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Seismic vulnerability and resilience of the water systems of Mexico City based on the evaluation of the effects of the 2017 Puebla-Morelos Earthquake

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Abstract

After the recent earthquakes it has been observed that many infrastructure has not remained functional, which has been a great problem for society. Due to this, in the last few years great efforts have been made to understand the behavior of the structures in unexpected conditions, particularly when they go beyond the fault. It has been worked on proposal new methods that estimate the seismic behaviour, but also it was proposed procedures to minimize the duration and costs rehabilitation. Nowadays, the scientific community has realized that a structure resilience is an important component of enhancing the sustainability of many of the infrastructure, particularly those that are vital for society such as the water systems supply. In this research on going emphasis is placed on understanding the performance of water systems supply under unexpected, such as the observed after of an earthquake. It shows the case of water network of two municipalities of Mexico City during the Puebla-Morelos earthquake of September 19, 2017, where the water supply and distribution systems of were severely damaged.

One of the unfortunate results of this earthquake was the severe damage suffered by the water supply and distribution systems in several municipalities of metropolitan Mexico City Due to the connectivity of the water system, the event drastically disrupted the basic services of the city leaving many people without water, a condition already experienced in a major city during Michoacán earthquake of September 19, 2017. This research on going describes the water system in Xochimilco, Tláhuac, Iztapalapa, Iztacalco y Ciudad Nezahualcóyotl the main features of the local subsoil conditions and the engineering aspects of the earthquake, highlighting their relationship to lifeline earthquake engineering. It concentrates on the on-going research on the statistics of the damage produced on the buried segmented pipelines of the water system of two municipalities. The paper analyzes the type of documented damage, taking into consideration the characteristic of the earthquake and the peculiar soil and topographic conditions of the valley where both two municipalities are situated. Statistic on breaks/leaks occurring in aqueducts distribution networks and service connections are presented. Where appropriate, observed damage is correlated with local soil conditions and earthquake characteristic the functionality, here referred as serviceability, of the water supply systems of both municipalities is studied, considering as main variables an index of serviceability given in terms of the number of breaks/leakages per km of pipeline at different zones of the water networks. Finally, general recommendations regarding water system seismic vulnerability and resilience are drawn.

Keywords: lifelines, resilience, water distribution network, vulnerability, serviceability

1. Introduction

During the Puebla-Morelos earthquake of September 19, 2017, the water supply and distribution systems of Metropolitan Mexico City were once more severely damaged leaving an estimated 3.3 million people without water just as it happened during the 1985 Michoacán earthquake that left without water 5.3 million people, both conditions never experienced in a major city affected by earthquake, [1].

As it occurred in the 1985 earthquake the damage to above ground structures was of enormous proportions, capturing most of the local and international interest. However, the amount of physical damage to the water system as well as the effects this damage had upon the population did not attract the same attention regardless that this effect represented a very important issue to the community resilience after this event. Most of the distribution pipeline damage occurred in the Lake Zone, It is quite possible that catastrophic consequences would have resulted if adequate actions had not been taken. This fact makes evident the necessity of investigating and learning from the experience of Mexico City (CDMX). Through an analysis of this event, the main factors involved in the seismic vulnerability of water systems can be understood, problem areas and solutions can be identified, and recommendations for the seismic design of new systems and the upgrading of the existing systems can be proposed.

This paper presents a thorough investigation of the available information on underground pipelines damage caused by the Puebla-Morelos earthquake in Metropolitan Mexico City. The information is presented for the most affected areas of Metropolitan Mexico City which includes the part of the State of México City as well as the part within the State of Mexico. Statistics on breaks/leaks occurring in aqueducts, distribution networks and service connections are presented. Where appropriate, observed damage is correlated with local soil conditions and earthquake characteristics. Where information was available the resulting reduction in supply and distribution capability as well as some of its effect on the population are given. General conclusions regarding water system seismic vulnerability and resilience of the water systems of Metropolitan Mexico City are drawn.

2. Water system damage due to prior earthquakes

In this section, earthquakes in Mexico prior to the September 19 2017 event that caused damage to water systems is discussed. The recorded evidence suggests that in the past, as in contemporary systems, the lack of flexibility (ductility) of the pipelines, particularly at pipe joints, is the major cause of seismic pipeline damage. Damage to water supply and distribution systems in Mexico caused by earthquakes has been documented to some extent since 1818; However, the information on water system damage before 1818 is not available although there is a 500-year record of earthquakes in Mexico. A summary of the earthquake damage to water systems for the period 1818 through 2017 is showed in the table 1. It should be noted that the amount of damage in Metropolitan Mexico City has generally increased with the increasing size of the city (see Fig. 1).

