Geotechnical Extreme Events Reconnaissance Association
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GEOTECHNICAL ENGINEERING RECONNAISSANCE OF THE 19 SEPTEMBER 2017 Mw 7.1 PUEBLA-MEXICO CITY EARTHQUAKE

Version 1.0

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Geotechnical Engineering Reconnaissance of the 19 September 2017 M_w 7.1 Puebla-Mexico City Earthquake: Version 1.0

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We acknowledge and thank UNAM for the resources, space, and personnel provided to the GEER team during this reconnaissance effort. Acknowledgement and thanks are also extended to Arup, Parsons, and the National Aeropuerto Internacional de Ciudad de México (NAICM) project personnel for providing the team with a tour of the NAICM site, particularly Tom Wilcock (Arup), Bashar Altabba (Parsons), Marco Reyes (Parsons), Ricardo Hidalgo (NAICM), and Luis R Velázquez (NAICM). We also acknowledge and thank the support given to professors Gonzalo Montalva and Christian Ledezma by SOCHIGE (Sociedad Chilena de Geotecnia) and their corresponding home universities. Professor Gabriel Candia was partly funded by Universidad del Desarrollo and by the National Research Center for Integrated Natural Disaster Management CONICYT/FONDAP/15110017 (CIGIDEN).

Executive Summary

An intraslab subduction zone earthquake of moment magnitude 7.1 occurred on September 19, 2017 approximately 60 km southwest of Puebla, Mexico, and 120 km southeast of Mexico City, Mexico. The earthquake occurred at a depth of 57 km as a normal faulting mechanism near the point of maximum curvature of the Cocos plate, which is being subducted beneath the North American plate. The event was recorded by over 80 strong ground motion instruments located in Mexico, and produced strong ground motions that exceeded an intensity level VII in Mexico City and Puebla according to the Modified Mercalli Index (MMI).

Immediately following the September 19 event, a joint geotechnical engineering reconnaissance effort was organized between the Universidad Nacional Autónoma de México (UNAM) and the Geotechnical Extreme Events Reconnaissance Association (GEER), which is sponsored by the U.S. National Science Foundation (NSF). Two UNAM-GEER teams of researchers were sent to the region to investigate and document the effects from the earthquake: an advance team (from September 24 to September 30) and a main team (from September 29 to October 6). This Version 1 summary report presents the preliminary observations from the UNAM-GEER advance team, which were used to inform and assist the UNAM-GEER main team in its investigation. The forthcoming Version 2 of this report will contain the detailed observations and recommendations from both the advance and main UNAM-GEER teams.

At the time of preparing this report, only a portion of the recorded ground motions were available to the UNAM-GEER team and the public. However, available ground motion records that were recorded on soft rock showed a much higher frequency content in this event than was recorded previously in the 1985 Michoacan earthquake that ravaged Mexico City. Based on the few ground motion records that the team could study at the time of preparing this report, the rock ground motions appeared to resonate in transition zone soils (Zone II) and lake zone soils (Zone IIIb) in the western half of Mexico City, causing large horizontal spectral accelerations at periods between 0.8 seconds and 1.5 seconds and resulting in significant damage to many structures between five to eight stories in height. As would be expected, unreinforced masonry and adobe structures did not perform well in this earthquake, particularly when approaching the epicentral region through the state of Morelos. Relatively little structural damage was observed by the advance team in Puebla, but more was observed by the main team, which will be described in the Version 2 report.

Observed foundation performance in areas of structural damage varied considerably. Despite the high plasticity lacustrine clays that are predominant in Mexico City, numerous cases of seismic-induced settlements ranging from 1 to 15 cm were observed in the free-field soils around end-bearing pile-supported structures. Several cases of tilted structures (1 to 3 degrees) were observed. These structures generally were supported on a combined friction pile and mat slab foundation system.

Beyond settlements, several other instances of ground deformation were observed by the UNAM-GEER advance team. These deformations included cases of slope instability near the southern boundaries of Mexico City in throughout the state of Morelos, as well as groundwater subsidence cracks near Xochimilco and Colonia del Mar that were worsened and accelerated by the earthquake. These subsidence cracks caused significant damage to structures and lifelines in the area.

The UNAM-GEER advance team observed relatively little damage to dams, bridges, and other lifelines from the September 19 event.

Contents

Introduction

An earthquake of moment magnitude (Mw) 7.1 (USGS) struck the central region of Mexico on September 19th of 2017 at 18:14:40 GMT (13:14:40 local time) (Figure 1). The epicenter was located at 18.40 north latitude and -98.72 west longitude according to The National Seismological Service of Mexico (SSN) at a depth of 57 km. The United States Geological Survey (USGS) located the epicenter at 18.5838N and 98.3993E at a depth of 51 km. This earthquake occurred in a complex region of normal and reverse faults with a regional tectonic mechanism associated with the subduction of the Cocos plate under the North American plate. The focal mechanism was normal faulting. The strike of the rupture plane was approximately 112 degrees and dipped to the north or south at about 42 degrees. The epicenter was located 12 km southeast of the city of Axochiapan in the state of Morelos. As expected, there was no surface expression of the fault rupture reported by any of the reconnaissance teams dispatched to the area.

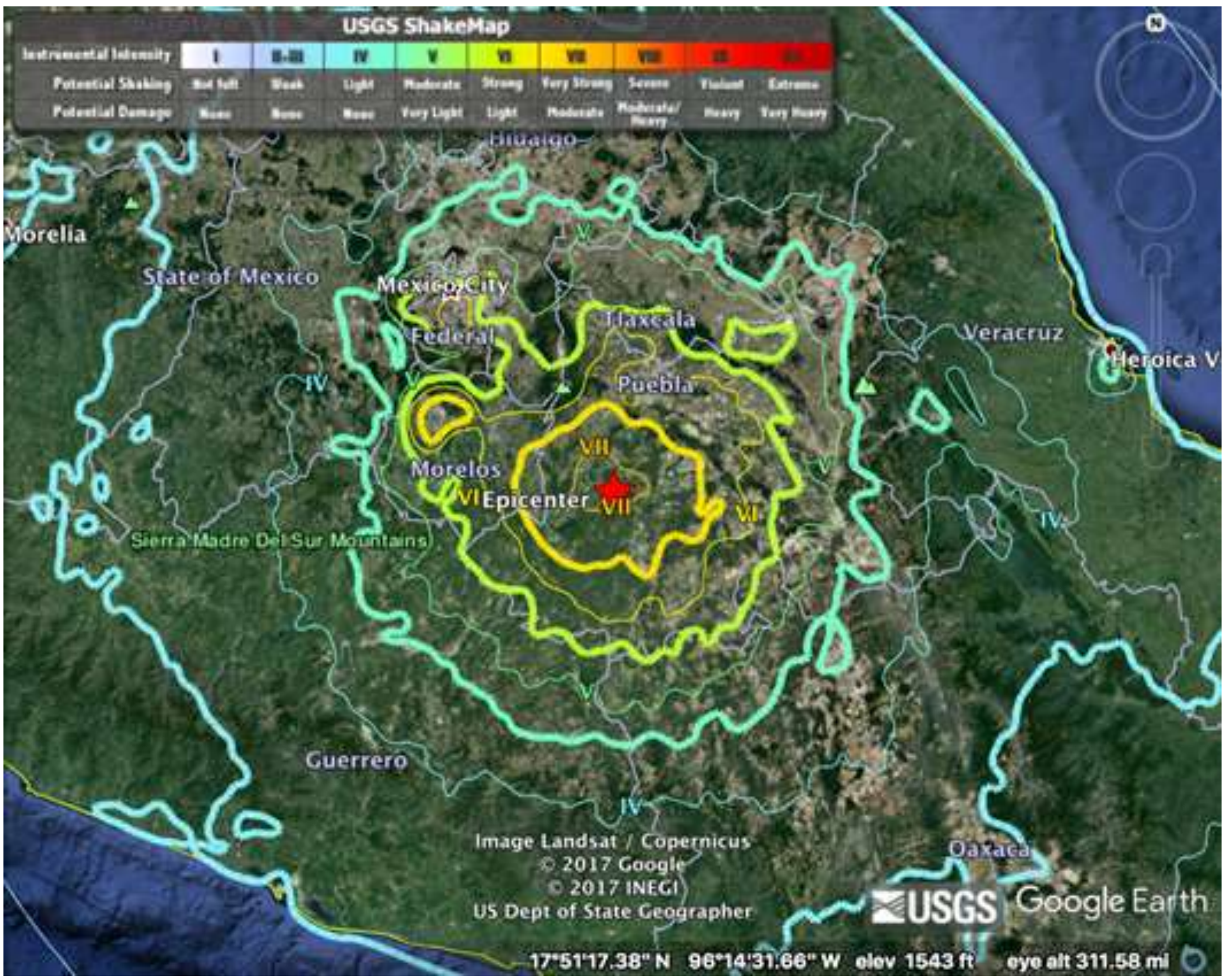


Figure 1. Map of Mexico showing the epicenter and intensity contours of the September 19th 2017 event (USGS, 2017)

According to USGS (2017), the focal mechanism solutions indicate that the earthquake occurred on a moderately dipping fault, striking either to the southeast, or to the northwest. Further, the USGS final fault interpretation suggest that the rupture occurred right at the “elbow” of the Cocos plate, where it turns sharply and is subducted beneath the North American plate, as depicted in Figure 2.

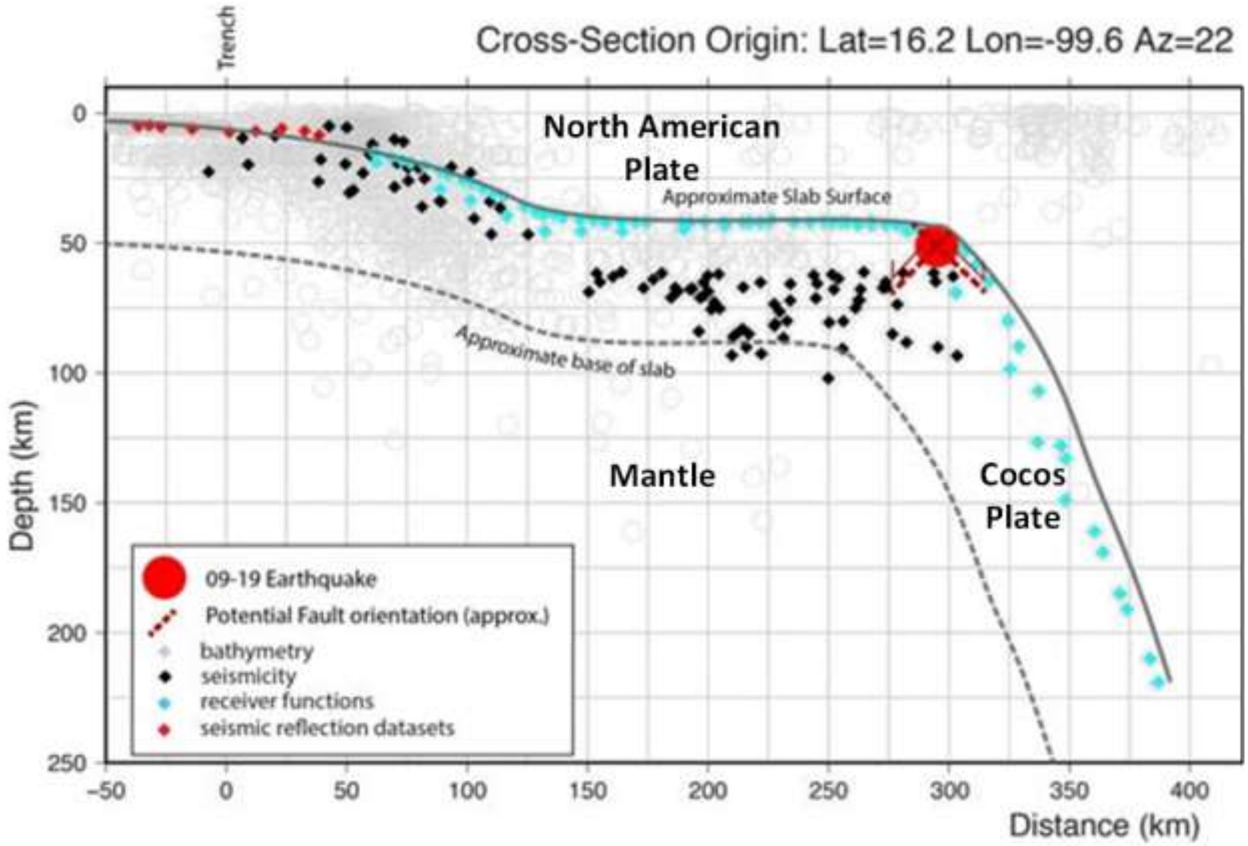


Figure 2. Cross section of the subducting Cocos plate and the overriding North American Plate, with the approximate location of the September 19th fault rupture (modified from USGS, 2017)

This event was similar in nature to several large-magnitude (Mw>6.5) intermediate-depth (60-100 km) events that have occurred in the central region of Mexico (e.g., Singh et al. 1999, Alcantara et al. 1999). Particularly on September 7th, just twelve days before the event, an 8.2 Mw earthquake occurred in the Tehuantepec Gulf at 133 km southeast of Pijijiapan in the Chiapas state. The epicenter was at 14.85 north latitude and -94.11 west longitude at a depth of 58 km (SNN). This earthquake caused major damage in houses in the states of Oaxaca and Chiapas. These states have a population of approximately four million people. Several geotechnical problems like landslides, topographic effects, and site effects were observed in these areas. Specifically, in Oaxaca 325 historical buildings suffered important damage according to the National Institute of Anthropology and History (INAH).

Other recent earthquakes with a similar moment magnitude (Mw ~7.0) that occurred near the area were the 1999 events of June 15 and June 21, with depths ranging from 60 to 90 km (Pestana et al., 1999) which also affected the central region of Mexico. According to Servicio Sismológico Nacional, SSN, the focus for the 15 June 1999 event was located at 18.40 north latitude and 97.45 west longitude at a depth of 71 km and for the 21 June event, at 18.34 north latitude and 101.49 west longitude with a depth of 50 km.

The NSF-funded Geotechnical Extreme Events Reconnaissance (GEER) Association mobilized an advance team to the Mexico City - Puebla area from September 24-30 2017, and a Main team from September 29 to October 6, 2017. Both teams (hereafter referred to as “the team”) worked closely with Mexican research colleagues from the Universidad Nacional Autónoma de México (UNAM). In addition to these, geotechnical engineers from Chile and Ecuador independently joined the reconnaissance effort and were incorporated into the team. The objective of the UNAM-GEER team was to collect and document perishable data that is essential to advance knowledge of earthquake effects, which ultimately leads to improved procedures for characterization of seismic hazard and mitigation of seismic risk.

The UNAM-GEER team was comprised of geotechnical and structural engineering experts with experience in a wide range of disciplines within the fields of geotechnical and structural earthquake engineering. For the collection of data from this event, the team combined published information and lessons learned from prior earthquakes in Mexico City with traditional field observations on the ground and state-of-the-art geomatics and remote sensing technologies.

To better serve the technical community, emergency responders, and the public this brief report has been prepared to communicate the preliminary activities, principal findings, and recommendations of the UNAM-GEER advance team. A more complete presentation of the UNAM-GEER team activities and findings will subsequently be developed and shared in a Version 2 report.

Earthquakes and Mexico City

Mexico City presents an interesting but dangerous combination of high seismicity and challenging soil conditions. Observations from previous earthquakes in Mexico City have led to many important lessons learned regarding ground motion amplification and site effects, but at a tragically high cost. To establish context for the observations made by the UNAM-GEER team from this event, a brief background regarding soil conditions in Mexico City and significant past earthquake is provided here.

Soil Conditions in Mexico City

Mexico City and its surroundings are located within an old basin that comprises the former Texcoco Lake and the Xochimilco-Chalco Lakes. These lakes have largely disappeared due to both underground water extraction and land reclamation for urban development (Figure 3). Thus, while the peripheral part of the city is underlain by rock and hard soil deposits (layer of fractured lava overlying soft rock with a shear wave velocity of 450 m/s to 600 m/s), the central part of the city is located on soft lacustrine clay deposits of variable thickness (Seed et al., 1988). The former Texcoco Lake is located to the north of the city, and is separated by a ridge of hills across the northern edge of the Xochimilco-Chalco Lake. Both of the lake beds are now essentially filled with clay deposits, but the clays have different characteristics. The Xochimilco-Chalco Lake clays are stiffer and stronger than the Texcoco Lake clays.

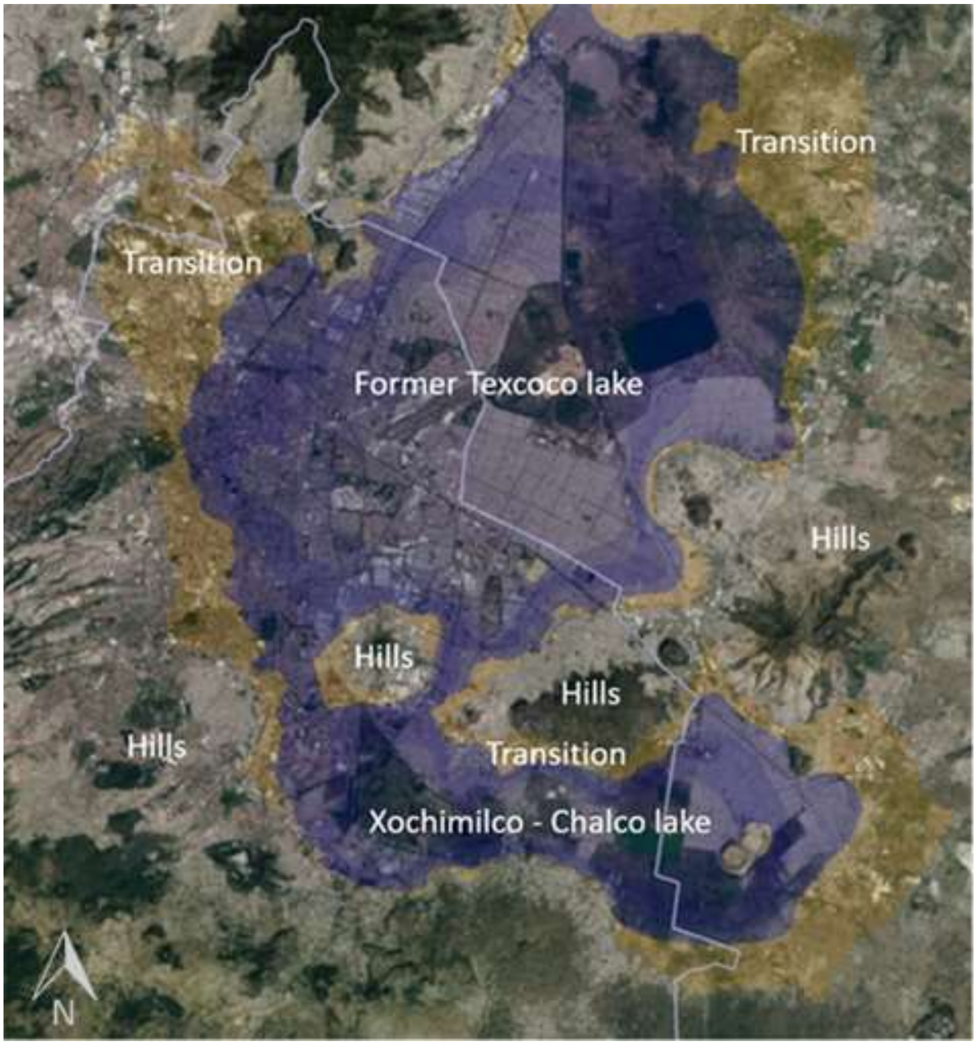


Figure 3. Mexico City Main Geotechnical Zones

Mexico City has been divided into three main zones for geo-seismic zonation purposes according to the local Building Code (RCDF 2004) (Figure 4): Zone I (Hills), Zone II (Transition), and Zone III (Lake). Zone III has further been subdivided into Zone IIIa, IIIb, IIIc and IIId to account for the increasing depth of the clay deposits when moving from the hill zones to the center of the old lakes.

