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CONSTRUCTION AND RISK EVALUATION OF A WATER DISTRIBUTION NETWORK UNDER SEISMIC HAZARD IN CENTRAL CHILE

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Abstract

Water distribution is of critical importance under regular conditions, and more so in times of an emergency induced by a large natural event, which also stresses the performance of other lifelines and critical infrastructure. Being able to compare the network operation in normal conditions with, that during an extreme event, is useful for decision makers in defining investment priorities for mitigation plans. This work aims to perform risk analysis under seismic hazard on the water network of a large conurbation in central Chile formed by the cities of Valparaíso and Viña del Mar. A hydraulic network model of the water network was developed first considering the physical properties of network elements and their estimated head losses. Herein, the methodology for the network construction is described, which combines datasets available in official repositories. As a first attempt, damage scenarios are generated using peak ground acceleration maps constructed using a ground motion prediction model. Pipeline failure is evaluated using fragility functions available in the literature; hydraulic analyses are then carried out on the damaged network. The performance of the network is measured in terms of connectivity (loss) and percentage of unsupplied demand. Finally, a seismic risk analysis on these two indices is presented to enable identification of the relevant characteristics of the constructed network.

Keywords: seismic risk; water system network; connectivity loss

1. Introduction

A water distribution network system is vulnerable to several hazards in its lifecycle. To ensure continuous operation it is necessary to assess the network under failure conditions, induced, for instance, during an earthquake. Having updated information of its components, state, and vulnerability is critical for achieving a resilient city. There is extensive research on modeling the seismic performance of different component of water network systems. These studies included the performance of the water system components under seismic loading [1-4], and other critical components such as tanks and pumps [5-7]. Due to the progress of computational capacity, research has focused on studying the whole network, considering several performance indices [7-9].

All studies on water distribution network systems can be grouped as hard or soft analysis [10]. Hard analyses focus on the intensity measures and the damage associated with each element; they focus on the seismic response analyses and seismic risk analyses. On the other hand, soft analyses can be applied to elements and networks; they include damage analyses, reliability and redundancy analyses, post-earthquake restoration, seismic mitigation, socio-economic analyses, and real-time monitoring. Both analyses complement each other to assess reliability, and several researchers have proposed different methods to integrate them.

A reliability analysis is the assessment of the system probability to perform according to defined criteria. This can be accomplished by means of operability and serviceability measures, which involves the components performance and the hydraulic analyses of both undamaged and damaged networks. Reliability evaluation is a complex process because it takes into account several factors associated with fulfilling demands, pressure, water quality characteristics, firefighting capabilities, and other requirements that reflect serviceability of the system. For a water network system, reliability can be defined as the ability to supply water in the required quantity at target residual heads throughout its lifecycle; this it also involves the probability that the system performs within specified limits for a given time window. Reliability of the system can be affected by several causes such as failure rate of supply pumps, power outages, loss of flow capacity in transmission mains, deterioration on the pipelines, pipe breaks and failures, and changes in demands as the population changes. Physical damage obtained from damage analyses is generally used as an input for reliability analysis.

The most prevalent elements in a water network system are pipelines, which are usually the aim of soft analyses. Pipelines have been analyzed in different ways; in terms of material they are classified into brittle and ductile pipes. Damage states for pipelines are usually classified as breakage and leakage [11]. Pipe breakage can be produced by: (i) round flexural cracks in brittle segmented pipes and welded continuous pipe; (ii) longitudinal crack in brittle, ductile and riveted steel segmented pipelines; and (iii) crushing at joints in segmented pipelines with bell and spigot joints. Likewise, failure modes of leakage are classified as: (i) pull-out in brittle, ductile, riveted steel and concrete segmented pipelines; (ii) local tear of pipe wall or welded slip joints on welded continuous steel pipeline; and (iii) local loss of pipe wall on brittle, ductile, and riveted steel pipelines. Other elements that have major influence on pipelines behavior are diameters and site conditions. Because of the vastness of different conditions and characteristics makes the water network analysis complex, to assess seismic damage in buried pipelines, the main metrics are damage rate and probability of damage. The former considers the number of pipeline damage incidents per kilometer, or it can also be measured as the number of repairs per unit length. The probability of damage is commonly assessed with fragility curves. Most of the damage due to seismic demand is caused by transient ground deformation or permanent ground deformation [9]. Nevertheless, other authors like Katayama [12] also used peak ground acceleration (PGA) to plot damage rate of pipelines. It was shown that the relationship considers the damage caused by permanent ground deformation and transient ground deformation, and fragility curves have been developed using this ground motion intensity parameter.

