3rd International Conference on Natural Hazards & Infrastructure

5-7 July 2022, Athens, Greece

Investigation on the Precision of Local Site Conditions in the Systemic Risk Assessment of Utility Systems at City Scale

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ABSTRACT

Proper functioning of critical infrastructures and utility systems is crucial for an urban area to facilitate society. Concerning the seismic risk assessment of such systems, the interdependencies between the components of a system, as well as between different systems might have a strong impact on the estimated risk. During and after an extreme event like earthquakes, interdependencies between different critical infrastructures might lead to exacerbated impact. To ensure comprehensive planning for disaster risk mitigation, it is crucial to understand the interdependencies and the effect that they pose during and in the aftermath of the events. Also, it is well known that the local site conditions may significantly affect the structural response. Local site conditions may generally be represented in terms of average shear wave velocity up to 30 meters depth, $V_{s,30}$, because of its broad usage by the majority of the ground motion prediction equations, as well as seismic code provisions. When we consider critical infrastructures, due to the interdependencies the effect of the site conditions might not be limited to the single component/structure but have cascading or propagating effects to other components and eventually to the other interconnected systems as well. In this study, we aim to investigate whether a more detailed knowledge of local site conditions in terms of $V_{s,30}$ affects the overall performance of utility systems at the urban scale, compared to a more simplified approach for estimation of $V_{s,30}$, commonly used for urban/regional scale analysis, considering also the systemic approach. Specifically, the interdependencies between the water supply system and electric power network have been considered and the performance is measured in terms of water connectivity loss. The city of Thessaloniki, Greece is taken as the study area, as detailed knowledge of the site conditions is available.

Keywords: Systemic Approach, Interdependencies, Local Site conditions, Water Connectivity Loss

1. INTRODUCTION

The consideration of seismic loss and risk assessment of critical infrastructures is crucial in the field of disaster and risk management. Damage in critical infrastructures during and after an earthquake does not only have a direct impact on the damaged infrastructures, but interlinkages to other infrastructures lead to greater consequences than what is generally expected (Pitilakis et al., 2014). For the purpose of better preparedness and recovery process before and after the earthquake event, it is important to consider the interdependencies between different infrastructures to assure strategic planning and a holistic approach.

One of the components to be considered in any seismic risk or loss assessment regards local site conditions. The study of the site effects when considering critical infrastructures is more crucial as the components of critical infrastructures are interlinked with other components in the same system and also to other systems. For example, if a component of the electric power network (EPN) is damaged after an earthquake, then the impact is not only limited to that structure or the deprivation of electricity in a certain area but poses other consequences to other systems too. For example, pumping stations of water supply system (WSS) may not be operable\functional due to their dependencies to EPN, leading to end-users being deprived of water supply even at the other end of the city. Similarly, hospitals would not be able to run in a normal condition without ample electricity and water supply. This study aims to investigate these cascading effects, related to the interdependencies between different utility systems, focusing on the role of local site condition modelling.

Local site conditions are mostly represented in terms of $V_{s,30}$ (average shear wave velocity up to 30 meters depth) in seismic risk applications. Despite its limitations, $V_{s,30}$ is the most commonly used parameter for site amplification in Ground Motion Prediction Equations (GMPEs), and is broadly used in seismic codes for the site classification. $V_{s,30}$ for a site can be obtained directly from site investigations or approximately from correlations with available topographical data (e.g. Wald and Allen, 2007), which is a common practice at regional or urban scale analyses.

In this study, the role of the local site condition is investigated with regard to the performance of the critical infrastructures considering the interdependencies. Specifically, two different $V_{s,30}$ models (a rigorous one obtained from directly measured values and a simplified one obtained through correlation to topographic slope) are used to investigate the impact of the precision of local site conditions modelling to connectivity loss for the water supply system (WSS) of Thessaloniki, Greece, interdependent to the electric power network (EPN) of the city, for a scenario-based analysis.