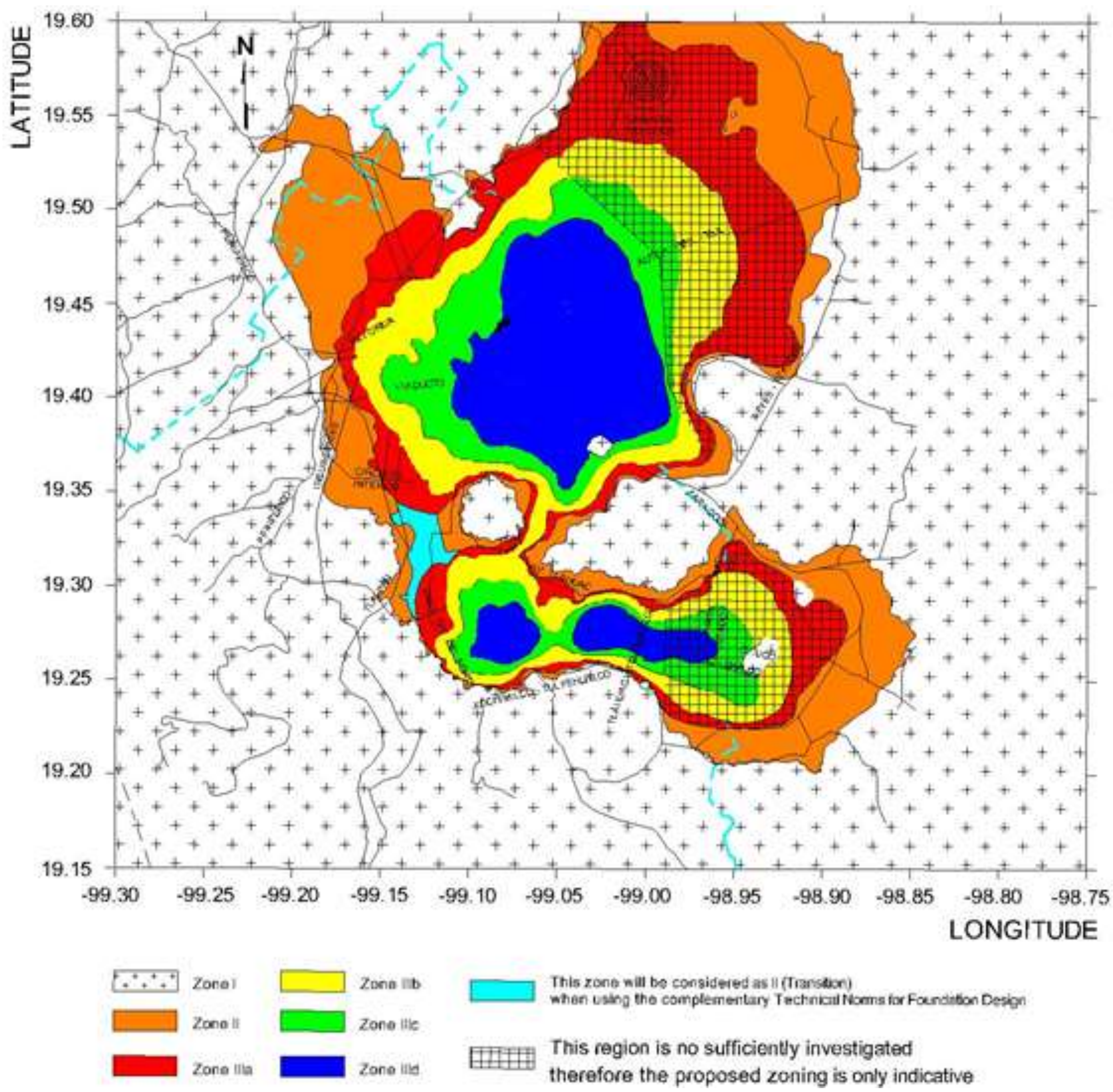


Figure 4. Geo-seismic Zoning of Mexico City

The typical soil profile for Zone III (Lake Zone), shown in Figure 5, includes a desiccated crust of clay at the top extending down to a depth of 1 to 2 meter (m) on average, underlain by a soft to very soft clay layer that is approximately 25 to 35 m thick, with thin interbedded lenses of sandy silts and silty sands (i.e. the first clay formation). Underlying the upper soft clay, a layer of very dense sandy silt, usually 4 to 7 m thick, is found, which in turn, is resting on a stiff clay deposit, which thickness often ranges from 50 to 60 m (i.e. the second clay formation). This stratum is intercalated with very dense sandy silt and silty sands lenses. Beneath the lower stiff clay is commonly found a competent layer of very stiff to hard sandy silt and silty clay. The profile shown in Figure 5 also includes shear wave velocity measured with P-S suspension logging technique in the Texcoco Lake area (Mayoral et al., 2016). Seismic properties determination of high plasticity clays, such as those found in the Mexico City Valley and its surroundings, have been only marginally studied. Previous research shows that these soils exhibit no significant reduction in shear modulus even for shear strains as high as 0.1% (see Figure 6). Similarly, there is no significant increase in the damping ratio until angular distortions of the order of 0.3% are reached (e.g., Romo et. al., 1988; Seed et al., 1988; Mayoral et al., 2008; Mayoral et al., 2015).

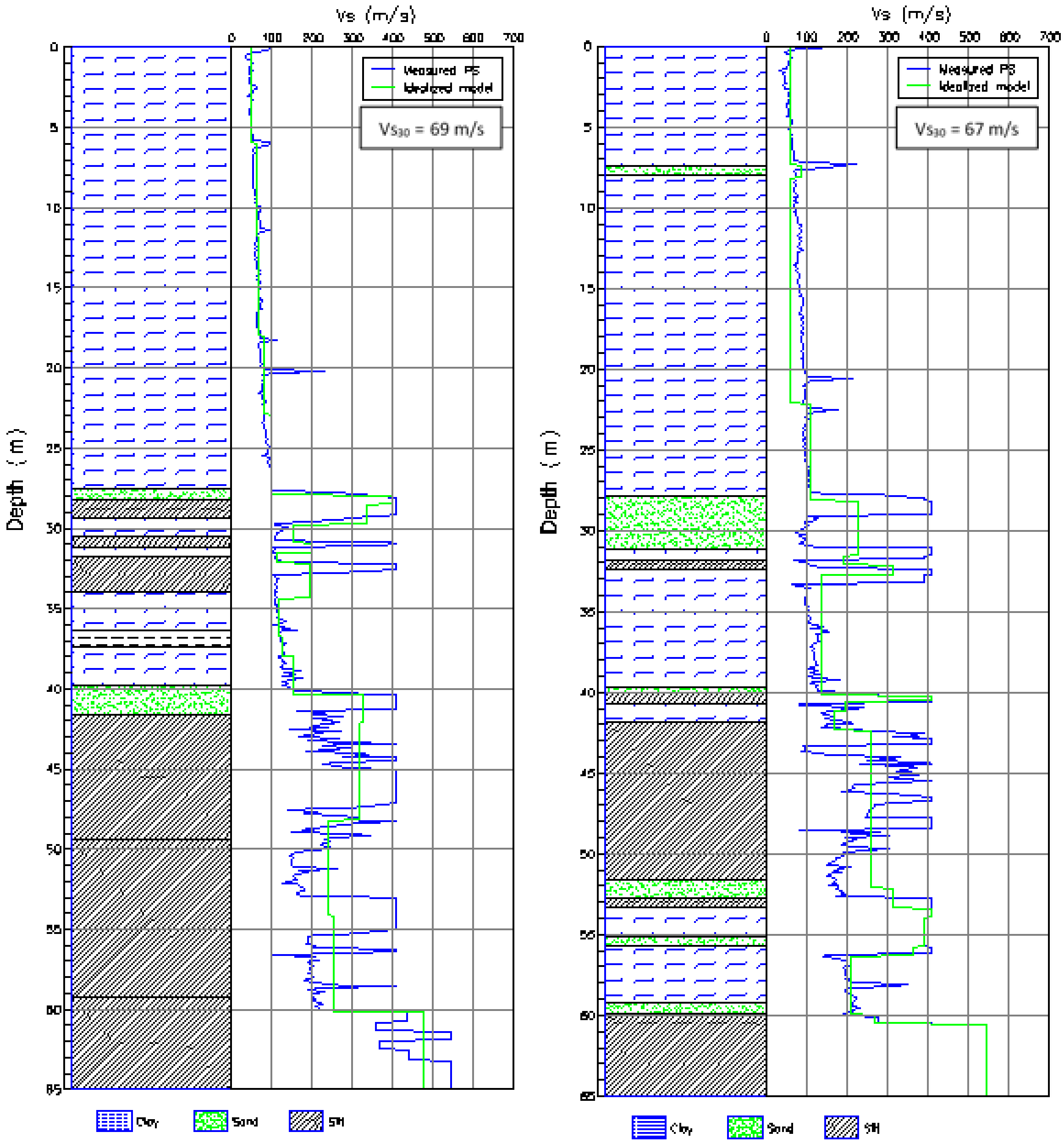
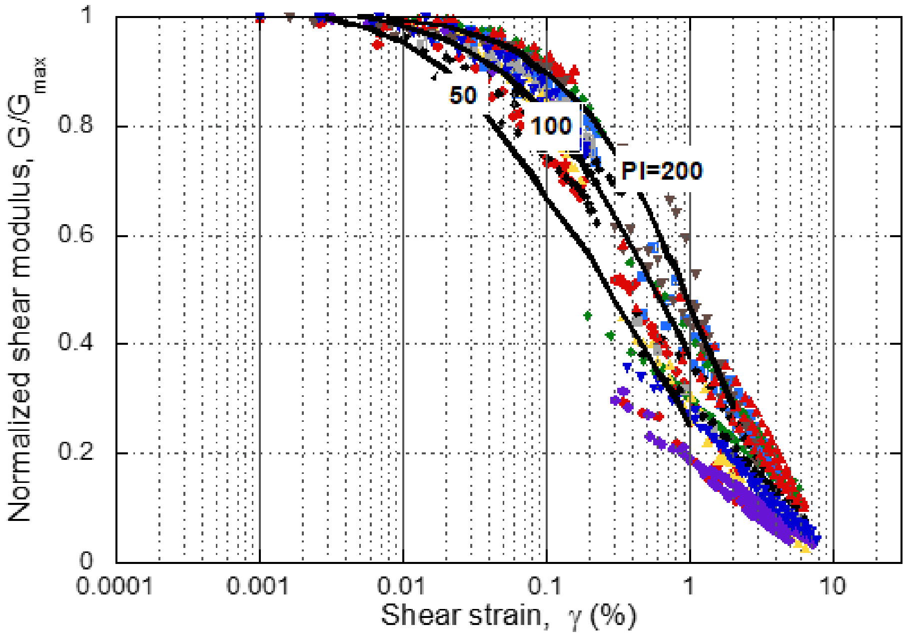


Figure 5. Typical soil profiles for Zone III (Mayoral et al., 2016)



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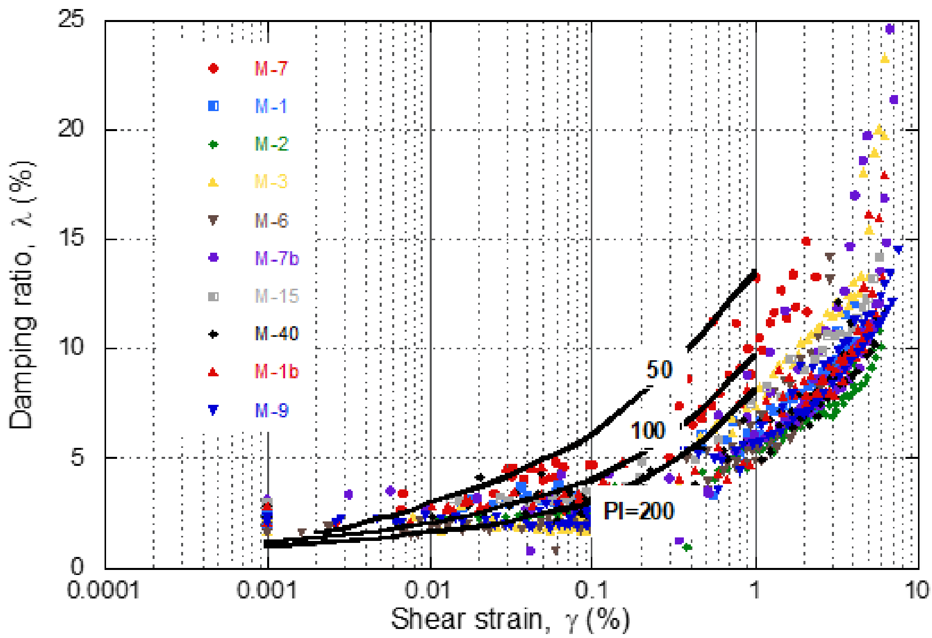


(b)

Figure 6. (a) Typical strain-dependent normalized shear modulus reduction and (b) typical strain-dependent material damping curves for Texcoco clays (Mayoral et al., 2016)

The dynamic response of Mexico City clay deposits is nearly elastic even for shear strains as high as 0.3%, which leads to a high potential of amplification of seismic waves. During the 1985 Mw 8.1 Michoacán earthquake, recorded peak ground acceleration (PGA) on soft soils was on the order of five (5) times larger than the corresponding PGA on rock outcrop, while the corresponding spectral acceleration ordinates for 5% structural damping of recorded ground acceleration at the surface ranged from about 0.4g to 1.0g at periods of approximately 2.0 seconds (s) (e.g., Seed et al., 1988; Mayoral et al., 2008). The Lake Zone, due to its unique clay properties, has been extensively studied since the 1985 event; among others, seminal publications [Romo et al. 1988, Romo 1995, Mayoral et al. 2008]. Table 1 shows a summary of some typical index properties of the Lake Zone soils, as summarized by Mayoral et al. (2016).

In Zone II soils (i.e., Transition Zone), soft clay deposits interbedded by series of thin silty sand and sandy silt layers and lenses, which range in thickness from 0-20 m are underlain by stiffer soil deposits that are comprised of sandy silts and silty sands with interbedded clay layers of varying thickness ranging from a few tens of centimeters to meters. A typical soil profile and corresponding shear wave velocities from the Transition Zone is presented in Figure 7.

Table 1. Soils characteristics and index properties of the Lake Zone soils (Mayoral et al., 2016)

Site	**Hole**	**Sample**	***Water Content w* (%)**	***Liquid Limit LL* (%)**	***Plastic Limit PL* (%)**	***Plasticity Index PI* (%)**	***Specific Gravity*** G_s	***Rigidity index*** I_R	***USCS***
TXS1	SM-2	M-7	370	284	90	194	2.65	-0.44	CH
TXS1	SS-1	M-1	275	311	107	204	2.78	0.17	CH
TXS1	SS-1	M-2	303	360	71	288	2.82	0.2	CH
TXS1	SS-1	M-3	280	243	108	135	2.53	-0.27	CH
TXS1	SS-1	M-6	139	173	122	51	2.4	0.66	MH
TXS2	SM-1	M-7	308	302	75	226	2.7	-0.03	CH
TXS2	SM-1	M-15	399	326	125	201	2.51	-0.37	CH
TXS2	SM-1	M-40	280	310	81	229	2.82	0.13	CH
SOSA	SM-1	M-1	331	368	159	210	2.45	0.18	CH
SOSA	SM-1	M-9	311	306	156	150	2.74	-0.03	CH
TX-TP	SS1-TP	M2	264	287	153	135	2.58	0.17	CH
TX-TP	SS1-TP	M4	247	284	91	193	3.03	0.19	CH
TX-TP	SS1-TP	M7	118	182	59	122	2.71	0.52	CH
TX-TP	SS4-TP	1A	106	113	53	60	2.65	0.12	MH
TX-TP	SS4-TP	4A	247	271	75	195	3.24	0.12	CH
TX-TP	SS6-TP	M1	251	268	114	154	2.49	0.11	CH

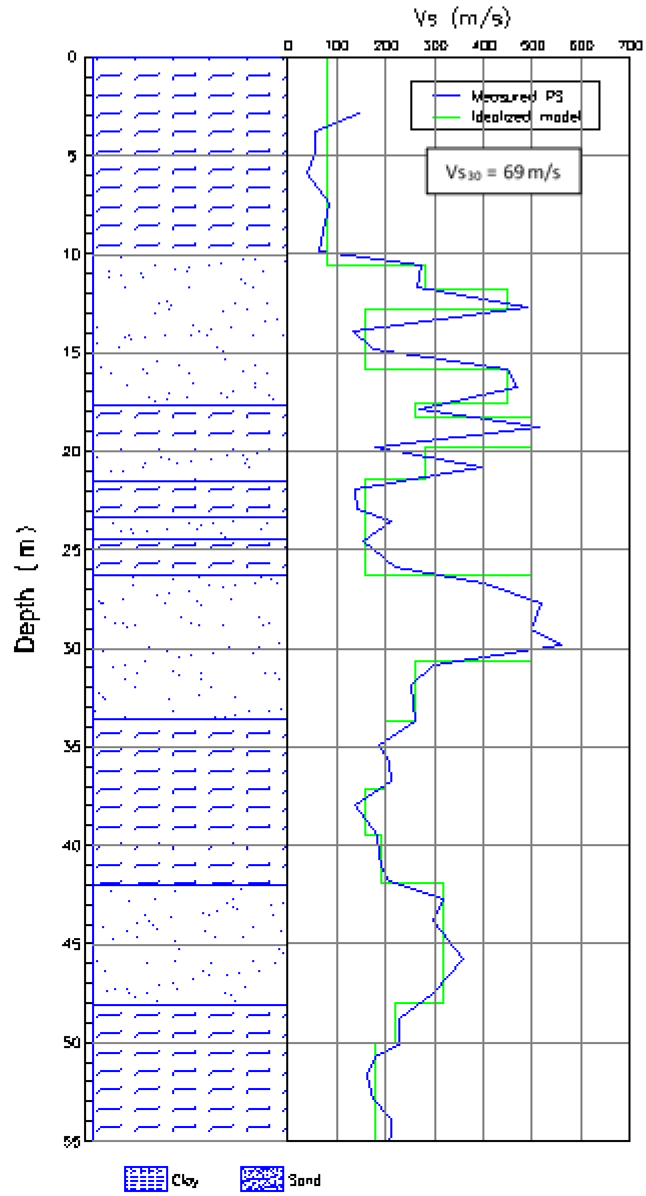


Figure 7. Typical soil profile for the Transition Zone (after Mayoral et al., 2016)

In Zone I (i.e., the Hills Zone), the soil deposits are generally comprised of volcanic rock and/or stiff soil, with occasional superficial or interbedded loose sand deposits and/or relatively soft cohesive materials. In this zone, it is common to encounter undocumented and uncontrolled landfills, cavities in volcanic rocks, and caves and underground excavations in the stiff soils due to past mining activities.

