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PERFORMANCE OF COLLAPSE PREVENTION DESIGNED BUILDINGS DURING THE SEPTEMBER 19, 2017 EARTHQUAKE IN MEXICO CITY

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Abstract

The September 19, 2017 earthquake (M_w=7.1) was the strongest and most damaging earthquake that stroke Mexico City since the September 19, 1985 earthquake. However, taking aside the south center-east region of the lakebed zone of Mexico City, where spectral accelerations were close or even higher than those recorded at the SCT site in 1985, the fact is that in the historically most heavily damaged zone of Mexico City, spectral accelerations were more than well-covered by the design spectra of Mexico City building codes since 1987. Yet, there was an important inventory of buildings constructed since 1986 which were severely damaged or even collapsed during this recent September 19, 2017 earthquake. In this paper, and based upon a detailed database of more than 2,500 structures compiled and processed by the authors, it is reported and discussed the observed behavior in Mexico City of more than 700 buildings designed with collapse-prevention codes (1976 to date) and the relationships of observed damage with: a) building code date, b) number of stories, c) conditions of structural irregularity, d) soil settlements, tilting and soil-structure interaction effects, e) structural pounding, d) deterioration and previous damage, e) elastic design spectra ordinates vs. those assessed from recorded ground motions and, f) assumed global deformation capacities and damage indexes in terms of ductility factors vs. ductility demands assessed from recorded ground motions Although it can be concluded that structural collapses and severe damage have been reduced for buildings designed according to the collapse-prevention design philosophy in Mexico City in comparison to former older codes, the observed global results were not good enough, not only from an engineering viewpoint, but primary from social and economical viewpoints. Then, in the opinion of the authors, engineers should start thinking seriously on moving forward towards resilient-based seismic design strategies in future building codes that would satisfy better the needs of the society.

Keywords: September 19 2017 earthquake, building codes, collapse prevention, structural irregularities, soft soils

1. Introduction

On Tuesday, September 19, 2017 at 13:14:40 Mexican Central Time, a strong earthquake M_w=7.1 normal faulting earthquake (strike 112^0, dip 46^0, slip -93^0) with epicenter located at longitude -98.72^{0}W, latitude 18.40^{0}N and a focal depth of 57 km occurred near the border of the Mexican States of Puebla and Morelos (Fig. 1), according to the information of the Mexican National Seismological Service [1]. The closest town was Axochiapan, Morelos, 12 km towards the southeast. The earthquake affected several towns and cities of the states of Morelos and Puebla primarily, but also in the neighboring states of Guerrero, Tlaxcala, Estado de México and former Mexico´s Federal District (Ciudad de México since January 31, 2017), which is about 120 km to the northwest from the epicentral region (Fig. 1).

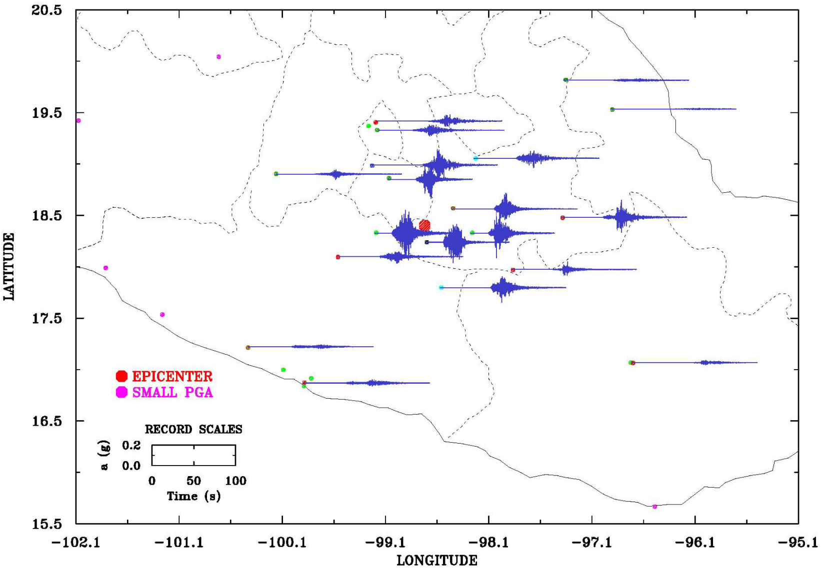


Fig. 1 – Location of the epicenter and some E-W acceleration time histories recorded on rock sites for the September 19, 2017 earthquake

The location of the epicenter is shown in Fig. 1 with a full circle in red, whereas some of the strongest ground motions recorded in rock sites at the states of Puebla, Morelos, Guerrero and Ciudad de México (closer to the epicentral region) and also in Estado de México, Oaxaca and Veracruz (somewhat far from the epicentral region) are shown. To ease comparisons, all records are drawn in the same time and acceleration scales. Only the first 150 seconds of recorded ground motions are shown for each record. It can be observed from Fig. 1 that the most intense accelerations in rock sites occurred in a geographical area which can be framed in a rectangle from 17.75^{0}N to 19.50^{0}N in latitude and from -98.1^{0}W to -99.60^{0}W in longitude, whereas outside that box ground accelerations attenuate fast towards all cardinal directions. Largest peak ground accelerations recorded at the epicentral region were 0.276g in Tehuitzingo, Puebla (black circle) and 0.268g in Quetzalapa, Guerrero (light green circle). In Mexico City, the historical reference stations for rock sites, Ciudad Universitaria (red circle) and Tacubaya (dark green circle), recorded peak ground accelerations of 0.060g and 0.064g respectively. Whereas peak ground accelerations are not very high in comparison with those registered in other parts of the world, the records of Mexican earthquakes (normal faulting and primarily subduction earthquakes) are always characterized by their long durations.

