A methodology to couple vulnerability and condition of buried pipes in seismic risk assessment: Application to a subsystem of the Lisbon wastewater system

15 WCEE
LISBOA 2012

V. Sousa, N. Almeida
Instituto Superior Tecnico, Universidade Tecnica de Lisboa, Lisboa

M. Luísa Sousa, A. Campos Costa
Laboratório Nacional de Engenharia Civil, Lisboa

J. Saldanha Matos
Instituto Superior Tecnico, Universidade Tecnica de Lisboa, Lisboa

SUMMARY:
Usually, seismic risk assessment of buried pipes is done using empirical vulnerability functions, derived by regression of failure rates on buried pipelines observed in past seismic events. By doing so, it is assumed a uniform seismic performance for all the pipes within each defined pipe category. However, from the extensive research into asset management of this type of infrastructures, it is known that the structural condition of the buried pipes can vary significantly within a network of buried pipelines.
This paper presents an original methodology to estimate quantitatively the variability of buried pipes vulnerability based on existent vulnerability functions and use this information to differentiate the seismic performance of buried pipelines based on their condition. This paper also presents an application of this methodology to estimate failure rates of sewers of a wastewater subsystem of Lisbon city for different seismic scenarios.

Keywords: buried pipes, structural condition, lifelines, seismic risk, vulnerability

1. INTRODUCTION

Modern lifestyle is supported by a set of infrastructures that satisfy essential basic needs of the individuals and the communities. These infrastructures are usually referred to as lifelines and their purpose include (Chen and Scawthorn, 2003): i) providing energy (electric power, gas, petroleum); ii) control the water cycle (potable water treatment and supply, wastewater and stormwater collection and treatment); iii) allow communication (telephone, television, internet); and iv) support mobility and transportation (roads, railroads, airports, and harbors). These lifelines constitute complex systems that perform like channels allowing the flux of goods, information and people, contributing to the evolution and wellbeing of humans in modern societies.

Lifelines are valuable assets that, given their functions, play a crucial role at different levels, including health, safety, environment and economy. During their operation stage, natural disasters, such as earthquakes, represent threats with a significant destructive potential. Within the Portuguese context, the relevance of earthquakes is best represented by the 1755 Lisbon earthquake and can be found presently in documents such as the *National Assembly Resolution n. 102/2010* recommending the government to "…create, articulating with the local authorities, a national plan for the reduction of the seismic vulnerability of the industrial, health, schools, government, transportation, energy, communications, water and wastewater infra-structures networks". According to Elnashai and Sarno (2008), much recent research is focusing on ways to minimize earthquake risk to lifelines. The *American Lifelines Alliance* (ALA), in the USA, commenced in 1998 with the support from the *Federal Emergency Management Agency* (FEMA) and the *National Institute of Building Sciences* (NIBS), and several projects in Europe (e.g., LESSLOSS, 2007) are examples of such efforts.

A significant fraction of several lifelines is comprised by buried pipelines that extent for several kilometers over significant geographical areas. Wastewater networks are one of the lifelines that fall within this group. According to Duran et al. (2002) wastewater networks in developed countries reach 5000 km of pipelines per million inhabitants, with the majority being buried gravity pipes. Additionally, the components of wastewater networks are not individual entities but a complex system which is continuously and simultaneously solicited. Consequently, asset management of these infrastructures as received significant interest, particularly during the last two decades with a transition from reactive to pro-active strategies and adopting performance-based approaches (e.g., Matos et al., 2003, Cardoso et al., 2004).

Since wastewater networks were build and intervened along the years and the deterioration rates can vary significantly within a single system, one of the main concerns of the extensive research on asset management to identify the pipes in worse structural condition to establish priorities for intervention. Among the numerous decision support tools developed to assist in managing wastewater networks (e.g., APOGGE - MacGilchrist and Mermet, 1989, MARESS – Reyna, 1993, PIPES - Lim and Pratti, 1997, PRISM - Ariaratnam and MacLeod, 2002), only the model developed by Zhao et al. (2001) accounted for earthquakes by weighting the seismic zone where the pipes are installed. However, given the longevity of these infrastructures and the impacts resulting from their failure in seismic events (e.g., see Azevedo et al. 2010), it should be an aspect to be considered in the decision process in seismically active regions.

The present paper presents a methodology to couple structural condition with seismic vulnerability of buried pipes to differentiate their seismic performance. The approach is based in the estimation of the variability associated with the vulnerability functions developed for buried pipelines and assuming that the differences in structural condition of the buried pipes is the most significant factor for it. This approach can be seen as conservative since it attributes all variability to the difference in structural condition of the pipes. An application of the developed methodology to the Chelas subsystem, a part of the SIMTEJO system, in Lisbon, is also presented.