Table 1 – Historical Earthquake in Mexico with reported damage to water systems

Year	M	Water System Damage
1818 May 31	7.3	Broken arches in aqueducts in Mexico City
1820 May 4	6.2	Damage to above ground aqueducts in Mexico City
1835 Jan 6	7.0	Damage to above ground aqueducts in Mexico City
1864 Oct 3	7.3	Damage to buried clay pipes in Mexico City
1882 July 19	7.5	Damage to buried clay pipes in Mexico City
1907 April 14	8.2	Damage to buried clay pipes in Mexico City
1932 June 3	8.4	Extensive damage to buried pipelines in Mexico City
1973 June 30	7.5	Damage to buried main aqueducts (20 locations) in Orizaba and Cordoba (Orizaba EQ)
1979 March 14	7.6	Damage to a buried aqueduct in Mexico City (Guerrero EQ)
1985 Sept 19	8.1	Extensive damage to buried pipelines and buried aqueducts in Mexico City (Michoacán EQ)
2017 Sept 19	7.1	More damage to aqueducts in Mexico City (Puebla EQ)

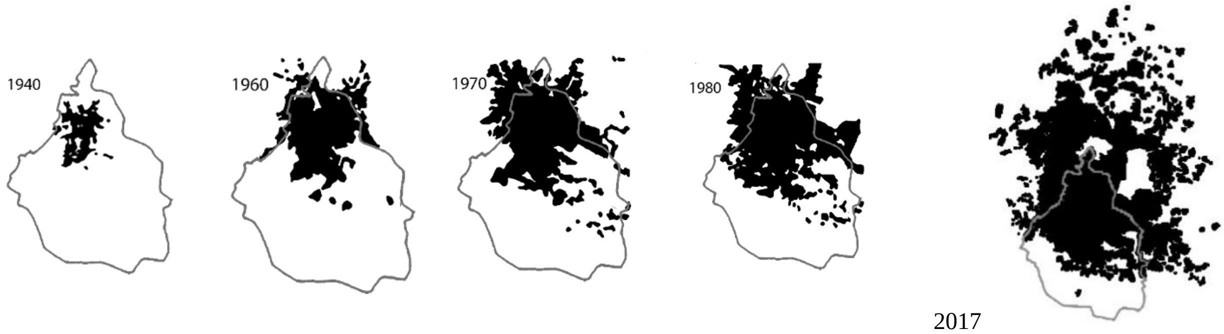


Fig. 1 - Growth of the urban sprawl of Metropolitan Mexico City, 1940-2017

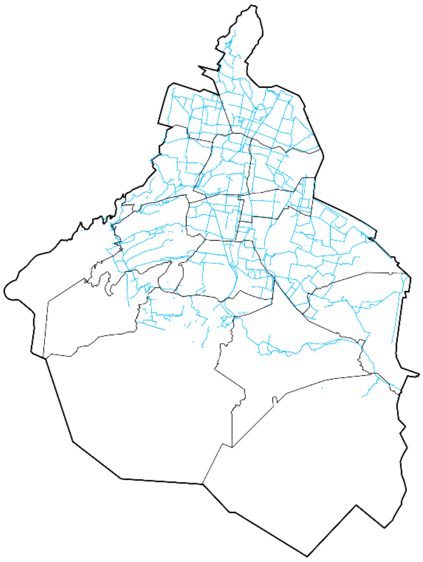
Of engineering importance is the fact that during the 1973 Orizaba earthquake, the main aqueduct (buried transmission line) supplying water to the city of Cordoba was severely damaged at a minimum of 20 points along its length. The aqueduct was a 36" reinforced concrete pipeline with 'lock joint' type joints. During this earthquake, all of the pipeline failures occurred at the joints. The 1979 Guerrero earthquake damaged a 72" buried reinforced concrete aqueduct at 10 locations along its 6 kilometre length in southeast Mexico City. The pipeline failures due to this earthquake were mainly compressional crushing and/or pull-out of the bell and spigot joints of the pipes, accompanied in some instances by rotations of these joints. An evaluation of the damage indicates that the failures were due to a lack of flexibility in the system as opposed to a lack of strength.

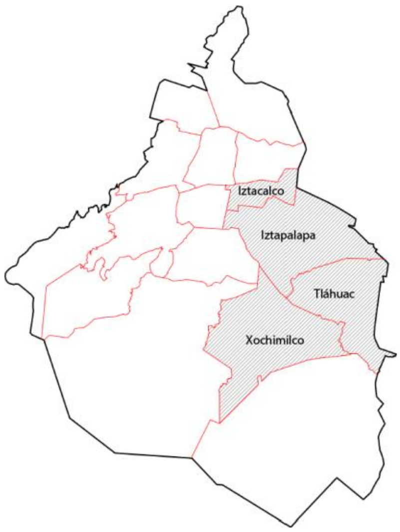
3. Metropolitan Mexico City water supply system

The metropolitan Mexico City currently covers an approximate surface area of 1800 km^2 with a population that exceeds 22 million people. The Municipalities within CDMX are provided with a flow of 61 m^3/s. The primary distribution network consists of about 940 km of pipelines with diameters ranging from 20" to 72" and the secondary network is composed of about 11,400 km of pipe with diameters ranging from 2" to 18" (see table 2). This system has evolved from the beginning of the century with part of the network as old as 8 decades and with many new lines having just been constructed, because of this a complete census of the material and type of pipe as well as the precise location of some of the lines is not available. Based on the information gathered and reconstructed by the authors, this paper shows the location of the most important primary distribution and transmission lines with diameters 20" and above (see Fig. 2a). Most of the damage in the water network and the corresponding outage was concentrated in the southeast of the metropolitan Mexico City, particularly in the Municipalities of Iztacalco, Iztapalapa, Tláhuac and Xochimilco (see Fig. 2b). Regarding the networks of the metropolitan area located in the State of Mexico, known as Ciudad Nezahualcóyotl, the total length of the system is approximately 900 km, (see figs 3a y 3b).

