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OPTIMAL RESTORATION STRATEGY OF A WATER PIPELINE NETWORK IN SURIGAO CITY, PHILIPPINES

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ABSTRACT: Quick recovery of water services immediately after an earthquake is critical. This is to minimize hazards to environmental sanitation and consequent health problems caused by the lack of potable water supply. It is necessary therefore that water lifeline operators establish restoration strategies to deal with damage scenarios in their respective concession areas specifically during extreme seismic events. The recent 6.7 magnitude earthquake in Surigao City due to the movement of the Philippine Fault Zone: Surigao segment underscored this need. However due to the complexity of the network a systematic restoration sequence that minimizes restoration time and maximizes delivery of water service should be employed. In this research, the authors employed Horn's algorithm to determine the optimal restoration strategy of a pipeline network in Surigao City, Philippines. The repair sequence starts with the determination of a minimal spanning tree of the given pipeline network. The water source is designated as the root of this tree while the nodes represent the water demand at specific areas. The edges of the tree structure representing the pipelines connect the nodes. The assigned numeric value or weight of an edge (link) denotes the time to repair that specific pipeline. This value is a function of the length of the pipeline. The results show that an optimal job sequence may be carried out by considering maximal ratios of expanding family trees within the network. A least penalty function is a consequence of the optimal repair job sequence.

Keywords: water lifeline, seismic event, Horn's Algorithm, minimal spanning tree, penalty function

1. INTRODUCTION

The Philippines is frequented by extreme wind speeds (typhoons), earthquakes, extreme floods and thunderstorms due to its geology and geographic setting. Strong magnitude earthquakes which are considered as the most destructive is a constant threat to the country's built environment. The recent earthquakes in the country, e.g, Bohol Earthquake 2013, Batangas Earthquake 2017 and the Surigao Earthquake 2017, have shown that built structures such as schools, hospitals, power supply system (Mallari and Cinco, 2017), historical structures (Luces,2013) and water lifeline systems (Crismundo, 2017) can be damaged during strong ground motion events. In this regard, quick recovery of vital lifeline systems damaged by earthquakes is critical for post-earthquake activities. However, it should be emphasized that pre-disaster programs should be established to assess the vulnerability of the system and to manage the risk when a hazard strikes. The recent earthquake in Surigao del Norte that pulled-out some of the pipes from the support underscored the need to prepare contingency plans when ground strains exceed the capacity of buried pipes.

There have been several studies to manage lifelines under earthquake risk (Kameda 2000), optimize restoration of electric power, i.e. (Chi et. al. 2002), utility lifelines (Nojima 2012), redundancy index of lifeline systems (Hoshiya and Yamamoto 2002). In 2004, Ueno et. al. developed fragility curves of components of a gas system in Teheran due to seismic loads. On damage estimation, Toprak and Taksin (2007) estimated the buried pipeline damage relationships using eight scenario earthquakes. On the other hand, a stochastic simulation model of damage and restoration of water supply systems was presented and applied to Bay Area water supply systems under hypothetical earthquake scenarios (Porter 2016). Finally, Khin Aye Mon et al. proposed a simplified seismic design guidelines for buried pipelines for developing countries. In this paper, the authors discuss an algorithm first proposed by Horn [10] and then apply it to a water network system to determine an optimal repair sequencing of the damaged pipeline network.

2. STUDY AREA

Surigao City is the capital city of Surigao del Norte located in the southeastern part of the Philippines. The city proper is composed of three barangays namely: Washington, Taft and San Juan as shown in Figure 1. The city has a population of about 140,540 with a land area of 245 km^2.

