Proceedings of the 5th International Conference on Civil Structural and Transportation Engineering (ICCSTE'20)
~~Niagara Falls, Canada~~ Virtual Conference – November, 2020
Paper No. 281
DOI: 10.11159/iccste20.281

Restoration modelling of Water Network under seismic hazard: Role of Electrical and Power Network

Ghazanfar Ali Anwar[1], You Dong[1]
[1]Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University
Hong Kong, China
ghazanfar-ali.anwar@connect.polyu.hk; you.dong@polyu.edu.hk;

Abstract – The socio-economic wellbeing of a community depends on the proper functioning of its critical infrastructure system. Two most important critical infrastructure systems i.e., Water Network (WN) system, and Electrical and Power Network (EPN) system are crucial for the full functioning of the households, and socio-economic wellbeing of its citizens. After an extreme event, the functionality of the households will be reduced due to the damage in the WN and EPN. The functionality of the WN may also depend on the recovery of the EPN and should be considered for better estimates of the functionality recovery of interdependent critical infrastructure system. In this paper, the restoration modelling of WN is assessed under a maximum considered seismic hazard scenario, considering the dependence on the EPN network. The fragility and consequence functions are utilized for the damage and repair time assessment of each component. The repair times for each component are evaluated and the total repair time of the WN and EPN is determined. The WN and EPN restoration modelling is assessed through network models where the nodes represent the sub-components of a network and edges represent the connection restoration. In the considered example, the WN is fully repaired in 8 days after an earthquake event, while the EPN is fully repaired in 10 days. The WN will therefore be fully functional after 10 days since the power plant component of WN requires electricity from EPN network to pump water form reservoir to the water tank. It is therefore important to consider the dependencies of WN on the EPN for better estimates of functionality recovery of critical utilities to the households.

Keywords**:** Water Network; Electrical and Power Network; Recovery; Resilience; Seismic Hazard

1. Introduction

Communities proper functioning depends on the functioning of the built environment. The communities built-infrastructure consists of different physical systems which may include transportation system, water system, electrical power system, gas network system, and the building portfolio system etc [1]. The systems may be connected with each other and may consists of several subsystems. For instance, electrical and power network (EPN) system may include power generating subsystems, and power transmission subsystems, and the water network (WN) system may include several subsystems such as pumping plants, water tanks, wells, reservoir subsystem, and pipeline distribution subsystem. These systems and subsystems interact with each other in a way that functioning of one system may affect the functioning of another system [2]. The interactions of systems are referred herein as dependencies (i.e., functionality of one system may depend on the functionality of another system) and interdependencies (i.e., the systems are mutually dependent on each other and the functionality of both systems will affect each other). For instance, the WN system consists of power plant subsystem which requires electricity from the circuit distribution subsystem from EPN to supply water to the rest of the physical infrastructure systems. Therefore, the WN system has a dependence on the EPN system to function. The dependencies and interdependencies are significant for the functionality assessment, and therefore the physical systems should be studied considering the dependencies and interdependencies, rather than treating the physical systems individually [3].

The modelling of dependencies and interdependencies of systems is achieved through different approaches in the literature which include Empirical approaches, Agent based modelling, System dynamics, Economic theory based, Network based approaches, among others [4]. The past studies have investigated the seismic risk of the individual systems of the building environment, revealing vulnerabilities and importance of considering dependencies and interdependencies [5]. Guidotti *et al*. [3] investigated the role of network dependencies in terms of demand and pressure criteria and concluded the reduction in functionality of WN and EPN networks after an earthquake event due to the dependencies. In this paper a network-based approach is utilized to assess the role of EPN on the functionality recovery of the WN. The networks and the relevant dependencies are modelled through adjacency matrix, utilizing graph theory of network modelling. The maximum considered hazard scenario is simulated and the damage of all the components of the WN and EPN are determined through fragility function. The consequence functions are utilized to translate the damage to the repair time for each subsystem, and total repair time of WN and EPN is determined. The recovery of WN and the role of EPN network on the functionality of the WN is then investigated. The section 2 discusses the methodology for assessing functionality loss and recovery of WN and EPN, section 3 discusses the role of EPN on the WN to provide water service to the households, and section 4 presents the conclusions.