Table 2 – Length of the primary and secondary water network of the CDMX.

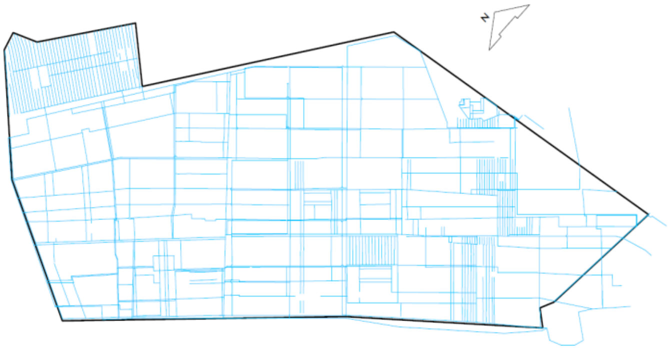
Municipality	**Primary, km**	**Secondary, km**	**Aqueducts, km**
Azcapotzalco	49.84	570.26	-
Cuajimalpa	21.1	290.5	-8.28
Gustavo A. Madero	134.45	1,587.52	-
Venustiano Carranza	49.7	643.46	-
Coyoacán	54.7	971.29	-
Iztacalco	38.93	524.94	-
Milpa Alta	6.4	256	18.93
Cuauhtémoc	62.52	256	-
Magdalena Contreras	21.3	288	9.34
Miguel Hidalgo	52.3	726.3	8.9
Xochimilco	34.7	617.7	28.59
Álvaro Obregón	64.9	834.9	17.4
Benito Juárez	85.99	812.2	-
Iztapalapa	158.2	1,956.90	10.85
Tláhuac	59.3	478.8	36.34
Tlalpan	45	598.8	-
Σ	940	11400	122





a) b)

Fig. 2 Municipalities of CDMX, a) primary water network, b) area where most of the damage in water system was concentrated



a) b)

Fig. 3 - Primary and secondary water network Ciudad Nezahualcóyotl. a) North zone, b) Centre-east zone

4. Water service disruption due to the S19 2017 Puebla-Morelos earthquake

Conservative estimates are that the S19 2017 Puebla-Morelos earthquake left 3.3 million people without water in CDMX, see table 3, that is, approximately 15% of the estimated 22 million people in Metropolitan Mexico City were without water immediately after the earthquake and for few days and sometimes weeks. The lack of water for this large portion of the population was caused by extensive damage to the buried transmission and distribution lines in Metropolitan Mexico City. There was some minor damage to wells, but reservoirs, storage facilities, and purification plants were essentially unaffected by this earthquake. The success of government officials in implementing an emergency response plan, which had never previously been in practice, is noteworthy. To supply water to the population, tank trucks and provisional cisterns were used.

Table 3 – Supply water to the population after Earthquake in Mexico with reported Affected people

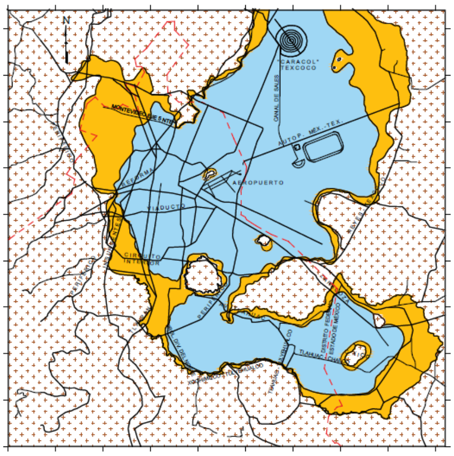
Earthquake	S19 1985	S19 2017
Magnitude	8.1	7.1
Supply	--	--
Affected people	5.3 million without service (service was restored after 40 days)	3.3 million without service (1.36 10^6 people with service restored on September 25; 300,000 on October 5)
Water supply using tank trucks	---	21.737 10^6 litres daily supplied using 753 tank trucks
Water supply using cisterns	---	53920 10^6 litres daily supplied

5. Subsoil conditions in metropolitan Mexico City and characteristics of the S19 2017 Puebla-Morelos earthquake

The CDMX is located in a closed basin surrounded by mountains of volcanic origin. Through geological time, the basin became a lake where volcanic ashes were deposited and decomposed into a lacustrine clay. This lake eventually dried exposing lake bed soils of unusual mechanical characteristics well recognized in the soil literature. To engineering purposes, subsoil conditions in the valley have been grouped in three zones are:

a. The Hill Zone; located in the hilly areas around the bed lake and formed basically of volcanic rocks, dense sand and silts.
b. The Transition Zone; located between the Hill and Lake Zones and formed of a shallow layer of clay founded on volcanic rock formations dipping toward the centre of the lake.
c. The Lake Zone; located in the lakebed and consisting primarily of soft lacustrine clays, with some clayey silty sands and medium dense clayey sands all of alluvial origin. Typical stratigraphy in

Geotechnical zoning map proposed for Mexico City building code and periods are showed in the Figs. 4a-b.