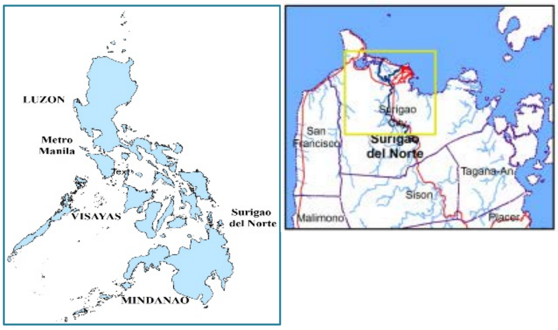

Fig.1 Study area

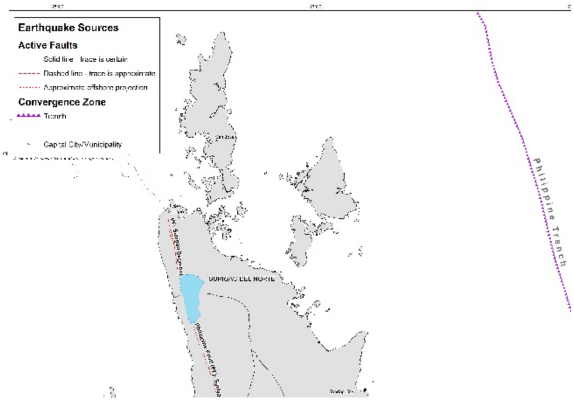

Fig. 2 Active Faults / Trenches in the study area

Fig. 3 SMWD pipe network system

Data from the Philippine Institute of Volcanology and Seismology (PHIVOLCS) show that the main earthquake generator around Surigao del Norte is the Philippine Fault Zone: Surigao Segment (see Fig. 2).

The water system operator of Surigao City is the Surigao Metropolitan Water District (**SMWD**). The pipeline network of the study area is shown in Figure 3. Data of the network provided by SMWD show that pipeline network consists of 416 nodes (junctions) and 415 links (pipes). Table 1 shows a sample data links with connecting nodes *i* and *j* and their lengths. The weight of each edge is assumed as the length of the edge.

Table 1. Link / Length of each pipe

Link	Node *i*	Node *j*	Length (m)
448	352	354	1432
564	354	355	425
562	348	347	1531
444	348	349	581

3. MATHEMATICAL FORMULATION

3.1 Minimum Weight Spanning Trees

Mathematically, a network consisting of nodes and edges linking the nodes may be denoted by a graph. A *graph is a* pair $G = (V, E)$ of non-empty sets V and E where E consist of two element subsets of V. The elements of V are the *vertices* or *nodes* of G and those of E are the *edges* or *links* of G. A *tree* is a connected graph with no closed paths called cycles. A *rooted tree* is a tree with one vertex designated as a root. A union of trees is called a *forest*.

A graph $H = (V', E')$ is called a spanning subgraph of $G = (V, E)$ if $V' = V$ and $E' \subseteq E$. If each edge e of a graph is assigned a real number $w(e)$ called its weight, then G is called a *weighted graph*. In the restoration work of a damaged network, a basic step is to find a minimum weight spanning tree of the network, that is, a tree which contains all the vertices of the network and whose edges have the least total weight. Such minimum weight spanning tree is obtained using Kruskal's algorithm which consists of intially arranging the edges in order of increasing weights. Edges that keep the graph connected and total weight minimum are then chosen. More information on Kruskal's algorithm may be found in [9].

3.2 Horn's Algorithm

In applying Horn's algorithm [8] to determine the optimal repair sequence of a damaged network, there are two assumptions: a rooted forest N is given and the vertices follow a precedence relation P. We say that x *precedes* y or xPy if there is a directed path from x to y in N. To each vertex x in the rooted forest, two nonnegative values $V(x)$ *and* $T(x)$ are assigned corresponding to the value of the restoration job at vertex x and the time to complete the job at node x respectively. The best ratio at x, denoted by $r(x)$, is defined as

$$r(x) = \max\left\{\frac{V(S)}{T(S)} : S \in T[x]\right\} \qquad (1)$$

where $T[x]$ denotes the set of all trees rooted in x and

$$V(S) = \sum_{u \in S} V(u) \qquad (2)$$

and

$$T(S) = \sum_{u \in S} T(u). \qquad (3)$$

A maximal family tree of x, denoted by F_x is an element of $T[x]$ for which the best ratio is achieved.

In order to find an optimal repair sequence, Horn defines a sequencing σ as a bijection $\sigma : V \longrightarrow \{1,2,3, \ldots, n\}$ assigning to each vertex $x \in V$, its position number $\sigma(x)$ in the repair sequence. An allowable sequencing is a sequencing σ with the property that if xPy, then $\sigma(x) \leq \sigma(y)$. Finally a linear delay penalty function is defined as

$$f(\sigma) = \sum_{x \in X} V(x)\left(\sum \{T(y) : \sigma(x) \leq \sigma(y)\}\right). \qquad (4)$$

This function is a measure of the penalty caused by delay in completion of the repair job at a node x. Thus, the objective is to find an allowable sequencing σ which gives the least linear delay penalty.