2. Water Network and Electrical and Power Network

In this paper, a network-based approach is utilized for the critical infrastructure restoration modelling after an earthquake event. The approach is applied on a community consisting of WN and EPN. The community is located in Islamabad, Pakistan and consists of twenty residential and a commercial sector. The critical infrastructure (i.e., WN and EPN) is modelled through nodes and edges. All the sectors are modelled as nodes and the interaction of the sectors is modelled as edges, as shown in Figure 1.

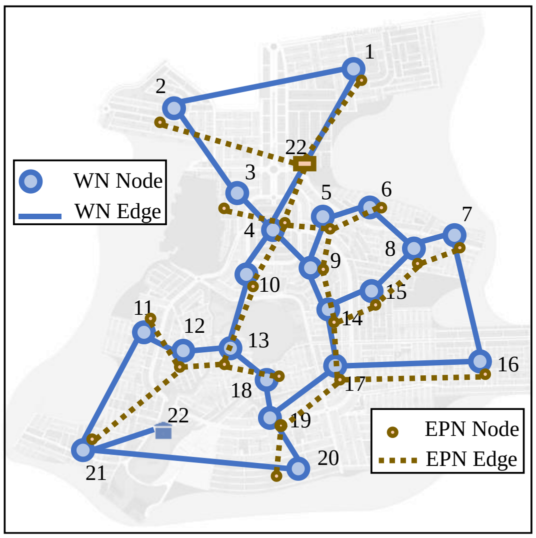

Fig. 1: WN and EPN of community modelled as nodes and edges

The WN from node-one to node-twenty-one consists of a small diameter pipeline distribution subsystem providing water to households, a water tanks, and a designated water pump for pumping water to the water tank. The node twenty-two is a designated node for a large reservoir providing water to the rest of the nodes. All the nodes are connected through pipeline distribution subsystem of the neighbouring nodes which plays a role of connecting edges. The EPN also consists of twenty-two nodes. The node-one to node twenty-one consist of circuit distribution subsystem providing electricity to the households, and node twenty-two is a grid-station providing electricity to all the nodes in each sector. The EPN nodes are connected with each other through the distribution lines acting as edges of the EPN.

2.1. Hazard Modelling

Waseem *et al*. [6] conducted seismic hazard assessment of Pakistan, and proposed updated ground motion values for different regions. Islamabad has an updated design level earthquake of 0.33g with a return period of 475 years, and a maximum considered earthquake of 0.56g with a return period of 2475 years. In this study, a maximum considered earthquake is simulated in the Islamabad region by utilizing an earthquake record of magnitude 5.1 with a depth of 19km west-southwest of Murree, Pakistan on 24th July 2015 20:59:54 (UTC). The intensity of the historical earthquake is increased to match the maximum considered earthquake scenario. The simulated intensity measures are shown in the

Figure 2. The different sectors of a community experience a PGA in the range of 0.5g to 0.6g, and the PGV in the range of 40cm/s to 50cm/s.

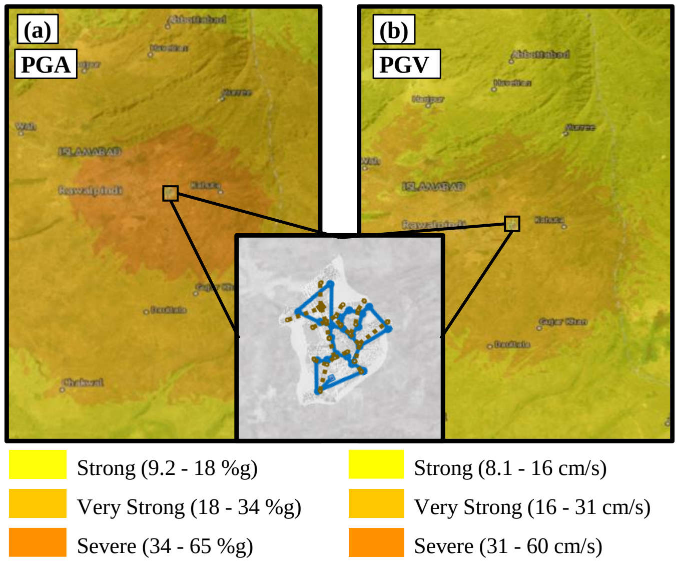

Fig. 2: Spatial distribution of the (a) Peak ground accelerations (PGAs), and (b) Peak ground velocities (PGVs)