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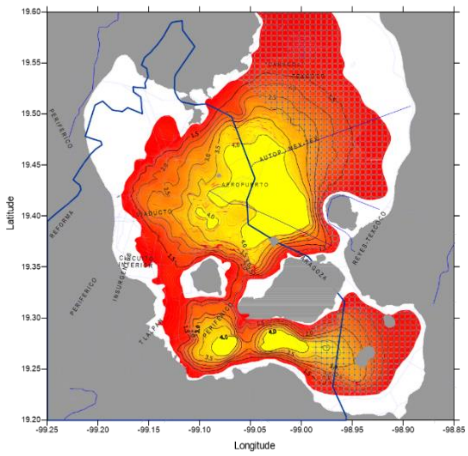
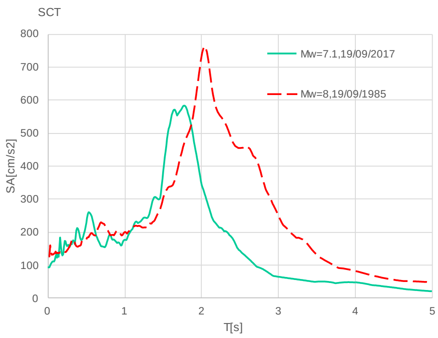


b)

Fig. 4 - Soil characteristics of the valley of Mexico, a) geotechnical zoning, b) site periods [3].

6. Characteristics of the Earthquake Motions

The S19 2017 Puebla-Morelos intraplate earthquake, originated about 120 km southwest of CDMX. The earthquake was generated at a depth of about 51 km in a zone where the Cocos Plate significantly bents. The epicentral area is within the area where strong earthquakes may occur. As a result, the instrumental information was extensive with numerous records in the epicentral area as well as at numerous locations in the Valley of Mexico (*i.e.*, Metropolitan Mexico City). Figs. 5a and b shows the response spectra the 2017 obtain of earthquakes recorded in lake and hill zone, [4].



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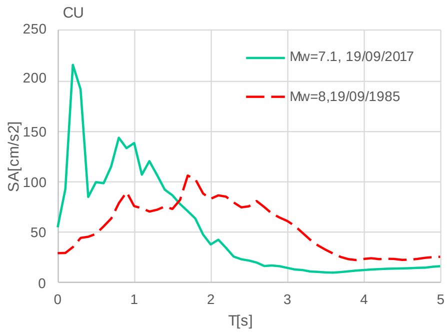

b)

Fig. 5 – Response spectra for the 1985 and 2017 earthquakes recorded at:. a) lake zone, b) hill zone.

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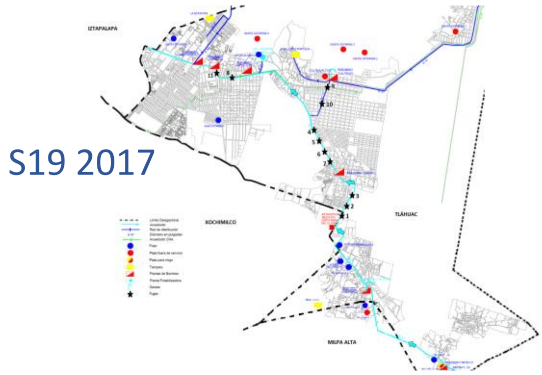
7. Water system damage in metropolitan Mexico City; segmented pipeline

Buried aqueducts located in the southeast part of the CDMX were severely damaged by the S19 2017 Puebla-Morelos. These large diameter prestressed concrete transmission pipelines had previously been damaged since the 1979 Guerrero earthquake. The damaged aqueducts were located southeast of metropolitan Mexico City, Chalco-Xochimilco, Xochimilco, Mixqui- Santa Catarina and Tláhuac- Nezahualcóyotl. These aqueduct systems pass through this area; the first two both aqueducts system is controlled by CDMX while the other is controlled by the CONAGUA. There was no observed evidence of liquefaction in the metropolitan area. This is not unexpected since the subsurface consists primarily of volcanic rock or soft clay overlaying volcanic rock. In addition, there were no landslides or faulting which effected the metropolitan water system. There was some earthquake induced ground settlement as evidenced by round cracks. However, the water system damage was not restricted to the ground settlement areas. Hence it appears that most of the water system damage was due to seismic wave propagation. This damage was mainly in the buried pipelines which comprise the transmission and distribution network. There was some isolated damage to well shafts but essentially no seismic damage to purification plants, pumping stations, reservoirs and other storage facilities.