2. METHODOLOGY

This work is mainly based on the approach developed during the SYNER-G project (Pitilakis et al., 2014). As mentioned already, considering the interdependencies with electric power network, the effect of the precision of site conditions modelling on the overall performance of water supply system in terms of connectivity loss is investigated for a scenario earthquake. The 6.5 Mw 1978 Thessaloniki earthquake, which is the latest major event in the study area, is used as a scenario event.

Firstly, a scenario seismic hazard analysis with an appropriate fault rupture model for the 1978 Thessaloniki earthquake is performed with the open-source earthquake hazard and risk software OpenQuake Engine, available from https ://github.com/gem/oq-engine (Pagani et al., 2014; Silva et al., 2014). Two different local soil conditions models, represented by $V_{s,30}$ of increasing accuracy, are considered. The models include i) a simplified one considering the global slope-based $V_{s,30}$ model developed by USGS (Wald and Allen, 2007) and ii) a rigorous one, with measured $V_{s,30}$ obtained from the microzonation study of the city (Anastasiadis et al., 2001). Appropriate intensity measures (IMs) required for the risk assessment of the systems are obtained. Then, with the help of fragility curves, the expected damages of all the vulnerable components of the water supply system (WSS) and the electric power network (EPN) are computed at an individual level. Then, connectivity analyses of WSS and EPN represented as networks, are performed by updating the functionality/operability of individual components. Operability/Functionality here has only two values, either TRUE for no to slight damage or FALSE when there is moderate damage to complete collapse. With this, disconnected or isolated WSS demand nodes are identified and overall water connectivity loss (WCL) is calculated for the city.

It is obvious that an electric power supply is required for WSS to operate. Therefore, for the consideration of interdependencies, the functionality of electric power substations of EPN corresponding to each pumping station of WSS to which it supplies the electric power is checked. Accordingly, the functionality of all pumping stations is updated due to the interdependencies and the connectivity analysis performed.

Eventually, comparisons are made to check the effect of the precision of local site condition modelling to connectivity loss of WSS considering the interdependencies. It should be noted that the local site conditions do not only affect the structures situated at each site but they might have additional or cascading effects on the overall impact on a greater scale due to the intra- and interdependencies which will be studied in the following case study.

3. CASE STUDY

The city of Thessaloniki has been considered in this study. The city of Thessaloniki lies in a highly active seismic zone characterized by strong historical earthquakes. Water is supplied to a population of about 1,000,000 in an area of 90 km^2. A simplified, yet realistic WSS network of Thessaloniki is shown in Figure 1 (Pitilakis et al., 2014) consisting of pumping stations, storage tanks and pipelines. As already stated, interdependencies with EPN are considered, and more specific functionality of electric substations is checked to ensure electricity supply to pumping stations. The substations of EPN are also shown in Figure 1.

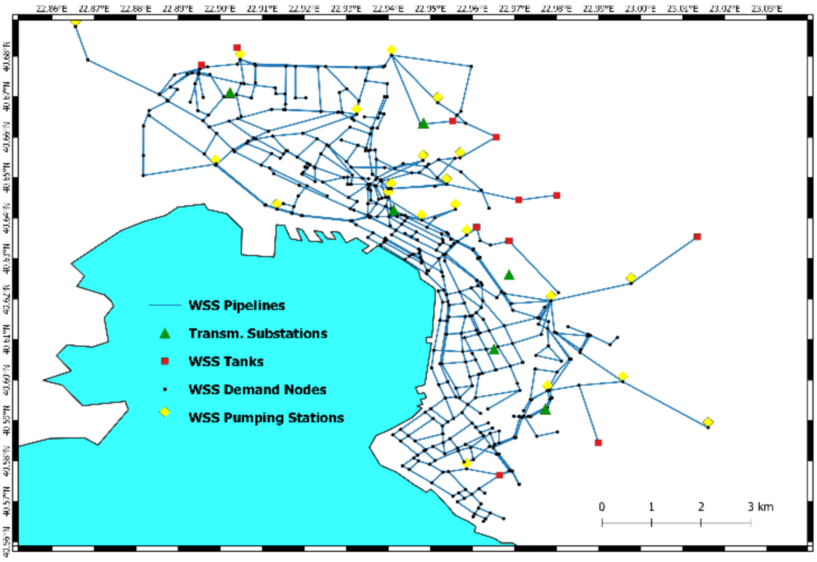

Figure 1: Water Supply System with electric transmission substations of Thessaloniki, Greece

