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RATIONAL DESIGN OF BURIED WATER PIPE SYSTEM

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SUMMARY

A methodology is presented to provide an assessing method to evaluate the relative adaptability of the buried water pipe systems which is subjected to earthquake loading. Localized weight of the pipe segment and the probability of failure of the pipe segment due to seismic loads are the main assessing factors. Objective function of the design project for the buried water pipe system is defined as a weighted sum of a number of desirable properties which are the probability of failure of localized segment. Practical examples are performed to demonstrate the application of the method.

INTRODUCTION

Follow the mathematical model developed by Wang (Ref. 1) and Shinozuka and Koike (Ref. 2), Hsu and Tsai (Ref. 3) derived a method to calculate the probability of failure of the water pipe system. In which, joint failure due to relative displacement at joint and segment failure due to strain failure of material are concerned. However, probability of failure of the concerned pipe system can only reveal the safety of the system (or the structure) itself. Once the application function of system is concerned, probability of failure may not be enough to assess the good or bad of the whole system. For instance, when the water pipe system are considered, as the structure is constructed over the whole urban area, the good or bad of the whole water supply system should be assessed according to the supply manner of the water over the whole areaand must be influenced by the supply quantity of the water from various pipe segment. The lower stream pipe is not so important as upper stream pipe. Even the probability of failure of segments at two different site are same, their influence to the whole system is different. On the point of view of the failure cost, the pipe supply the water to the low density population district is not so important as the pipe supply the water to the high density population district. In other words, the local weight of the pipe segment according to their district can not be ignored. When the whole water supply system is going to be assessed. According to the concept of the optimum design, the objective function, which would be trying to be minimized, can be derived as a weighted sum of number of desirable properties (Ref. 4). In our water supply pipe system, the objective function can be assigned follow the same concept. The probability of failure of each local pipe section representing the desirable property of that pipe section, while the weight of the local pipe section are calculated according to their location and water quantity supplied. Then the equation can be rewritten as

$$D.\,I. = \sum_{i=1}^{n} W_i \; P_{f,i} \qquad (1)$$

Where $P_{f,i}$ is the probability of failure of the pipe at the ith district; W_i is the weight of the pipe at the ith district. This weighted sum of probability of failure is then called the damage index (D.I.) of the whole pipe system of the concerned urban area. A case study of assessment of the pipe system at Tainan City area is performed in the project. Probability of failure of the pipe segment due to seismic load is calculated by the pre-mentioned previous work. It is recognized that the weight of different pipe segment is affected by many factors, population distribution and the water quantity supplied by distinct pipe are considered herein as the main factors in weighting calculation. Information needed for this case study including pipe distribution, water consuming in different area along pipe system, soil properties, seismic loading, joint type, material properties of pipe segment, ... etc, are collected from various companys and proper agencys (Refs. 5,6,7,8,9).

WEIGHTING DETERMINATION

Weight of the distinct pipe is determined by the water supply quantity controlled by this pipe. In order to calculate the controlled quantity of water supplied by each pipe section, the principle followed are : the failure of the lower stream pipe does not influence the supply function of the upper stream pipe and the failure of the upper stream pipe does influence the supply function of the lower stream pipe. Totally thirty four regions are divided through the city of Tainan as shown in Fig. 1. According to the surveyed results, the controlled water quantity of each pipe can be calculated and the weight of each pipe are then calculated by the following formula

$$W_i = \frac{C_i}{\sum_{i=1}^{34} C_i} \qquad (2)$$

Alternatively, W_i can be estimated by the following regulation:

The combination of pipe system are modelled in four basic types. They are 1. divide type, 2. combine type, 3. combine-divide type, and 4. divide-combine type. Let M_i denoting the relative importance of the i^{th} pipe segment according to the district characteristics ; w_i stands for the weight of the i^{th} segment; Q_i stands for the water flow quantity of the i^{th} pipe segment. Four mentioned basic types are shown in Fig. 2 and the weight of each of their pipe segment can be formulated as following:

1. divide type:

$$w_1 = M_1 + (M_1 + M_2) \;; \qquad w_2 = M_2 \;; \quad w_3 = M_3$$

2. combine type:

$$w_1 = M_1 + \frac{Q_1}{Q_1 + Q_2} M_3; \qquad w_2 = M_2 + \frac{Q_2}{Q_1+Q_2} M_3, \quad w_3 = M_3$$

3. combine - divide type:

$$w_1 = M_1 + \frac{Q_1}{Q_1+Q_2}(M_3+M_4) \;; \quad w_2 = M_2 + \frac{Q_2}{Q_1+Q_2}(M_3+M_4)$$

$$w_3 = M_3 \;;\; w_4 = M_4$$

4. divide - combine type:

$$w_1 = M_1 + M_2 + M_3 + M_4 + M_5 + M_6 + M_7 + M_8 \;;$$

$$w_2 = M_2 + M_4 + M_7 + \frac{Q_4}{Q_4+Q_5} M_6 \;; \qquad w_3 = M_3 + M_5 + M_8 + \frac{Q_5}{Q_4+Q_5} M_6 \;;$$

$$w_4 = M_4 + \frac{Q_4}{Q_4+Q_5} M_6 \;; \qquad w_5 = M_5 + \frac{Q_5}{Q_4+Q_5} M_6 \;;$$

$$w_6 = M_6 \;; \quad w_7 = M_7 \;; \quad w_8 = M_8$$

Finally, the weight of each pipe in the whole pipe system is converted into normalized weight by the formula

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{3}$$

PROBABILITY OF FAILURE OF PIPES AT REGIONS

Probability of failure of the pipe system with m-pipe segments and n-joints in the region i can be calculated by the following formula (Ref.3)

$$p_{f,i} = \sum_{m=1}^{m} p^{s}_{j,i,m} + \sum_{n=1}^{n} p^{j}_{f,i,n}$$

$$= \sum_{m=1}^{m} \sum_{I=1}^{12} (p^{s,I}_{f,i,m} \times P(I_{MM}=I)) + \sum_{n=1}^{n} \sum_{I=1}^{12} (p^{j,I}_{f,i,n} \times P(I_{MM}=I)) \tag{4}$$

Where the superscript s stands for the strain failure and the superscript j stands for the joint failure. The terms $p^{s,I}_{f,i,m}$ and $p^{j,I}_{f,i,n}$ are calculated according to the following two formulas.

$$p^{j,I}_{f,i,m} = P\{((\text{strain resistance or allowable strain}) \leq (\text{strain induced by applied seismic load}))\,|\,I_{MM} = I\} \tag{5}$$

$$p^{j,I}_{f,i,n} = P\{((\text{allowable joint relative displacement}) \leq (\text{joint relative displacement induced by seismic load}))\,|\,I_{MM} = I\} \tag{6}$$

Pipe types in these 34 regions, from the surveyed information, are more or less modified in later on calculation.

Three typical types of pipe used are : prestressed concrete pipe (PSCP), steel pipe (SP) and cast iron pipe (CIP). Their properties are listed in Table 1 (Ref. 7,8)

Table 1 Properties of pipes (Ref. 7, 8)

Type	Young's modulus (10^6 kg/cm^2)	Yielding stress (kg/cm^2)	Yielding strain
PSCP	0.294	400	0.0013
SP	2.000	2300	0,0011
CIP	0.900	2250	0.0025

The system subjected to the seismic load of I_{MM} = 5.4 which is from the record of an earthquake occurred on April. 14, 1976, with the epicenter sited about ten miles from Tainan. Since the Intensity of the earthquake is small, the calculated probability of failure of the pipe segment is so small when compared to the joint failure probability. It is neglected in this project.

CALCULATION OF DAMAGE INDEX

Substitute the results obtained from the previous two sections in equation (4), and then equation (1), the Damage Index which is an objective value for assessing the whole pipe system can be obtained, Consequentely, the D. I. of Tainan City is found to be D.I. $=\Sigma W_i P_{f,i}$ =49.735 E-4 in this particular case study.