Although this earthquake caused extensive damage and economical losses in a vast region of Central Mexico, particularly in Morelos, Puebla and the northeast of Guerrero states, in following sections the authors would concentrate in Mexico City only and discuss some of relevant background and issues which must be considered to understand the large extent of damage observed within the city. In particular, the authors concentrate in showing and discussing the observed behavior of structures that were designed and constructed according to collapse prevention seismic codes (1976 to date), which it is widely used worldwide.

2. Mexico Valley Basin. Background and recorded ground motions in Mexico City

To better understand the large ground motions amplification phenomena (site effects) observed in what it is known today as Mexico City, it is important to briefly recall the history of this vast region. At the times that the Spanish conquerors arrive in 1519, the Mexica (Aztec) empire was in charge of this vast region, known at the time as The Great Tenochtitlan, which it was an island located in Lake Texcoco (Fig. 2), one of the five lakes that were interconnected in the Valley of Mexico: lakes Zumpango and Xaltocan to the north, lake Texcoco within the center and lakes Xochimilco and Chalco to the South (Fig. 2). After the conquest, Mexico City was founded initially in that island, and starting in the 17th century, the great channel (Tajo de Nochistongo) was built to start draining the Basin of Mexico to avoid flooding of the original island and the surroundings of the lakes during the raining season. That was the beginning of opening the basin and the progressive draining and drying of most of these lakes for the following four centuries (of course, with additional civil works, including those built during the 20th and 21th centuries).

Fig. 2 - Valley of Mexico in 1519 at the time the Spanish conquerors arrived [2]

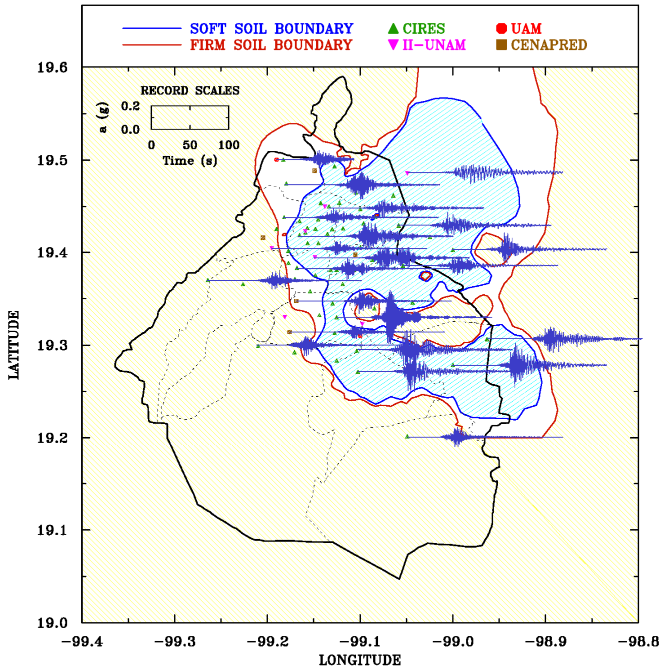


Fig. 3 – Some of the E-W acceleration time histories recorded in Mexico City Metropolitan area during the September 19, 2017 earthquake. Stations are identified with a different symbol according to the institution which operates them.

Therefore, a part of downtown area of Mexico City, where most of the ruins from the Aztec empire and churches and palaces from the colonial period are located, were built in this small island, but also many other buildings started to be built in the ground gained to the drained Texcoco lake. Mexico City became a very large city starting during the 1940s and, at the times occupied a vast region of the Texcoco Lake. At the time of the September 19, 1985 Michoacán earthquake (M_s=8.1), Mexico City also occupied all the interconnection between lake Texcoco and lake Xochimilco, besides some regions of lakes Xochimilco and Chalco. At the times of the September 19, 2017 Puebla-Morelos earthquake (M_w=7.1), Mexico City and its neighboring suburbs of Estado de Mexico occupied also most Xochimilco and Chalco lakes (Fig. 2). Mexico City and its metropolitan area are then mostly built in deep soft soil lake deposits surrounded by large mountains, as it originally was a perfect hydrological basin. Although the water of the lakes was mostly drained from the surface, the water table is very close to the surface in the entire original lake region. Besides, as most of the water for consumption within the city is extracted from deep water wells within the lakebeds, importance progressive soil settlements due to subsidence are developed, in the average are around 40 cm per year, but in some sites they can be as high as 100 cm per year. All the described phenomena make the seismic response of the structures in Mexico City very complex.

Ground motions in the soft soils of the lakebed region are always amplified with respect to those recorded on firm soils and mountains. During the September 19, 2017 earthquake, 74 stations within Mexico City Metropolitan Area recorded quality acceleration ground motions. These stations are operated by four institutions: CIRES (60 records), II-UNAM (7 records), Cenapred (5 records) and UAM (2 records). For illustration purposes, some of these ground motions are depicted in Fig. 3 in selected stations in firm soils, soft soil sites (lakebeds) and what it is known in Mexico as “transition zone”, which basically are the soils between the firm soils and the original shore of the lakes. Firm soils are identified with yellow shading, lakebed soft soils with cyan shading and transition soils are enclosed in white between them. E-W records were selected to ease understanding the space variation of the records from north to south and east to west in all soil types. Time and acceleration scales are the same in all records and only the first 200 seconds of recorded ground motions are plotted.

It can be observed from Fig. 3 that: a) no significant difference was observed in firm soil records from south to north, b) important amplifications are observed in transition soils, and it is of great interest the one observed in station GR27 (Granjas, Azcapotzalco District) in the northwest of Mexico City, with peak ground acceleration of 0.122g and a instrumental duration of 329s, c) as expected, larger amplification are observed within the lakebed region with respect to all stations in firm soils, d) a surprising observation for this earthquake is that although most stations in transition soils experience smaller PGA than those recorded on soft soils, some of them experienced ground shaking as intense or even larger than some recorded in soft soils and, e) larger PGA accelerations in soft soil sites were observed this time in the southeast of Mexico City (former lakes of Xochimilco and Chalco) rather than at the traditional central zone of Mexico City (former Texcoco lake), as it usually occurs during subduction earthquakes from the Mexican Pacific Coast.