3.1. UTILITY NETWORKS

The components of WSS includes water sources, water treatment plants, pumping stations, storage tanks, pipes, tunnels, supervisory control and data acquisition sub-system (SCADA). In the context of this paper, pumping stations, tanks, demand nodes and pipelines have been considered. The network modelling consists of 477 nodes (437 demand nodes, 21 pumping stations, 11 tanks) and 601 edges (pipelines). Due to the unavailability of the data, for now, all the components of pumping stations are considered to be anchored in a low rise R/C building with a high-level seismic design. Material type of pipelines includes asbestos cement, cast iron, PVC and welded steel.

3.2. SITE CONDITIONS

In this study, we used two $V_{s,30}$ models of increasing precision (Figure 2). Figure 2(left) shows the simplified global slope-based $V_{s,30}$ model that is adopted from U.S. Geological Survey (USGS) (Wald and Allen, 2007). For the considered study area, the majority of the regions are classified as soil class B according to Eurocode 8 (CEN, 2004b). Some areas near the coastal region are classified as soft soil (soil class C). Such simplified models are practical and easy to implement and are therefore widely used for large scale applications despite their shortcomings and the numerous uncertainties associated with their development. The combined use of topography and geology as proxies can help improve the accuracy of these models (Kwok et.al., 2018).

Figure 2(right) shows the measured $V_{s,30}$ model of the study area, available for Thessaloniki from its microzonation study (Anastasiadis et al., 2001), which is a more rigorous one. From this figure, it can be seen that the simplified model fails to identify the very stiff, rock-like formations (soil class A) at the eastern part of the area, while there is a rather good agreement between the remaining parts of the city. Even though such discrepancies can be considered acceptable for large scale estimations (e.g at regional or national scale) sometimes, it might have a significant effect at a local scale.