Seismic risk assessment in water pipelines can be defined as a procedure to estimate the damage and losses to a seismic event by combining seismic hazard with inventories of assets. Roughly, the process consists of three stages [10]: quantification of the seismic hazards for a given event, quantification of the inventory of the affected parts, and the combination of inventory data with the seismic hazard to assess impact. An ideal way to represent these analyses is through geographical information systems.

The results of soft analyses can be used as input for reliability and serviceability analyses. A reliability assessment of a water network system involves hydraulic analyses. They tend to be very complex as they involve aspects such as variations in demand, reliability of individual components and their locations, and fire flow requirements and their locations. This also involves the necessity to select performance measures for the damaged network, which are computed using reliability methods that usually involve Monte Carlo simulation techniques, graph algorithms, and fault tree analyses.

The law of mass conservation that is expressed by the equation of continuity assumes that in normal conditions all demands must be satisfied, but in the case of earthquake damage, demands at the damaged points will increase due to breaks and leaks and will be larger than the supply from reservoir and transmission sources [13].

Seismic risk analysis comprises several steps but starts by collecting the input data of the layout and topology of the network. It then focuses on the site conditions to obtain the seismic hazard, and the properties of the components, in our case the pipelines, to select proper fragility functions. The following stage is a probabilistic simulation of the performance of components considering their damage state using Monte Carlo simulation. This provides a measure of reliability once hydraulic analyses are conducted. Analyses can be done by deterministic or probabilistic methods. One of the most effective ways is a probabilistic analysis of several flow parameters in a deterministic hydraulic model of the damaged network [10]. For each scenario, the network connectivity is assessed. This also considers the introduction of different equations to change from a demand-driven analysis to a pressure-driven one; this approach enables the introduction of air in pipelines and avoids the problem of unreal negative pressures. However, this also considers a distinction between breakage and leakage in the system. At the end, using measurements of operativity and serviceability, a reliability index is computed for the seismic hazard, and a risk curve for that index is obtained. Given the extent of this research, this paper deals with the information gathering process, the setting of the hydraulic analysis in steady-state conditions, and the first two stages of risk analysis and a driven-demand hydraulic analysis of some of the damaged scenarios.

2. Water distribution network of Valparaíso

This study focuses on the region of Valparaíso, located in the central part of Chile, around 100 km west of the capital, Santiago (see Fig. 1). It is the third largest metropolitan area in Chile and its population is the second largest in the country. Water supply in the region of Valparaíso, as well as in Chile, is managed by private companies that are regulated by the Superintendence of Waterworks Services (SiSS), a public institution in charge of monitoring and regulating the proper functioning of water supply and wastewater disposal countrywide. The SiSS can inspect and fine private water companies if they are not in compliance with current legislation and standards. In the region of Valparaíso, water services are provided by the company ESVAL. Its pipe network covers the cities of Valparaíso, Viña del Mar and Concón, as seen in Fig. 1.

For this project, water supply pipe network was provided by the SiSS. The pipe network was characterized by GIS polyline shapefiles, with attributes including pipe material and diameter. Distribution tanks were characterized by GIS point shape files, with attributes including location, maximum and minimum water level elevation, from which the maximum values were considered for modelling. Water demand was also provided based on their monthly surveys on the meters installed throughout the entire network. Fig. 1 shows the water network layout of pipelines and distribution tanks.