2.2. Water Network Restoration Assessment

The WN consists of several damageable subsystems i.e., pumping plant, water tank, water reservoir, and a pipeline distribution subsystem. The modelling of loss of functionality and recovery requires fragility and consequence functions. The fragility functions translate the intensity measure to the damage states, and the consequence functions determines the time to recovery of each subsystem [7]. Table 1 shows fragility and consequence functions of WN subsystems for various damage states, extracted from HAZUS [8].

Table 1: Fragility and consequence functions of WN components.

WN Component	Damage state	Fragility function PGA (g)		Consequence function Repair time (Days)	
		Median	CoV	Median	CoV
Pumping plant	DS1	0.13	0.60	0.90	0.3
	DS2	0.28	0.50	3.10	2.7
	DS3	0.66	0.65	13.5	10
	DS4	1.50	0.80	35.0	18
Water Tank	DS1	0.18	0.60	1.20	0.4
	DS2	0.42	0.70	3.10	2.7
	DS3	0.70	0.55	93.0	85
	DS4	1.04	0.60	155	120
Water reservoir	DS1	0.15	0.75	0.80	0.2
	DS2	0.36	0.65	1.50	1.2
	DS3	0.72	0.65	10.5	7.5
	DS4	1.50	0.80	26.0	14

The probability of damage for a component with four damage states can be calculated from fragility function as described in Eq. (1):

$$P_{DS_i|IM} = \begin{cases} 1 - P_{DS_1} & DS_0(no\ damage) \\ P_{DS_1} - P_{DS_2} & DS_1(slight\ damage) \\ P_{DS_2} - P_{DS_3} & DS_2(moderate\ damage) \\ P_{DS_3} - P_{DS_4} & DS_3(Extensive\ damage) \\ P_{DS_4} & DS_4(Complete\ damage) \end{cases} \qquad (1)$$

where $P_{DS_i|IM}$ is the fragility curve relating intensity measure with damage state and P_{DS_i} is the probability of being in a certain damage state given intensity measure. The repair times are cumulative distribution functions relating the probability of damage with the repair time. The total repair time for a component can be determined by using Eq. (2):

$$Rt_{N|SS} = \sum_{DS=i}^{n} P_{DS_i}.Rt_{DS_i} \qquad (2)$$

where $Rt_{N|SS}$ is the total repair time of a subsystem of a network, P_{DS_i} is the probability of a damage state i from Eq. (1), and Rt_{DS_i} is the repair time consequence function. The pipeline distribution subsystem is sensitive to the PGV intensity measure. Therefore, the repair rate for the pipeline distribution subsystem is evaluated from the PGV intensity measure for each sector, and number of breaks and leaks is determined. Total number of breaks and leaks are then assigned workers and total repair time for repairing the WN distribution subsystem is determined for each sector. Figure 3 shows the repair of water network distribution pipeline subsystem for all the twenty-one nodes. It is observed that, for a maximum considered earthquake scenario, the distribution pipeline subsystem of the water network is fully recovered in 4 days of the investigated time interval.

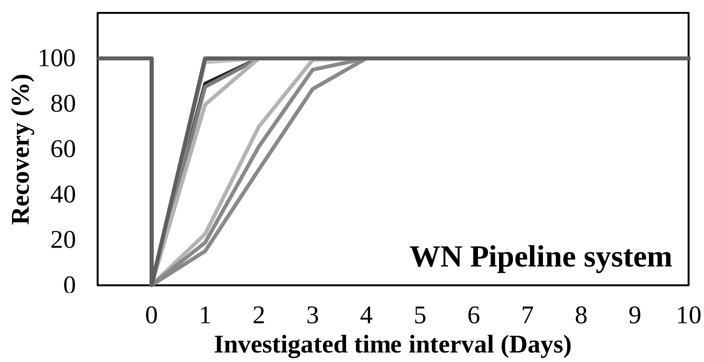

Fig. 3: Water Network pipeline functionality loss and recovery of twenty-one nodes