7.1 CDMX Aqueducts

There were 52 pipeline breaks along the CDMX aqueduct (see Fig. 6b). This damage ratio of 0.4 breaks/km in the affected zone in the southeast part of CDMX. Most breaks occurred at joints where adjacent segments crushed or separated due to insufficient joint flexibility. All of these breaks were in 36" or 72" diameter "lock joint" prestressed concrete. Other breaks occurred at a "T" junction in a 72" diameter lock joint line. These failures occurred in the line which formed the "stem" of the "T" (*i.e.*, the line dead ended by the trust block.). Again these failures were due to crushing and/or separation of the joints. In addition to the pipeline joint damage described above, the earthquake caused "punching shear" cracking of valve box walls. It is worth noting that much of the above mentioned damage occurred at joints close to junctions such as "T"s or elbows. Typical breaks in aqueducts of prestressed concrete are showed in the Fig. 6a

a)

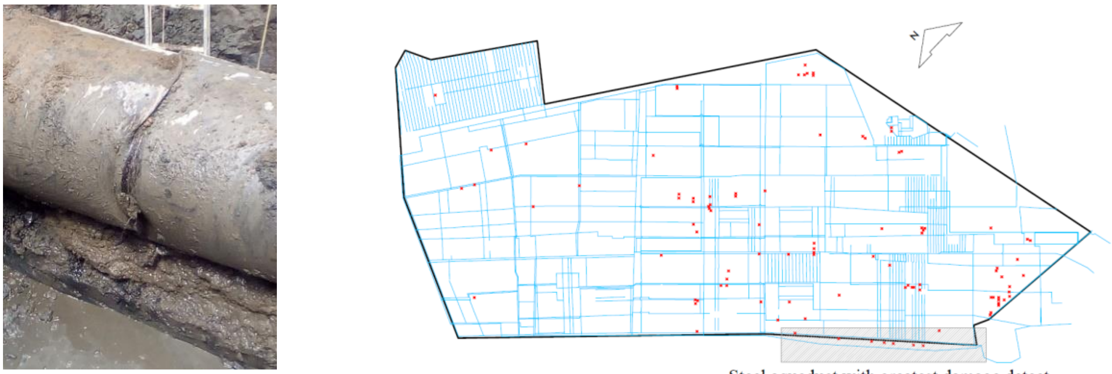


b)

Fig. 6 - Damage in water supply lines, a) typical broken reinforced concrete pipes (72"), b) location of the aqueducts that suffered damage during S19 2017

7.2. Nezahualcóyotl City Aqueduct

In the State of Mexico, a major transmission pipeline supplying about 1.6 m^3/s was severely damaged. The flow supplied by this pipeline represented 50% of the total in Ciudad Nezahualcóyotl. There were 9 pipeline breaks along the aqueduct (see Fig. 7b). The system was restored to its pre-earthquake condition by November. During the recovery period, water was also distributed using tank trucks. In this aqueduct, there were 8 breaks in a 48" lock joint" pipe and one break in a 42" pipe. Although the aqueduct damage was different in many respects to that which occurred in the CDMX. Aqueducts with a number of leaks significantly lower. The damage was due to seismic wave propagation in soft ground conditions. The leaks typically occurred in the large diameter steel pipeline, Figs. 7a.



a) b)

Fig. 7 - Damage to water systems in Ciudad Nezahualcóyotl, a) failure due to buckling in a 42 "steel aqueduct, b) location of the area where the greatest damage was concentrated

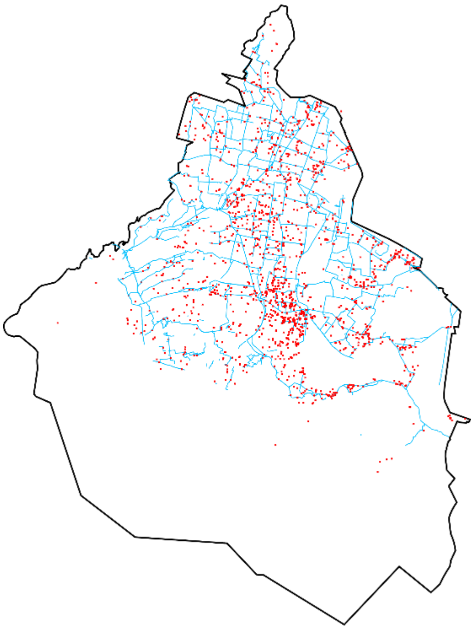
7.3 Damage in primary Distribution Pipelines in Mexico City

Within the CDMX, most of the damage to primary distribution lines (20" diameters and larger) were in asbestos cement and concrete pipes. The breaks were reported as transverse cracks in pipes, crushing or pull-out at joints, and fracture of special pieces at valve boxes. An example is a fracture of a "T" joint in a 30 in diameter pipeline. This line was constructed at the beginning of the century and is located in an open gallery in the older part of the city. The line had survived previous strong earthquakes without damage and had experienced no significant corrosion or cracking prior to the S19 2017 Puebla-Morelos event. Typical breaks in the primary water network are showed in Figs. 8a-b