In the former Chalco lake, the highest recorded PGA was 0.194g in station TH35 (Tláhuac, Tláhuac District) with a duration of 329s, whereas in former Xochimilco lake it was on station JC54 (Jardínes de Coyoacán, Coyoacán District) with a PGA of 0.225g and a instrumental duration of 353.8s. However, it is worth noting that the highest PGA and the strongest records were obtained this time in the former narrow connection between lake Texcoco and lake Xochimilco at station CH84 (Culhuacán, Coyoacán District), with a PGA of 0.230g, the highest ever recorded in soft soils within Mexico City´s lakebed region, and a instrumental duration of 338.6s. In fact, all the closest records to CH84 within that narrow region at Coyoacán District recorded very strong motions. For this earthquake, the well-known SCT2 station at the south-center of Mexico City recorded a PGA of 0.093g with an instrumental duration of 317s. Similar PGA were recorded in most stations located in the soft soils of former Texcoco lake in the most traditional central region of Mexico City, where most of the building inventory is found, as discussed in following sections.

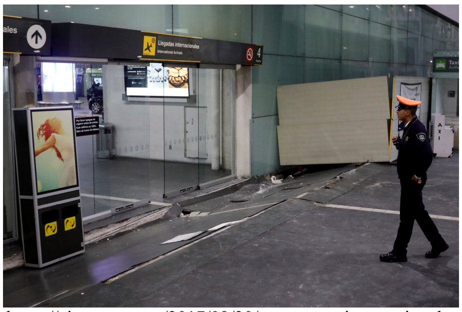
3. Observed damage within Mexico City

Mexico City Metropolitan area is one of the largest cities in the world and then, one should expect an important number of damaged buildings and houses when a strong earthquake strikes, such as the September 19, 2017 earthquake, particularly for the old inventory of buildings which were built and/o designed before modern seismic codes.

This research group started field reconnaissance surveys beginning the first days after the earthquake occurred. The extent of damage which we found in the first day was indeed large, then, the first two authors decided to continue this effort every week for several months in these and other Districts of Mexico City to document it well. The goal was to compile a comprehensive, detailed database, which it has been also enriched with information provided by friends and relatives, as well as those reported by other people and news through internet. In this compiled database, clear pictures of the damaged structures are available; at least from the exterior and their geographical coordinates, special configuration and previous state before the earthquake have been determined using Google Maps [3]. In fact, Google Maps was also used to check/corroborate the number of stories, plan geometries and other relevant conditions to assess conditions of structural irregularity and, in the case of recent buildings, the approximate year of construction (Google Maps Mexico has street view pictures for Mexico City starting 2008). The status of many of these buildings has been monitored during these past two and a half years, as some of them were finally demolished or are being repaired, but several of them are just abandoned. Up to January 2020, 1,321 structures have been classified using the information collected as described above, where 224 experienced light or no damage.

Simultaneously, a larger coordinated effort was started by Mexico City authorities and relevant Mexican technical societies (CICM, SMIE, SMIS, SMIG, CMIC, CAM) and public universities within Mexico City (UNAM, UAM-A, IPN), by organizing and processing the voluntary work of hundreds of civil engineers and architects (practicing engineers and architects, professors and even graduate and undergraduate students). As a result, thousands of structures were evaluated to assess their safety condition and damage from day one to several months and even more than a year after the earthquake stroke. Based upon those damage survey reports, Mexico City authorities were able to compile and offer a geographically referenced database of damaged structures originally available at the website Plataforma CDMX [4], including the damage assessment reports with pictures, special studies for the subject building (if available), etc. The first author learned about Plataforma-CDMX on April 2018, and he started downloading the public information available there (damage survey reports for each structure), mostly for buildings which were classified as of moderate risk or damage (yellow target), high risk (red target), high collapse threat (red target), in the demolition list and partial or complete collapse, as they were being updated. The first author meticulously reviewed each of this available information in order to classify the corresponding structures using exactly the same criteria that he used to classify the structures from the own team database, complementing the information with Google Maps [3]. Therefore, at least 150 structures were reclassified from the classification assigned in Plataforma CDMX [4]; some of them were classified in a higher damage category, whereas other structures were classified in a lower damage category. From this additional effort, up to January 2020, 2,135 structures from this database have been carefully classified, including 50 of them that were classified as lightly damaged or undamaged.

When compiling the information from both sources (our own information and the public information from City authorities) a total of 2,643 structures were available, as there were 813 common structures in both databases. This is important to highlight, our database has 508 structures that were not included in Plataforma CDMX database, 242 of them with moderate damage or above. Some of the non-reported damaged structures in Plataforma CDMX correspond to: a) damaged buildings of public autonomous universities in Mexico City (UNAM, IPN and UAM), b) some public and private hospitals, c) some federal government strategic installations (for example, Mexico City Airport Terminal 2 buildings (5 in total), which experienced large abrupt soil settlements (Fig. 4a), reduced tilting and light structural pounding between them) and, d) houses and buildings whose owners preferred private-confidential independent reports.