Significant Past Earthquakes and Corresponding Observations

Over the years, Mexico City has suffered the effects of many earthquakes, including the devastating September 19th, 1985 event. Although the epicenter of this Mw 8.1 event was more than 300 km from Mexico City, along the Michoacán coast, it led to significant damage in Mexico City. Other important cities near the coast and in central Mexico also suffered severe damage, but Mexico City was the most affected due to its particular site conditions. One of the most interesting effects of this earthquake was the enormous difference in shaking intensity and associated building damage in different parts of the city. Similar patterns of building damage intensities have been observed in previous earthquakes, but these differences were particularly accentuated during the 1985 event. Major structural damage from this event was concentrated in the central and north-west part of the city in the Lake Zone (i.e., Zone III). In the south-west part of the city, ground motions were moderately intense, and building damage was generally minor. Interestingly, the majority of the structural damage from this 2017 event is concentrated in the western and south-western part of the city. Figure 8 shows a map of building collapse locations from the 1985 event (plotted in green) and preliminary building collapse locations from the 2017 event (plotted in red) in the central area of the city.

Seed et. al (1988) investigated the pattern of building damage from the 1985 event. Ground motions recorded on rock and hard soil had peak ground accelerations (PGA) on the order of 0.04 g, peak spectral accelerations (PSA) for 5% damping of about 0.11 g, and a predominant period of about 2.0 s. However, ground motions recorded in soft clay deposits had a PGA of about 0.17 g and a PSA for 5% damping of about 1.0 g at a period of about 2.0 s. Sites that might be considered very similar from an engineering standpoint, but slightly different in soil conditions (i.e., depth and stiffness of the underlying soils), exhibited significant differences in the observed spectral response of the ground surface motions. Thus, the site response in areas of Mexico City underlain by lacustrine clay is extremely sensitive to small changes in the clay shear wave velocity, clay thickness, and overall soil layering.

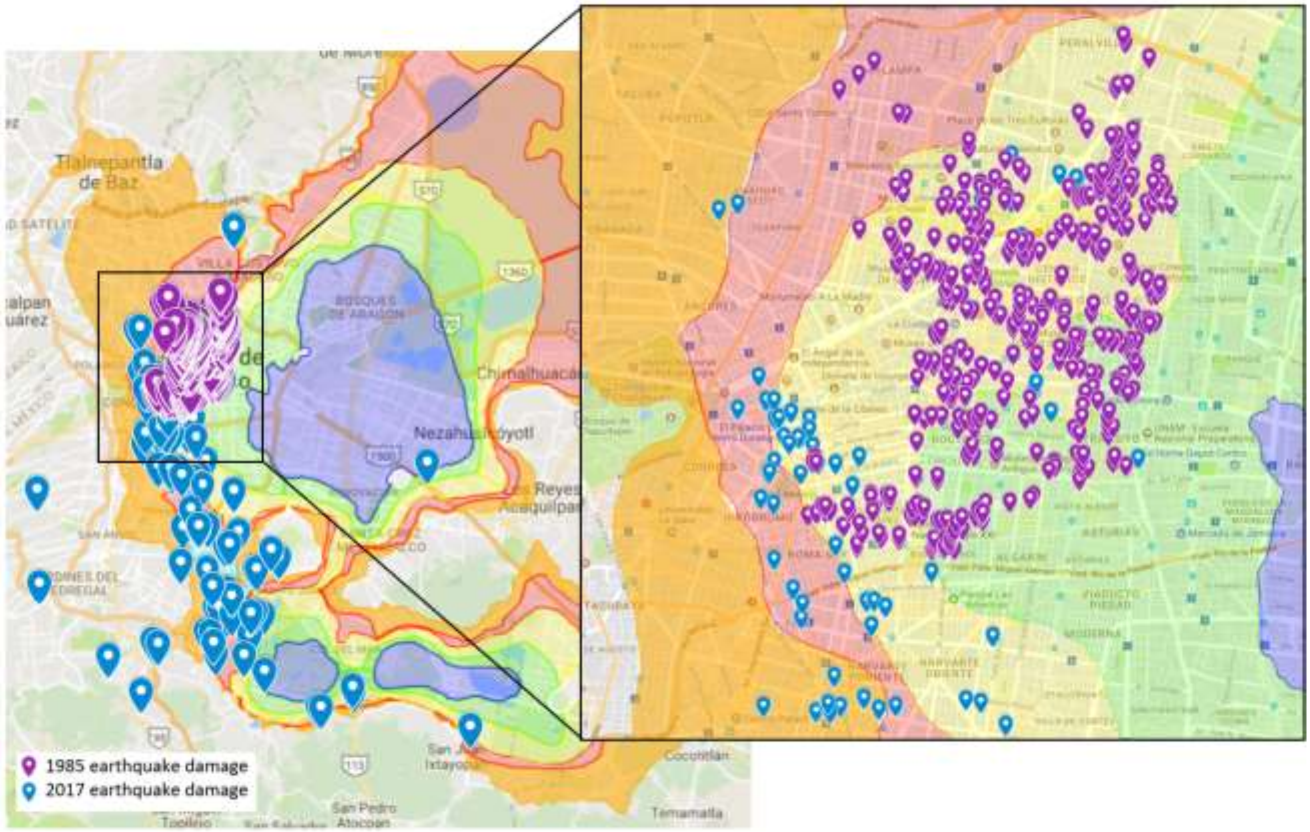


Figure 8. Collapsed buildings in the central region of Mexico City during the September, 19 1985 event and the September 19, 2017 event (preliminary mapping, in blue, Google maps, 2017)

Summary of the Observations Made by the UNAM-GEER Advance Team

Figure 9 presents the site vicinity of the Mexico City/Puebla/Morelos region, including the surface fault rupture projection and the GPS tracks of the advance team members between September 24 and September 30, 2017.

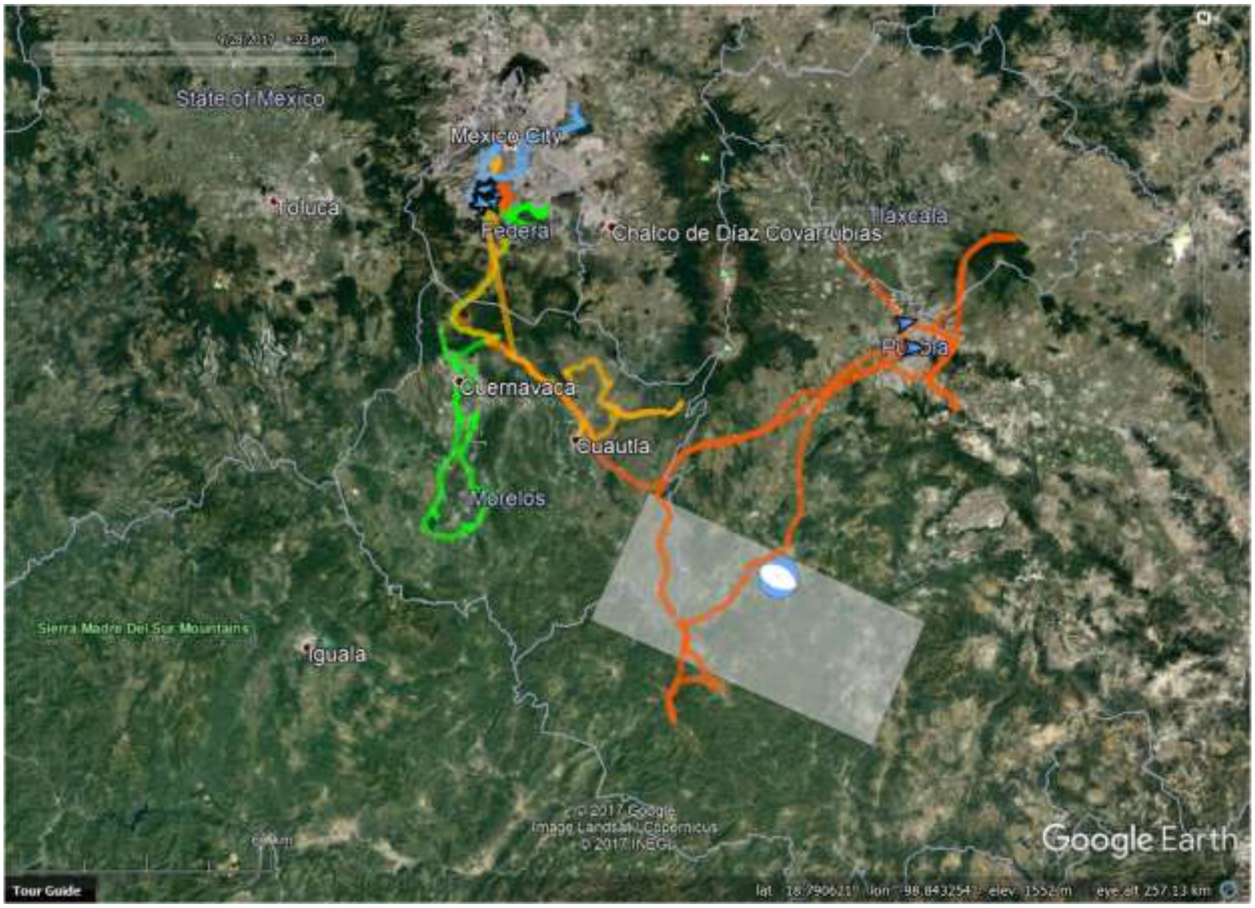


Figure 9. Site vicinity map of the Mexico City/Puebla/Morelos area including surface projection of the Mw 7.1 fault rupture and the GPS tracks of the advance UNAM-GEER team

This initial (version 1) report will present the most important preliminary observations from the UNAM-GEER advance team regarding the following:

1. Recorded Ground Motions
2. Site Response
3. Performance of Foundations and Structures
4. Observed Ground Deformations
5. Performance of Bridges
6. Performance of Dams
7. Observations of Slope Instability
8. Observations at Sites of Social and Cultural Interest

More detailed observations regarding these and additional topics will be provided in Version 2 of this report.

1. Recorded Ground Motions

Various organizations were operating and maintaining ground motion recording instruments at the time of the September 19th event. Among others, Centro de Instrumentación y Registro Sísmico (CIRES) was operating 53 strong motion stations at the time of the event, Red Acelerográfica de Movimientos Fuertes del Instituto de Ingeniería (IINGEN) at UNAM was operating 18 stations, and the Servicio Sismológico Nacional (SSN) del Instituto de Geofísica (IGEOF) of UNAM was operating 10 stations. However, not all of the CIRES, IINGEN, and IGEOF stations were working properly during the time of the earthquake. The locations of the IINGEN and IGEOF stations are presented in Figure 10.

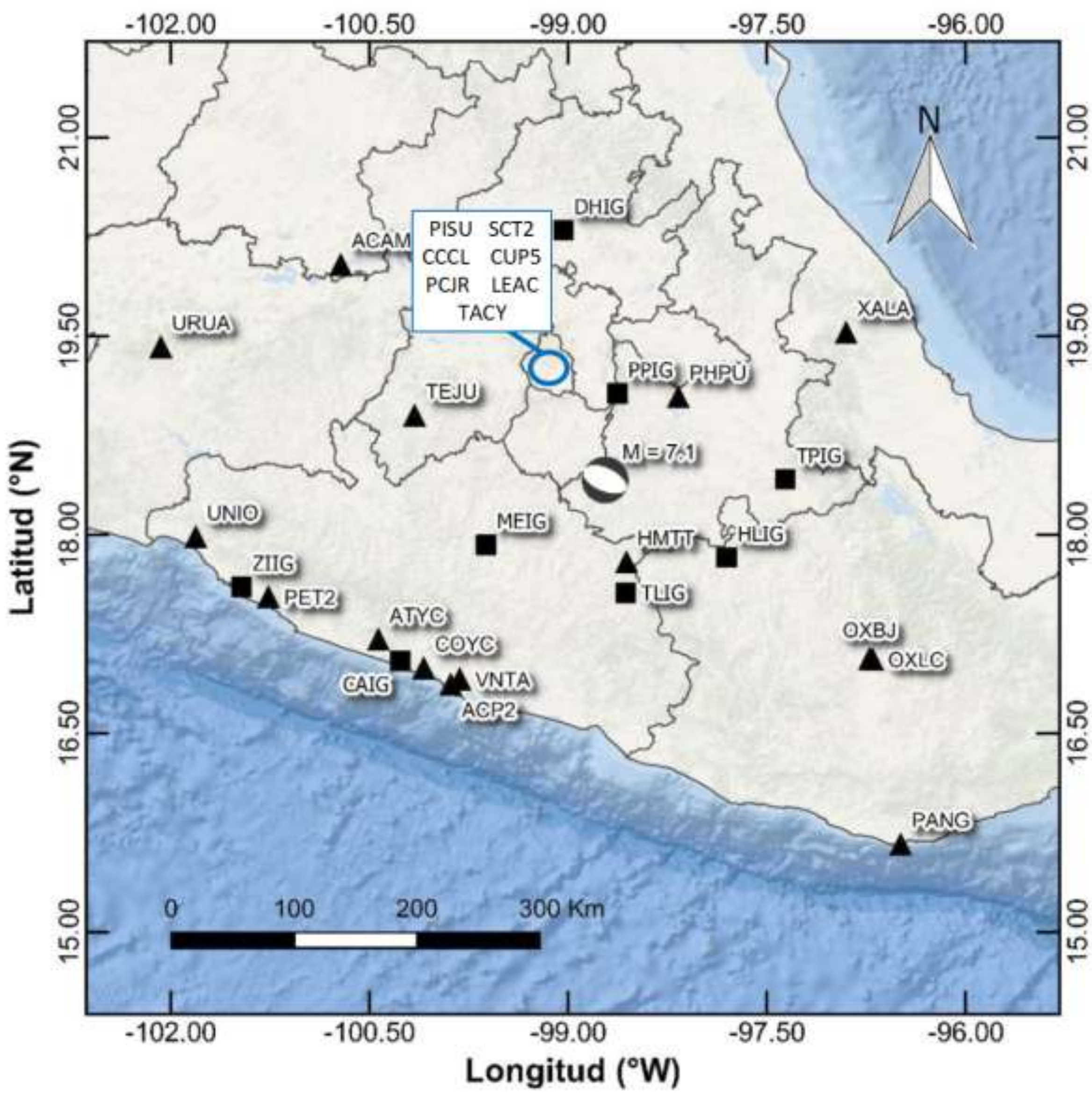


Figure 10. Locations of IINGEN (triangles) and IGEOF (squares) ground motion stations relative to the Mw 7.1 epicenter (modified from IINGEN 2017)

At the time of preparing this report, 25 of the IINGEN and IGEOF ground motion records and 49 of the CIRES ground motion records were made available to the UNAM-GEER team. A preliminary report prepared by UNAM (IINGEN, 2017) provided peak ground acceleration (PGA, g) for the 18 stations operated by UNAM. IINGEN seismic data are the product of the instrumentation and processing work of the Seismic Instrumentation Unit at the Institute of Engineering of the National Autonomous University of Mexico (UNAM). Figure 11 shows the seismological stations locations along with the corresponding seismic zonation, and Figures 12 and 13 present the response spectra of the measured free-field response in the Hill and Lake Zones, respectively. The only station operated by II-UNAM, located in the Transition Zone (LEAC), was placed within a structure, therefore will not be presented here because the record is not representative of a free-field response. Neither will be presented the PISU strong ground motion station, which is located near Impulsora Bridge.