The location of most of the CDMX primary distribution piping breaks were in the lacustrine soil region of the Texcoco lake (Lake Zone). It appears that approximately two thirds (66%) of the leaks/breaks occurred near such junctions while about one quarter (25%) occurred along nominally straight runs of pipe. The precise location of about one tenth (10%) of the leaks/breaks could not be determined. The number of breaks, per Municipality, for various pipe diameters as well as the corresponding damage ratios is showed in the table 4. The location of breaks in primary and secondary CDMX water network are showed in the Figs. 9a-b.

a) b)

Fig. 8 – Damage to the primary and secondary CDMX network, a) typical failure of reinforced concrete aqueducts, b) leaks in steel aqueducts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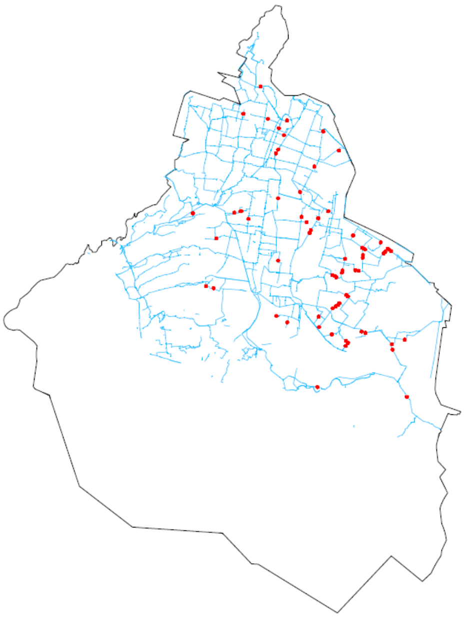

b)

Fig. 9 – CDMX damage distribution due to S19 2017, a) secondary network, b) primary network

Table 4 – Breaks in water network located in Iztacalco, Iztapalapa, Tláhuac, Xochimilco.

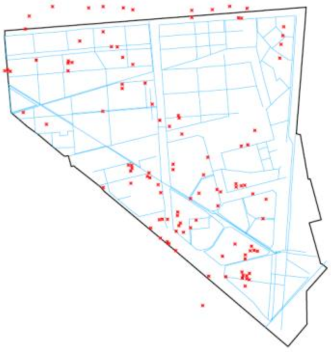
Municipality	Break/leaks		
	Primary network	Secondary network	Damage ratios
Iztacalco	3	64	0.077
Iztapalapa	32	291	0.202
Tláhuac	15	100	0.253
Xochimilco	11	142	0.317

7.3.1 Damage Secondary Distribution Pipelines in the CDMX

The secondary distribution system controlled by the Ciudad de México was also heavily damaged. As with the primary distribution system, secondary distribution pipelines in the Lake Zone were the most affected. In addition to the damage characteristics discussed above, a large number of old pipes made of clay and cast iron also broke. It appears that the older components were too rigid or too deteriorated to sustain any substantial earthquake induced deformation. Many special pieces, such as valves, connections, etc. in the 2" to 18" diameter range failed. The location of breaks in primary CDMX water network are showed in the Figs. 10a-b.

7.4. Damage in primary Distribution Pipelines in the State of Mexico

The distribution network in Ciudad Nezahualcóyotl, located in the State of Mexico, suffered about 150 leaks. Most of these occurred at joints close to fixed points such as crossings, bends, valve boxes etc. Failures in the body of the pipes were less frequent and from discussion with engineers in charge of the repairs, these occurred along pipes already weakened by relative settlements which is common in all the urbanized areas of the Lake Zone. As may have occurred in the CDMX, some of the failures may have occurred at the joints weakened by differential settlements. The location of breaks Nezahualcóyotl water network are showed in the Figs. 10a-b The failure rate for Ciudad Nezahualcóyotl was 0.24 breaks per km.



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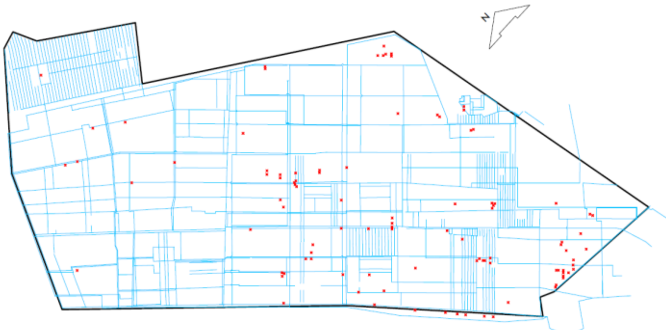

b)

Fig. 20 – Damage distribution in the water system of Ciudad Nezahualcóyotl due to S19 2017, a) north zone, b) central-east zone

7.5 Sewer System Damage

The S19 2017 Puebla-Morelos Earthquake caused minor damage to the sewer system of CDMX. It is concluded that the lack of significant seismic damage to the sewer system may be attributed in part to its burial depth larger than that that of the water systems as well as the difficulty in recognizing damage in an unpressurized system, (see Figs. 11a-b).

a)

b)