The repair time for the pumping plant and the water tank is determined using Eq. (2). The functionality loss and recovery during the investigated time interval can be determined using Eq. (3).

$$CIN_{FN}(t_j) = \frac{FF(t_o)}{2}\left\{1 - \cos\frac{\pi}{RT^i}\right\} \qquad (3)$$

where $CIN_{FN}(t_j)$ is the time-varying recovery of a critical infrastructure network subsystem i; $FF(t_o)$ is the Full Functionality of a building at an investigated time interval t_o; and RT^i is the repair time of the subsystem determined from Eq. (2). The recovery of water tank and pumping plant is determined from Eq. (3) and is shown in Figure 4. All the twenty-one nodes consist of a designated water tank and a pumping plant used for pumping water from the reservoir to the water tank. It is observed that, under a considered maximum hazard scenario, the water tanks of all the sectors are fully recovered in day 3 of the investigated time interval, and the pumping plants take 8 days.

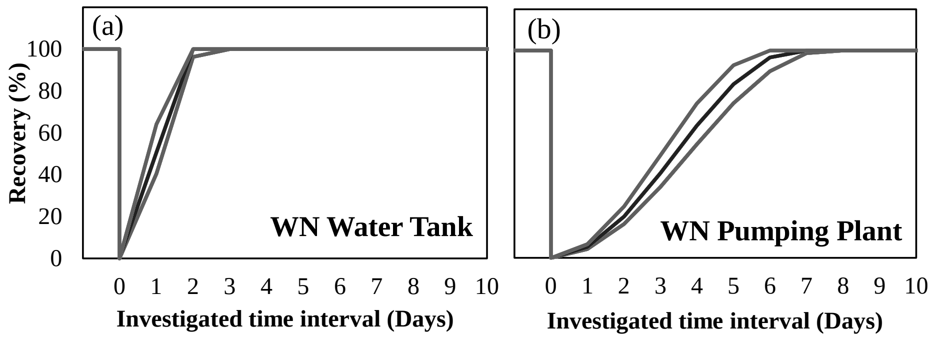

Fig. 4: Water Network functionality loss and recovery of twenty-one nodes for (a) Water Tank, and (b) Pumping Plant

WN recovery profile can be determined by considering all its subsystems (i.e., pipeline distribution system, water tank, pumping plant and the reservoir). It is observed that the WN is fully recovered in day 8 of the investigated time interval as shown in Figure 5.

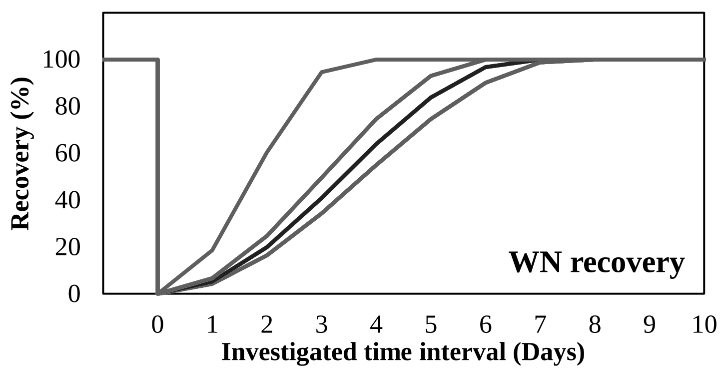

Fig. 5: Water Network functionality loss and recovery

2.3. Electrical and Power Network Restoration Assessment

The EPN consists of a circuit distribution subsystem (i.e., a subsystem of poles and electrical wires providing electricity to the household), and the electric substation which provides electricity to the circuit distribution subsystem at the required voltage. The fragility and consequence functions of the circuit distribution subsystem and the electric substation is shown in Table 2.

Table 2: Fragility and consequence functions of EPN components.