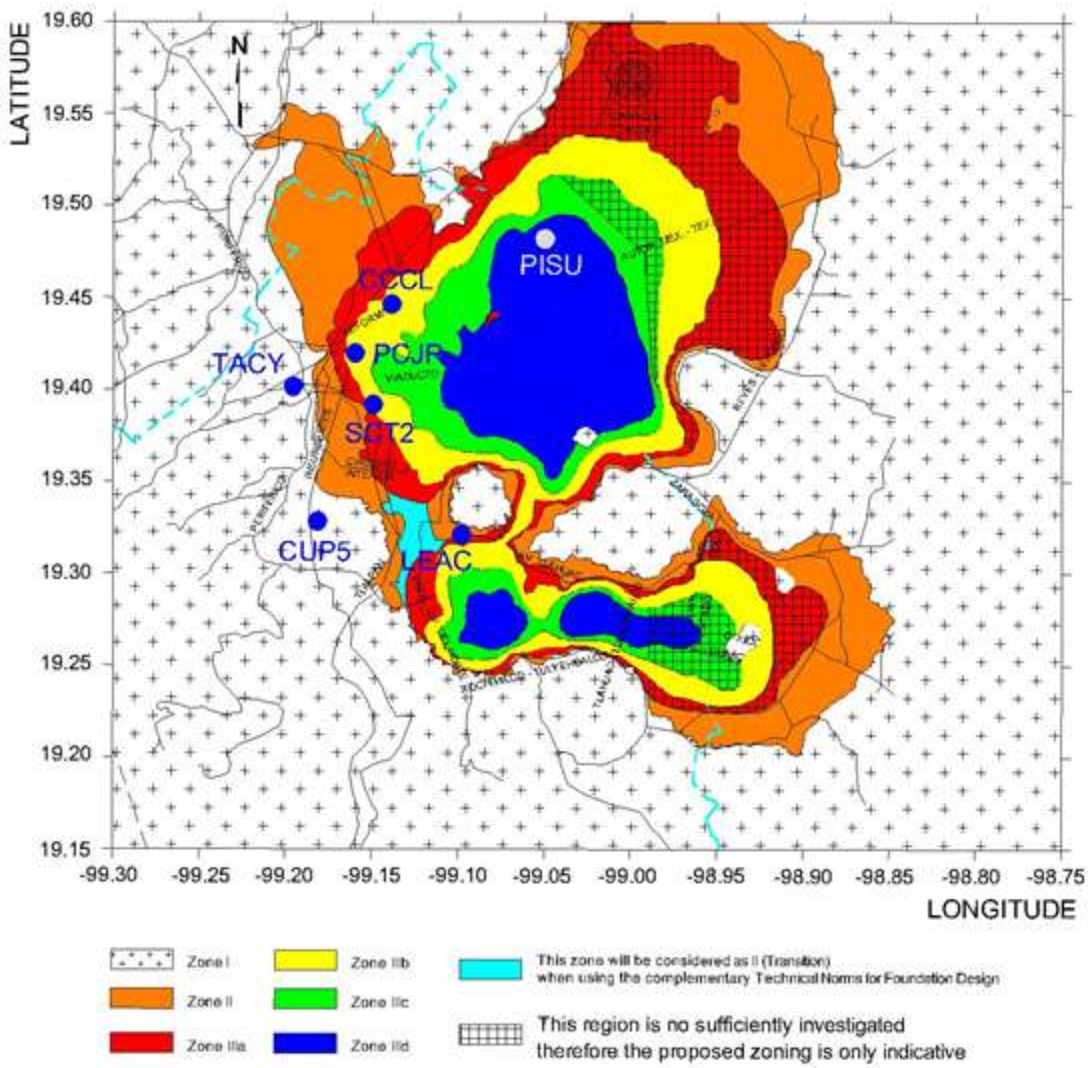
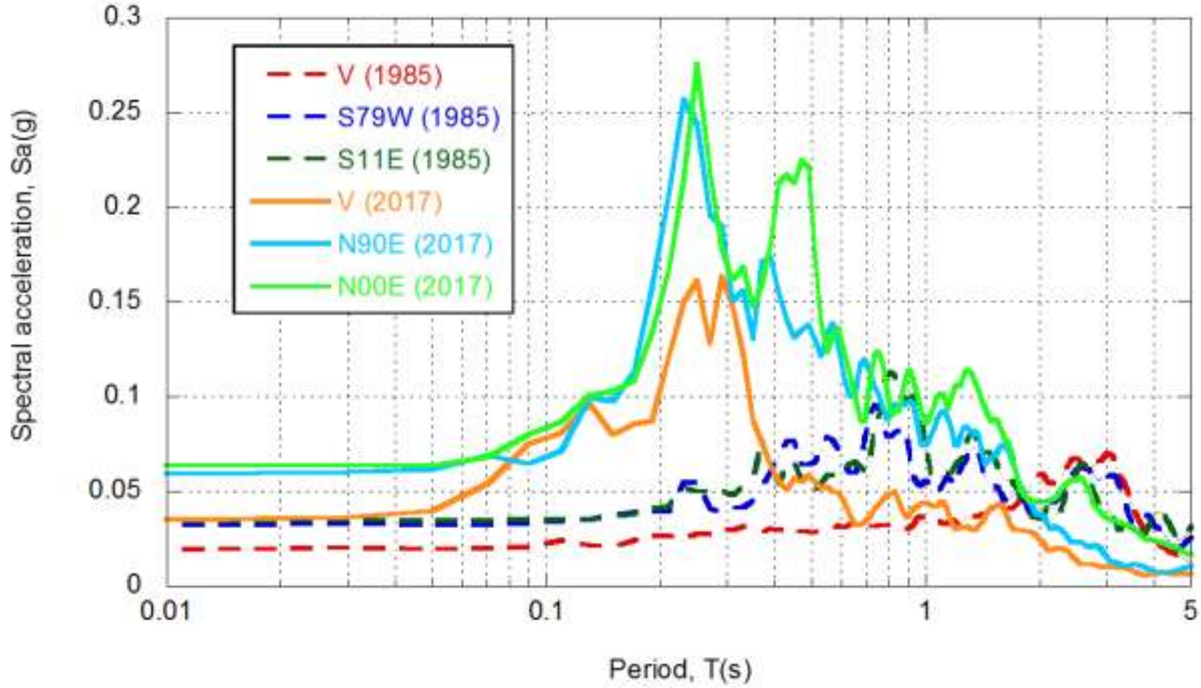


Figure 11. Seismological station location overlaid with Mexico City geo-seismic zoning



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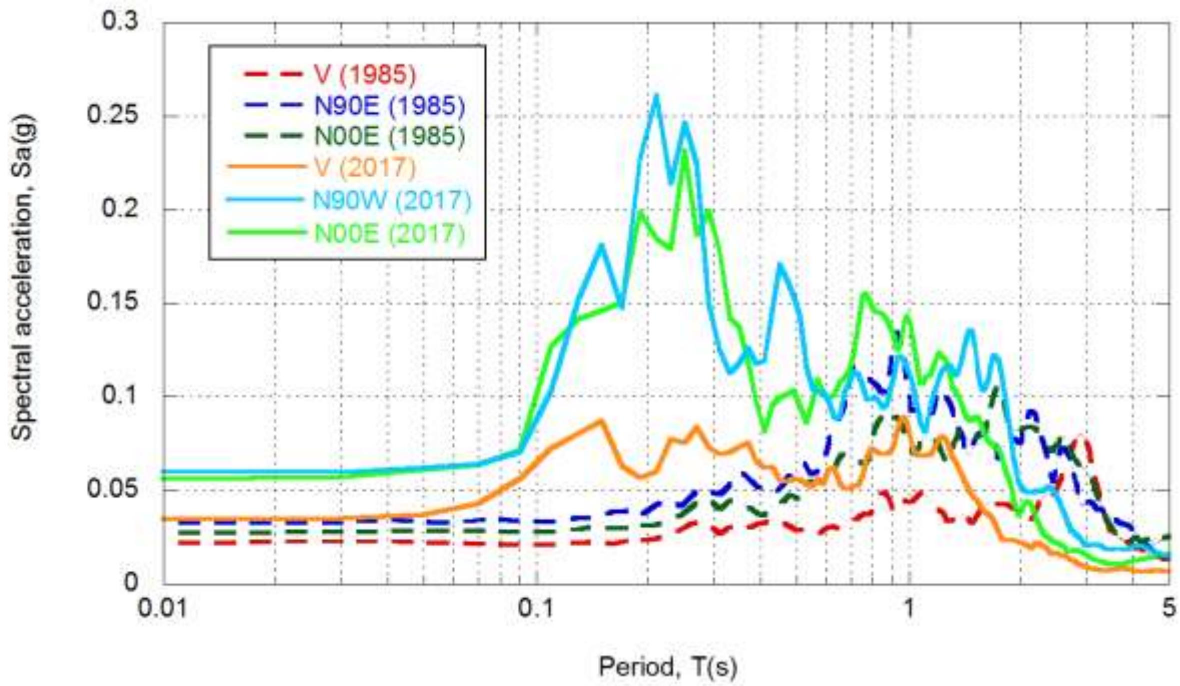
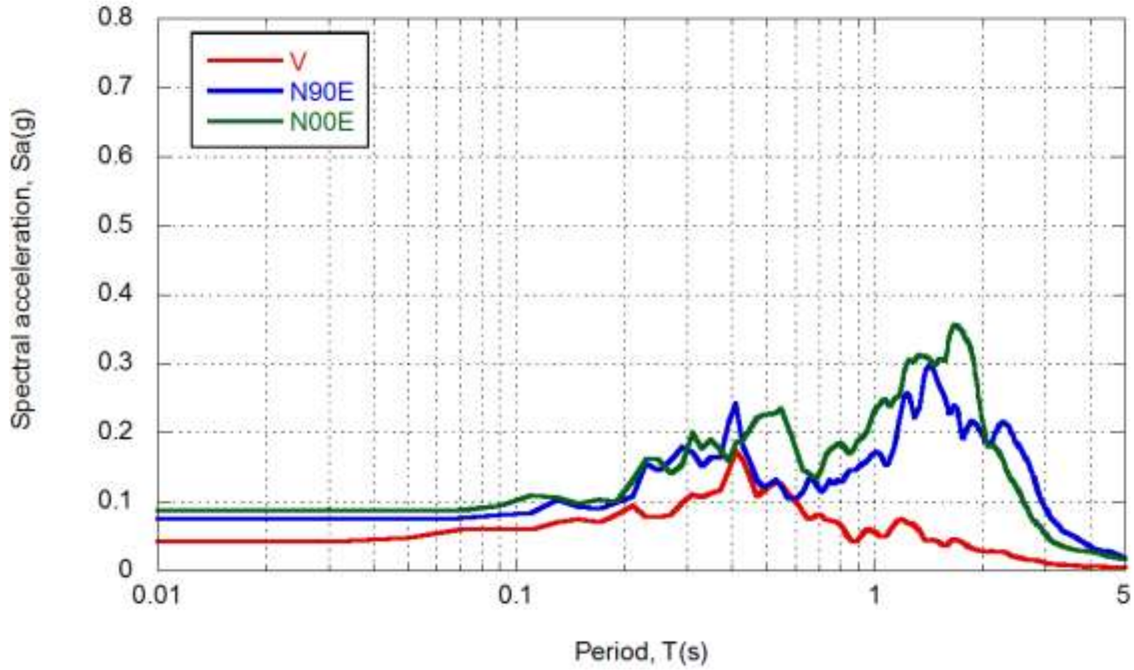


(b)

Figure 12. Acceleration response spectra (5% damped) of ground response measured at Hill Zone I: (a) TACY seismological station and (b) CUP5 station for the three earthquake components



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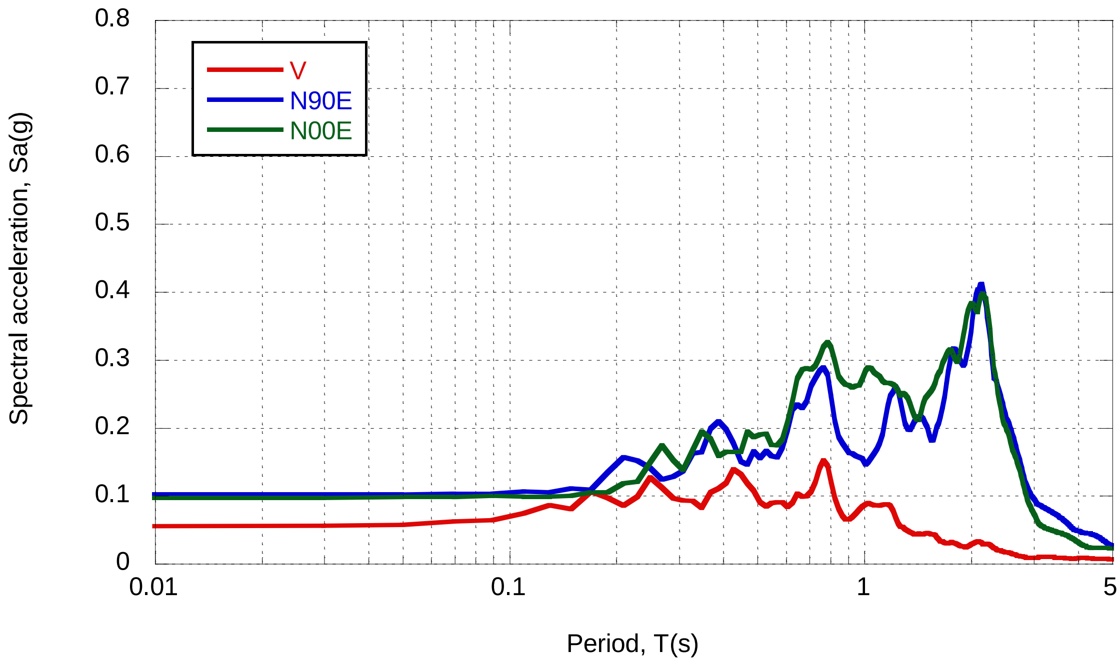

(b)

Figure 13. Seismic site response in Lake Zone IIIb at: (a) CCCL seismological station, and at (b) PCJR seismological station for the Sep 19, 2017 Event

Tables 2 and 3 present the peak ground accelerations, velocities and displacements recorded at the seismological stations operated by the Institute of Engineering at UNAM and CIRES, respectively.

Table 2. Peak ground accelerations in the east-west and north-south directions at select stations operated by the Institute of Engineering, at UNAM

Station	Zone	Coordinates		PGA (g)	
	NTC04	Latitude N	Longitude W	EW	NS
CCCL	IIIb	19.4498	99.137	0.07	0.09
CUP5	I	19.3302	99.1811	0.06	0.05
PCJR	IIIb	19.4228	99.1591	0.1	0.1
SCT	IIIb	19.3947	99.1487	0.09	0.09
TACY	I	19.4045	99.1952	0.06	0.06

Table 3. Peak ground accelerations in the east-west and north-south directions at select stations operated by CIRES

Station	Zone	Coordinates		PGA (g)	
	NTC04	Latitude N	Longitude W	EW	NS
AL01	IIIb	19.4356	99.1453	0.11	0.12
AO24	II	19.358	99.1539	0.12	0.11
AU46	II	19.3832	99.1681	0.1	0.08
BA49	IIIb	19.4097	99.145	0.12	0.09
BL45	IIIb	19.4253	99.1481	0.12	0.1
CH84	II	19.33	99.1254	0.23	0.15
CI05	IIIb	19.4186	99.1653	0.12	0.11
CJ03	IIIb	19.4097	99.1567	0.1	0.11
CO47	II	19.3714	99.1703	0.1	0.07
CO56	IIIb	19.4215	99.159	0.12	0.11
DX37	II	19.3322	99.1439	0.12	0.19

Table 3. Peak ground accelerations in the east-west and north-south directions at select stations operated by CIRES (continued)

Station	Zone	Coordinates		PGA (g)	
	NTC04	Latitude N	Longitude W	EW	NS
EO30	II	19.3885	99.1772	0.08	0.07
FJ74	I	19.299	99.21	0.09	0.09
GA62	IIIb	19.4385	99.1401	0.09	0.1
GC38	IIIb	19.3161	99.1059	0.12	0.13
HJ72	IIIc	19.4251	99.1301	0.1	0.09
JC54	II	19.313	99.1272	0.21	0.22
LI33	IIIa	19.3064	98.9631	0.11	0.14
LI58	IIIb	19.4263	99.1569	0.09	0.1
MI15	IIIa	19.2834	99.1253	0.14	0.21
MY19	IIIc	19.3461	99.0433	0.11	0.12
RM48	IIIb	19.4359	99.128	0.08	0.06
SI53	IIIa	19.3753	99.1483	0.18	0.13
TH35	IIIc	19.2786	99	0.19	0.19
TL08	IIIb	19.45	99.1336	0.08	0.08
TL55	IIIb	19.4536	99.1425	0.07	0.08
TP13	I	19.2922	99.1708	0.07	0.06
UC44	IIIb	19.4337	99.1654	0.13	0.13
UI21	I	19.37	99.2642	0.08	0.08
XP06	IIIc	19.4198	99.1353	0.11	0.08

Figures 14 and 15 present PGA Shakemaps based on the recorded UNAM data (IINGEN, 2017). More detailed observations regarding ground motions recorded from the September 19 Mw 7.1 event will be provided in Version 2 of this report.