Fig. 31 – Damage to the CDMX sewer system, a) subsidence of soil and sewer damage, b) replacement of a sewer pipe from the sewer system

8. Empirical vulnerability curves

The damage of the water network can be estimated using empirical vulnerability curves, which offer a behaviour indicator based on a measure of seismic intensity. Most of these curves derive from data from post-earthquake inspections. Some of the curves have been proposed by, [5], [6], [7], [8], [9]. The first correlation between seismic intensity parameters and damages observed in buried pipes (breaks/km) used the PGA. The empirical relations of vulnerability using the PGA for different earthquakes including S19 2017 are showed in the Fig. 12b. Distribution of leaks caused by S19, 2017, on maps of PGA is showed in Fig. 12a

Damage ratios for earthquakes that occurred in various parts of the world, breaks/km, have been also correlated with the maximum ground velocity, [7]. The distribution of leaks in the primary and secondary networks of CDMX caused by the earthquake of September 19, 2017, is showed on the map Fig. 13a. This map also shows the distribution of maximum ground velocities in the area where the majority of breaks in the CDMX water systems was detected together with the maximum ground velocity range recorded after S19 2017. The empirical vulnerability relationships for different earthquakes around the earth together with the data of S19 2017, is showed in the Fig. 13b where the damage ratios for different earthquakes, breaks/km are correlated against the maximum ground velocity. This graph includes the data of the S19 1985 earthquake that also damaged the water systems of CDMX.

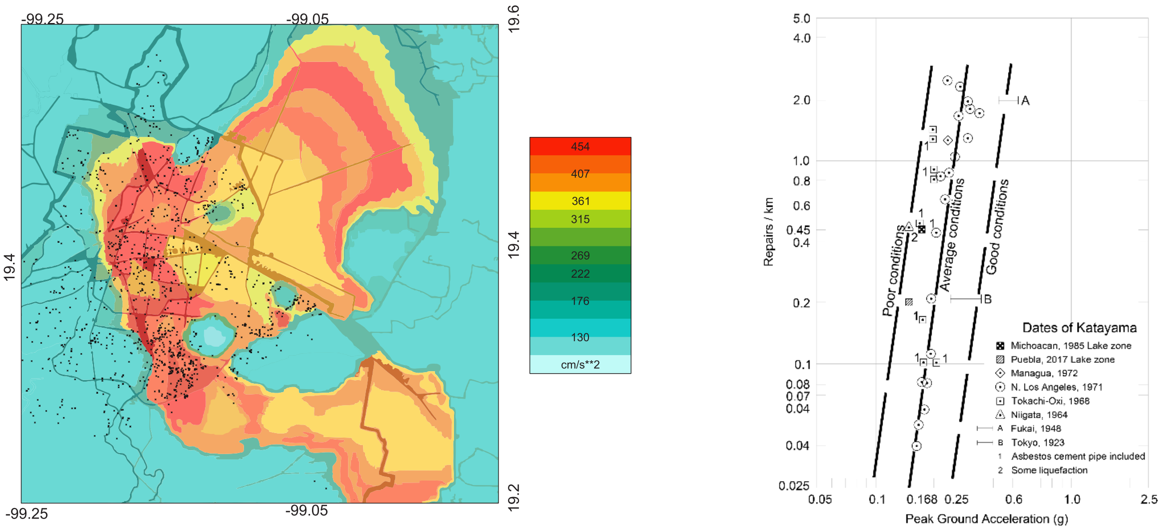

Fig. 42 - Seismic vulnerability of the CDMX water network according to empirical curves, a) map of PGA due to the S19 2017 earthquake [10], b)) empirical vulnerability curves for different earthquakes [5].

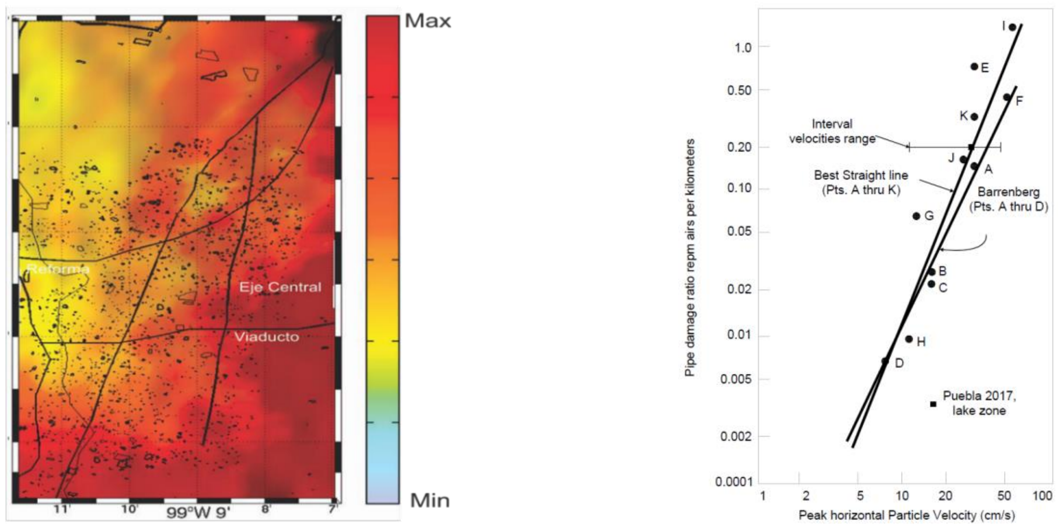

Fig. 53 - Seismic vulnerability of the water network according to empirical curves a) map of simulated maximum ground velocities due to S19 2017 [3], b) empirical vulnerability relationships for different parts of the world, [7]