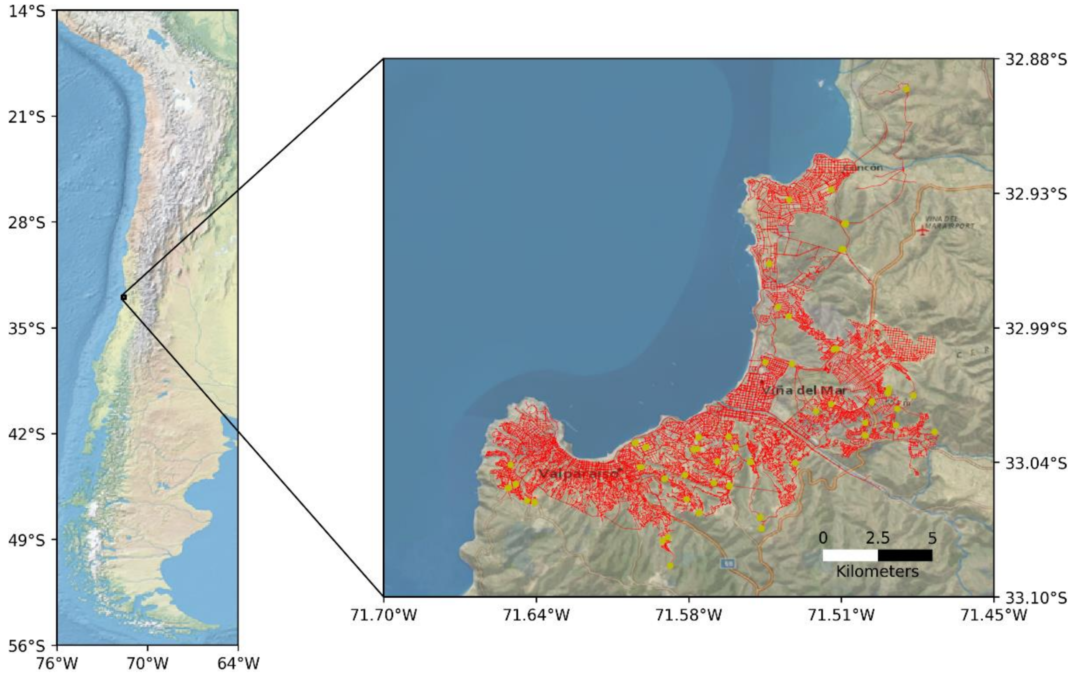

Fig. 1 –Valparaíso - Viña del Mar - Concón water supply network. Dots represent distribution tanks and the red lines represent pipes

Water distribution tanks are mostly located on the high grounds, but in order to provide proper pressure to each sector, pumping stations are installed across the network. Available pump data contains location, design pressure head provided and power, however, pump curves or operation regimes were not available. Therefore, pump pressure head was transferred to the water distribution tanks by adding the head to the water level elevation. Pressure reducing valves (PRVs) information is partially available, with location and diameter available, however there was no information regarding the head loss setting of these valves, which is a required value to be used in the EPANET model.

The information was collected and corrected to adjust connectivity for the hydraulic analysis, that was carried out using EPANET, a public domain water distribution system modeling software package developed by the United States Environmental Protection Agency (EPA). GIS shape files containing pipes and tanks were converted to EPANET pipes and reservoirs respectively. After this process, the resulting model has a total of 36,329 nodes, 39,890 pipes and 74 tanks. Although water distribution tanks are not infinite supply sources, for purposes of steady-state and normal network operation, they were modelled as reservoirs, given the fact that service interruption events are rare. Junctions were generated from the vertices of the pipes polylines and demand was assigned to these nodes based on proximity to the water meters. The network was constructed to be demand-driven, which means that demand is provided as input to the nodes and flow out of the nodes is equal to the respective demand. Pressure is computed through EPANET according to the network conditions.

Once the EPANET network model is ran, node pressure is analyzed. Chilean standards stipulate that normal operating pressure should not be less than 10 meters of water column and not more than 70 meters of water column [14]. This criterion will be used to determine if a node is being well supplied by the network or not. Fig. 3 shows the EPANET simulation for the water network under normal conditions. Fig. 2 shows that a significant portion of the network complying with regulation, however, there are sectors that present values outside the admissible pressure. These sectors reveal one of the main limitations of these study, which is the accuracy of the data (provided by the private water companies and received by the SISS). Further work will focus on improving the quality of data by directly consulting with the private companies. Nevertheless, these limitations do not jeopardize our goal of analyzing the risk of the network, since it is based on comparing the normal operation (steady state) with seismic conditions.