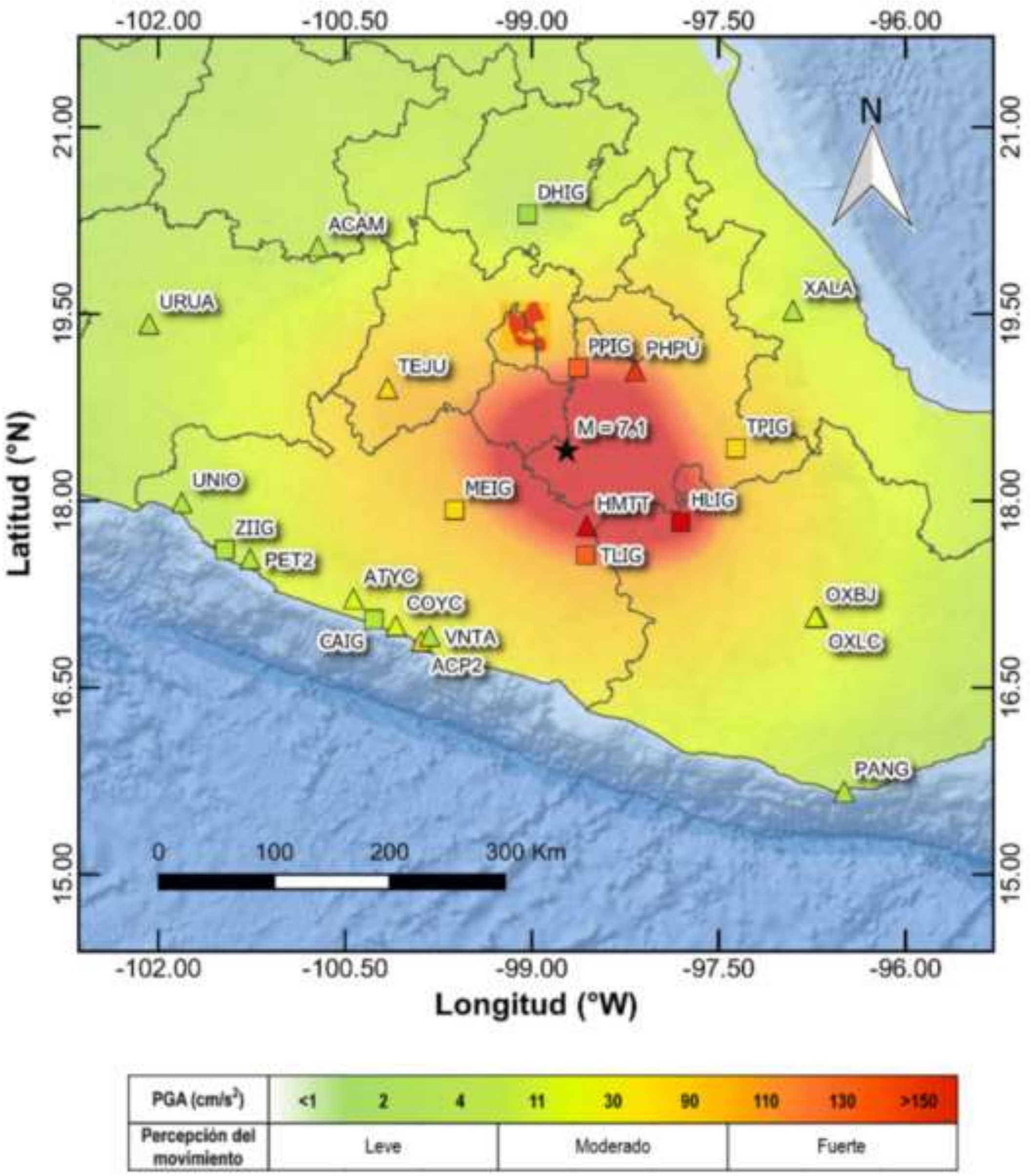

Figure 14. Regional PGA (cm/sec^2) map from the September 19 Mw 7.1 event (after IINGEN 2017)

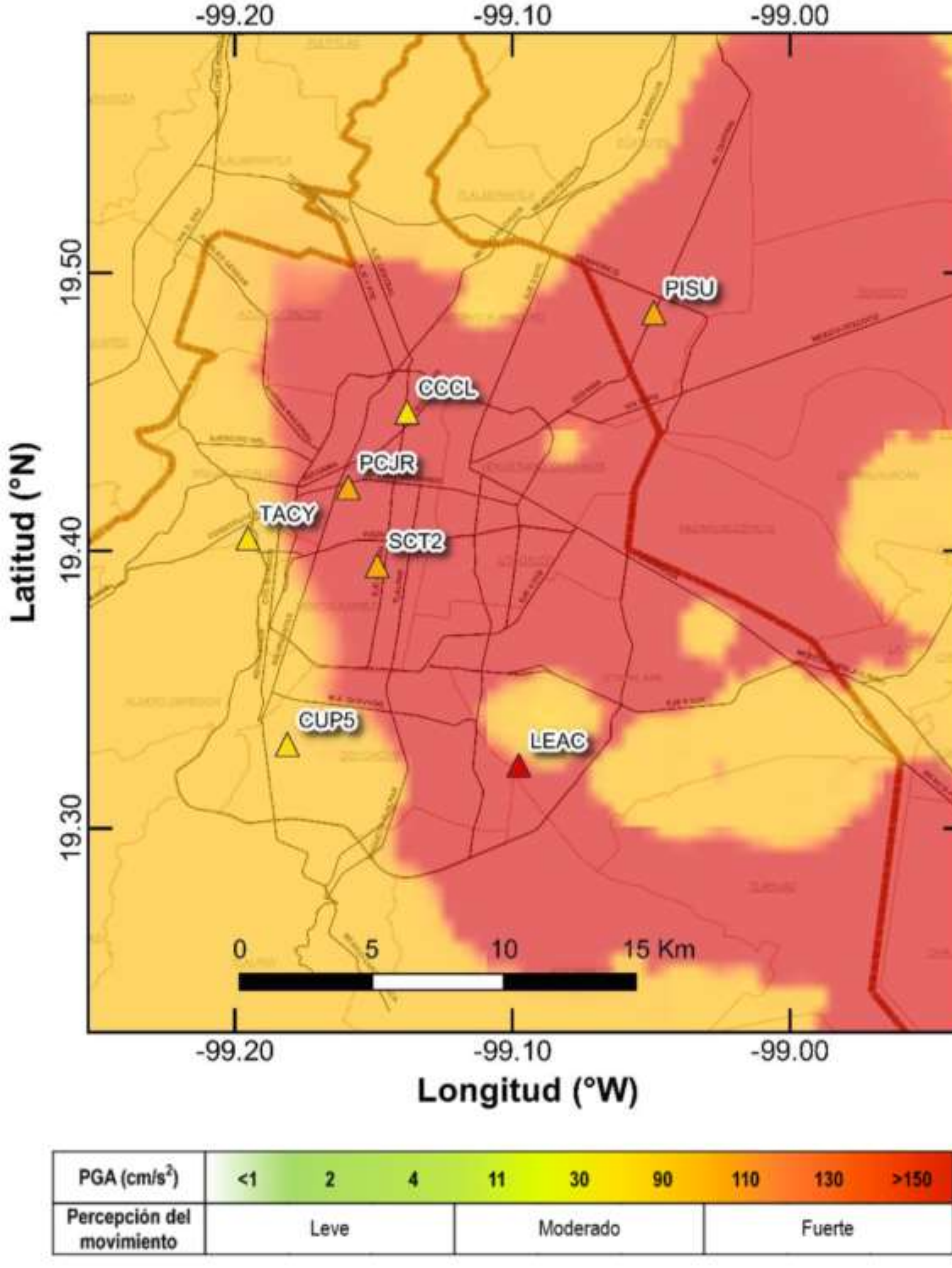

Figure 15. PGA (cm/sec^2) map of Mexico City from the September 19 Mw 7.1 event (after IINGEN 2017)

2. Site Response and Structural Damage

During the September 19th 2017 earthquake, most of the major structural damage in Mexico City was located in the west and southwest Transition (Zone II) and Lake zones, IIIa, and IIIb, as depicted in Figure 16. These zones exhibit 1D predominant periods ranging from 0.8 to 1.5 s according to the map by Arroyo et al. (2013), which accounts for the changes in predominant periods due to regional subsidence effects (Figure 17). This map is slightly different from that included in the Mexico City Seismic Design Code, NTCs. The UNAM-GEER team conducted H/V test at selected locations in the City. These 1D site response periods are expected to be slightly smaller than those reported in 2013, due to its continuous evolution over time. Figure 16 demonstrates that a majority of the notable structural damage is located within a 7 km by 20 km area adjacent to the boundary between Lake Zone (Zone III) sediments (in blue) and stiffer Transition Zone (Zone II) sediments (in yellow) on the western side of the city. The green boundaries in Figure 16 represent stiff/dense Hill Zone (Zone III) sediments and volcanic rocks. Based on the mapped damages and the field observations from the UNAM-GEER team, the neighborhoods of Mexico City that were most severely impacted by site response and structural damage/collapse from the September 19th event appeared to be Cuauhtemoc, Juarez, La Condesa, Roma, Hipodromo, Hipodromo Condesa, Roma Sur, Roma, Col del Valle NTE, Narvarte Poniente, and Col del Valle Centro.

Interestingly, Figure 12 in the previous section presents the surface ground motion response spectra measured during the September 19th, 1985 and the September 19th, 2017 earthquakes in firm Hill Zone soil. As can be noticed from comparing these spectra, the peak spectral response from the 2017 event for the horizontal components ranges from 0.23 to 0.27 g, and the predominant period varies from about 0.22 to 0.24 s. However, there remains a substantial amount of energy concentrated within periods ranging from 0.6 to 1.1 s, which led to ground motion amplification in the affected Transition and Lake Zone areas. Table 4 shows the corresponding predominant periods and amplification factors between a soft rock site (i.e. CUP5 seismological station), and the rest of the stations. This data shows that the maximum amplification factor occurs at the stations located within the Lake Zone IIIb.

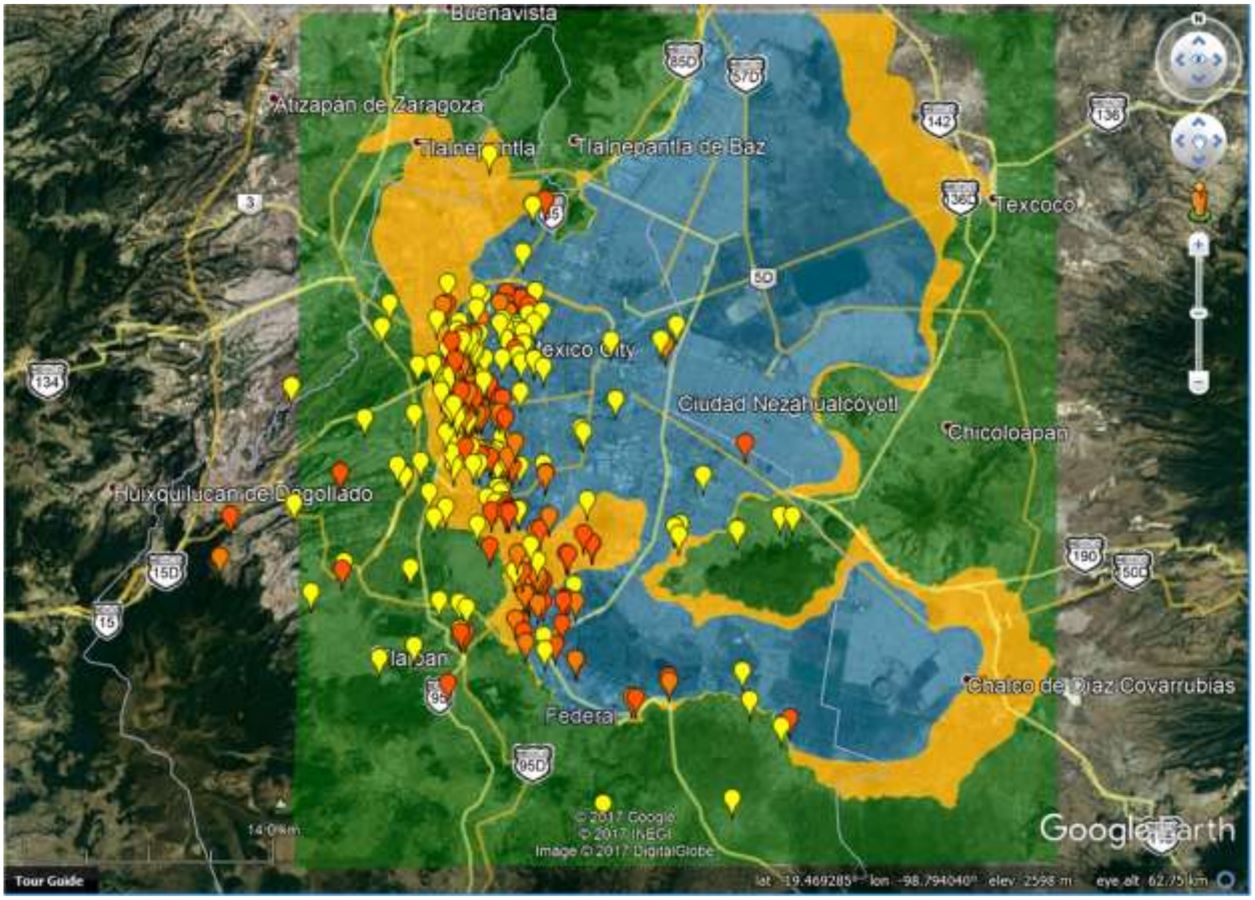

Figure 16. Mapped structural damage and collapse (Google Maps, 2017) combined with mapped soil zones for Mexico City. Green is stiff Zone I (Hill Zone), yellow is Zone II (Transition Zone), and blue is soft Zone III (Lake Zone). Red points indicate structural collapse, yellow and orange points indicate moderate and minor structural damage, respectively.

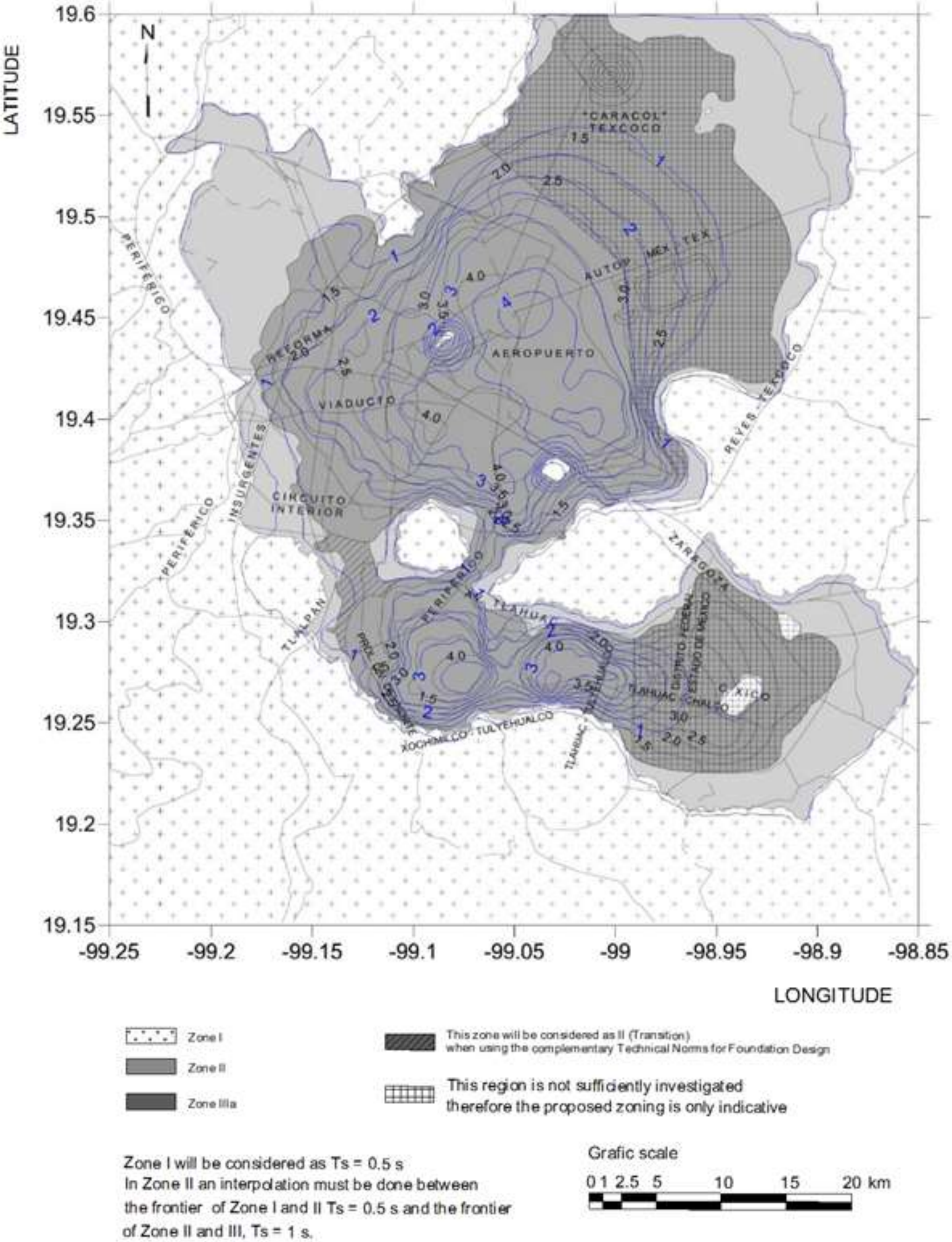

Figure 17. Map of predominant periods proposed by Arroyo et al. (2013) as a modification to the NTC

Table 4. Amplification ratios at seismological stations operated by II-UNAM

Zone RCDF-04	Station	Component Vertical	N-S	E-W
I	CUP5	1.00	1.00	1.00
I	TACY	1.02	1.06	1.06
IIIb	CCCL	1.21	1.55	1.25
IIIb	SCT2	1.23	1.63	1.56
IIIb	PCJR	1.57	1.71	1.68

The amplification of the earthquake ground motion at select periods in the lacustrine deposits below certain parts of Mexico City predominantly affected structures with similar natural frequencies. Table 5 shows the number of buildings severely damaged in each of the geo-seismic zones. The periods reported by Arroyo et al. (2013) in La Condesa and Roma Sur were verified in situ by the UNAM-GEER team at several locations (Figure 18 and Table 6). H/V ratios measured by the team in the east-west direction across La Condesa, Hipodromo, and Roma Sur using passive geophysical sensors indicate site periods generally ranging from about 0.73 s (in La Condesa) to 1.25 s (in Roma Sur) (Table 6). Site periods therefore increased as the Lake Zone sediments were approached going from west to east. Buildings that collapsed or that were heavily damaged in these areas generally ranged from about 5 to 8 stories in height (i.e. stiff buildings with periods of $T \cong 0.1N \cong 0.5 \rightarrow 0.8$ sec; or more flexible buildings $T \cong 0.2N \cong 1.0 \rightarrow 1.6$ sec). It must be noted, however, that the observed distribution of structural damage in Mexico City from the September 19th event cannot solely be attributed to 1-D site response. Other important factors such as age of the structure, structural design and symmetry, accrued and unrepaired damage from prior earthquake events, as well as quality of construction certainly contributed to the structural performance observed by the UNAM-GEER team; while the inhomogeneous concentration of damage in the west-southwest sections of the transition zone could be also suggestive of more complex, three-dimensional site effects such as basin edge focusing.

Table 5. Number of severely damaged building cases reported in each geo-seismic zone (Google Maps, 2017)

Zone	Number of buildings
I	13
II	35
IIIa	45
IIIb	49
IIIc	5
IIId	None

Figure 18. Layout of ambient noise measurements taken by the UNAM-GEER advance team (Test date: September 26 and 28, 2017).

Table 6. Data sheet of micro-vibration measurements, with GPS locations and fundamental periods

Point	Latitude	Longitude	Fundamental Frequency (Hz)	Fundamental Period (s)
F01	19.412576°	-99.183767°	1.37	0.73
F02	19.411324°	-99.179979°	1.15	0.87
F03	19.411359°	-99.178563°	1.14	0.88
F04	19.411388°	-99.177896°	1.13	0.88
F05	19.411389°	-99.177505°	1.07	0.93
F06	19.411391°	-99.176875°	1.05	0.95
F07	19.411408°	-99.175824°	1.10	0.91
F08	19.411432°	-99.175251°	1.00	1.00
F09	19.411445°	-99.174821°	0.99	1.01
F10	19.411449°	-99.174411°	1.11	0.90
F11	19.411457°	-99.172319°	0.84	1.19
F12	19.411468°	-99.171637°	0.86	1.16
F13	19.412673°	-99.170838°	0.86	1.16
F14	19.411486°	-99.170505°	0.86	1.16
F15	19.411314°	-99.169838°	0.90	1.11
F16	19.410172°	-99.166193°	0.80	1.25
F17	19.410897°	-99.164459°	0.82	1.22
F18	19.411118°	-99.163356°	0.83	1.21

As would be expected, unreinforced masonry and adobe construction in many of the towns throughout the state of Morelos suffered heavy damage. Numerous towns, particularly Jojutla and Tlaquiltenango, experienced a large number of collapses of these types of structures. Somewhat surprisingly, little significant structural damage was observed in the city of Puebla by the UNAM-GEER advance team. However, a more thorough investigation was performed by the main UNAM-GEER team in Puebla, and more structural damage was observed that will be documented in the Version 2 report.