2. SEISMIC RISK

2.1. General model

Typically, the seismic risk is represented as a function of the (ALA 2004a, FEMA 2004): i) seismic hazard; ii) seismic vulnerability/fragility; and iii) exposure. Since there is uncertainty is each of these elements, it is common to express them mathematically as a function of seismic loss, $\mathrm{P}(\mathrm{L} > l)$, in probabilistic terms:

$$\mathrm{P}(\mathrm{L} > l) = \int_{\mathrm{D}} \int_{\mathrm{H}} \mathrm{P}(\mathrm{L} > l|\mathrm{d})\mathrm{P}(\mathrm{D} > d|h)\mathrm{f_H}(\mathrm{h})\,\mathrm{dh}\ \mathrm{dd} \tag{2.1}$$

where $\mathrm{P}(\mathrm{L} > l|\mathrm{d})$ is the conditional probability of the loss exceeding a level l, given a damage level d, $\mathrm{P}(\mathrm{D} > \mathrm{d}|\mathrm{h})$ is the conditional probability of the damage exceeding d, given a hazard level h, and $\mathrm{f_H}(\mathrm{h})$ is the probability density function of the seismic hazard. However, since the loss is highly multidimensional (e.g., monetary loss, life loss, environmental loss) it can be extremely difficult to fully quantify it. Therefore, it is common practice to reduce the seismic risk to the probability of exceeding a given level of damage, $\mathrm{P}(\mathrm{D} > \mathrm{d})$:

$$\mathrm{P}(\mathrm{D} > d) = \int_{\mathrm{H}} \mathrm{P}(\mathrm{D} > d|h)\mathrm{f_H}(\mathrm{h})\,\mathrm{dh} \tag{2.2}$$

This simplification represents a transition from a risk concept to a reliability concept, but whenever the losses are mainly economical (and direct) the conversion is much simpler. From the two remaining components of seismic risk, seismic hazard and vulnerability, the present paper will focus in the later because it is where there are differences depending on the type of element submitted to a seismic action. The seismic hazard in a given location is independent from the characteristics of the elements that may be exposed to it. In this communication it was chosen to use historical earthquakes to estimate the seismic actions instead of a given level of seismic hazard so simplify the demonstration of the purposed approach.

2.2. Vulnerability models

Seismic vulnerability relates the damages caused with the intensity of the seismic action or with its collateral effects. For the former, there are three main categories of vulnerability models (Chen and Scawthorn, 2003): i) expert models; ii) empirical models; and iii) analytical models. Expert models make use of the experience of individuals competent in the earthquake engineering field to obtain vulnerability functions. For that purpose, several techniques exist to assist elicit expert opinion, such as the Delphi Method. In the empirical models, also so known as statistical models, the vulnerability functions are derived through statistical analysis of the damage observed and seismic solicitation observed in past earthquakes. Typically, linear or multiple linear regression are used to fit the vulnerability functions. Finally, the analytical models approach the problem from a physical or mechanical perspective. The effects of the seismic action are translated into forces and deformations and, using constitutive relations of the materials comprising the elements, the damage state is determined.

Despite the existence of analytical formulations to evaluate the vulnerability due to wave propagation for segmented and continuous buried pipes and limited analytical models for permanent ground deformation for all types of buried pipes, in practice the empirical models are more commonly recommended (e.g., see HAZUS MH4 – FEMA, 2003) and used (e.g., see LESSLOSS, 2007). Empirical vulnerability functions for buried pipes generally follow one of the following formulations:

$$\mathrm{FR} = \prod \mathrm{K_i}\ \ \mathrm{a\ SA} \tag{2.3}$$

$$\mathrm{FR} = \prod \mathrm{K_i}\ \ \mathrm{b\ SA^c} \tag{2.4}$$

where FR is the failure rate, $\mathrm{K_i}$ are corrective factors (e.g., accounting for pipe material, diameter, soil type and joint type), a, b and c are empirical parameters, and SA is the descriptor representing the seismic action. Within this paper the peak ground velocity (PGV) is the descriptor considered for wave propagation effects, whereas for permanent ground deformation the peak ground displacement (PGD) is adopted. Other descriptors have been used by different authors, particularly for wave propagation (e.g., Katayama, 1975, Isoyama and Katayama, 1982, Eguchi, 1991, O'Rourke et al., 1998, Hwang and Lin, 1997 and Isoyama et al., 2000 use peak ground acceleration; Ballantyne et al., 1990 and Eguchi, 1991 use Modified Mercalli Intensity Scale; Barenberg, 1988 and O'Rourke and Deyoe, 2004 use soil deformation). Additionally, some authors consider combinations of descriptors (e.g., Yeh et al., 2006 use peak ground acceleration and soil deformation; Pineda-Porras and Ordaz, 2007 use PGV and peak ground acceleration). Comparison of adjustment using different descriptors can be found in Chen et al. (2002) and Hwang et al. (2004). Pineda-Porras and Najafi (2010) reviewed the selection of descriptors for vulnerability functions due to wave propagation.