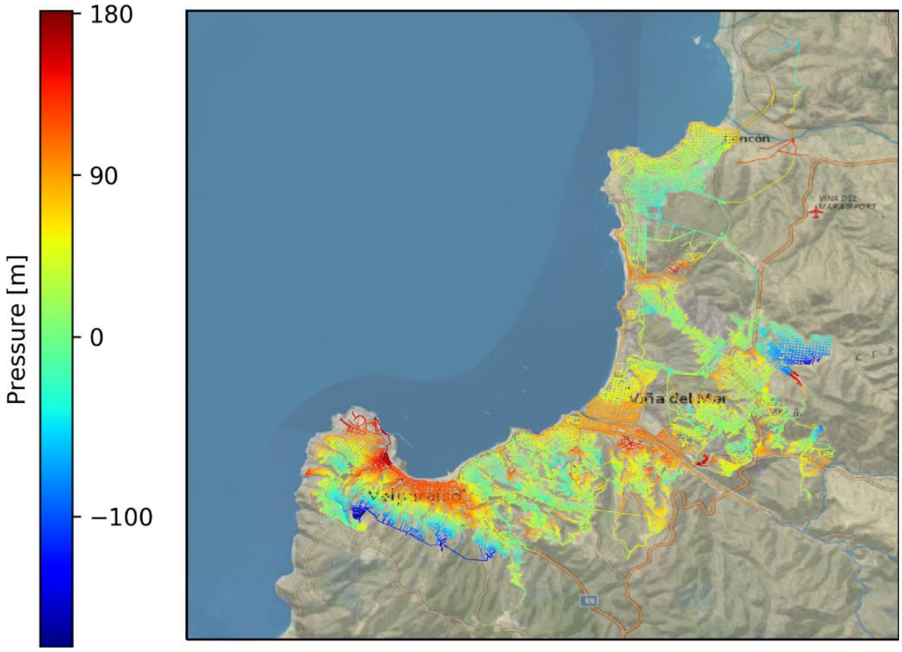

Fig. 2 – Distribution of water pressure in the network operating under normal conditions

3. Seismic hazard simulation

The region of study is located in the subduction zone formed by the convergence of the Nazca and South American Plates, which is one of the most seismically active in the world. The network was subjected to a set of synthetic earthquake scenarios in order to assess its seismic risk. Monte Carlo simulation was used to sample scenarios that are consistent with the regional probabilistic seismic hazard. The simulation starts by sampling earthquake magnitudes and hypocentral locations using the earthquake recurrence model developed by Poulos et al. [15] for subduction interface and intraslab events in the region. Seismic events with epicentral distances greater than 500 km to the network were not considered since there contribution to the seismic hazard is negligible. Crustal faults were not considered in the analysis since no active faults that could affect the city have been found to date.

The efficiency of the simulation was improved with the importance sampling scheme used by Poulos et al. [16], which consists in sampling earthquake magnitudes from a uniform distribution instead of the usual truncated exponential distribution derived from the Gutenberg-Richter relation of earthquake frequency. This method significantly decreases the proportion of low magnitude earthquakes that are sampled, which are overrepresented by the original truncated exponential distribution, and increases that proportion of scenarios with moderate to high magnitudes.

After a magnitude and epicentral location is obtained, peak ground accelerations (PGAs) throughout the city were sampled assuming that their natural logarithms are multivariate normally distributed. Mean and standard deviations values were obtained from the ground motion model developed by Abrahamson et al. [17], which was developed using a worldwide database of subduction ground motions. This model considers site effects by using the average shear wave velocity over the top 30 m of soil, which was obtained from the [18]. Correlations of PGA between sites were computed using the model proposed by Jayaram & Baker [19].

A total of 100,000 earthquake scenarios with corresponding PGA maps for the region were simulated for risk assessment. An example PGA map of one of these scenarios is shown in Fig. 3, which corresponds to a hypothetical Mw 8.5 subduction interface earthquake offshore from Valparaíso.