3. Performance of Building Foundations

In general, the UNAM-GEER team observed three types of structural foundations commonly used in the affected areas of Mexico City: (1) end-bearing piles, (2) friction piles combined with mat foundations, and (3) shallow or excavated mat foundations with floating superstructure. The end-bearing pile foundations that were observed were either permanent and fixed (e.g. Figure 19), or incorporated adjustable controls (termed “control pile”, e.g. Figure 20) to mechanically lower the superstructure incrementally in an effort to level the structure with the ground surface, which is settling at an average rate of 10 cm per year due to groundwater extraction from beneath the city.

Figure 19. An end-bearing pile structure built in 1966 that experienced approximately 3 cm of settlement in the soil surrounding the structure; otherwise, the structural components of the building were generally undamaged. Note that the building entrance used to be level with the sidewalk, but is now 1.25 meters above the sidewalk elevation, due primarily to pre-event settlement (GPS: 19.4146, -99.1705)

Figure 20. End-bearing control piles supporting the La Plaza Condesa building (19.4132, -99.1721)

Performance of the different types of foundations was observed to be the worst in the affected western portions of Mexico City in the Transition Zone II soils and Lake Zone IIIb soils. End-bearing piles generally performed well, with occasional settlements ranging from 3 to 8 cm in the ground or hardscape surrounding the structure, as shown in Figure 19 (as shown on the stairs) and in Figure 21. The only tilt that was observed by the GEER advance team in an end-bearing pile structure was at the La Plaza Condesa (19.4129, -99.1722; see Figure 22), which is supported by controlled piles. While up to 1 degree of tilt was measured on the north side of the building, the team was not able to determine whether this tilt is due to the earthquake or to uneven maintenance/adjustments of the controlled pile foundations.

Figure 21. Settlement of approximately 15 cm in the soil surrounding an end-bearing pile-supported structure (19.4146, -99.1684)

Figure 22. The 12-story La Condesa building (19.4129, -99.1722), which was tilting approximately 1 degree to the north

Many structures founded on friction piles with mat foundations did not perform well in the earthquake. While little to no differential settlement between the structure and the surrounding soil was generally apparent because the structure tended to settle over time with the surrounding ground, there were observed cases of permanent structural tilt following the earthquake, as shown in Figure 23. This damage likely occurred as the rocking structure with its corresponding friction piles weakened the underlying lacustrine clays sufficiently to induce cyclic softening and reduced shear strengths beneath the structure and along the friction piles. As a result, piles on one side of the building were uplifted, and the mat foundation on the opposite side of the structure caused shear-induced deformation and bearing capacity failure in the underlying clay. While is it certainly possible that many of the damage that affected areas of Mexico City were caused by structural deformations following the 1985 and 2017 earthquakes, many of the tilted buildings that the UNAM-GEER advance team inspected in La Condesa showed no signs of structural distress (e.g., cracking, exposed rebar, spalling, etc.). The advance team did not address whether the observed damage was due to the 1985 or 2017 earthquakes; however, future efforts should do so to refine the observations that were gathered.

Figure 23. Permanent tilt of approximately 2 degrees in the friction pile-supported structure on the left; the structure on the right is vertical (19.4118, -99.1711)

Relatively few structures in the affected areas of western Mexico City appeared to be constructed on shallow mat foundations. Those that were confirmed as such were usually more than 70 years old and less than two stories in height. Among these structures and their foundations, the ones that were inspected by the advance team performed relatively well

4. Observed Ground Deformations

The advance team reconnaissance revealed few incidences of co-seismic ground deformation, most likely due to highly plastic lacustrine clays that are abundant in Mexico City. This observation does not include slope instabilities and landslides, which will be summarized in Section 7 below. As described in Section 3 above, the UNAM-GEER observed several occurrence of settlements on the order of 1 to 15 cm in the lacustrine clays of Mexico City. These settlements became apparent when the soil surrounding end-bearing pile-supported structures settled relative to the fixed structure, as demonstrated in Figure 24.

Figure 24. Settlement of the ground surrounding a pile-supported structure in La Condesa (19.4126, -99.1719)

Extensive ground deformation was observed by the UNAM-GEER team in the vicinity of Colonia del Mar, Tlahuac, near the southern rim of Mexico City. A series of cracks and trench-like depressions were observed throughout the neighborhood that rendered settlements as large as 50 cm, with widths ranging from 15 meters to 25 meters across. These bands of settlement extended over several city blocks, passing beneath structures and causing damage to several pipelines. Figure 25 shows a band of settlement passing beneath residences, causing many of the structures to tilt. The UNAM-GEER team originally postulated that these bands of settlement may have been caused by buried alluvial stream deposits with varying thickness that may have settled or moved laterally during the earthquake. However, subsequent investigation by team members revealed that numerous cracks from settlement-induced subsidence had been previously mapped throughout that portion of the city (CENEPRED, 2017). The mapped location of the cracks (Figure 26) corresponded well with our observed cracks in Colonia del Mar. While it is clear that the earthquake likely initiated additional settlement and lateral displacement along existing cracks, preliminary assessment suggests that new cracks may have developed. This assessment is currently being refined, and new findings will be reported in Version 2 of this report.

Figure 25. Images of ground cracking from subsidence in Colonia del Mar at: (top) 19.2839, -99.0571, and (bottom) 19.2846, -99.0578

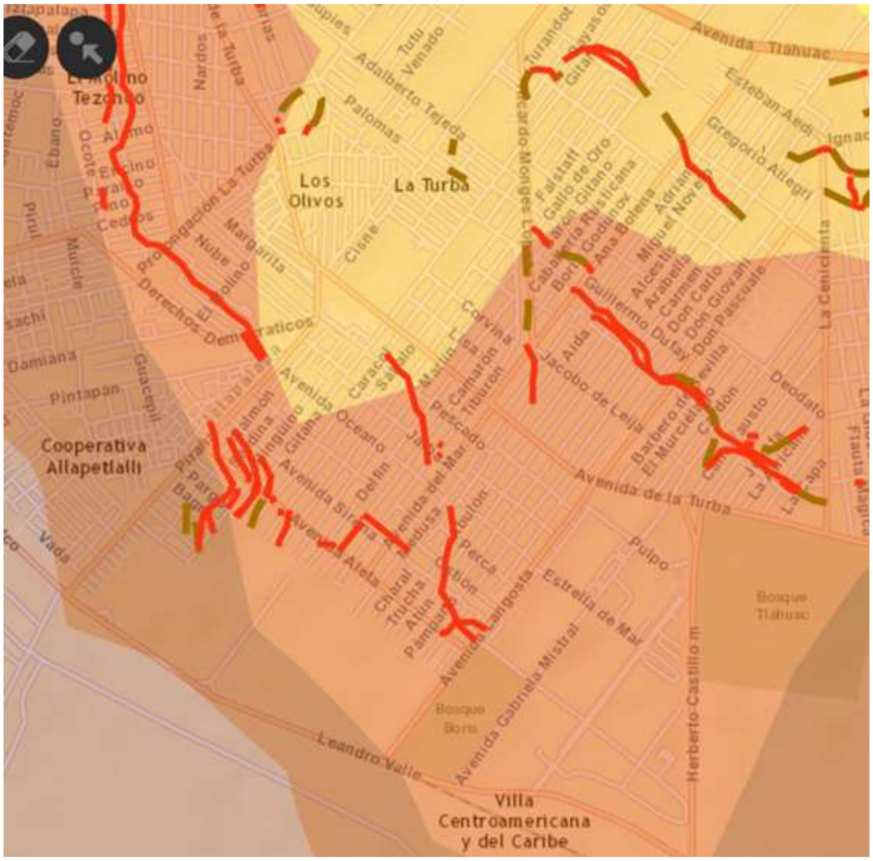

Figure 26. Mapped groundwater subsidence cracks in the Colonia del Mar neighborhood in Tlahuac (after CENAPRED, 2017)

5. Performance of Bridges

More than 70% of the bridges in Mexico were constructed before 1970 without any seismic design (Landa-Ruiz, 2008). Moreover, no bridge retrofit program has occurred since then to address this vulnerability. In contrast, most new bridges are designed using the American Association of State Highway and Transportation Officials (AASHTO) Bridge Design Specifications (BDS), which includes some seismic design criteria. However, they also have to comply with local codes such as the Normas Técnicas Complementarias para Diseño por Sismo (Complementary Technical Standards for Earthquake Design) (NTS), which is part of the Mexico City Building Code or with the CFE (Civil Engineering) Seismic Design Manual.

Bridges performed very well during the September 19th 2017 earthquake. Only a few cases of damage and collapse were reported. No extensive information is available about the bridge's shear and displacement capacities, and only a few cases of damage associated with seat displacement were observed (e.g., Metro Viaduct in CDMX). Many bridges with short superstructure seats were identified, yet no movement during the earthquake (Figure 27 and 28) was observed. Photographs of bridges at sites investigated by the UNAM-GEER team and by Prof. Eduardo Miranda are shown below.

Figure 27. Left: Two span Pedestrian OC across 95D in Coajomulco (19.0323, -99.2057), Right: 3 Span OC across 438D in Santiago Atzitz Huacan (18.8268, -98.6038).

Figure 28. Two bridges in Cuautla, assessed on September 27th 2017, no visible sign of damage across both structures, left: Carlos Pacheco Bridge (18.8091, -98.9490), right: Solidaridad Bridge (18.8106, -98.9473).

Despite the overall good bridge performance that was observed, some bridge damage and even bridge collapse did occur. A pedestrian overcrossing in Mexico City collapsed during the earthquake, unfortunately falling onto a taxi (Figure 29). In the town of Puente de Ixtla the GEER team drove past a collapsed bridge (18.6122, 99.3182), but were unable to stop. The main UNAM-GEER team was able to collect more information regarding this bridge, which will be presented in the Version 2 report.

Figure 29. Left: Collapsed POC across Blvd. Adolfo Ruiz Cortines (19.2913, -99.1105), Right: POC (taken from Google Earth) shown before the earthquake (19.2913, -99.1105).

Other bridges like the Metro Viaduct (see Appendix) were damaged but did not collapse due to the light shaking. Collaborator Prof. Miranda of Stanford shared some photos of the Circuito Interior Avenida Rio Churubusco (19.3696, -99.12248) in Mexico City. These parallel box girder viaducts on pier walls rocked during the earthquake (the pier walls were too stiff to bend) and a masonry abutment was damaged (Figure 30). More information regarding this and other bridge inspections conducted by the UNAM-GEER Main team will be included in Version 2.

Figure 30. Damage to the Circuito Interior Avenida Rio Churubusco (19.2913, -99.1105).

6. Performance of Dams

No damage was reported at dams in the Puebla-Mexico City vicinity following the September 19th 2017 earthquake. A dam, located in the epicentral region, was visited for potential damage observations. The Manuel Ávila Camacho (Valsequillo) Dam, built in 1946, is located at 18.9123 N -98.1084 W (see Figure 31) and is a 3,900 m long and 23 m high rockfill dam. The dam has created the largest reservoir in the State of Puebla (with a surface area of 740,000 acres). The dam site is located approximately 49 km northeast from the epicenter. The dam site was visited on September 28th, and was at full capacity with excess water running through the spillway during the visit. The crest and both upstream and downstream slopes of the dam did not show any signs of distress or longitudinal or transverse cracks, as shown in Figure 32. No permanent displacements or deformations were observed either. At the toe of the downstream slope no cracks or impounded water were noticed. The spillway structure did not show any apparent damage and was properly working releasing water during the visit. It seems that during the earthquake the dam was also at full capacity. Overall the seismic performance of the dam was satisfactory.

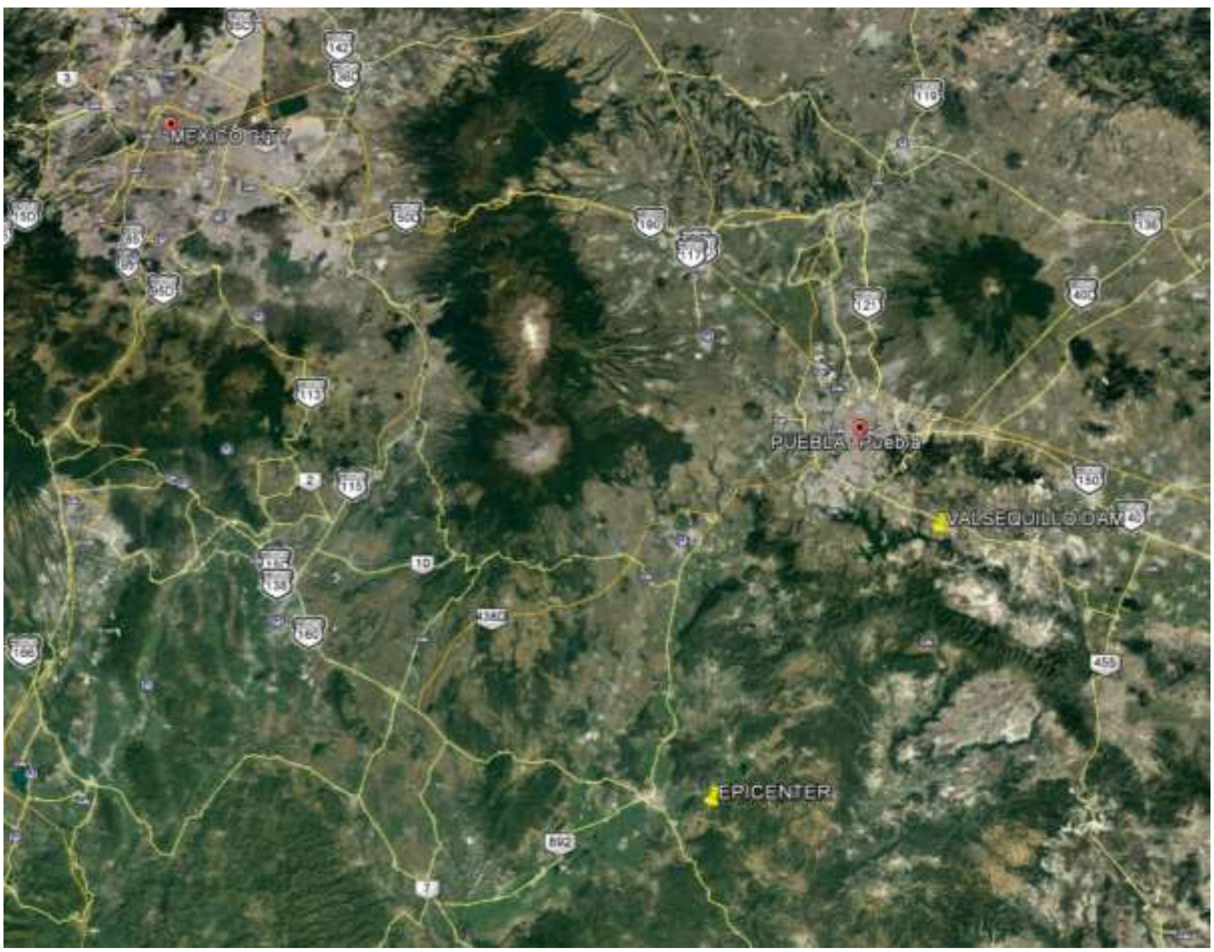

Figure 31. Location of the Valsequillo Dam with respect to Epicenter, Puebla and Mexico City

Figure 32. Downstream side of the Valsequillo Dam (18.9123, -98.1084)

7. Observations of Slope Instability

Relatively moderate slope stability problems were observed within the city boundaries of Mexico City. The UNAM-GEER advance team investigated one site located near Xochimilco and several more outside Mexico City. The Xochimilco slope instability (Figure 33) was of concern as ongoing deformation due to groundwater pumping and increasing ground earthquake-induced deformation indicated concurrent slide movement. The site is fully inhabited with residential construction. In addition, the district's water pumping station is located at the bottom of the slope.

More frequent slope instability cases were observed in the rural regions of the state of Morelos. Noticeable case studies include the Tlayacapan rockslide, the Totolapan landslide, the Atlatlahucan landslide series, and the Lake Tequesquitengo bank failure (Figure 34). Locations and details regarding each of these are provided in the Appendix. Some of the slope instabilities were expected given previous movements and slide activities at the respective location. Ongoing rain storms in the region during the visit made both the Totolapan and Atlatlahucan landslides of further interest given preliminary observations of additional extension cracks at the top plateau of each slide. Both landslides appear to consist of clayey and residual soils and volcanic deposits. The Atllatlahucan and Totolapan site seemed to be an old quarry with occasional mining activity according to google earth imagery. Limited slope instabilities were reported near the epicenter (e.g., Mount La Malinche slide), which caused no visible damage.

Figure 33. Photo of unstable hill site Xochimilco, red lines indicated documented cracking

Figure 34. Totolapan debris slide in old quarry (top left; 18.9816, -98.9246), Tlayacapan debris (rock) flow (top right; 18.9486, -98.9837), and Atlatlahucan landslide region (18.9378, -98.8784)

8. Observations at Sites of Social and Cultural Interest

Significant damage was observed in historic church buildings throughout the entire regions visited by the UNAM-GEER team. Many churches lost bell towers, showed cracked facades, severe interior damage, roof (and/or dome) collapse and were closed for further inspection. World Heritage buildings, such as the Cuernavaca Cathedral in the state of Morelos, suffered moderate structural damage, while other churches in the southern region of Morelos suffered significant damage and will require significant repair or demolition. Municipal buildings with similar architectural features (e.g. free-standing facades with towers, etc.) showed similar damage patterns. Many historical buildings were adobe construction, with limited to no reinforcing elements. Figures 35 through 38 show several examples of damage to churches and municipal buildings observed by the team.