Complementarily to the fact that wave propagation and permanent ground displacement represent two different mechanical actions over the pipes, resulting in significant discrepancy in the order of magnitude of the resulting failure rate, the existence of separate formulations is also related with the nature of the damage observed. For wave propagation, the failure rate is comprised by 20% of failures (structural disruption) and 80% of ruptures (service disruption), whereas for permanent ground displacement the distribution is inverted (FEMA, 2003, ALA, 2004b).

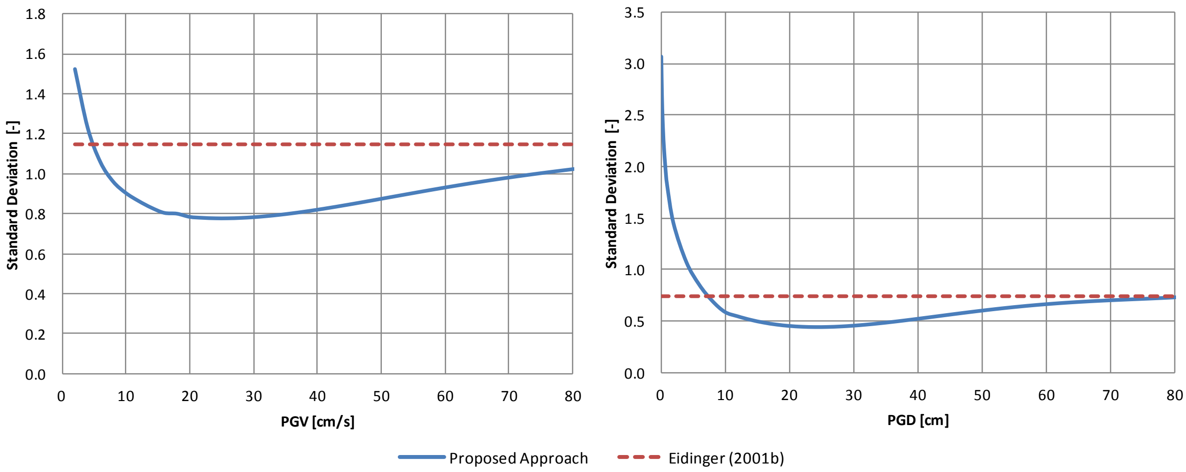
3. PROPOSED APPROACH

Usually, seismic risk assessment of buried pipes is undertaken using empirical vulnerability functions. These vulnerability functions have been derived by regression of failure rates on buried pipelines observed in past seismic events. This procedure assumes a uniform seismic performance for all the pipes within each defined category considered in the process of derivation of the vulnerability functions. Therefore, for a given seismic action, the functions provide a single point estimate of the failure rate. Given the complexity of the processes and the randomness in the failure of buried pipelines under seismic action, this approach has merits for management purposes, despite its simplicity. However, the dispersion observed in the results provided by the different empirical models is a strong indicator of the high level of uncertainty involved. Consequently, the correlations between predictions and observations in new seismic events may be small (e.g., Kurtulus, 2011).

Urban (2006) endorses the importance of conducting seismic risk analysis considering, explicitly, both the expected value and the range of possible values. Among the models identified (see Sousa et al., 2010b for a complete list of the models studied), only the models proposed by Eidinger (2001a), and adopted by the American Lifeline Alliance (ALA, 2001), provide a quantification of the variability by indicating a value for the standard deviation. Complementarily, it is assumed that the possible values for the rate of failure around the average value provided by the models are fitted by a lognormal distribution. According to Eidinger (2001b), the value predicted by the models should be considered accurate within a ±50% band, for large networks (over 15 km in length), or within a ±60% band, for small networks (under 15 km in length). These ranges reflect about a 67% probability of the actual pipe rate of damage will be within these bounds.

Instead of considering a constant standard deviation of the failure rate, Sousa et al. (2010b) proposed an approach to estimate the variability of the failure rate based on the following procedures: i) estimate the average value of the failure rate for a given intensity of seismic action using all models available for each pipe material, ii) estimate a unique standard deviation for a given intensity of seismic action using all models for cast iron pipes. The assumption underpinning the approach is that the differences between the vulnerability functions translate the variability in vulnerability for each category of pipes following a lognormal distribution.

The approach leads to a standard deviation variable with the intensity of the seismic action, as can be observed in Fig. 3.1 for cast iron pipes. A comparison of the values obtained with the models and constant standard deviations determined by Eidinger (2001b) and the approach proposed by Sousa et al. (2010) is presented in Fig. 3.2.