CONCLUSION

The assessment of water pipe system can be performed by the presented method. Various designs of the water pipe system in the same urban area lead to different values of Damage Index. As a matter of fact, another design has been done and corresponding damage index has been calculated. For the same amount of water supply in Tainan City, value of damage index can be reduced to almost half of the value calculated in the above section.

For those of ring typed pipe system, instead of tree typed pipe system, Hardy cross method can be used to calculate the balanced controlled water quantity which is needed for the weight calculation.

The value of D.I. is limited between 0 and 1 (i,e.$0 \leq$ D.I. ≤ 1). The smallest D.I. corresponding to the best design. In this project, pipe direction is assumed to be coincided to the orient of the seismic wave propagated for the sake of simplifying the calculation task. In order to have more efficient results, oriented problem should be considered. A case with wave orient problem considered is performed. Pipe system with its general information (length, diameter) is shown in Fig. 3. Balanced flow quantity can be found and is also shown in Fig. 3. Normalized weight of each pipe segment are claculated according to equation (3), with M_i are assumed to be proportional to pipe length, and the results are presented in Fig. 3 beside each of the pipe segment. Damage index is calculated and plotted with respect to the wave direction θ in Fig. 4. It is shown that wave direction is a significant factor in assessment of the pipe system.

ACKNOWLEDGMENTS

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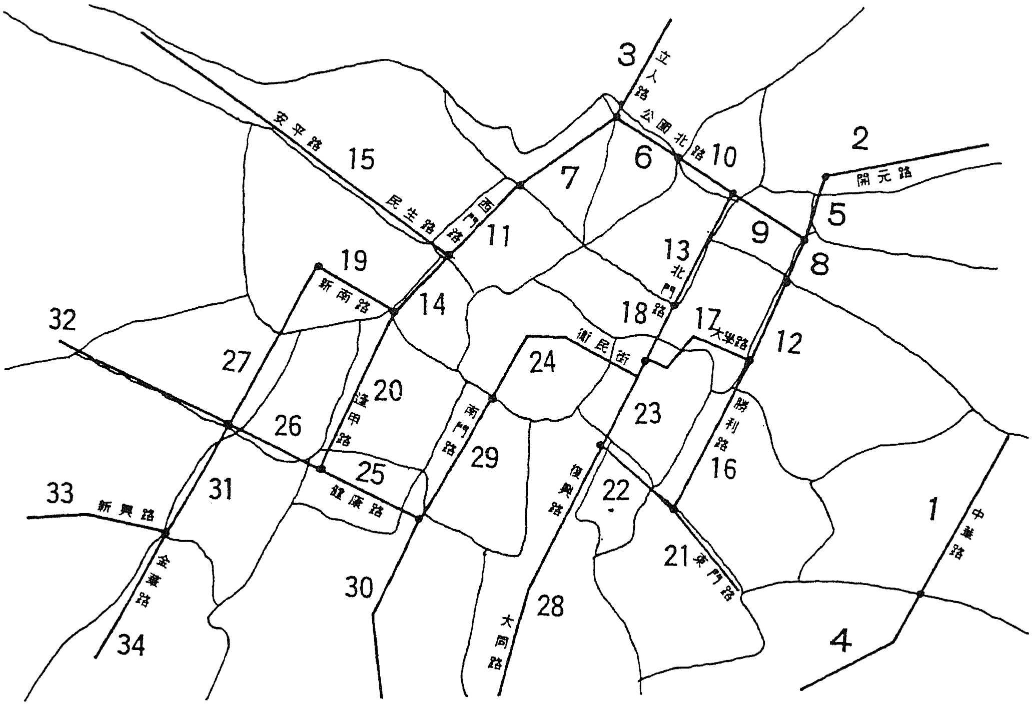
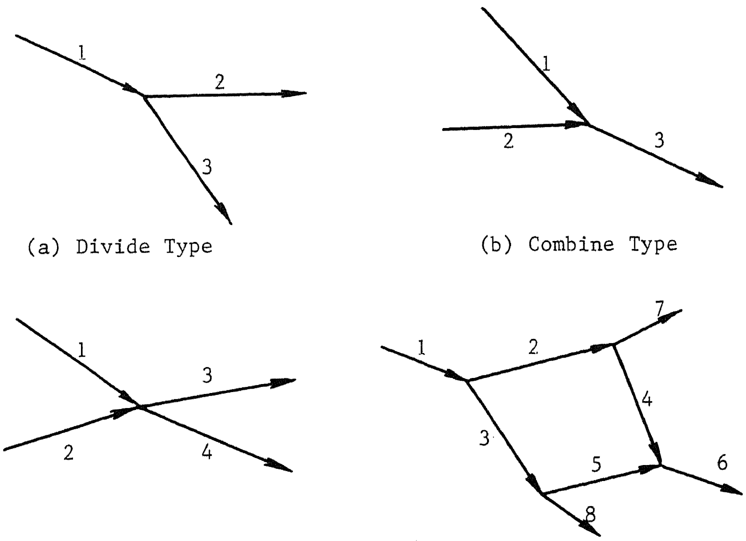