EPN Component	Damage state	Fragility function PGA (g)		Consequence function Repair time (Days)	
		Median	CoV	Median	CoV
Distribution circuits	DS1	0.13	0.64	01	0.5
	DS2	0.26	0.50	03	1.5

	DS3 DS4	0.34 0.74	0.40 0.40	07 30	3.5 15.0
Electric substation	DS1 DS2 DS3 DS4	0.24 0.33 0.58 0.89	0.25 0.20 0.15 0.15	0.3 01 03 07	0.2 0.5 1.5 3.0

A probabilistic approach is utilized for the distribution circuit in which a random damage state is generated depending upon the intensity measure, and relevant repair time is assessed for each distribution circuit using Eq. (3). The electric substation damage states and the total repair time is determined from Eq. (1-2), and the functionality loss and recovery for all sectors is determined as shown in Figure 6. It is observed that the circuit distribution of all the twenty-one sectors is fully recovered in day 5 of the investigated time interval, and the electric substation is recovered in day 10 of the investigated time interval.

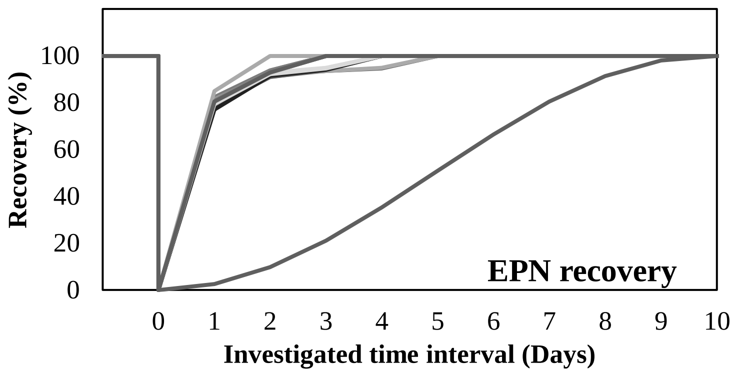

Fig. 6: EPN functionality loss and recovery

3. Role of Electrical and Power Network Restoration

The WN restoration at an investigated time interval is shown in Figure 7. It is observed that the water reservoir at node 22 is fully repaired and connected in day 4, the WN is 68% repaired in day 7, and is fully repaired in day 8 of the investigated time interval.

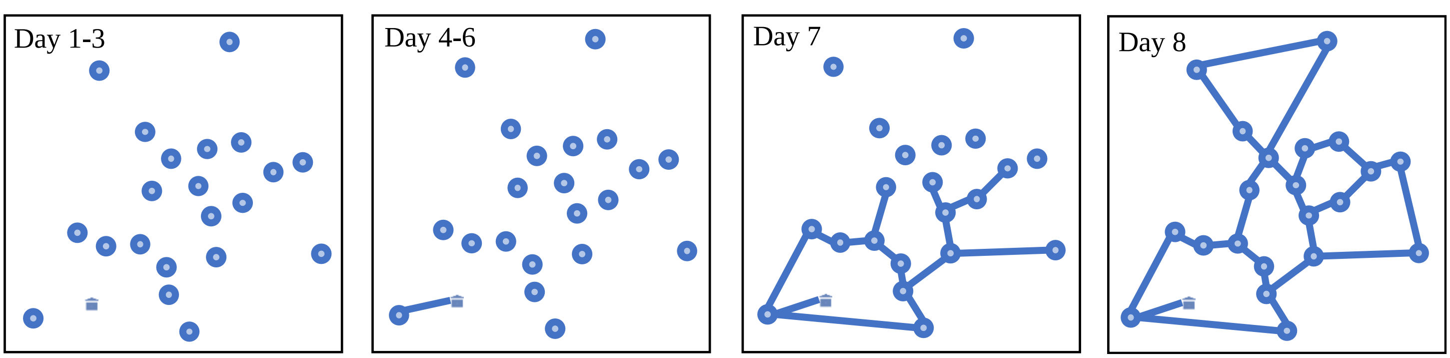

Fig. 7: Water Network restoration at investigated time interval

It is important to note that, although the WN is fully repaired in day 8 of the investigated time interval, it may not be able to provide water with full functionality until the power plant subsystem of the WN at each node gets electricity from the EPN network. The EPN restoration for the investigated time interval is shown in Figure 8. The EPN is 18% recovered at day

3 of the investigated time interval, 68% and 86% recovered at day 4 and 5, and fully recovered in day 10 of the investigated time interval. Since the electric substation provides electricity to the rest of the distribution system of all the nodes, therefore the households and the pumping plants will get electricity in day 10 of the investigated time interval. Therefore, the households will receive water facility with full functionality in day 10, although the water network is fully repaired in day 8 of investigated time interval. This highlights the important of dependency of WN on the EPN.