Figure 35. Severe damage at the historical municipality building in Tlayacapan, a 2 story unreinforced masonry building (18.9565, -98.9832)

Figure 36. Damage at the historical Tlayacapan Church (complete closure) (18.9561, -98.9821)

Figure 37. Left: Collapsed Church tower in Cuautla (18.8125, -98.9542), right: Crack on bell tower of church in Juitepec (19.0285, -99.2675)

Figure 38. Left: Severe cracking of the Tlaquiltenango church (18.6296; -99.1607), Right: damage to municipality building and entire historic downtown district of Cuautla (18.8122, -98.9553)

Investigation of the culturally important historical structures in the historical portion of Mexico City revealed little to no damage from the 2017 event. Google Maps (2017) identified damaged historical structures were all unreinforced masonry structures such as that shown in Figure 39, many of which had allegedly remained abandoned since the 1985 earthquake. While many of the historical masonry structures in this part of Mexico City showed significant tilting and evidence of differential settlement, as is presented in Figure 40, local residents and employees confirmed that the structures were already in that condition prior to the earthquake.

Figure 39. Unreinforced masonry structure that collapsed from the 2017 event in the historical district of Mexico City (19.4388, -99.1413), and San Gregorio Church with collapsed bell tower (19.2535, -99.0568)

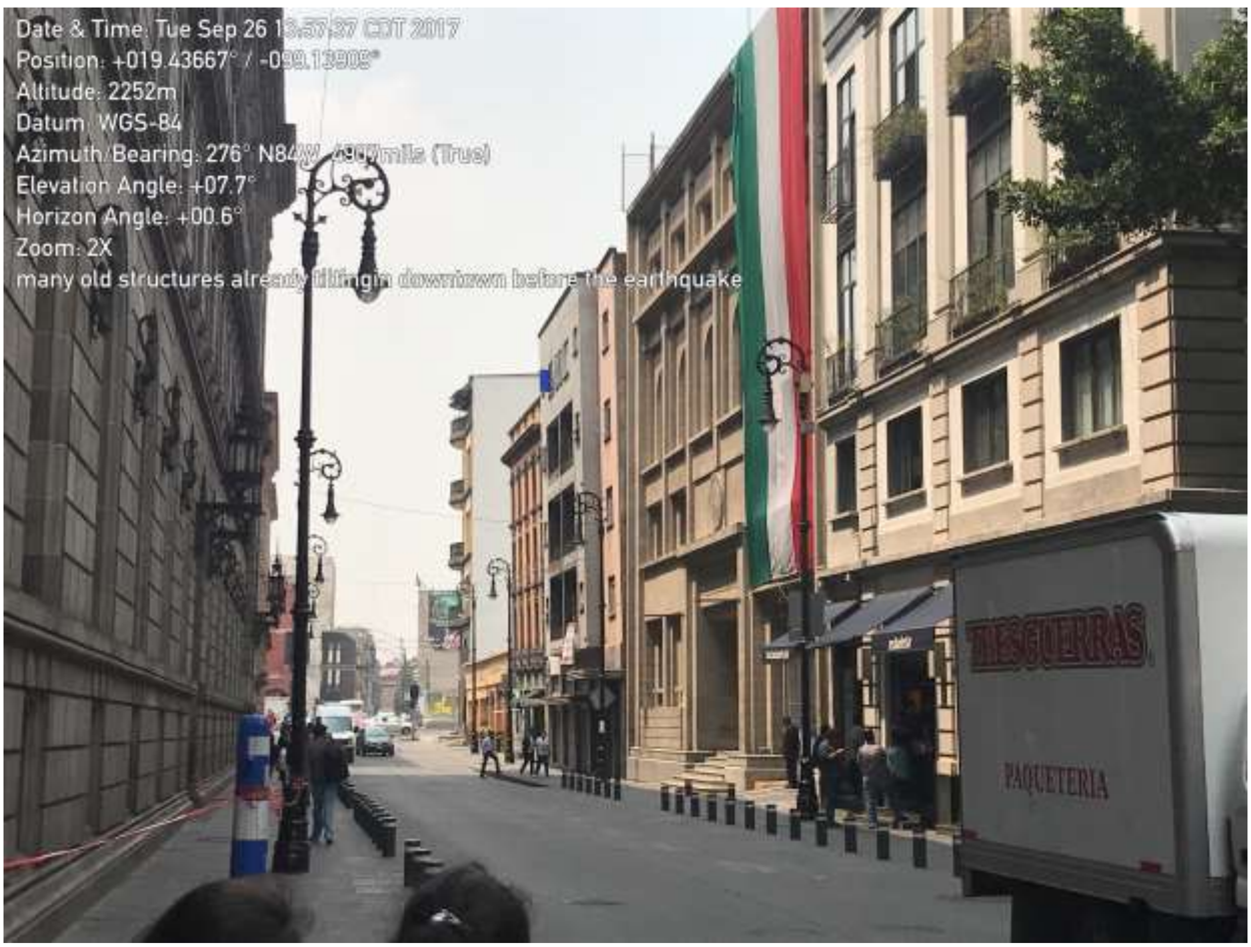

Figure 40. Common example of the type of structural tilting that is prevalent in the historic district in Mexico City; local residents confirm that these structures were already tilting prior to the 2017 event

The UNAM-GEER advance team was specifically requested to investigate the performance of the New Aeropuerto Internacional de Ciudad de México (NAICM) construction site. This multi-billion dollar project is located in the northeastern portion of Mexico City on top of very soft and deep Texcoco Lake clays. Figure 41 shows an approximate site vicinity map of the NAICM site and its relative location to Mexico City.

At the time of the UNAM-GEER team site visit at NAICM, the reinforced concrete slab for the main terminal was being constructed (Figure 42). This area is only illustrative, the actual size of the NAICM site is much larger than the one shown in Figure 42. The slab consists of 1.6 meter thick concrete heavily reinforced with #12 high strength steel rebar. The slab had already settled 8 cm at its center, causing it to pond water from the rain the night before the team visit (see the visible water on the slab in Figure 42). According to the designer ARUP, the terminal building raft is built in 20x20m segments. Each of the segments suffers an undrained settlement of about 60 to 80mm at its center and 30-40mm at the edges. The first segment of the raft was built where the crane is, which is actually a bit higher that the areas where water is ponded. According to current surveys there is a maximum differential elevation of about 100mm between the highest and the lowest point of the 30,000m^2 of raft already built. Full area of the terminal building raft is about 320,000m^2. We observed that many of the piles located around the perimeter of the site were bent out of plum, as shown in Figure 43. The site foreman informed us that these piles were out already tilted before the earthquake, but the earthquake made them worse.

Figure 41. Site vicinity map showing the approximate location of the NAICM airport project in white

Figure 42. UAV image of the NAICM terminal construction site at the time of the UNAM-GEER team site visit (19.5052, -98.9967)

Figure 43. Tilted driven pile near the perimeter of the excavation for the NAICM terminal construction

Flights with the UAV around the perimeter of the 5 m deep excavation showed numerous small tension cracks forming in places. Many of these cracks had apparently been in place before the September 19th 2017 earthquake, but the earthquake widened existing cracks and also precipitated new cracks. An example of these observed cracks are shown in Figure 44.

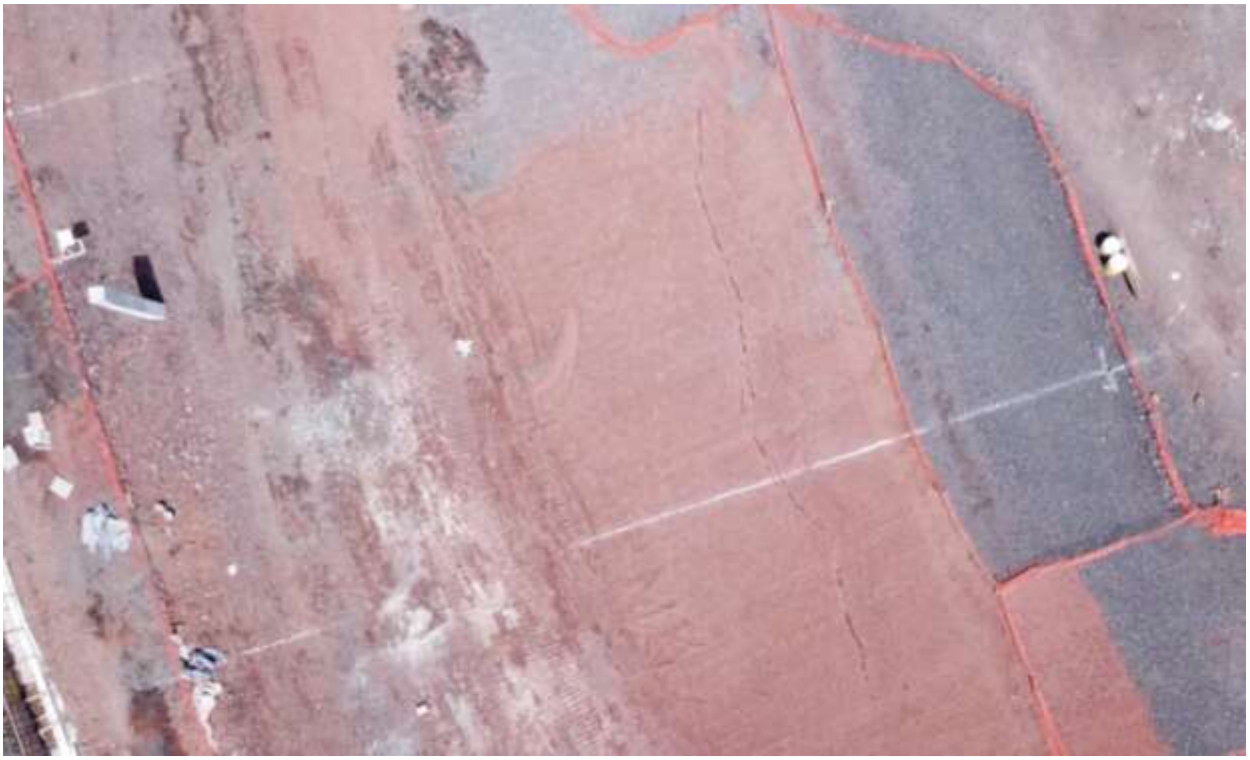

Figure 44. Tension crack observed in the NAICM excavation from a UAV flown at an altitude of 50 meters; driven pile is visible towards the left of the image (19.5050, -98.9957)

The final part of the NAICM construction project that was visited by the UNAM-GEER advance team was the construction site for the new control tower. At the time of the team visit, the foundation was under construction, and no superstructure was yet in place. The foundation design consisted of 480 friction piles connected to 1m thick circular raft foundation. The system will eventually support the base-isolated control tower for the NAICM. An aerial image of the control foundation tower being constructed is presented in Figure 45.

Figure 45. UAV image of the construction of the new control tower foundation at NAICM (19.5223, -98.9971)

Summary

The September 19th, 2017 Mw 7.1 intraslab subduction zone earthquake that impacted the regions of Mexico City, Puebla, and Morelos caused significant damage to many structures between 5 and 8 stories in height and collapse of over 40 buildings. Unfortunately, it resulted in the loss of more than 350 lives and significantly affected three states. Most of the damage to modern infrastructure is concentrated near the mapped boundary of the Transition Zone sediments (Zone II) and the Lake Zone sediments (Zone IIIb) along the western portion of Mexico City. Ground motions appeared to be amplified between periods of 1 and 2 seconds based on ground motion recordings near the Transition Zone boundary. Settlements of 1 to 15 cm were observed in the clayey soils surrounding many deep-founded structures. With a few exceptions, little damage was observed within the bridge infrastructure, though some individual cases of damage ranging from slight to collapse were observed by the UNAM-GEER team. No significant damage of dams was observed by the UNAM-GEER team. Several instances of slope instability were observed near the southern rim of Mexico City and to the south in the state of Morelos.

This report is intended to provide a concise and brief summary of the observations, findings, and recommendations of the UNAM-GEER advance team. More detailed information will be presented in the Version 2 report that is forthcoming.

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Appendix: Recommended Sites for Additional Study

This section incorporates 17 sites/activities that the advance team recommended for additional study by the UNAM-GEER main team. These sites had geotechnical, structural or geo-structural features worth examining with UAV and/or LiDAR survey methods, seismic testing, and/or additional structural inspections.

A1. Mexico City - Zone 1

Zone 1 in Mexico City was delineated as is shown in Figure A1 below, and included the heavily damaged neighborhoods of La Condesa, Hipódromo, and La Roma. The zone also includes historic downtown Mexico City, in which relatively little damage was reported at the time of the advance reconnaissance. A few of the most interesting potential case histories are briefly described below.

Figure A1. Delineation of Zone 1 for the UNAM-GEER advance reconnaissance mission

A1.1. Site 1: La Condesa, Hipódromo, and Roma Structural and Site Period Assessment (approximately 19.4130, -99.1710)

Description of Buildings: Based on a rapid assessment by UNAM-GEER team personnel in the city blocks located between La Parque de Mexico and La Parque Espana (see Figure A2), numerous building and foundation types were observed, as well as a wide range of building performance. Structures generally ranged from two to 12 stories in height. Observed foundations included end-bearing piles (both fixed and controlled), friction piles with mat slabs, and floating mat slabs.

Description of Damage: Damage ranged from minor cracking in the exterior masonry to total collapse. Several multi-story buildings were tilting between one to three degrees, and numerous buildings were observed to be resting on the adjacent building. Several gas line breaks were reported in the area, but the gas supply had apparently been shut off to the affected area prior to our team's arrival.

Description of Response: Numerous streets were closed off to the public and were under police and/or military guard. All of the structures in the investigated vicinity had been evacuated. Various teams of engineers were working to identify and classify damage states at the various structures.

Data obtained: Area was assessed via drone flight. Detailed video images of two collapsed structures was obtained, as was overhead images of the entire highlighted area in Figure A2. Site response measurements (i.e., H/V ratios) were taken across the affected area along Avenida Michoacan and Avenida Coahuila. Measured site periods ranged from 0.73 to 1.25 seconds, and generally increased as the team progressed to the east towards the mapped Lake Zone III deposits.

Follow up/Interest: This area in many ways comprises the heart of the structural damage from this earthquake. More structures were damaged in these neighborhoods than in any other neighborhood in Mexico City. Additionally, two CIRES ground motion stations are located very near this area (see Figure A2). The team could not access these ground motion stations because they are located inside schools, and were under military guard at the time of advance reconnaissance. However, it is known that significant structural damage occurred in the vicinity of both of these ground motions stations. It would be interesting for future researchers to carefully classify the structural and foundation performance in this area of the city, and compare that performance against the CIRES recorded ground motions once they become available. It would also be interesting to perform north-south and east-west lines of Vs and site period measurements across this area, and use that information to see if our current site response analysis methods can match the observed ground motion response in this area. In particular, the city blocks to the north of the UAV flight zone, just west of the ground motion station C105, would be very interesting to study further. Note that Google Maps (2017) currently shows few of the damaged structures that were observed by the UNAM-GEER team in this area. However, the map continues to include more damaged and collapsed buildings each day.

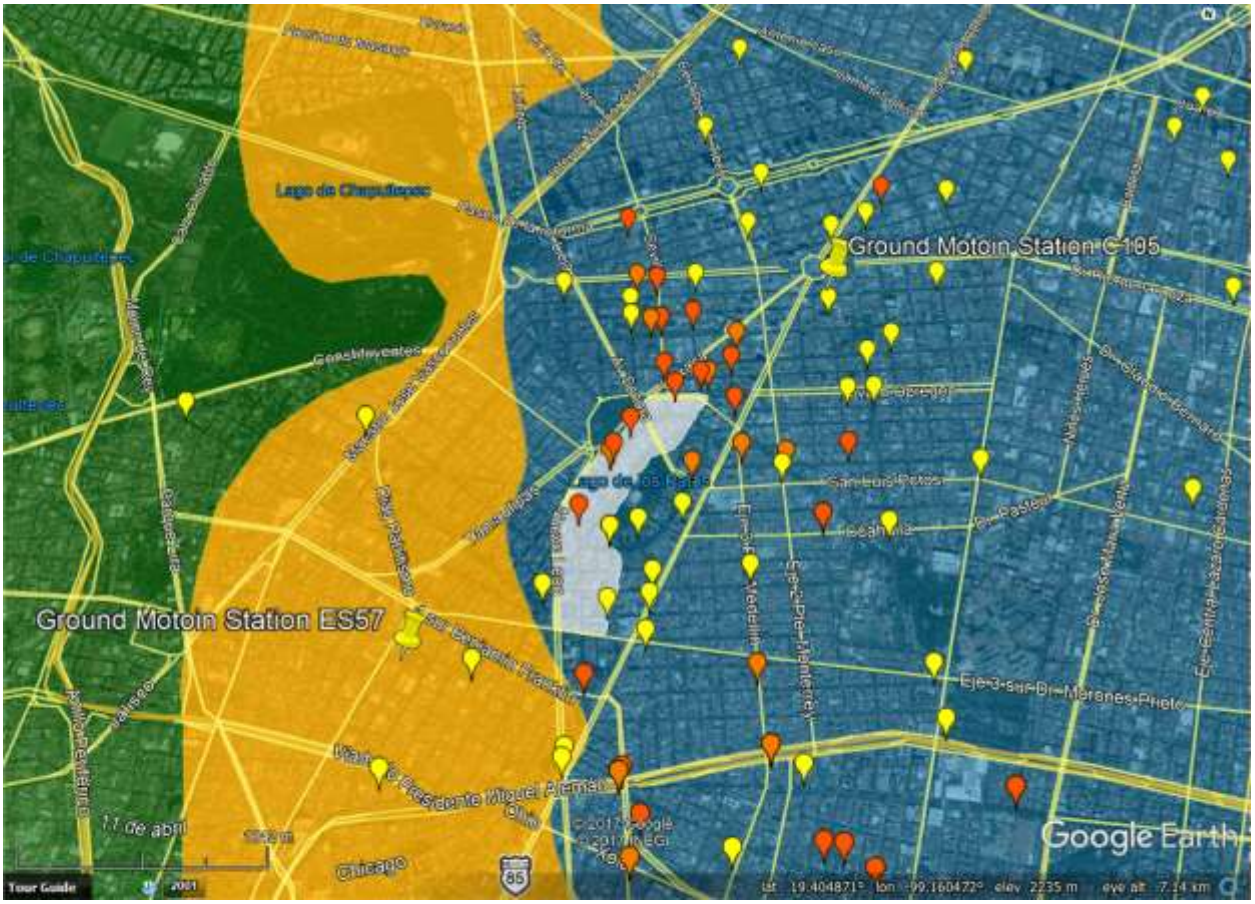

Figure A2. Delineated zone of preliminary UAV flight in La Condesa and Hipódromo; note the relatively high number of collapsed and damaged structures from Google Maps (2017) to the north of the preliminary UAV flight area, as well as the CIRES ground motion station C105

A1.2. Site 2: La Plaza Condesa Structural and Foundation Performance (19.4129 N 99.1722 W)

The Plaza Condesa building described in Section 3. Performance of Building Foundations is a particularly interesting structure for future studies because of its significance

Description of Building: The Plaza Condesa building is described in Section 3. Performance of Building Foundations is a particularly interesting structure for future study because of its significance to the community, its adequate performance in an area where other surrounding structures were heavily damaged, it's confirmed use of controlled end-bearing piles, and its unique U-shaped design.