The methodology consists of three components:

1. Given a network, find a minimal weight spanning tree.
2. For each node x in the network, calculate the best ratio $r(x)$ and the maximal family tree F_x.
3. Generate the optimal repair sequence of the network based on the best ratios obtained and calculate the linear delay penalty function.

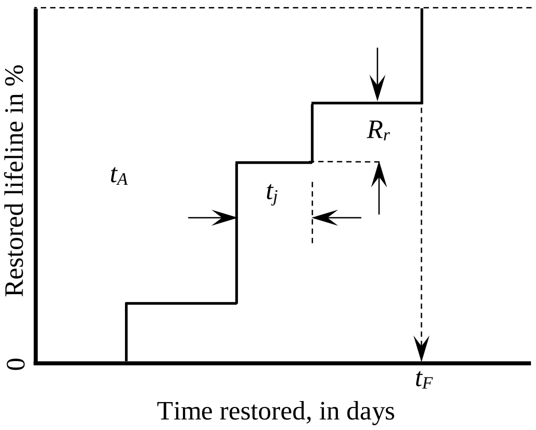

Fig.4. Restoration Curve ([14])

3.4 Restoration Curve

A restoration curve is a time dependent function which is constructed by plotting the restored lifeline (in %) in the y-axis versus the time completed (x–axis) as shown in the Figure 4. The time t_j represents the time to fix a certain link (from several possible links) which is determined using Horn’s algorithm. On the other hand, R_r is the cumulative demand that is restored divided by the total demand.

4. DATA AND RESULTS

In this study, data on the pipeline network of Surigao City, was used to construct a repair sequence scenario in the event of massive earthquake where all pipelines are assumed damaged. The network consists of 416 nodes (junctions) and 542 links (pipes). The nodes represent the water demand in a specific area and the links represent the supply pipes. Each node x has a value $V(x)$ corresponding to the base demand in liters per second. Furthermore we define $T(x)$ to be the time (proportional to the length of the pipe in meters) to supply water to node x. A table of sample data is shown in Table 2.

Table 2. Sample nodes with corresponding values of $V(x)$ and $T(x)$

Node (x)	$V(x)$ (in lps)	$T(x)$ (proportional to length in m)
393	0	5691
360	0.89	313
358	0.081	95
357	0.89	234
310	0.79	55
306	0.214	10

Using Kruskal’s algorithm, a minimal spanning tree for the entire network is obtained with root at junction 376. The spanning tree consists of 416 nodes and 415 links, removing 127 links from a total of 542 pipes as shown in Figure 3. Due to the huge data, only a portion of the minimum weight spanning tree is shown in Figures 5 and 6.

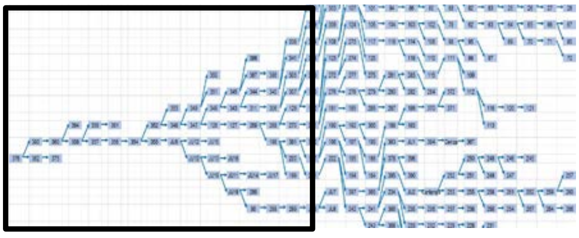

Fig.5 Minimal weight spanning tree

This spanning is rooted at node 376 because this is the water supply source.

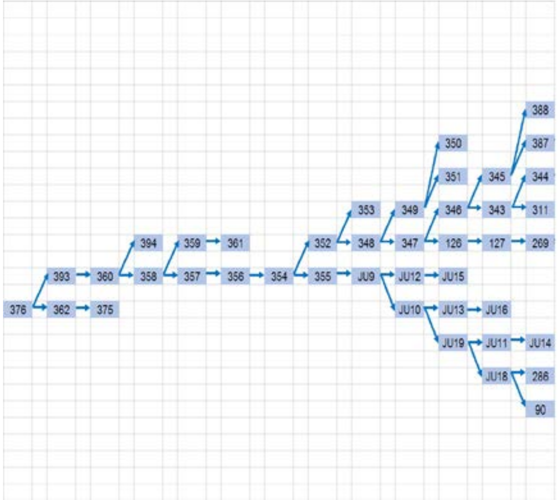

Fig. 6. A portion of the minimum weight spanning tree (rooted at node 376)