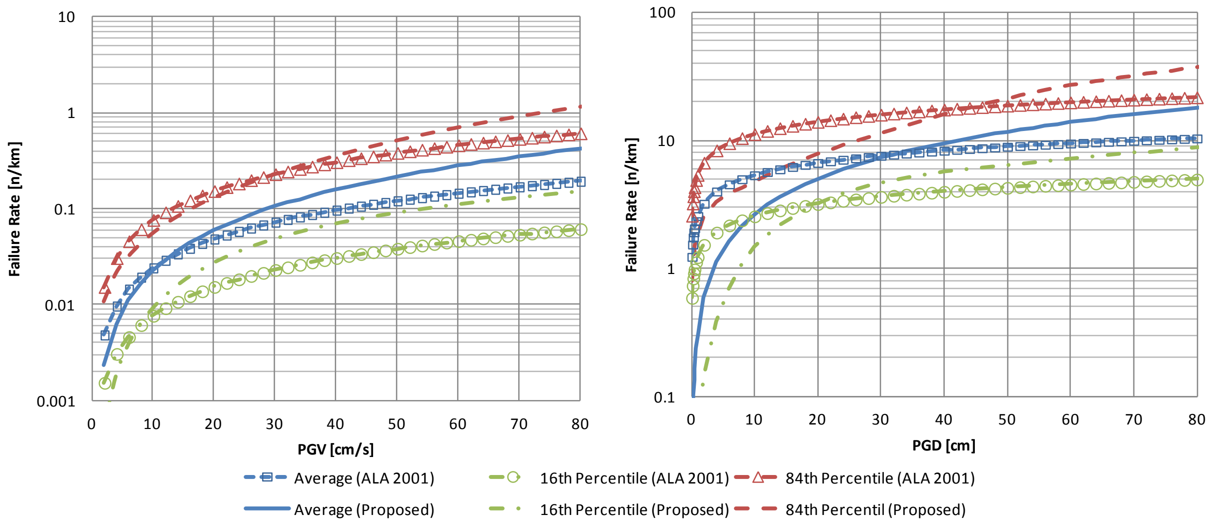


a) b)

Figure 3.1. Evolution of the standard deviation of the failure rate with a) PGV and b) PGD

Additionally to the pipe material and diameter, junction type and soil corrosivity, for which some models provide correction factors, the variability between the values from the various models can be explained by observation limitations and local and pipe particularities (e.g. see Eidinger, 2001a). Regarding pipe particularities, probably the structural condition of the pipe is one of the most relevant aspects and, except for relatively new pipes, encloses the issues of construction quality, maintenance practices and usage history.

From the extensive research into asset management of this type of infrastructures, it is known that the structural condition of the buried pipes can vary significantly, even within each pipe category considered in the definition of the vulnerability functions. Pipe condition can range from perfect (excellent condition) to near failure (very poor condition). For instance, in the USA it is predicted that in 2020 33% of the total sewer pipe length will be in excellent condition, 11% good, 12% poor and 23% will be in very poor condition. The remaining 9% of the sewer pipe length will be over their lifetime (over 100 years old) (USEPA, 2002).



a) b)

Figure 3.2. Comparison of the evolution of the average and the 16th and 84th percentiles failure rates with a) PGV and b) PGD, for cast iron pipes

Since it is licit to consider that the structural condition contributes significantly for the performance of buried pipes under seismic action it is assumed that it explains most of the variability observed in the failure rates. Considering that for high seismic actions both good and poor conditions pipes are equally affected whether for low seismic action only poor condition pipes are prone to be affected, the assumption supports a possible explanation for the evolution of the standard deviation of the failure rate observed in Fig. 1.

Based on the exposed it is proposed to couple structural condition with the variability of the failure when assessing seismic risk of buried pipelines. This allows differentiating the seismic performance of pipes that have the same vulnerability function but are known or expected to present distinct structural conditions. Along the limitations of the procedure used to estimate the vulnerability function variability, the major simplification of the approach is to assume that the structural condition explains most of the variability. Another valid argument is that the uncertainty regarding the values of the seismic actions in the historical records used to derive the vulnerability functions may be the largest source of variability.

4. APPLICATION TO A CASE STUDY

4.1. Chelas subsystem

SIMTEJO, Saneamento Integrado dos Municípios do Tejo e Trancão S.A., was created in 2001 to operate the bulk wastewater system in the Lisbon region, in Portugal. The system serves the municipalities of Lisbon, Loures, Mafra, Odivelas and Vila Franca de Xira municipalities and a part of the Amadora municipality. Serving about 1.5 million inhabitants, the SIMETJO system covers a total area of more than 1,000 km^2 and includes 26 wastewater treatment plants (WWTP), 55 pumping stations and 125 km of sewers.