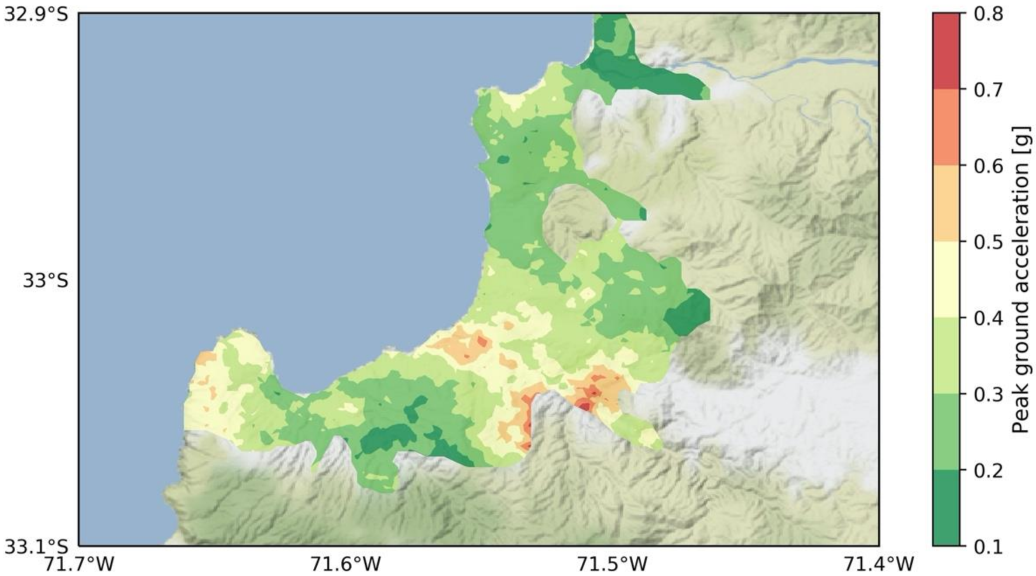

Fig. 3 – Peak ground acceleration map for a single synthetic earthquake scenario

4. Damaged network

This section presents the simulation of component damage, the decrease of connectivity, and the hydraulic performance for the sampled earthquake scenarios. In this study only damage in the pipelines was considered, so tanks are supposed to continue working after an event occurs. This is not necessarily correct and further work has to be done in this topic.

Water pipelines generally employ vulnerability curves based on damage rate and peak ground velocity (PGV) to determine the probability of failure for each pipeline of the system [20]; however, for the sake of simplicity, a fragility curve developed by Yoon et al. [21] is used, given by Eq. (1):

$$F(PGA_i) = \Phi\left(\frac{\ln(PGA_i)\,/c_k}{\xi_k}\right) \tag{1}$$

where $F(PGA_i)$ is the probability that the i-th pipeline is damaged; PGA_i is the PGA at the location of the i-th component; and Φ is the standard normal distribution. For this study, the fragility curve for major damage and soil properties known was selected, i.e. values of c_k = 0.917 and ξ_k = 0.654 were used ([21]). Monte Carlo simulation is then performed to probabilistically sample the damage of each network component using the computed damage probabilities. Damaged components are assumed to have a complete loss of functionally, with no intermediate damage being considered.

After the simulation of network damage, the hydraulic analysis of the disrupted network is performed, and some reliability measures are calculated as the final results [10]. For illustration purposes 8 scenarios will be displayed: S39, S9099, S19692, S30239, S34714, S38906, S39403, and S39838, where the names represent the number of disconnected pipes. Table 1 shows demand, median pressure and number of nodes connected as metrics of network performance. In general, pressure distribution decreases as the number of damaged pipes increases since more distribution tanks get cut off from the network. However, this trend does not necessarily translate to the comparison of two scenarios, as evidenced by the median pressure from scenarios S34714 and

S38906. It is interesting to note that the amount of demand not supplied grows slower than the loss of connectivity. This means that sectors with higher demands are more redundant, which helps to avoid abrupt losses of the service.

Table 1 – Network metrics for the selected scenarios

Scenario	Median Pressure (wcm)	Satisfied Demand (m^3/s)	Normalized demand not supplied [%]	Connected nodes	Simple connectivity loss [%]
S39	36.22	100,111	0.03	36,302	0.07
S9099	35.83	78,793	21.32	28,367	43.85
S19692	24.74	46,900	53.17	18,757	82.25
S30239	25.68	27,503	72.54	8,944	98.51
S34714	38.22	9,133	90.88	4,864	99.28
S38906	29.87	1,526	98.48	928	99.88
S39403	3.73	1,118	98.88	466	99.97
S39838	0.67	14	99.99	52	99.99

Pressure distributions obtained for the selected damage scenarios are shown in Fig. 4. The current results exhibit several sectors with negative pressures that are not realistic. As mentioned earlier, the Chilean norm for drinking water [14], the allowable pressures should be between 10 and 70 wcm, but smaller and greater pressures are observed, especially for cases with more failure in pipelines. Reliability measures must be selected adequately to avoid increase in reliability when considering these pressures.