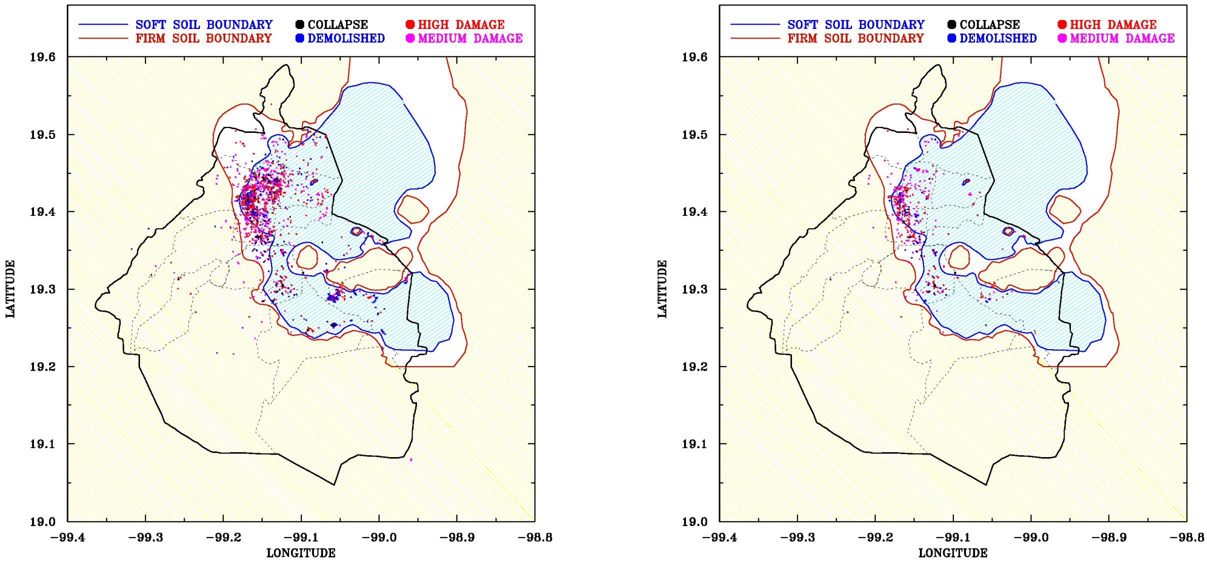
a) https://airgways.com/2017/09/20/aeropuerto-internacional-mexico-interrumpe-servicios-por-terremoto/

b) https://news.culturacolectiva.com/mexico/el-hundimiento-del-suelo-es-un-riesgo-geologico-amenaza-mexico/

Fig. 4 – Sudden soil settlements and soil tensile cracks occurred at soft soils, in: a) Terminal 2 of Mexico´s City International Airport and, b) Colonia del Mar, Tláhuac District

The damaged building and structures of most interest to the authors are those classified in the following final categories: a) medium damage (yellow category), b) high damage (red category), c) demolished structures (blue category) and, d) high risk and collapse (black category). Therefore, the common database compiled up to January 2020 under such categories includes 2,414 buildings and houses: 1,037 medium damage, 902 high damage, 386 demolished and 89 that are still of high risk or collapsed. It is worth noting that in the compiled database, each building belongs to one category only: the worst one, as in Plataforma CDMX some buildings used to be in several categories as the information was in progress and count them twice (for example, a partially collapsed building that was later demolished was in both categories, or a building with high damage that was later demolished were also in both categories).

The geographical distribution of the 2,414 buildings and houses are depicted in Fig. 5a, where to improve visibility, a magenta color is used for the medium damage category. As it can be observed in Fig. 5a, most of the experienced strong damage occurred in the soft soils of the former lakes of Texcoco, Xochimilco and Chalco. Strong damage was more concentrated and extended in the west part of former Texcoco lake, despite the fact that ground motions were not very intense there (Fig. 3), as a natural consequence that the hearth of the city is there, and there are many buildings, some of them very old. However, very strong damage also occurred in buildings located in soft soils of former Xochimilco lake nearby the connection with the Texcoco lake (Fig. 5a), where the highest strong motions occurred (Fig. 3). The extent was not as large as these buildings are more recent and the building density in that region is considerably smaller than at the traditional central part of the city. Something that was very surprising to Mexican engineers in this event was the important number of damaged and collapse buildings in transition soils, as in previous strong earthquakes this did not happen in such extent. Other hot spots were Tláhuac District (specially Colonia del Mar) and Xochimilco District (primarily the town of San Gregorio Atlapulco), both in the south-east part of Ciudad de México (Fig. 5a), located near former boundary between Xochimilco and Chalco lakes (Fig. 2) where ground motions were also strong (Fig. 3). In these sites, many houses collapsed or were severely damaged and demolished, particularly for the impressive sudden soil settlements and soil tensile cracks that occurred there (Fig. 4b), in part because these soft soils are not consolidated.



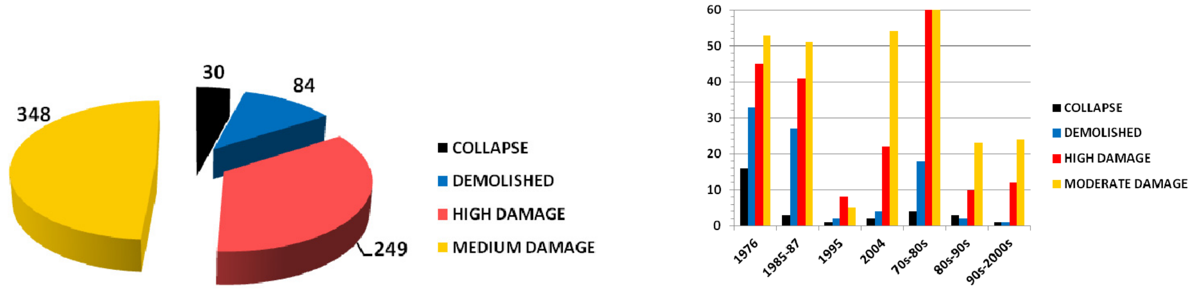
a) All buildings and houses b) Buildings designed with 1976 to 2004 codes

Fig. 5 – Geographical distribution of buildings, houses and structures in Mexico City Metropolitan area which experienced moderate to strong damage, partial or total collapse during the September 19, 2017 earthquake, of have been already demolished.

