-earthquake recovery command center and hospital, which belongs to the service targets of the key urban pipeline. It is an important guarantee for the prompt restoration of urban functions after the earthquake. Therefore, this node is identified as a target node.

Step 2: Calculate the importance degree. The connection reliability analysis of node 21 and water plant nodes, and the pipeline importance degree analysis was carried out. The results are shown in Table 2 and Table 3.

Step 3: Pipeline stratified segmentation. According to the importance degree results and grading standards of water supply pipeline disaster prevention importance in Table 1, the network area is stratified to determine the key pipe network layout plan. The outer branch of the main pipe network sets the valve, especially in dense branch pipe network; Key pipe network set up the valve to achieve the key pipe network and urban trunk pipe network segmentation. Proposed calculation of pipe network node 6, node7, node8, node19 and node20 set valve wells to facilitate repair after the earthquake. It is suggested to set up emergency water supply points at the locations as shown in the diagram. Since the water supply of emergency water supply points is taken from the key pipe network, the basic domestic water for residents can be guaranteed during the post-earthquake emergency recovery stage.

Table 2. Reliability calculation results and evaluation of node 21.

| Seismic grade | Specific node reliability | Reliability evaluation          |
|---------------|---------------------------|---------------------------------|
| magnitude-6.0 | 96.00%                    | reliable                        |
| magnitude-7.0 | 84.76%                    | slight unreliability            |
| magnitude-8.0 | 53.33%                    | medium unreliable               |

Taking the magnitude-7.0 earthquake as an example, the probability importance degree and critical path importance degree of each section are shown in Table 3.

Critical path importance degree
$I_{Pr_i}$, Probability importance degree. $\overline{Q_I}_{Pr_i}$, Critical path importance degree.

### Table 3. Probability importance degree and $X_i$

|   | X1   | X2   | X7   | X8   | X9   | X10  | X11  | X12  | X15  |
|---|------|------|------|------|------|------|------|------|------|
| $I_{Pr_i}$ | 0.2276 | 0.0306 | 0.0337 | 0.0769 | 0.1968 | 0.0997 | 0.0606 | 0.0215 | 0.1892 |
| $\overline{Q_I}_{Pr_i}$ | 0.0438 | 0.0029 | 0.0060 | 0.0136 | 0.0348 | 0.0192 | 0.0058 | 0.0027 | 0.0297 |
|   | X16  | X17  | X18  | X19  | X20  | X21  | X22  | X23  | X24  |
| $I_{Pr_i}$ | 0.1729 | 0.0434 | 0.1712 | 0.1572 | 0.0686 | 0.0451 | 0.0440 | 0.2686 |   |
| $\overline{Q_I}_{Pr_i}$ | 0.0272 | 0.0041 | 0.0323 | 0.0183 | 0.0080 | 0.0052 | 0.0042 | 0.0507 |   |

Step 4 and Step5: Failure mode analysis and strategy analysis.

**Failure Mode One:** When the pipe network is under the effect of seismic intensity of magnitude-6.0, the selected main pipe network of the city is in good condition and can operate well after the earthquake to ensure the urban water supply needs. Pipeline may have leaks, leak detection and pipeline maintenance with small diameter, the older pipeline as the key target, the individual branch of the pipe network maybe leak. As there maybe leakage occurred, we should strengthen the epidemic prevention of tap water testing.

**Figure 2. Key water supply pipelines and pipe network segmentation in Tieling city**

Failure Mode Two: When the pipe network is under the effect of seismic intensity of magnitude-7.0, the main urban pipe network is basically intact and can basically meet the demand of the functions of urban water supply. The main pipe network gives full play to the system redundancy and works with leakage; Some branch pipelines have been damaged, thus should strengthen the epidemic
prevention and water quality testing. After the earthquake, it is possible to shut down the main branch pipelines of the main pipe network for leak detection and maintenance as soon as possible.

At the same time, key pipelines shall be leak-checked and repaired according to the key reliability of each pipeline of the main pipe network. According to the calculation results of Table 3, pipeline $X_{24}, X_{1}, X_{9}, X_{15}, X_{16}, X_{18}, X_{19}$ in FIG.1 should be leak-checked and repaired in the first time after the earthquake. It is proposed to reinforce, repair or replace part of the main pipe network to ensure the safety of key pipe network pipelines and to set up emergency water supply points along the key pipelines, as shown in FIG. 2.

Failure Mode Three: When the pipe network is under the effect of seismic intensity of magnitude-8.0, the city's main pipe has certain damage, the key pipelines are basically intact, the outer branch pipelines of the main pipe network are greatly damaged, and some pipelines and networks lose the basic functions of urban water supply demand. After the earthquake emergency phase, after the earthquake in the first time, you can close the value outside the key pipe network (one or two pipelines) for leak detection recovery, residential water supply by planning emergency water supply point. The key pipe network is based on the probability and critical importance of the pipelines, and the calculation result of nodes where each specific disaster prevention object is located and other water supply requirements. Calculate the key pipelines of the pipe network as shown in FIG.2, plus the black pipelines. The dotted circle is the range of the selected pipe network. After the completion of the key pipeline in the first time after the earthquake recovery, enter the second failure mode to resume working mode.