The Chelas subsystem, located in the municipality of Lisbon, serves around 140 000 inhabitants and includes four main trunk sewers. The subsystem also comprises one treatment plant, five pumping stations and various weirs and overflows in order to separate domestic effluents from the combined system and transport them to the interceptors (Fig. 4.1).

Figure 4.1. Chelas subsystem representation

With a total length of 3300 m and 131 manholes, the gravity sewers include circular and oval pipes of various materials installed at depths up to 5 m. The ceramic pipes (concrete, vitrified clay and fiber cement) extent for 1300 m, the metallic pipes (cast iron) are 1700 m long and the polymeric pipes (high density polyethylene – HDPE, polyvinyl chloride – PVC, and corrugated polyvinyl chloride – PVCC) account for the remaining 300 m.

4.2. Pipe condition

Usually, sewer pipes condition is determined using protocols to evaluate internal images of the pipes obtained through CCTV inspections. Most of the protocols distinguish between structural and service (hydraulic and environmental) conditions and are based on the seminal work developed in the by the Water Research Council (WRc) in the 1960’s and 1970’s, which culminated in the publication of the first edition of the Sewerage Rehabilitation Manual (WRc, 1984). The structural condition is determined based on the visual observation of number and characteristics the defects such as cracks and fissures, pipe deformations or joints displacements, and usually classified in a scale of 1 (as new) to 5 (near collapse).

However, general and regular inspection of the sewer systems is restricted to a limited number of developed countries (e.g., UK, Germany; Canada; USA). In most countries only a restrict number of municipalities are performing regular CCTV inspections of the totality of the network. In Portugal, only one wastewater agency is already doing it. Therefore, to assist in the implementation of proactive management plans, an expert-base model was developed for SIMTEJO to estimate the pipe condition by applying the following general expression (Sousa et al., 2007, 2009):

$$\mathrm{E} = \mathrm{K}\sum \mathrm{S_i W_i} \tag{4.1}$$

with E representing the evaluation result (1 to 10), K is a correction factor, taken into account the know-how about the system performance (higher than 0), $\mathrm{S_i}$ is the score of performance parameter i (0 to 10), and $\mathrm{W_i}$ is the weighting of performance parameter i (0 to 100%). The results obtained with this model are not to be considered in an absolute scale but rather as a probabilistic classification for a given area. Therefore, the results are categorized into three classes according to the probability of deficient performance: i) $\mathrm{E} > 5.5$ – poor condition, $5.5 \geq \mathrm{E} \geq 3.5$ - medium condition, and $\mathrm{E} < 3.5$ - good condition. Further details regarding the model and its application can be found in Sousa et al. (2007, 2009). For the purpose of the present communication, the relevant results are presented in Fig. 4.2 were that, in terms of structural collapse, 5% of the sewers where classified as high probability (considered equivalent to condition state 4 and 5), 38% as medium probability (considered equivalent to condition state 3) and 57% as low probability (equivalent to condition state 1 and 2).

The model was developed for gravity pipes only and does not apply to pressures mains. The latter are submitted to different external and internal solicitations that drive distinct deterioration mechanisms. These tend to be similar to what is observed in water mains, with factors such as corrosion type and depth, pressure extremes and variations and temperature playing important roles.