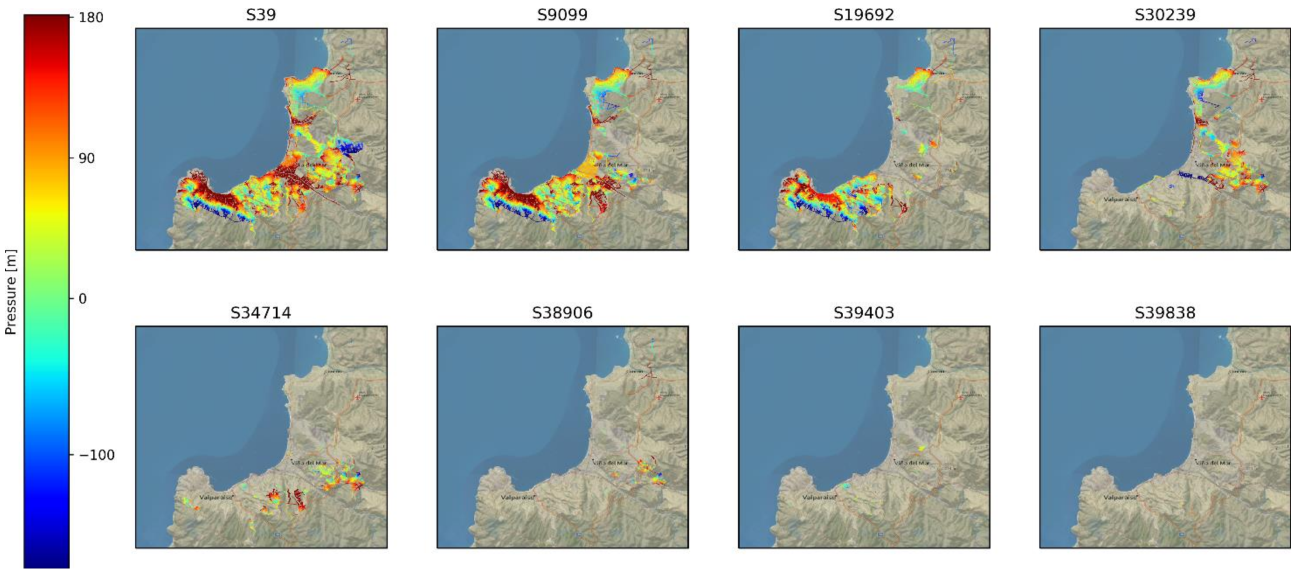

Fig. 4 –Pressure distribution of the damaged network for the selected scenarios. Components that were damaged or disconnected are not shown in the figure

5. Seismic risk analysis

The seismic risk of the system was evaluated using two indexes. First, in order to evaluate the robustness of the network, a simple connectivity loss (SCL) index was obtained [22], i.e.

$$\mathrm{SCL} = 1 - \frac{1}{|\mathcal{N}|}\sum_{i\in\mathcal{N}}\frac{N_S^i}{N_0^i} \quad (2)$$

where $\mathcal{N}$ is the set of all nodes with water demand, $|\mathcal{N}|$ is the cardinality of the set (i.e., the total number of nodes with water demand), and N_S^i and N_0^i are the number of sources (water tanks) connected to node i in the damaged and undamaged scenarios, respectively. Fig. 5 shows the mean annual frequency of the SCL index. From the curve it is possible to see that the losses up to 70% of the connectivity are highly expected in time windows of 100 years. One explanation of this could be that the network is highly susceptible to few but very punctual damages that affect the entire system, as for example the pipelines that connect tanks to the rest of the system.