In order to protect the water supply function of node 21 in failure mode three, namely 8 degrees earthquake, it is suggested to add a trunk pipeline between node14 and node15 to increase the redundancy of the calculated pipeline network.

Pipeline Z6 directly provides water source for node 5 in FIG. 1 which is of high importance. Due to the crossing of the hills, traffic congestion may occur after the earthquake, which making it difficult to repair. It is suggested to improve the anti-seismic capacity of the pipeline. The pipe should adopt thick-walled steel pipe and adopt the welded joint, and the joint of the upper and lower level should adopt the anti-seismic joint.

4. Discussion
The main purpose of the stratified segmentation strategy is to straighten out the effectiveness of the network through stratified segmentation so as to overcome the existing unfavorable conditions in the old urban area to the utmost extent, make the pre-earthquake planning and post-earthquake restoration as a whole unified, make the disaster recovery orderly, efficient and low cost.

4.1. Reliability and risk management
The hypothesis of the study is that the city water supply network earthquake disaster can be described by the concept of risk, that is, which R represents the risk of damage to the water supply network, indicates the possibility that the network cannot reach the expected recovery goal and indicates the consequences of a specific network failure severity. Compared with the reliability theory of urban water supply network, the concept of risk is more comprehensive, more quantitative to reflect the relationship with people, engineering and society, and also is a more scientific, comprehensive and systematic evaluation and management techniques. The concept of risk not only focuses on project safety, pays more attention to public safety, emphasizes on risk management, focuses on forecasting, prevention, early warning and contingency planning, but also reflects the systematic and integrated disaster management. Considering from China's national conditions, the earthquake resistance and disaster prevention of old urban water supply network should not only pay attention to the possibility of network failure itself, but also consider the seriousness of the consequences of network failure. The stratification strategy provides a framework for disaster prediction, seismic damage analysis, recovery and economic analysis of the old urban water supply network so as to comprehensively manage the earthquake and disaster prevention of the network.
4.2. Segmentation and reliability
Many old urban areas in China is not clear on the division of disaster prevention function in the planning of water supply network. In addition, the vulnerability of the old pipe network structure reduces the overall disaster prevention capability of the pipe network system, the higher the earthquake grade, the destruction of the pipe network accelerated, and the dependency of pipe network restoration on the connectivity of the pipe network showed a decreasing trend. Earthquake grade reached a certain level, and even the entire pipe network system damage, loss of water supply function, which was evident in the Wenchuan earthquake in China. Stratified segmentation strategy is not to weaken the network connection of pipe network system. On the contrary, this strategy aims to strengthen the connectivity reliability of key networks through stratified segmentation so as to achieve the goal of disaster prevention and reduction.

4.3. Segmentation and informatization
The application of information technology represented by 3D-GIS is the development trend of disaster prevention and safety of urban water supply network, and it will surely bring about revolutionary changes to urban disaster prevention and mitigation. The research strategy in this paper does not exclude informatization, but the degree of dependence on informatization is not high. On the contrary, if it has the latest information technology guaranteed, the segmentation strategy will be implemented more efficiently.

5. Conclusion
From the results of case strategy analysis, we can find that the target of stratified segmentation strategy is clear, direct and effective, especially for small and medium-sized pipe network, which is feasible and low cost. We also noted that:

Using this strategy can make the cost of renovation of municipal facilities effectively controlled, and the quantitative analysis of earthquake damage risk provides the basic data for the coordination analysis of disaster prevention investment cost and disaster prevention effect.

Using this strategy can complete disaster prevention planning and post-earthquake recovery program formulation under the case of that the degree of information is not high, and even some pipe network information is lacking.

Using this strategy can realize the grading, batch and sub-period pipe network post-earthquake detection and repair, and it can maximize mitigate the tension problems of maintenance engineers after the earthquake and realize an orderly and efficient recovery.

Predictably, the development of the integrated disaster prevention planning, the construction of integrated urban safety and disaster prevention system and the establishment of comprehensive defense system of regional and urban agglomerations are the development directions of urban disaster prevention. The research on post-earthquake recovery strategies and countermeasures of water supply network will be embedded in the integrated urban safety with the development of disaster prevention standardization technology, promote the comprehensive disaster prevention ability of the city. Disaster recovery in the old urban water supply network has a certain stage and time sequence, and the coupling with other lifeline systems is also obvious such as water supply construction, water supply equipment, transportation and electricity and so on. It is recommended that more strategies under the coupling effect of lifeline disaster can be developed through research in order to increase our understanding on disaster prevention and mitigation strategies to achieve water security.

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