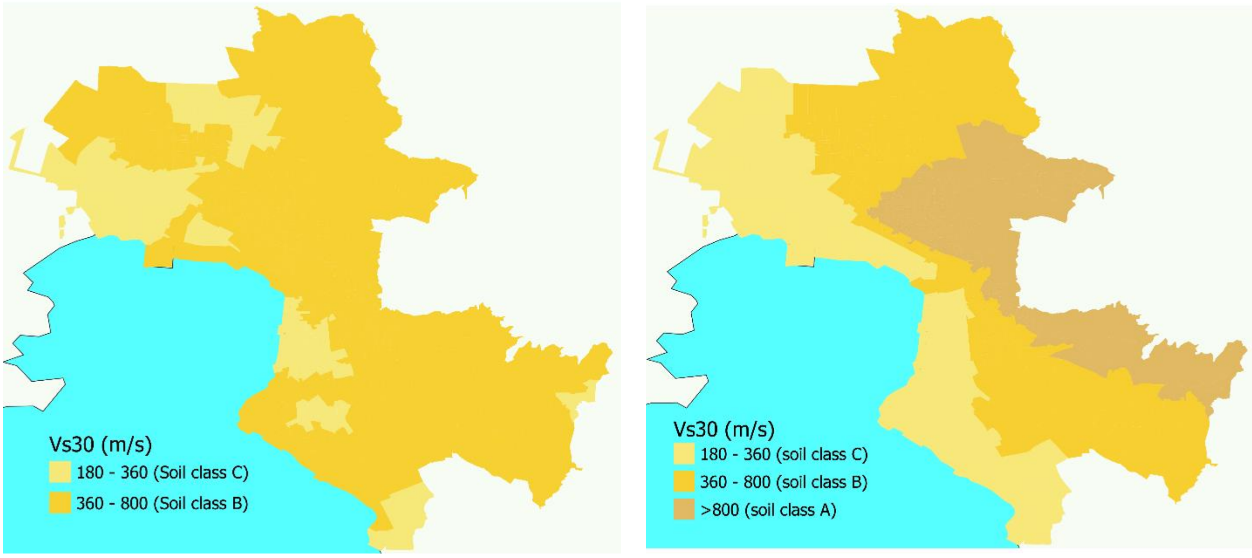

Figure 2: Spatial distribution of Vs.30 models of Thessaloniki according to USGS slope based model (left) and measured values (right)

3.3. SEISMIC DEMAND

For seismic hazard, a scenario-based analysis that simulates the 6.5 Mw 1978 Thessaloniki earthquake was performed in the OpenQuake engine. The event was simulated as an earthquake rupture using the fault rupture model by Roumelioti et.al (2007). For strong ground motion modelling, we used the GMPE model for active shallow crustal regions by Akkar and Bommer (2010). 1000 ground simulations were generated considering the variability. Spatial distribution of median PGA and PGV values for the study area enclosing all the demand nodes considered is shown in Figures 3 and 4 using both $V_{s,30}$ models. It can be seen that the discrepancies lie in both the PGA and PGV values obtained from the different $V_{s,30}$ models. In some of the coastal areas, the simplified (USGS) $V_{s,30}$ model underestimates PGA and PGV compared to the measured $V_{s,30}$ model. On the contrary, in some other areas of the eastern part, the values are overestimated by the simplified USGS model. Consequently, the direct damage to the demand nodes may vary much when two $V_{s,30}$ different models are considered. However, as the study focuses more on the differences in the impact of the system due to interdependencies, demand nodes are not considered to be vulnerable components. Also, the responsibility of the repair of the demand nodes may not come directly under the responsibility of the public authority.

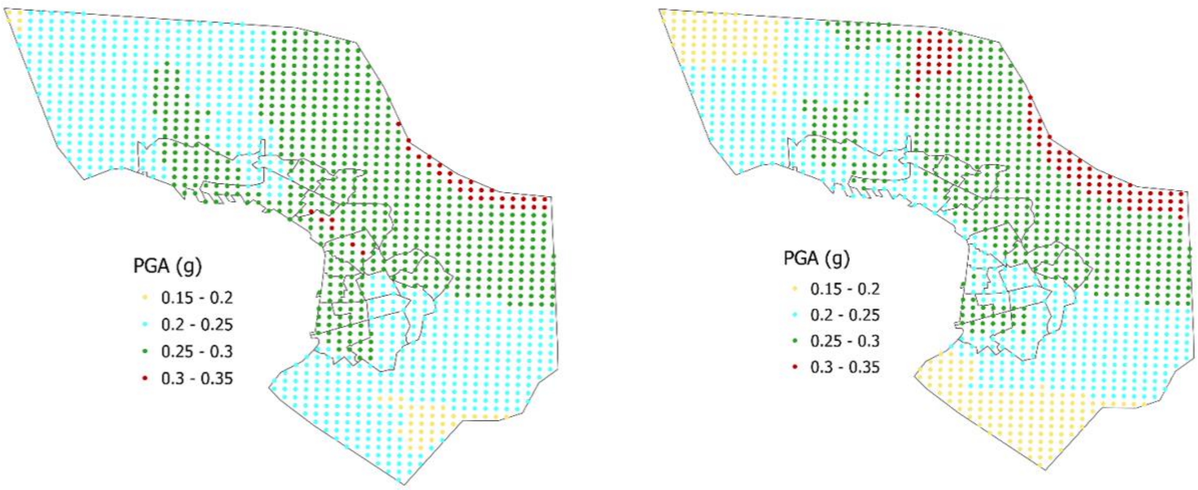

Figure 3: Median PGA values of Thessaloniki enclosed by demand nodes of WSS considering the $V_{s,30}$ model from USGS (left) and measured value (right)