4. Damage statistics in Mexico City for collapse-prevention designed buildings

Since the first days of the damage reconnaissance surveys, the first author had the impression that many buildings which should have been designed according to collapse prevention seismic building codes of Mexico City (1976 to date) was large, not only old buildings. This impression is confirmed with the geographical distribution of the 711 buildings depicted in Fig. 5b, which according to the compiled database to date, belong to that category. The estimated number of buildings under each category is shown graphically in Fig. 6a, where one can found that at least 114 buildings collapsed or were demolished and other 249 were severely damaged. It can be observed in Fig. 5b that most of these seriously damaged buildings were located in soft and transition soils of Cuauhtémoc and Benito Juárez Districts (mid and west portion of former Texcoco lake and its corresponding transition zone). It is worth noting that ground motions in that region were not particularly high (Fig. 3). Fewer buildings which either collapsed or were demolished were located in the most demanded south-east region located at soft soils of former Xochimilco Lake nearby the intersection with former Texcoco Lake (Figs. 3 and 5b). Most of the damaged buildings are reinforced concrete buildings, but there are also many confined masonry buildings and some steel buildings (Fig. 7).

The specific statistics for each collapse-prevention seismic code for the considered damage categories are depicted in Fig. 6b. It is worth noting that in Fig. 6b, the 70s-80s category groups buildings which approximate date of construction was not available yet, but the best estimate from the first author is that they may belong to the 1976 code, with a smaller probability that some of them may belong to other code (1985 or even 1966). A similar explanation can be done for the 80s-90s category (suspected to belong to the 1985-87 code) and 90s-2000s category (suspected to belong to the 1995 code). It can be observed from Fig. 6b that most of the damage was concentrated for the 1976 code category (Figs. 7a-b) and the 70s-80s category, and this should be expected, as spectral ordinates for this building code were not very high and their corresponding the seismic detailing for RC buildings corresponded to intermediate moment frames. Nevertheless, there were an important number of damage buildings for the 1985-87 (Figs. 7c-d) and 80s-90s categories. Finally, it was also very surprising -and frankly disappointing- the large number of damaged buildings which were recently constructed according to the 2004 seismic code (Figs. 7e-f).



a) Global stastistics b) Statistic by seismic code or decade category

Fig. 6 – Damage statistic for buildings in Mexico City designed according to collapse-prevention seismic codes (1976 to date) during the September 19, 2017 earthquake

It is worth noting here that the first collapse prevention seismic code for Mexico City was the 1976 code, which it was published on December 14, 1976, so the first buildings designed and built according to this code might be from the midterm of 1977. After the September 19, 1985 earthquake, this code was changed for the 1985 emergency regulations, where spectral ordinates were amplified to cover the extraordinary spectral accelerations observed in that earthquake, particularly for the SCT site in soft soils and these regulations become later the 1987 Code [5]. The 1995 seismic code was basically and endorsement of the 1987 code, with just few changes [6]. The ruling building code at the time the September 19, 2017 earthquake stroke was the 2004 code [7], where the most salient features were: a) the definition of elastic acceleration and displacement spectra which have realistic sizes and shapes and, b) design spectra varied depending on site conditions, which were characterized by the predominant ground period, so a continuous variation of predominant ground period was proposed to define design spectra in soft and transition soils.

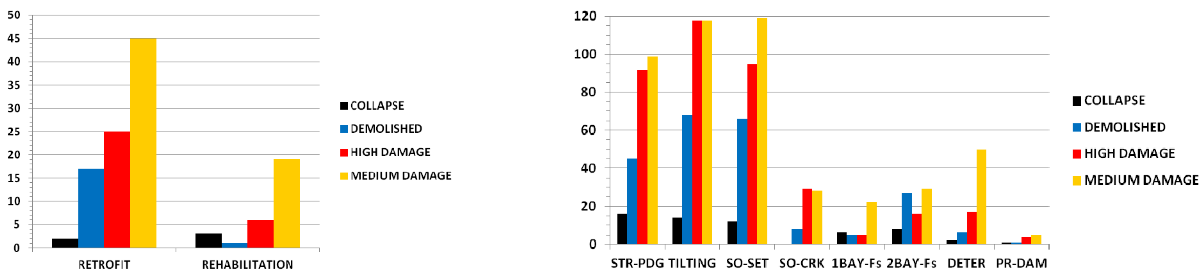
It is worth noting that in this database of 711 buildings designed according to collapse prevention codes, the authors included buildings that were retrofitted or rehabilitated after the March 14, 1979 Petatlán earthquake (these buildings must comply the 1976 code) and, of course, after the September 19, 1985 Michoacán earthquake (these buildings must comply with either the 1985 emergency regulations or the 1987 code, even the 1995 code). The results are shown in Fig. 8a, where it can be observed that 89 previously retrofit buildings experience important damage again: 17 of them were demolished, 2 collapsed and 25 were severely damaged. These bad seismic performances require an extensive, serious analyses for each particular building to understand the reasons why the retrofit strategy was unsuccessful, which are beyond the scope of this paper for space constraints. Rehabilitated buildings did not perform any better.

The statistics of some undesirable conditions that favor the damage of buildings during strong earthquakes are shown in Fig. 8b for the 711 building inventory. Of course, in many buildings some of these conditions simultaneously affected their seismic response. As most buildings are founded in soft soils, differential or sudden soil settlements (SO-SET) were observed in 292 buildings (41%) and different levels of tilting were present in 318 buildings (44.7%). A large amount of structural pounding (STR-PDG) of different intensities was observed, affecting 255 of these buildings (35.9%). This problem is directly related to the fact that in Mexico City building separations according to building codes [6] are not really enforced, and they usually range between 5 cm to 10 cm. In addition, structural pounding is also favored by soil-structure interaction effects in soft soils, particularly due to rocking, as well as previous tilting. Tensile cracks in soft soils (SO-CRK) affected primarily Tláhuac (Fig. 4b), Iztapalapa and Xochimilco Districts, and since there were no many buildings belonging to this category in those zones, they affected 65 of these 711 buildings (9.1%). Aging or deterioration (DETER) because of the lack of an adequate maintenance was observed in 75 buildings (10.6%). Also, 11 buildings (1.6%) had previous damage before the earthquake stroke (shear or soil settlement cracks, corrosion of steel reinforcement, etc.). Finally, 118 buildings (16.6%) had one-bay (1BAY-Fs) or two-bay (2BAY-Fs) frames in one of the resisting orthogonal directions, usually the most damaged one, confirming that weakly redundant buildings in one orthogonal direction are prone to experience important damage.