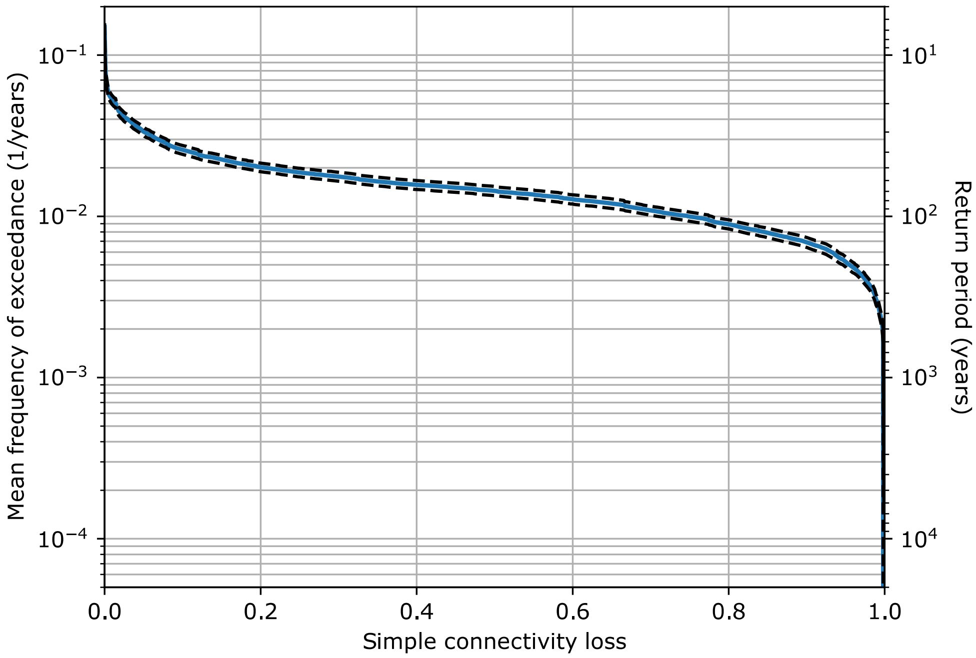

Fig. 5 – Mean annual frequency of exceedance of the SCL index. Dashed lines represent a 99% confidence interval

The second index analyzed was the fraction of demand not supplied (DNS), which is the ratio between the unsupplied demand and the total demand of the system, i.e.

$$\mathrm{DNS} = 1 - \frac{\sum_{i\in\mathcal{N}} s_i}{\sum_{i\in\mathcal{N}} d_i} \quad (3)$$

where s_i is water flow supplied to the i-th node following the earthquake and d_i is the demand of the i-th node. Fig. 6 shows the mean annual frequency of exceedance of the DNS. The return period of events that produce unsupplied demand is roughly 20 years and the return period of events that stop water distribution completely is approximately 1100 years. Unlike the SCL, in this case the curve decreases faster. When analyzing this, it is necessary to recollect that SCL is associated to the number of tanks connected to each node, but most importantly, tanks were assumed with infinite capacity. Also, it is important to note that this work overestimated DNS since, as explained before, it only uses a single damage state representing the total loss of functionality of a component and does not consider possible leaks due to partial damages. So, it should be expected that the slope of the curve to change to a more horizontal shape when correcting these assumptions.