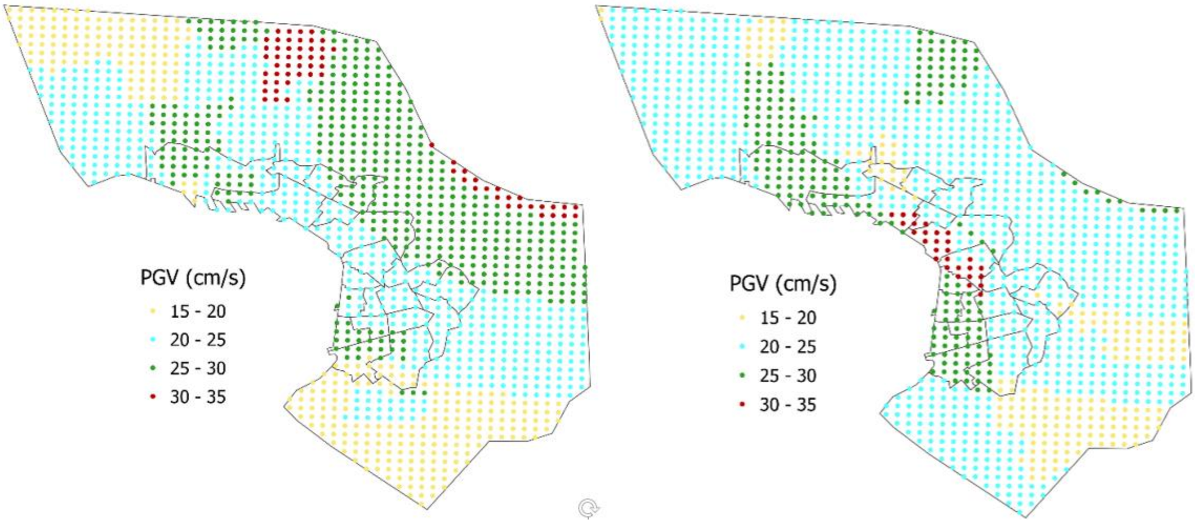

Figure 4: Median PGV values of Thessaloniki enclosed by demand nodes of WSS considering the $V_{s,30}$ model from USGS (left) and measured value (right)

3.4. FRAGILITY MODEL

In this study, for the EPN, only transmission substations are considered to be vulnerable components. Three types of substations are identified, i.e. closed type, open type and mixed type (one whose some components are enclosed by the building) and the fragility model is employed from SRM LIFE (2007) (Table 1). In the case of WSS, only pumping stations and pipelines have been considered as vulnerable components. For now, all the pumping stations are considered to be anchored components in low rise R/C buildings with high-level seismic design (Table 1) (Pitilakis et al., 2014; SRMLIFE, 2007). For the pipelines, the fragility model is employed from ALA (2001). For substations and pumping stations, the adopted intensity measure (IM) is PGA. For pipelines, it is important to consider both PGV and PGD as IMs. PGV is most widely used for linear structures like pipelines as there exists a direct link between longitudinal ground strain and PGV. Also, experience from past earthquakes like 2007 Niigata and 2011 Christchurch showed that the failure of the buried pipelines is mainly due to permanent ground deformation. According to HAZUS, ground failure is more likely to present a break whereas ground shaking induces more leaks-related damage (NIBS, 2004). In the present study we investigate damage due only to ground shaking and hence PGD is not taken into account in the analysis.