a) 1976 code (RC) b) 1976 code (RC) c) 1987 code (RC)

d) 1987 code (RC) e) 2004 code (RC) f) 2004 code (Steel)

Fig. 7 – Some of the heavily damaged buildings design according to collapse prevention codes. Buildings shown in figures a) to d) have already been demolished. Front building in e) collapsed and the rear one was demolished. Building shown in f) was already retrofited with concentric steel braces

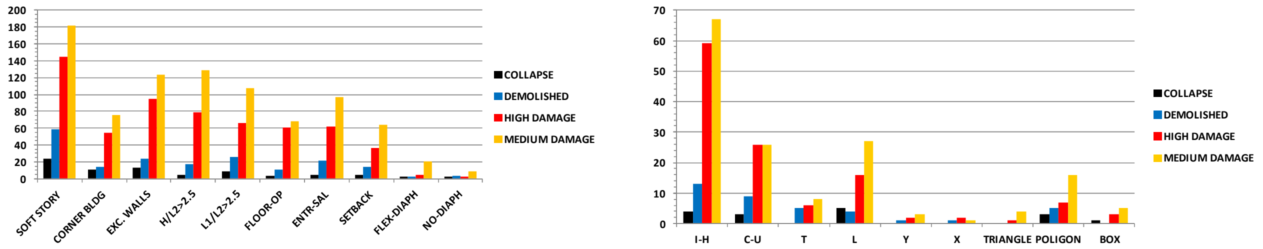


a) Retrofit or rehabilitated buildings b) Conditions that favor damage

Fig. 8 – Damage statistic for buildings in Mexico City designed according to collapse-prevention seismic codes (1976 to date) during the September 19, 2017 earthquake

It is also known that conditions of structural irregularity affect adversely the seismic response of buildings during earthquakes. For this reason, the main conditions of recognized structural irregularities were classified according to the definitions of the seismic codes of Mexico from 1987 to 2004 [6]. Also, irregular plan shapes were specially monitored using available information and corroborated with the help of Google Maps [3]. The statistics of the relationship of damage with conditions of structural irregularity and irregular plans are shown in Fig. 9. It is worth noting that often a buildings has more than one condition of structural irregularity. In fact, the average of this database was 2.93 conditions of structural irregularity per building!

As it can be observed from Fig. 9a, most building had a soft-story configuration (usually the first story), as there were 410 of them (57.7%), although fortunately, not many of them developed a weak-soft story failure, taking aside some of the collapsed and demolished buildings, primarily corresponding to designs according to the 1976 code or 70s-80s category. About 155 corner buildings (21.8%) were found, and most of them indeed favored torsional responses. Additional torsional sources were found in 255 buildings (35.9%) which had eccentric shear or infill walls, primarily because of the location of stairs or elevator cube shafts. There were 230 slender buildings (H/L_2>2.5), which corresponds to the 32.3%, and 208 buildings (29.3%) with slender rectangular plans (L_1/L_2>2.5) or a portion of the plan (a web or flange) in case of irregular plans (Fig. 9b). Large openings or multiple openings higher than 20% the plan area were found in 143 buildings (20.1%). Re-entrants and “outback” plans (ENTR-SAL) higher than 20% were found in 184 buildings (25.9%). Setbacks were found in 118 buildings (16.6%), and they were mostly one-story, last story setbacks, where the last story area was at least 50% of the previous one. Flexible diaphragms (FLEX-DIAPH) were mostly counted for buildings that had “modern” RC floors systems with very large Styrofoam blocks; 29 recent buildings (4.1%) had this floor system. Buildings with no diaphragms (No-DIAPH) were counted when a truss-based roof system was simply supported on walls and, in some instances, in columns; 16 buildings (2.3%) had that roof system, usually factories or retail stores.



a) Main conditions of structural irregularity b) Irregular plans

Fig. 9 – Damage statistic for buildings in Mexico City designed according to collapse-prevention seismic codes during the September 19, 2017 earthquake with conditions of structural irregularity

It is worth noting that 333 buildings (46.8%) had irregular plans (Fig. 9b). The most common irregular plans in this building category were the I-H shape (143 buildings, 20.1%) and the C-U (64 buildings, 9%), which were typically used in apartment buildings in the middle portion of a street. The L shape was found in 52 buildings (7.3%), mostly corner buildings. T shapes were less common (19 buildings, 2.7%), but many irregular poligonal plans were observed (31 buildings, 4.1%). Finally, triangular, box, Y-shaped and X-shaped plans were less common, but there are buildings with such configurations.

The correlation of damaged buildings with respect to the number of stories is presented in Fig. 10. It is worth noting here that stories were counted since the ground level. Also, when in the last story additional rooms that covered more than 50% the floor area were built by owners, it was counted as a floor and a last-story setbacks (Fig. 9a). As it can observed, most of the severe damaged buildings ranged from 1 to 14 story buildings, but most of the strong damage was concentrated in buildings between 4 to 9 stories. The most affected buildings had 5, 6 and 8 stories, particularly if one count collapsed and demolished buildings only.