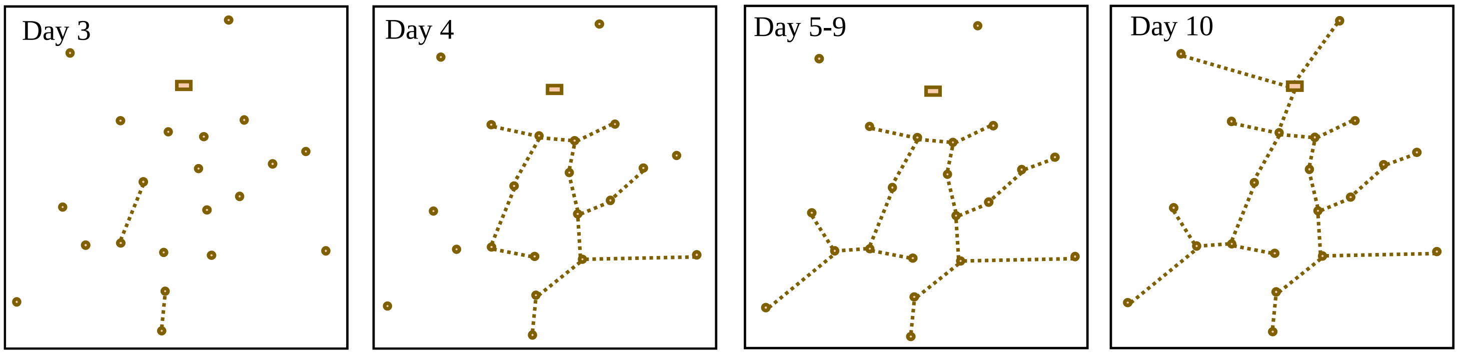

Fig. 8: Electrical and Power Network restoration at investigated time interval

4. Conclusion

This paper considered the role of EPN on the WN under a maximum considered hazard scenario. The fragility and consequence functions for all the components of the considered network were extracted and the total repair time was determined. It was observed that the EPN distribution circuit subsystem was repaired in day 5 of the investigated time interval. The electric substation which is crucial in providing electricity to all the nodes of a community was repaired in day 10 of the investigated time interval. It was also observed that although the WN fully recovered in day 8, but was not able to provide water service at full capacity until day 10 of the investigated time interval due to the dependence of water pump subsystem of WN on the EPN.

References

[1] M. Koliou, J. W. van de Lindt, T. P. McAllister, B. R. Ellingwood, M. Dillard, and H. Cutler, "State of the research in community resilience: progress and challenges," *Sustainable and Resilient Infrastructure,* pp. 1-21, 2017.

[2] M. Ouyang and Z. Wang, "Resilience assessment of interdependent infrastructure systems: With a focus on joint restoration modeling and analysis," *Reliability Engineering and System Safety,* vol. 141, pp. 74-82, 2015.

[3] R. Guidotti, H. Chmielewski, V. Unnikrishnan, P. Gardoni, T. McAllister, and J. van de Lindt, "Modeling the resilience of critical infrastructure: The role of network dependencies," *Sustainable and Resilient Infrastructure,* vol. 1, no. 3-4, pp. 153-168, 2016.

[4] M. Ouyang, "Review on modeling and simulation of interdependent critical infrastructure systems," *Reliability Engineering and System Safety,* vol. 121, pp. 43-60, 2014.

[5] A. Vespignani, "The fragility of interdependency," *Nature,* vol. 464, no. 7291, pp. 984-985, 2010.

[6] M. Waseem, S. Khan, and M. A. Khan, "Probabilistic Seismic Hazard Assessment of Pakistan Territory Using an Areal Source Model," *Pure and Applied Geophysics,* pp. 1-21, 2020.

[7] G. A. Anwar and Y. Dong, "Seismic resilience of retrofitted RC buildings," *Earthquake Engineering and Engineering Vibration,* vol. 19, no. 3, pp. 561-571, 2020.

[8] HAZUS, "Multi-hazard loss estimation methodology, earthquake model," *Washington, DC, USA: Federal Emergency Management Agency,* 2003.