Table 1: Parameters for fragility curves for the various components of EPN and WSS

COMPONENTS OF EPN AND WSS (SRM-LIFE,2007)	DAMAGE STATE	PEAK GROUND ACCELERATION	
		MEDIAN (g)	LOG-STANDARD DEVIATION
Transmission Substations (Open Type)	Minor Moderate Extensive Complete	0.18 0.32 0.43 0.65	0.55 0.50 0.50 0.50
Transmission Substations (Closed Type)	Minor Moderate Extensive Complete	0.13 0.19 0.26 0.60	0.50 0.55 0.55 0.50
Transmission Substation (Mixed Type)	Minor Moderate Extensive Complete	0.18 0.32 0.43 0.65	0.55 0.50 0.50 0.50
Pumping Stations (Anchored component-low rise R/C building with high-level seismic design)	Minor Moderate Extensive Complete	0.15 0.30 1.1 2.1	0.30 0.35 0.55 0.70

3.5. CONNECTIVITY LOSS

After obtaining, the ground motion parameter in terms of IM in the whole area (see Figures 3 and 4) for the two $V_{s,30}$ models, which allows the fragility analysis to compute the damage state and functionality at the component level, connectivity analysis is done to check whether the demand nodes are isolated or still connected. To check the overall performance of the study area, water connectivity loss *WCL* is calculated as follows:

$$WCL_i = 1 - \frac{N_i^s}{N_o}$$

Where, i is the earthquake event, N_i^s is the number of nodes connected after ith earthquake event and N_o is the number of connected nodes before the earthquake event.

3.6. INTERDEPENDENCIES

To be precise, dependencies is the term that defines unidirectional relationships, whereas interdependencies mean bidirectional relationships. In this study, interdependency represents both unidirectional and bidirectional relationships. Here, the interdependency considered refers to the linkage between electric transmission substations of EPN and pumping stations of WSS. It means that the functionality/operability of the pumping station is not only dependent on its own vulnerability/damageability but also on the functionality and damages of a particular substation through which it gets an electric supply.

4. RESULTS

Water connectivity loss was calculated using both $V_{s,30}$ models. Regardless of the adopted $V_{s,30}$ model, the average values of WCL are comparable. The average value for the whole water system considering the simplified model is found to be 0.051 while considering the rigorous measured $V_{s,30}$ model it is found to be 0.054. Box plot, a rectangle showing that second and fourth quartile including line indicating median value, for the values of WCL obtained considering the two $V_{s,30}$ models are shown in Figure 5. From this plot, it is seen that the quantiles of both models are also comparable except for some extreme values observed with the simplified $V_{s,30}$ model. A more detailed presentation of the results is given in Figure 6, which illustrates the isolation (in percentage) of each node for the two $V_{s,30}$ models considering 1000 simulations. Some discrepancies are observed between the two models at a local scale. Specifically, the percentage of isolated nodes falling between 40% to 50% is increased when considering the rigorous $V_{s,30}$ model.

It is important to note that only the main transmission substations have been considered in this study. Introducing additional local EPN substations might lead to higher losses of the system. Also, further discretization of the pipeline network may affect the results and the losses as the mean value of the water connectivity loss will be certainly affected capturing better the effects due to local soil conditions. Furthermore, peak ground displacement which is very crucial for the pipelines is to be considered. This will be part of further studies.

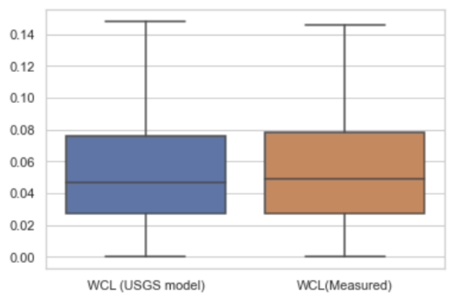

Figure 5: Box plot of water connectivity loss considering values from USGS model and detailed site investigation $V_{s,30}$ model