To try to understand the severity of the ground shaking of this inventory of damaged buildings, their elastic design spectra according to building codes of interest (1976, 1987 and 2004) were compared with the elastic response spectra of acceleration records of seismic stations. As the site ground period (T_s) varies significantly within the lakebed region [6, 7], for space constraints and illustration purposes, only three characteristic ground periods T_s of interest are shown, taking into account the geographical distribution of severe damage, collapse and demolition (Fig 5b) and the intensity of the ground shaking in those sites (Fig. 3). For each T_s, the two strongest records with similar periods were selected to ease comparisons and they are shown in Fig. 11; in fact, the selected records are near to collapsed or demolished buildings. Then, T_s=1.15s and T_s=1.5s are shown for sites within Lake Texcoco and T_s=1.39s for Lake Xochimilco. In Fig. 11, the magenta vertical lines denote the approximate range of fundamental periods for RC moment frame buildings between 1 and 18 stories, taking into account the number of story statistics shown in Fig. 10 and that the fundamental periods of such buildings in soft soils (including soil-structure interaction) can be roughly assessed for practical purposes as T=0.126N, where N is the number of stories [8].

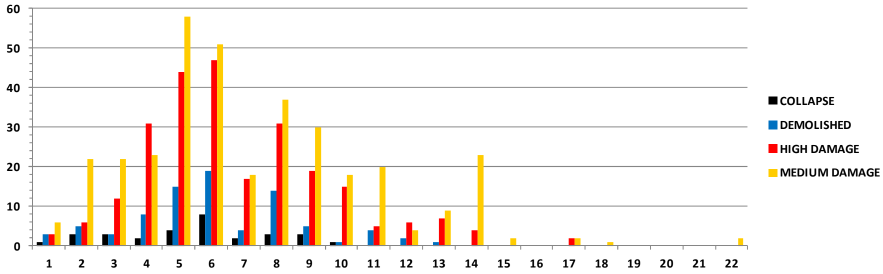


Fig. 10 – Damage statistic for buildings in Mexico City designed according to collapse-prevention seismic codes during the September 19, 2017 earthquake. Correlation with the number of stories.

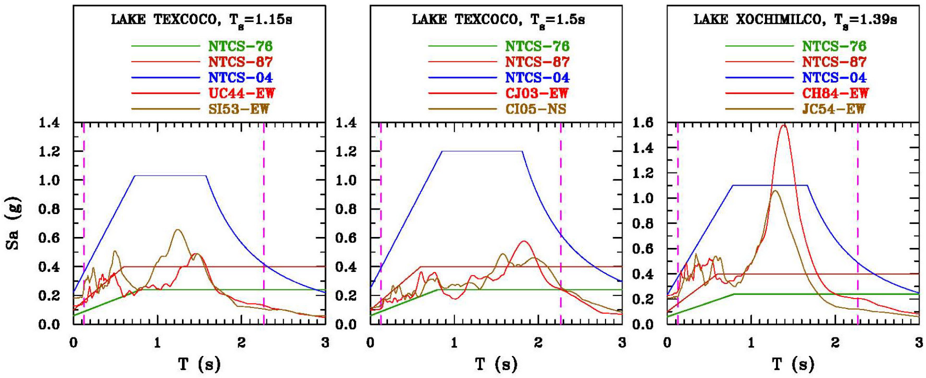


Fig. 11 – Comparison of elastic design spectra for the 1976 to 2004 seismic codes of Mexico City vs elastic response spectra of strong ground motions recorded during the September 19, 2017 earthquake

It can be observed from Fig. 11 that: a) the elastic design spectra por the 1976 code (NTCS-76) was importantly surpassed in most of the period range of interest for all considered sites, and this fact allows one to explain the extent of observed severe damage and collapses associated to this building code (Fig. 6b), b) for the 1987 code, one has to bear in mind that the design spectra (NTCS-87) is a sort of an "equivalent elastic design spectra" already reduced by dividing the real elastic design spectra by a constant overstrength factor Ω=2.5 in the plateau, as explained in detail elsewhere [5]. In fact, if one multiplies the depicted spectra by this 2.5 factor, the plateau reaches S_a=1g. Therefore, with this fact in mind, it is clear that the real elastic design spectra for the 1987 code covers by a large margin the elastic design spectra of the strongest ground motions recorded at the sites of interest in Lake Texcoco, and it may be only surpassed at Lake Xochimilco by the strongest record recorded in Culhuacán (CH84-EW) and, c) the elastic design spectra for NTCS-04 code covers by a large margin all the strongest ground motions recorded at Lake Texcoco, but they were highly demanded at Lake Xochimilco, where the CH84-EW record surpassed the plateau in the period range 1.25s≤T_s≤1.52s. Attending to this information, the question to try to answer is: why are there so many severely damaged buildings in Lake Texcoco zone designed according to the 1987 and 2004 code? It is worth noting that the demolished building shown in Fig. 7d (1987 code) is in Lake Texcoco zone (near to CJ03-EW, Figure 11) and the collapsed building shown in Fig. 7e (2004 code) is also in Lake Texcoco zone (near to SI53-EW, Figure 11). From the elastic design spectra in Lake Xochimilco and the elastic response spectra obtained from stations located there, one can understand right away that severe damage should be expected for buildings built according to the 1987 and 2004 codes (building in Fig. 7c, a 1987 code design, is around that region).