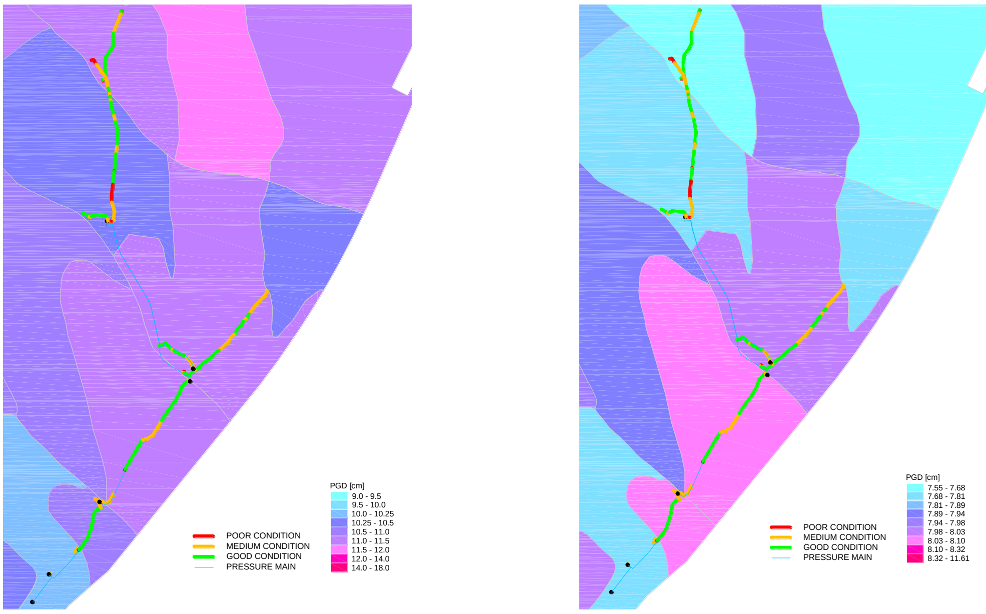
4.3. Seismic scenarios

Two different scenarios were generated for the region of interest, aiming at reproducing seismic ground motion occurred in past earthquakes. For a near distance, moderate magnitude scenario, the 1531.01.26 earthquake was chosen, with an estimated magnitude of 7.3, located at the Lower Tagus Valley fault, nearly 30 km northeast of Lisbon. The maximum reported earthquake intensity was X (MSK) making it one of the most disastrous earthquakes in the seismic history of Portugal. Approximate epicenter coordinates inferred from the macroseismic field are 38.9ºN, 9.0ºW but its tectonic source remains uncertain (Baptista and Miranda, 2009). The 1755.11.01 earthquake, known as the 1755 Lisbon earthquake, was chosen to represent an offshore, long distance, high magnitude scenario. The 1755 event has an estimated magnitude of Mw=8.5–8.9. Although the earthquake epicenter was located offshore, its position remains controversial, because, presently, it’s not known a single tectonic structure able to generate an earthquake with such a magnitude (Sousa et al., 2010a). The attenuation laws published in Sousa et al. (2008) were adopted in both scenarios.

4.4. Damage rates

Crossing pipe condition with the intensity of the seismic effects, namely PGV and PGD, the damage rates were estimated considering the following rules: i) average value minus one standard deviation for pipes in condition 1 and 2, ii) average value for pipes in condition 3, and iii) average value plus one standard deviation for pipes in condition 4 and 5.

To limit the paper length only the PGDs resulting from the 1531and 1755 earthquakes are presented in Fig. 4.2. For sewer crossing limits of the seismic action intensity the most severe was adopted as reference.



a) b)

Figure 4.2. PGD affecting the Chelas subsystem gravity sewers as a result of the a) 1531 and b) 1755 earthquakes

The maximum and minimum failure rates estimated for the three main pipe categories due to seismic wave propagation and permanent ground displacement are presented in Table 4.1 for both scenarios. For the scenarios considered in the case study it is estimated that the majority of the failures result from permanent ground deformation. For the 1531 earthquake scenario there were estimated 3 failures on ceramic pipes and 4 failures on metallic pipes. For the 1755 earthquake scenario there were estimated 2 failures on ceramic pipes and 3 failures on metallic pipes. In both cases the estimated number of failures on polymeric pipes was less than 1.

Table 4.1. Estimated maximum and minimum failure in the Chelas subsystem gravity sewers rates due to transient and permanent soil deformation

Pipe Material	Failure Rate [n/km]							
	1531 Earthquake				1755 Earthquake			
	PGV		PGD		PGV		PGD	
	Max	Min	Max	Min	Max	Min	Max	Min
Ceramic	0.18	0.03	5.49	1.39	0.07	0.01	5.24	1.00
Metallic	0.29	0.05	6.31	1.90	0.14	0.02	5.90	1.45
Polymeric	0.06	0.02	1.96	1.08	0.02	0.01	1.58	0.77

5. FINAL REMARKS

Usually, the damage rates in buried pipes due to an earthquake are estimated based on empirical vulnerability curves. However, these curves only account for distinct pipe characteristics (e.g., pipe material and joint type) and do not take into account the different structural condition in which the pipes may be. Nonetheless, due to varied factors, similar pipes along the same network may present marked variances in their structural condition. Thus, it is licit to assume that they will present different performances when submitted to seismic actions.

The proposed methodology aims at accounting for the effect of the pipe structural condition in the estimation of the damage rates. The major assumption behind the followed approach is that a main cause for the differences between the various empirical vulnerability curves that have been proposed is the average structural condition of the pipe networks affected by the historical earthquakes used in the regressions. One may argue that other factors are relevant to explain the differences, such as the quality of construction, maintenance strategies, nearby structures, soil conditions or water table level. However, except in the case of relatively new networks, most of those differences will also result in different deterioration rates and distinct structural conditions over time.

In the present case study a simplified decision support tool was used to estimate the structural condition of the pipes. However, several utilities around the world are already performing regular CCTV inspections and assessing the condition of their wastewater networks, particularly in developed countries.