9. Water supply resilience

As proposed by [10], the area under the restoration curve, R, is defined as a measure of the loss of resilience. Less area indicates less impact, faster recovery, or both, R is defined in Eq. 1.

$$R = \int_0^{t_1} \left(1 - Q(t)\right) dt \qquad (1)$$

where Q (t) is the degree of functionality as a fraction of the complete service at a time t, and the times $t = 0$ and $t = t_1$ denote the initial event (the earthquake) and the complete restoration time, respectively. R can be seen as the average number of days that a particular network loses functionality. To estimate resilience, it is essential to estimate the total economic impact of the loss of functionality, which is more related to the number of days without service. In our case, to estimate the resilience of the water network, the economic loss of a municipality must be estimated in terms of the loss of service functionality plus the financial losses of the users. An example of the losses involved in the repair of leaks in south CDMX is shown in table 5.

Table 5 . Losses associated to breaks in a water network located in south CDMX.

Concept	**Cost per break/leak**
Labor days 12 y 13 of may	€ 4300.00
Machinery and equipment	€ 8530.00
Material	€ 8930.00
Σ	€ 21750.00

10. Conclusions and recommendations

Relevant information on the seismic vulnerability and statistics of seismic damage to the water systems of Metropolitan Mexico City caused by the S19 2017 Puebla-Morelos event was compiled and analysed in this paper. All known sources of information were explored and data was used from those considered reliable.

10.1 Conclusions

The characteristics of the Puebla-Morelos earthquake and the local soil conditions in CDMX led to widespread damage to the water systems in the metropolitan area. Approximately one third of the 18 million residents of the metropolitan area were without water after the earthquake.

The water service disruption is mainly attributed to seismic wave propagation damage to buried pipelines and the collateral effects of failures of electric energy supply with similar quantitative and qualitative characteristics of what it was observed after the 1985 Michoacán earthquake. Other water system components such as tanks, pumping stations and treatment facilities were not as significantly damaged.

Most of the damage occurred in segmented pipelines which comprise the vast majority of the transmission and distribution networks in four municipalities of the CDMX and in Ciudad Nezahualcóyotl. As it occurred during the 1985 earthquake, a continuous steel pipeline in Ciudad Nezahualcóyotl was also heavily damaged. The observed damage to this structurally competent pipeline is attributed to demands with dominance of surface waves with fairly high peak ground velocities and very soft soil conditions.

The damage in the segmented pipelines, typically at soft ground locations occurred at joints due to their inability to accommodate earthquake induced axial and rotational displacement demands. These leaks/breaks often occurred near T's, elbows, junction boxes or other hard spots. Likely contributing factors to this damage are the evident subsidence and surface cracking particularly evident in the Southeast of the CDMX condition that reduced the ability of the pipelines to accommodate without failure the additional deformations induced by the S19 2017 Puebla-Morelos event.

The significant damage of the large diameter buried segmented pre-stressed concrete aqueduct in the Southeast of the CDMX is attributed to the large local variations in ground motion in a part of the valley between two nearby hills. Damage was also extensive in smaller diameter asbestos-cement and concrete piping. One important observation in relation to the numerous leaks/breaks in small diameter pipes and piping components is that they generally occurred at or close to galvanized iron service connections recognised as fragile.

10.2 Recommendations

Reducing the seismic vulnerability and increasing the seismic resilience of an existing water system is a formidable task, particularly in a city the size of Metropolitan Mexico City. For almost all such systems, replacing the existing elements with ones which have enhanced seismic resistance would be economically impractical. However, the authors feel that the following recommendations are worthy of consideration:

All new construction, as well as routine maintenance and replacements of existing parts of the system, should be made in accordance with current design recommendations using seismically resistant elements. For buried segmented pipelines, this can be accomplished by using pipes with joint designs allowing larger slacks to accommodate the axial extensions, compressions and rotation induced by the earthquake

An emergency response plan should be prepared. This would include designation of emergency headquarters and alternate at earthquake vulnerable sites with and established line of command provided with system maps, easy access to the stockpiles of components or their emergency purchase. As part of routine maintenance, shutoff valves should be regularly checked and replaced if not functioning.

New evaluation formats should be designed so that seismic damage to water systems can be properly documented. This would serve to detailed information on location and specific damage will allow researchers and water system officials to better understand the problem. It is necessary to develop a clear and robust methodology to estimate the cost and time of repair, and time of the factors that prevent the start of repairs in a water network before the damage caused by a seismic event.

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