Therefore, ductility demand spectra, as proposed by the first author [9] were computed to better understand the observed damage. For this exercise, only RC buildings were considered, and the Takeda hysteretic model with parameters β_0=0.1 and β_1=0.9 was used. As the most damaged buildings are around 5 stories or more in height, to assess the nominal strength according to the 1987 and 2004 code, a period T=0.126N=0.63s was assessed for the 5-story buildings. As most of the damaged RC buildings for these codes are intermediate moment-resisting frames (RC-IMRFs), a global ductility reduction factor Q=μ=2 was considered. Given that most structures possessed in the average more than two conditions of structural irregularity, the design spectra was affected for the irregularity condition factor α=0.8, as explained elsewhere [10]. Then, according to the design spectra for the 1987 code, an effective base shear coefficient V/W=0.25 is obtained when considering nominal strength only (in fact, for all the plateau, as the plateau starts in T=0.6s). For NTCS-04, it was a little bit more complex, as T=0.63 is still in the ascending branch, so for a site with T_s=1.15s, V/W=0.277, V/W=0.282 for T_s=1.5s and V/W=0.281 for T_s=1.39s. To account for overstrength, and given that most damaged buildings have several conditions of structural irregularity, a conservative overstrength factor Ω=1.4 was considered, based upon results of assessed overstrength for soft and weak strory structures [10]. Then, the corresponding effective yield strength considering this overstrength factor were V/W=0.35 for NTCS-87 and for NTCS-04, V/W=0.388, V/W=0.395 and V/W=0.393 when T_s=1.15s, T_s=1.5s and T_s=1.39s respectively.

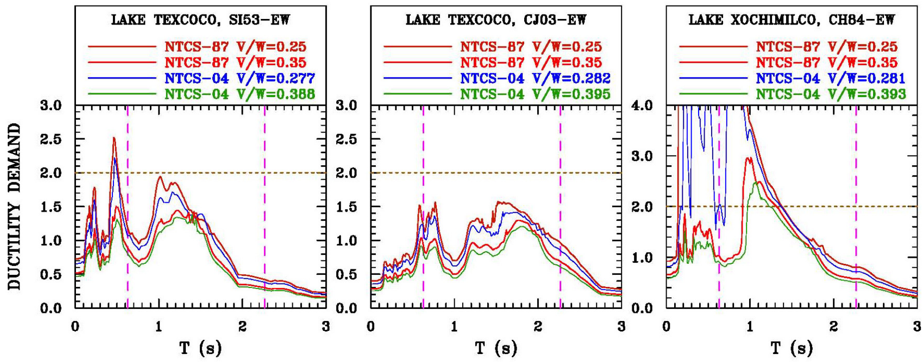


Fig. 12 – Ductility demand spectra for irregular buildings designed according to the 1987 and 2004 seismic codes of Mexico City when considering the strongest ground motions recorded during the September 19, 2017 earthquake in soft soils of former Texcoco and Xochimilco lakes

The resulting ductility demand spectra for the strongest record at each site (SI53-EW, CJ03-EW and CH84-EW for T_s=1.15s, T_s=1.5s and T_s=1.39s respectively) when considering these nominal strength and overstrength are depicted in Fig. 12, where the vertical broken lines define the region for 5-story to 18-story buildings and the horizontal broken line depicts the global ductility factor assumed. Attending to nominal strength curves only, it is observed that near SI53 station (San Simón), RC-IMRFs buildings with fundamental periods 1s≤T≤1.4s (8 to 11 stories) should experience some moderate to severe damage and RC-IMRFs with periods shorter than 0.6s (less than 5-stories) should experience also severe damage. However, when a more realistic, but still conservative assessment of their expected lateral yielding strength is done using an overstrength factor Ω=1.4, peak ductility demands are considerably reduced and only low to moderate damage should be expected. For the zone near CJ03 station (Roma Sur), only moderate damage should be expected for RC-IMRFs for 0.6s≤T≤0.8s (5 to 7 stories) and 1.2s≤T≤2.0s (9 to 16 stories) when considering nominal strength, and basically no damage or very light damage when considering even a small overstrength Ω=1.4. Therefore, attending to the fact that all structures that are designed according to the code and are well supervised in the construction process develop higher overstrengths, it is somewhat clear using this approximate strategy that the extent of severe damage, collapses and demolitions observed in Lake Texcoco for 1987 code and 2004 code are excessive, given the intensity of the ground motions there. Also, it is also clear using the ductility demand spectra concept that when a collapse prevention methodology is favored in codes by allowing ductility reductions (some very large) and overstrength reductions for design, one should expect at least moderate damage even if the ground motions yield elastic response spectra less than half of those considered in their design (Fig. 11). The results obtained for the displacement ductility demand spectra for station CH84 (Culhuacán) in particular (Fig. 12), and Lake Xochimilco region in general, just confirms that, in that site, since the elastic demands are close or even surpass the elastic design spectra (Fig. 11), the collapse prevention scenario could be reach by a large inventory of structures, even considering overstrength sources (Fig. 12). Then, the amount of severed damaged, collapsed and demolished buildings in that region (Fig. 4b) is completely justified.

5. Concluding remarks

In this paper, and based upon a detailed database of more than 2,500 structures compiled and processed by the authors, where more than 700 buildings designed with collapse-prevention codes (1976 to date), the authors want to succinctly do the following reflection (for space constraints), based upon the presented material. Although it can be concluded that structural collapses and severe damage have been reduced for buildings designed according to the collapse-prevention design philosophy in Mexico City in comparison to former older codes, particularly starting with the 1987 code to date, the observed global results were not good enough, not only from an engineering viewpoint, but primary from social and economical viewpoints. There were many buildings that collapsed, were demolished or experienced severe or moderate damage, particularly in soft soil zones of former Texcoco lake, where they should have responded much better, given the comparisons of their real elastic design spectra vs elastic response spectra of the more intense ground motion records available in that zone, as well as considering a minimum overstrength Ω=1.4 to indirectly account for the structural irregularities when using inelastic demand spectra. Many people living in those structures have been unable to use them for several months to more than two years (many of those buildings are still waiting today a decision about retrofit/demolition); many have lost their main patrimony or are in debt to pay engineering and construction services to retrofit/reconstruct their buildings. Then, in the opinion of the authors, engineers should start thinking seriously on moving forward towards seismic design strategies that would satisfy better the needs of modern societies, and one option is to implement resilient-based seismic design in future building codes. This is an enormous task and challenge that is worth working, starting today, at least for the Mexican earthquake-resistant community.

6. References

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