Regardless of the possibility of applying the proposed methodology for seismic risk assessments, the main purpose behind its development was for using in the scope of asset management of wastewater networks. Namely, the seismic risk can be an additional criterion to consider when deciding which sewers with similar structural condition should be given priority of intervention.

ACKNOWLEDGEMENT

Vitor Sousa gratefully acknowledges the support ICIST Research Institute, from IST, and the Earthquake Engineering and Structural Dynamics Division, from LNEC. Vitor Sousa and Nuno Almeida were financially supported by FCT, the Portuguese National Science Foundation, through their PhD grants SFRH/BD/35925/2007 and SFRH/BD/39923/2007, respectively.

REFERENCES

ALA (2001). Seismic Fragility Formulations for Water Systems: Part 1 - Guideline. American Lifelines Alliance (ALA) , USA.

ALA (2004a). Wastewater system performance assessment guideline: Part 1 - Guideline. American Lifelines Alliance (ALA), USA.

ALA (2004b). Wastewater system performance assessment guideline: Part 2 - Commentary. American Lifelines Alliance (ALA), USA

Ariaratnam, S. T. and MacLeod, C. W. (2002). Financial outlay modeling for local rehabilitation strategy. *Journal of Construction Engineering and Management* 128:6, 486-496.

Azevedo, J., Guerreiro, L., Bento, R., Lopes, M. and Proença, J. (2010). Seismic vulnerability of lifelines in the greater Lisbon area. *Bulletin of Earthquake Engineering* 8, 157–180.

Ballantyne, D. B., Berg, E., Kennedy, J., Reneau, R. and Wu, D. (1990). Earthquake loss estimation modeling for the Seattle water system. Report to U.S. Geological Survey under Grant 14-08-0001-G1526, Technical Report, Kennedy/Jenks/Chilton, Federal Way, WA.

Baptista, M. A. and Miranda, J. M. (2009). Revision of the Portuguese catalog of tsunamis. *Natural Hazards Earth Systems Science* 9, 25–42.

Barenberg, M. E. (1988). Correlation of pipeline damage with ground motions. *Journal of Geotechnical Engineering* 114:6, 706-711.

Cardoso, M. A., Coelho, S., Matos, R. M. and Alegre, H. (2004). Performance assessment of water supply and wastewater systems. *Urban Water Journal* 1:1, 55-67.

Chen, W. and Scawthorn, C. (Eds.) (2003). Earthquake Engineering Handbook, CRC Press.

Chen, W. W., Shiha, B.-J., Chen, Y.-C., Hung, J.-H. and Hwang, H. H. (2002). Seismic response of natural gas and water pipelines in the Ji-Ji earthquake. *Soil Dynamics and Earthquake Engineering* 22, 1209–1214.

Duran, O., Althoefer, K. and Seneviratne, L. D. (2002). State of the art in sensor technologies for sewer inspection. *IEEE Sensors Journal* 2:2, 73-81.

Eguchi, R. T. (1991). Seismic hazard input for lifeline systems. *Structural Safety* 10, 193-198.

Eidinger, J. (2001a). Seismic fragility formulations for water systems. G&E Engineering Systems, Inc.

Eidinger, J. (2001c). Fragility curve for water transmission system components. Proc. *2nd Japan and U.S. Workshop on Seismic Measures for Water Supply*, AWWA, 6-8 August, Tokyo, Japan.

FEMA (2003). Multi-hazard Loss Estimation Methodology: Earthquake Model: HAZUS®MH MR4 Department of Homeland Security Emergency Preparedness and Response Directorate, Federal Emergency Management Agency (FEMA), USA.

FEMA (2004). Primer for design professionals: Communicating with owners and managers of new buildings on earthquake risk. FEMA 389, Risk Management Series, Federal Emergency Management Agency (FEMA), USA.

Hwang, H., Chiu, Y., Chen, W. and Shih, B. (2004). Analysis of damage to steel gas pipelines caused by ground shaking effects during the Chi-Chi, Taiwan, earthquake. *Earthquake Spectra* 20:4, 1095–1110.

Hwang, H., Lin, H. (1997). GIS-based evaluation of seismic performance of water delivery systems. Technical Report, CERI, the University of Memphis, Memphis, TN, USA.

Isoyama, R., Katayama, T. (1982). Reliability evaluation of water supply systems during earthquakes. Report of the Institute of Industrial Science, University of Tokyo, 30(1), Serial No. 194.

Katayama, T., Kubo, K., Sato, N. (1975). Earthquake damage to water and gas distribution systems. Proc. *U.S National Conference on Earthquake Engineering*, 18-20 June, Ann Arbor, USA.