Table 3. First 40 restoration jobs in an optimal sequencing

order σ(*x*)	node *x*	order σ(*x*)	node *x*
1	393	21	117
2	360	22	118
3	358	23	114
4	357	24	110
5	356	25	119
6	354	26	115
7	352	27	111
8	348	28	109
9	347	29	104
10	126	30	103
11	127	31	102
12	269	32	106
13	268	33	100
14	129	34	101
15	122	35	94
16	123	36	86
17	124	37	87
18	108	38	91
19	107	39	79
20	105	40	68

Applying Horn's algorithm to the rooted tree obtained above yields an optimal repair sequence for in the network. The sequencing of repairs of the first 40 nodes of the network is shown in Table 3. The table indicates that node 393 must be the first to be repaired, followed by node 360, and so on. The value of the least penalty function is $f(\sigma) = 7773252.522$. Figure 7 below shows the portion of the water pipeline network in the areas of Barangay Canlanipa with node identification numbers. In Figure 8, the same water pipeline network is shown but with the corresponding values of $\sigma(x)$ indicating the number of node x in the cue of the repair work that must be executed.

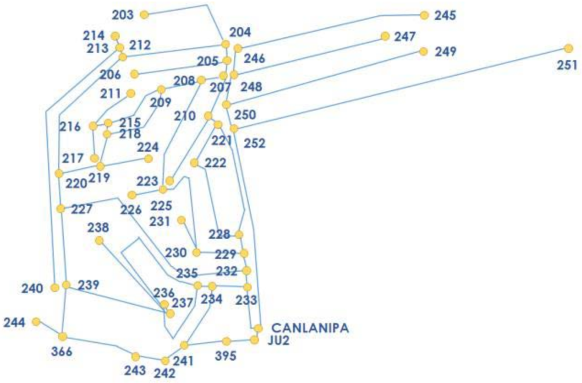

Fig.7 Minimal weight spanning tree of Barangay Canlanipa

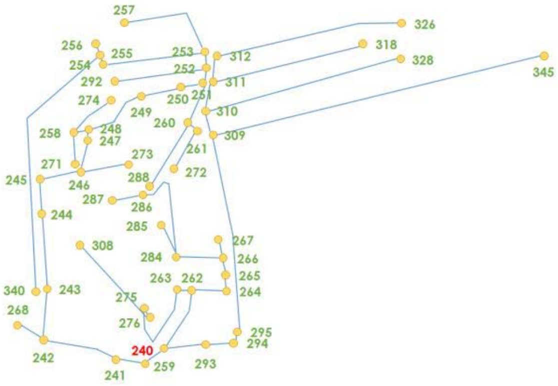

Fig.8. Sequence of restoring the network portion of Barangay Canlanipa

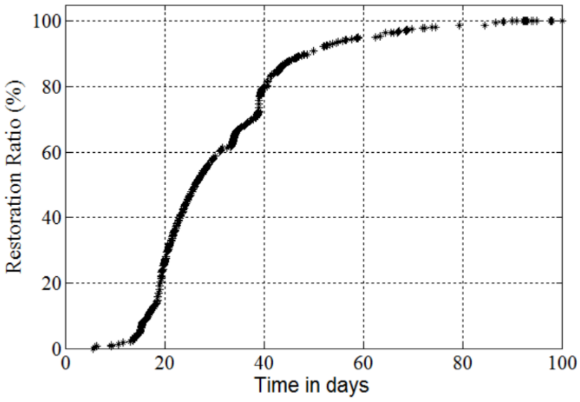

Fig. 9. Restoration Curve

Figure 9 shows the restoration process of the water pipeline of SMWD. This restoration curve is a non-decreasing function (Nojima and Kameda,

1992) and shows the repair on a node-to-node basis until the entire network is full operation.

5. CONCLUSION

A plan for restoring a pipeline network in a post-earthquake scenario takes into account the best ratio $r(x)$ at each node x of the network. This value is the maximum ratio of the demand of water supply associated to the node over the time it takes to repair the pipe leading to the node and is taken over all family trees rooted in node x. In Surigao City, a minimum weight spanning tree is first obtained from the network to ensure that all nodes will be supplied with water using pipes with minimum total length. At each node a best ratio is calculated measuring how urgent the repair of the link to a node is over the time to repair the link. Finally the optimal sequence of restoring the network is accomplished by starting at the root node and choosing the node with largest best ratio at each step. For future work, it is interesting to calibrate the restoration strategy with actual damage during strong seismic events. The methodology used in this study can be replicated to other tree-like systems, e.g. water, electric power, in any area.

6. ACKNOWLEDGEMENTS

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