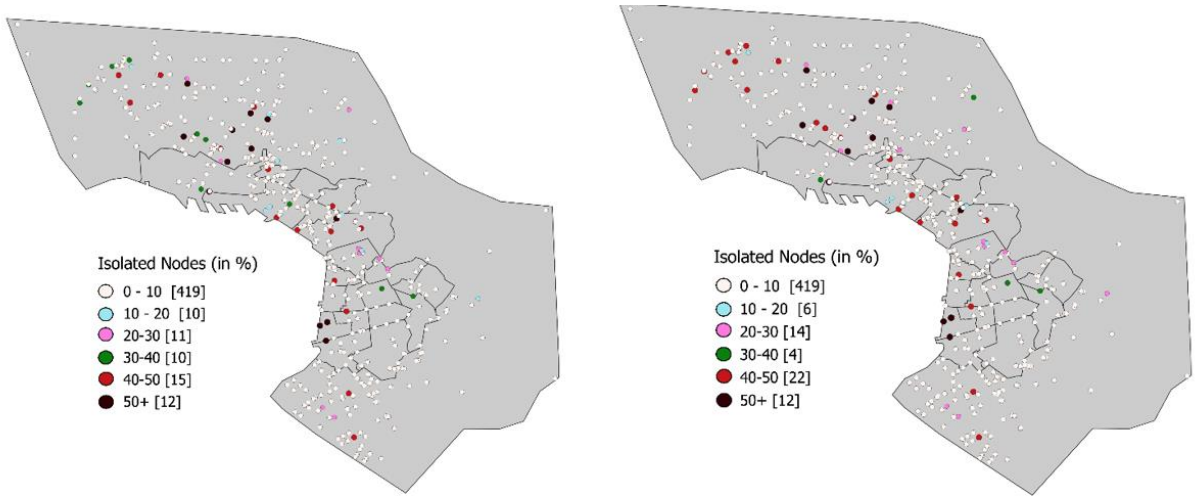

Figure 6: Isolation of each node considering all simulations (in percentage) of WSS using the $V_{s,30}$ model from USGS (left) and the detailed $V_{s,30}$ model (right)

5. CONCLUSIONS

We investigated the impact of the precision of local site conditions modelling on the risk assessment of a water supply system (WSS) at a city scale in terms of vulnerability and connectivity analysis at both component and system level . For that, two $V_{s,30}$ models were considered. The first one is a simplified one obtained through correlation with topography, while the second is obtained from detailed site investigation in the framework of past microzonation studies in the city of Thessaloniki. The overall performance is conducted in terms of water connectivity loss. The intra dependencies i.e. among the different components of the water supply system itself and interdependencies between the water supply system and electrical power network (EPN) were also taken into account. The main conclusion of this study is that for large scale applications and connectivity analyses the precision of $V_{s,30}$ model to overall water connectivity loss is not very significant at city or urban scale. In the same time, at the local scale when each node was examined according to the percentage of isolation, some discrepancies were found. The low impact of the precision of site modelling on the overall performance of water system may be attributed to some of the following reasons: (a) Inadequate resolution and detail of the EPN transmission substation modelling with respect to the $V_{s,30}$ model at city scale. On a local scale where the differences between the two site condition models are inevitably higher, the role of the precision of $V_{s,30}$ modelling is expected to be more important and the rigorous model may lead to higher losses provided that local EPN substations are also considered. (b) Inadequate resolution and detailing of the WSS grid and spatial modelling details of the water pipelines and nodes in relation to the site conditions mapping and detail. A higher discretization of the pipeline network might result in a better capturing of the effects due to local soil conditions. (c) Adopted fragility curves and intensity measures (IM). Instead of considering both PGV and permanent ground displacements (PGD) as IMs, considering only ground shaking (i.e PGV) may lead to underestimation of WCL especially in the coastal area where soft soil conditions are dominant.

In summary, a preliminary conclusion of this study is that the overall connectivity loss of a water supply system at a city scale may be quite accurately estimated using simplified $V_{s,30}$ models to describe site conditions and consequently the IM. However, when critical facilities are concerned like hospitals and fire-fighting stations or in densely populated areas within the city, it is important to use more rigorous site conditions and site effect models even if they are estimated using only $V_{s,30}$ values whose scrutinization would be the part of the further studies.

6. ACKNOWLEDGEMENT

The present work has been done in the framework of grant agreement No. 813137 funded by the European Commission ITN-Marie Sklodowska-Curie URBASIS-EU project. Also, we would like to acknowledge all the contributors to the SYNER-G project that was funded from the European Community's 7th Framework Program under grant No. 244061.

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