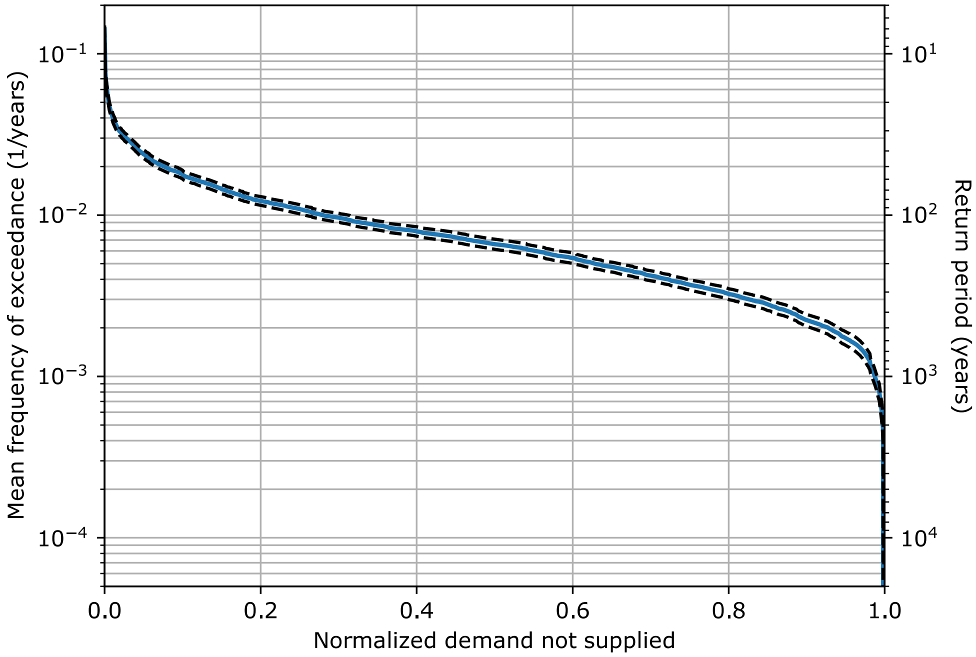

Fig. 6 – Mean annual frequency of exceedance of the DNS index. Dashed lines represent a 99% confidence interval

6. Conclusions

This work presents the construction and a preliminary seismic risk assessment of the water distribution system of the Valparaíso region in central Chile. The network was constructed from data of the SiSS, considering pipelines, tanks, pumps and demands from a regular month. The system was subjected to 100,000 synthetic earthquake scenarios that are consistent with the seismic hazard of the region. Ground shaking was used to estimate pipeline damage throughout the system, and a hydraulic analysis was used to simulate the distribution of water in the disrupted system. The response of the system to an earthquake event was summarized using a connectivity loss index and the unsupplied demand. Finally, the seismic risk of the system was computed by combining the response of the system to all earthquake scenarios, resulting in mean frequency of exceedance curves for the two selected output variables.

The most significant conclusions are in terms of the mean annual rates of exceedance of two indices representing connectivity loss and unsupplied demand. It is apparent that the resulting rates are considerably flatter for the SCL than for the DNS. This implies that the network system is more robust in terms of demand not supplied than connectivity loss, since changes in the number of connected nodes (for a wider range) do not change significantly the mean annual rates.

There are several limitations and assumption in this work that could be improved in the future. For example, in terms of the hydraulic model, a different approach could be addressed. EPANET, just as other available software to compute hydraulic network analysis, is aimed for systems that work in regular conditions, this is incompressible water flow in a pressurized network that follows the laws of mass and energy conservation. In these analyses all demands must be satisfied to satisfy the equation of continuity, because water flows from points of high energy to low energy. Due to the small value of velocity, it is usually neglected in the hydraulic head. The algorithm uses total head difference to satisfy demands and does not make a difference among positive and negative pressures, this forced satisfaction of all demands that in turn leads to unrealistically high negative pressures. This problem has been addressed by Markov et al. [23] considered that the pipelines are not airtight and pressures smaller than atmospheric levels and created rules to eliminate negative pressure nodes. Nodes with negative pressures are divided depending on their flow condition, first no-flow nodes and their adjacent pipes are eliminated sequentially, flow and pressure is recalculated after each elimination. This might isolate a part of the network, that are removed from the system. A similar procedure is followed with partial-flow nodes that are adjusted first.

Whenever there is damage in the system elements, the software might give solutions with unrealistically high pressures. However, the ability of water systems to sustain negative pressures is scarce. The occurrence of negative pressures in the system leads to overprediction of available flows in the system, and then to unconservative estimates of system serviceability.

Finally, the current results enabled us to identify the main characteristics of the network, which is highly sensitive to extensive damage and failure of very few elements. Further developments of this work might include determining the best layout for tanks which will maximize the connected nodes against most possible earthquake scenarios. Also, the use of additional damage states in the fragility curves, including the use of PGV and PGD maps, is necessary in order to obtain realistic results. It has been shown that pipelines are more affected by these parameters than PGA [3]. Using different state damage, leaks can be incorporated. Tanks also should be included in this analysis, with possible effects such as lower capacity or the impossibility to operate. New results, with corrected assumptions, should be presented in upcoming works.

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8. Copyrights

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