Fig. 1 Main pipe constructed in Tainan Area



(a) Divide Type

(b) Combine Type

(c) Combine-divide Type

(d) Divide-Combine Type

Fig. 2 Four Basic Types

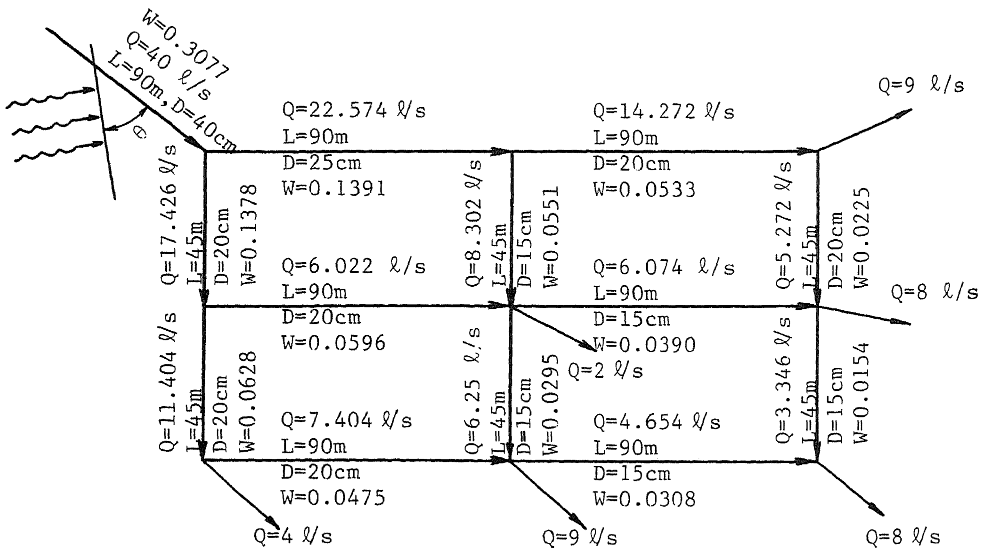


Fig. 3 Simulated Water Pipe System

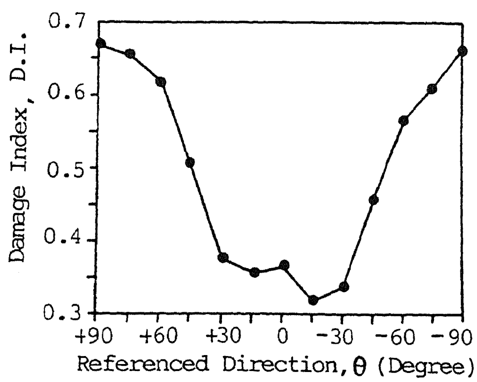


Fig. 4 D.I. of the Water Pipe System