Kurtulus. A. (2011). Pipeline vulnerability of Adapazarı during the 1999 Kocaeli, Turkey, earthquake. *Earthquake Spectra* 27:1, 45–66.

LESSLOSS (2007). Deliverable117 - Damage scenarios for selected urban areas (for water and gas systems, sewage mains, metro tunnels and water front structures, Tessaloniki, Istanbul (European side), Düzce. LESSLOSS: Risk Mitigation for Earthquakes and Landslides Integrated Project, Project No. GOCE-CT-2003-505488, Sub-Project 11 - Earthquake disaster scenario and loss modeling for infrastructures.

Lim, E. and Pratti, R. (1997). Pipe Evaluation System (PIPES). ESRI International User Conference, 8-11 July, San Diego, USA.

Macgilchrist, R. and Mermet, M. (1989). APOGEE 94: Towards an operational system. Proc. *Urban Stormwater Quality Enhancement - Source Control, Retrofitting and Combined Sewer Technology*, Urban Water Resources Research Council, Davos Platz, Switzerland, pp. 534-544.

Matos, R., Cardoso, A., Ashley, R., Duarte, P., Molinari, A. and Schulz, A. (2003). Performance indicators for wastewater services. Manual of Best Practice, International Water Association (IWA), London, UK.

O'Rourke, M. and Deyoe, E. (2004). Seismic damage to segmented buried pipe. *Earthquake Spectra* 20, 1167–1183.

O'Rourke, T. D., Toprak, S. and Sano, Y. (1998). Factors affecting water supply damage caused by the Northridge earthquake. Proc. *Sixth US National Conference on Earthquake Engineering*, May 31-June 4, Seatle, USA.

Pineda-Porras, O. and Najafi, M. (2010). Seismic damage estimation for buried pipelines: Challenges after three decades of progress. *Journal of Pipeline Systems Engineering and Practice* 1:1, 19-24.

Pineda-Porras, O. and Ordaz, M. (2007). A new seismic intensity parameter to estimate damage in buried pipelines due to seismic wave propagation. *Journal of Earthquake Engineering* 11, 773–786.

Reyna, S. M. (1993). Optimal planning of sewer systems rehabilitation. PhD. Thesis, Purdue University, USA.

Sousa, M. L., Carvalho, A., Bilé Serra J. P. and Martins, A. (2010a). Simulation of seismic scenarios in Algarve region. Proc. *14th European Conference on Earthquake Engineering*, Macedonia.

Sousa, M. L., Carvalho, A., Bilé Serra, J., Mateus, M. and Martins, A., (2008). Estudo do risco sísmico e de tsunamis do Algarve (ERSTA). Relatório final. Report 295/2008, LNEC Lisboa. (in portuguese)

Sousa, V., Silva, M., Veigas, T., Matos, J., Martins, J. and Teixeira, A. (2007). Technical management of sewer networks: A simplified decision tool. *LESAM 2007 - 2nd Leading Edge Conference on Strategic Asset Management*, IWA, 17–19 October, Lisbon, Portugal.

Sousa, V., Almeida, N., Sousa, L., Costa, A., Matos, J. (2010b). Contribuição para a gestão do risco sísmico em sistemas de drenagem de águas residuais. *14º ENASB/SILUBESA - Encontro Nacional de Saneamento Básico/Simpósio Luso-Brasileiro de Engenharia Sanitária e Ambiental*, APESB, 26-29 Outubro, Porto, Portugal. (in portuguese)

Sousa, V., Ferreira, F., Almeida, N., Matos, J., Martins, J., Teixeira, A. (2009). A simplified technical decision support tool for the asset management of sewer networks. *Water Asset Management International*, IWA 5:1, 3-9.

Urban, M. (2006). Earthquake risk assessment of historical structures. PhD Thesis, Department of Architecture, Civil Engineering and Environmental Sciences of the Technische Universität Carolo-Wilhelmina zu Braunschweig and Faculty of Engineering Department of Civil Engineering of the University of Florence.

USEPA (2002). The clean water and drinking water gap analysis. EPA-816-R-02-020, Office of Water, United States Environmental Protection Agency (EPA), Washington DC, USA.

WRc (1984). Sewerage rehabilitation manual. First Edition, Water Research Center (WRc), England.

Yeh, C.-H., Shih, B.-J., Chang, C.-H., Chen, W.Y. W., Liu, G.-Y. and Hung, H.-Y. (2006). Seismic damage assessment of potable water pipelines. Proc. *4th International Conference on Earthquake Engineering*, 12-13 October, Taipei, Taiwan, paper 247.

Zhao, J. Q., McDonald, S. E. and Kleiner, Y. (2001). Guidelines for condition assessment and rehabilitation of large sewers. Institute for Research in Construction (IRC), National Research Council of Canada (NRC), Ottawa, Canada.