Description of Damage: Some settlement of the ground around the structure. Up to 10 cm of settlement of the ground was observed along the east side of the building (see Figure 25 of the report). A slight tilt of less than 1 degree to the north was observed in the La Plaza Condesa building, but it is not clear if this tilt occurred because of the earthquake or uneven leveling/maintenance of the controlled pile foundation. The building was occupied and in use at the time of the UNAM-GEER advance reconnaissance.

Description of Response: No response was occurring at the building. The building owner talked with the UNAM-GEER team and allowed us to investigate and photograph the controlled pile foundation of the structure. However, our investigation was limited due to the advance team's mission objective to rapidly collect preliminary information of interest.

Data obtained: Aerial images of the structure were captured with UAV. Photographs were captured of the controlled pile foundations supporting portions of the structure. The Theodolite app was used to optically measure the structural tilt of approximately 1 degree to the north.

Follow up/Interest: It would be interesting to study why the structural response of La Plaza Condesa was so favorable, particularly when the U-shaped structure likely should have contributed to significant structural torsion during the earthquake. Also, many Mexican engineers communicated to the team that controlled pile foundations gained a poor reputation following the 1985 Michoacan earthquake. However, the performance of the foundation system in this earthquake seemed quite good based on our preliminary assessment.

A2. Mexico City - Zone 2

Zone 2 (see Figure below) was characterized by numerous moderate and small cases of structural damage. Several buildings that reported damage during the 1985 earthquake were visited. Most retrofitted buildings performed well, several buildings showed cracking along exterior walls, and internal masonry walls. Not all buildings were accessible, a few of the most interesting cases are described below:

Figure A3. Delineation of Zone 2 for the UNAM-GEER advance reconnaissance mission

A2.1. Site 1: Escocia 4, De Valle (19.3877, -99.1637)

This site is located at the intersection of Escocio and Calle Gabriel Mancera. Two buildings experienced complete collapse, and are currently being demolished.

Description of Building: Based on google earth pre-earthquake photos, the collapsed corner building was a 7-story residential structure, likely confined masonry construction

Description of Damage: Total Collapse

Description of Response: Building and surrounding streets were completely closed off, search of survivors and fatalities ongoing, manual demolition of all building components by hand through volunteers

Follow up/Interest: Immediately adjacent to the collapsed building were 2 structures that experienced severe damage, but no collapse. Buildings were evacuated but area was not accessible at the time for further investigation. Of interest are the different site conditions, foundation types, structural lateral force resisting system.

Data obtained: Area was assessed via drone flight. Site response measurements (i.e., H/V ratios) were taken nearby. A site period of 0.87 seconds was measured.

Figure A4. Before (left) and after (right) shots of the Escocia 4 Building (19.3877, -99.1637)

Figure A5. The Building across Escocia 4 (i.e., Escocia 14) also seemed to have collapsed, but was not listed as one of the damaged/collapsed buildings in the initial list (19.3877, -99.1637)

A2.2. Site 2: Enrique Rebsamen and La Morena (19.3984, -99.1587)

This site also consisted of a group of buildings that showed significantly different behavior. One building experienced severe damage (corner building), one building showed only sign of small damage, and one building experienced total collapse. The response of each individual structure might be related to the foundation type (unknown), age and structural system. A smaller structure adjacent to the green (collapsed) building was also majorly damaged and demolished. Overview Photos:

Figure A6. UAV photographs of the Escocia/La Morena intersection with 4 buildings of interest (19.3984, -99.1587)

1. Corner Building at Enrique Rebsamen 249 and La Morena (19.3987, -99.1589)

Description of Building: 8 story residential structure, ground floor seemed to be constructed as a reinforced concrete system.

Description of Damage: Major damage/collapse of the concrete elements (shear walls and columns) at the ground floor. Lack of transverse reinforcement, and/or rebar spacing beyond allowable spacing limits. Building currently stabilized with temporary wood columns. Building showed strong tilt.

Follow up /Interest: Around the corner of this site (i.e., at Calle J Enrique and La Morena) a similar building as the corner building experienced very modest damage but seemed to have a similar configuration.

Description of Response: All Buildings were evacuated; the entire area is closed off to the public.

Figure A7. Top: Before and after shots of the corner building (19.3987, -99.1588), Middle and Bottom: Damage observed at the ground level

2. Enrique Rebsamen 241 (19.3990, -99.1588), Narvarte Poniente, 03020 Ciudad de México, CDMX, Mexico

This building, which was located extremely close to the above mentioned structure experienced a total collapse and was being demolished at the time of our visit.

Description of Building: Based on google earth pre-earthquake photos, the collapsed building (#241) was a 5 story residential structure. This building was reported to have been damaged before the earthquake, and residents repeatedly requested inspection. There is a potential lawsuit going on with respect to this building collapse.

Description of Damage: First floor (soft story) collapse led to completed building collapse. Building might have rocked during the EQ, significant impact damage (pounding) is visible at the adjacent building (the center building that did not show any damage)

Description of Response: Building and surrounding streets were completely closed off, the collapsed building was currently being demolished

Follow up/Interest: Between the two damaged/collapsed structure there was one structure with no damage. Structural configurations are of interest.

Data obtained: Area was assessed via drone and on-site photography. Site response measurements (i.e., H/V ratios) were taken nearby.

Figure A8. Enrique Rebsamen #241 photographs during site visit; top left: google pre-earthquake shot, remaining photos: frontal shots taken on site of damaged structure (19.3990, -99.1588)

3. Intersection of La Morena and Calle J. Enrique Pestalozzi (19.3986, -99.1581)

This building was located just one short block away from the above described structures. The corner building seemed similar in construction as the Enrique Rebsamen 249 building, but showed only modest damage compared to the building above.

Description of Building: 8 story residential structure

Description of Damage: Moderate damage, cracks in wall elements, pounding damage between this structure and the adjacent structure over the height of the first 3 stories.

Description of Response: Building and surrounding streets were completely closed off, building was evacuated

Follow up/Interest: Even though damage was observed in this structure and the nearby structures described above, almost no structural damage was observed in any of the nearby 5-6 story buildings along La Morena street.

Data obtained: Area was assessed via drone/ and on-site photography. Site response measurements (i.e., H/V ratios) were taken nearby.

Figure A9. Moderate damage at 8 story residential structure (19.3986, -99.1581)

A3. Mexico City - Zone 3

Significant damage and extensive collapse was reported in CDMX Zone 3. This zone included the neighborhoods of Campestre Churubusco, Pueblo Culhuacan, Los Reyes, STA. Ursula Coapa, and Huipulco. This zone is located in the lake-bed zone (see Figure 17).

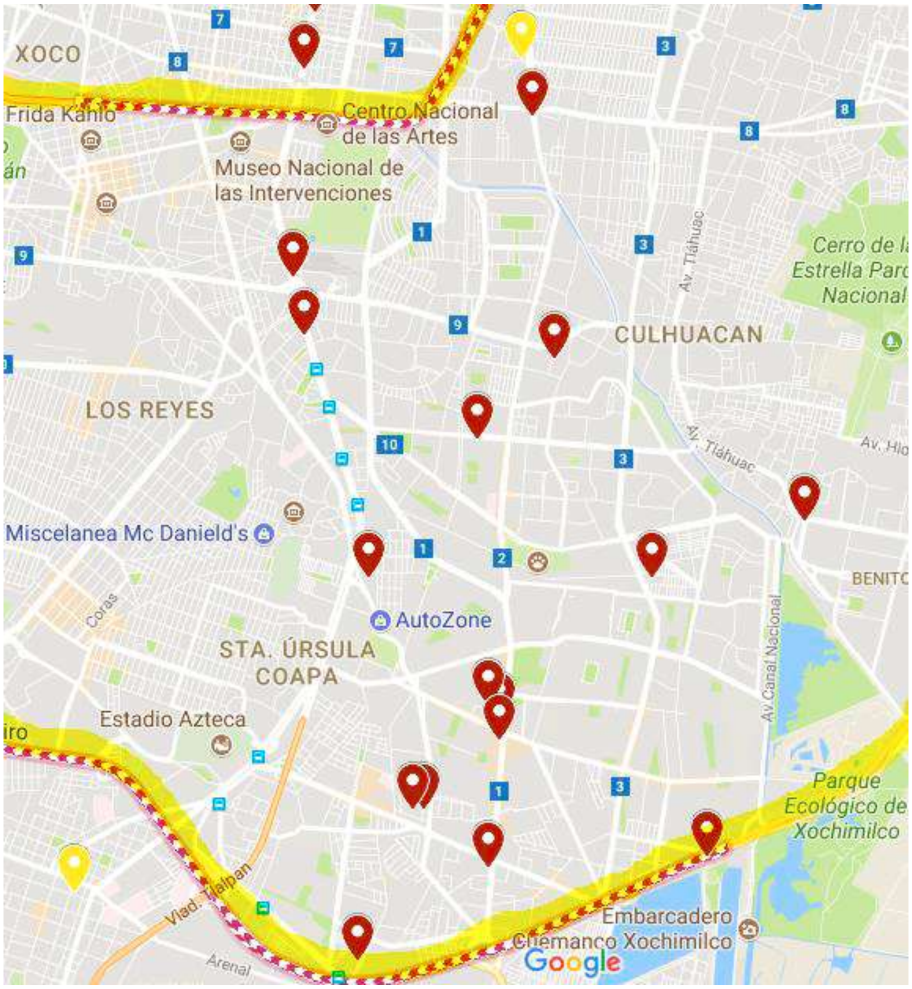

Figure A10. Delineation of Zone 3 for the UNAM-GEER advance reconnaissance mission

A3.1 Site 1: Gallerias Coapa (19.3030, -99.1225)

Description of Structure: Two story reinforced concrete structures on piles.

Description of Damage: Brick facing cracked and spalled and ground settled above stairs (due to underground parking structure?)

Description of Response: Buildings were closed until repairs could be made.

Follow Up: Find out why this ground settlement occurred.

Figure A11. Stairway drop in front of Gallerias Coapa (19.3030, -99.1225)

A3.2. Site 2: Multifamiliar Tlalpan Site (19.3383, -99.1421)

Description of Structure: This is a low-income housing project along Calz De Tlalpan that was built in 1966. All the buildings are five story reinforced concrete structures with a brick façade. The foundation type of the buildings is unknown.

Description of Damage: Of particular interest was a collapsed building which was oriented east to west. The building was narrow but seemed to collapse in the stiffer direction. The first story didn't collapse but continued to support the collapsed second to fifth floors.

Description of Response: Search and Rescue teams were still actively searching for casualties a week after the earthquake. Rescue teams were carefully pounding on the slabs in preparation for removing each floor.

Follow Up/ Interests: The site is unique as only this specific structure collapsed, while all other structures (that seemed to be oriented north-south) remained intact. Of interest are the building plans, structural configuration, the effect of the building geometry. Of further interest are soil conditions and effects of directionality.

Figure A12. Photograph (left) and Location (right) of collapsed residential structure in Multifamilia Tlaplan (19.3383, -99.1421)

A4. Mexico City - Zone 4

Zone 4 in southern Mexico City consisted of the Xochimilco, Tlahuac and Colonia del Mar neighborhoods. Significant damage was observed in this zone, with an unstable embankment, damaged churches, and collapsed of 1 and 2 story houses in Xochimilco, and an intricate network of cracks and depression bands in Tlahuac and Colonia del Mar. As described in the executive summary, the soils in this zone consist of lacustrine clays which are somewhat stiffer than the clays found in zones 1, 2 and 3.

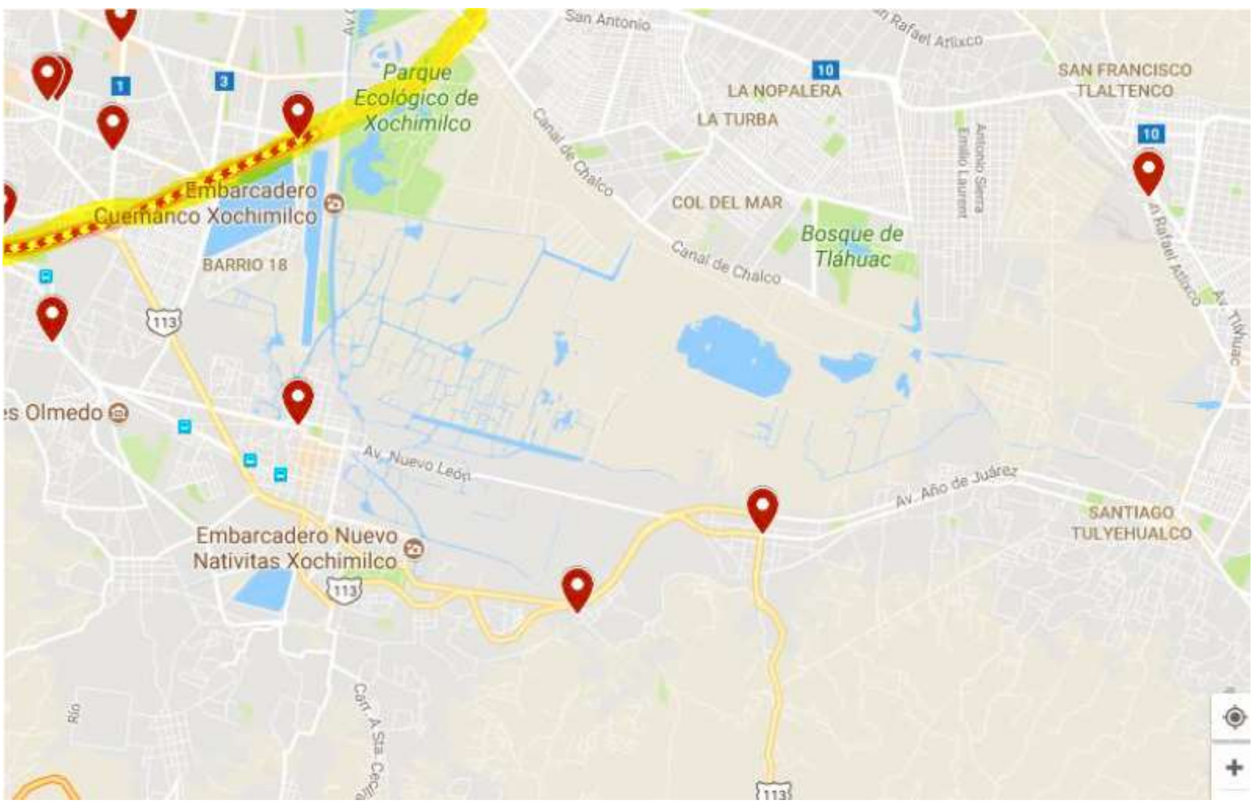

Figure A13. Delineation of Zone 4 for the UNAM-GEER advance reconnaissance mission

A4.1. Site 1: Xochimilco Slope Instability (19.2467; -99.0872)

Description of Site: A large slope (suspected to be a fill slope) directly above several residential structures, a local market and one of the major pump stations for CDMX. Local residents reported ongoing slope displacements both before and following the earthquake. The retaining wall supporting the embankment was built in 1906; the preexisting slope instability is most likely due to water pumping that causes subsidence of terrain around extraction station.

Description of Damage: Approximately 450 m of intermittent surface cracks indicating slope failures on lower step above market, and 50 m of cracks along upper step. infill slope with the failure occurring along the interface between natural soil and the fill used to create the road paths.

Description of Response: The road (see photo below) was closed to cars, residents were not evacuated. No traffic access on the cracked road was permitted.

Follow up: UAV or Lidar flight, along with measurements of crack widths and other displacement indicators might be of interest.

Figure A14. Aerial view of the slope instability with cracks marked along the road

Figure A15. Surface cracks along lower step above market(left: 19.2469; -99.0895), (right: 19.2467; -99.0872)

Figure A16. Crack along the street (left) and cracks on retaining wall holding upper step (right), (19.2470, -99.0875)

A4.2. Site 2: Colonia Del Mar Cracks and Settlement, Tlahuac

Description of Site: Two interesting failure features were apparent in the Colonia del Mar neighborhood. One set of failures is comprised of a series of pipeline cracks, and another one consisting of a series of curving surface cracks with terrain settlement that crossed several city blocks. While the pipeline failure was an earthquake induced failure, the general settlement and subsidence cracking along a longer stretch in the neighborhood was noticed before, although to a much a lesser magnitude.

Description of Damage: Large sewage pipelines (5 to 6 m in diameter) and fresh water pipelines (1 m in diameter) broke at several sections along parallel streets (separated by several blocks). The breaks occurred in several sections along the same street, some of which were already being repaired. The soil on that street settled as much as 2 ft relative to the houses and small structures, which did not show signs of settlement. The depression bands crossed streets and entire city blocks. A UAV flight revealed, and later data from CENAPRED corroborated, that the network of depression bands extended for kilometers. The soils were clayey, possibly transitional sediments between the lake soils and the rocky soils close to the hills in the south.

Description of Response: Pipeline repair was currently underway. Roads with pipe breakage were closed. Water supply in the neighborhood was initially provided through water trucks. Partial pipeline repair enabled freshwater supply (observed during a later visit).

Follow up: UAV or Lidar flight, of the entire region, including adjacent neighborhoods, as cracking pattern is known to extend beyond the area investigated. Shear wave measurements of soil within and outside depression bands.

Figure A17. Aerial representation of damages in Colonia del Mar, showing pipeline breaks and ground depression bands (yellow pins indicate locations where pipelines broke; green lines indicate streets with pipeline breaks; white squares indicate ground depression bands, with the five located on the left side of the image being mapped from observations on foot, bottom right one observed while driving on the road, and remaining ones mapped from aerial photographs; blue line indicates interpreted extent of ground depression band; red squares showing other ground depression bands).

Figure A18. Damage in pipes due to ground settlement (19.28687; -99.0544)

Figure A19. Settlement along ground depression band (left) (19.2868, -99.0604), sidewalk settlement close to damaged pipeline (19.2868, -99.0604), aerial shot of cracks on pavement.

A4.3. Site 3: Metro Elevated Train Viaduct (19.2982, -99.0339) and (19.3017, -99.0520)

Two damage locations were reported for the Metro Train Viaduct. Site one showed damage at the superstructure (pounding) and ground cracking due to column rocking (floating foundations), on another site a support column was severely damaged. Both sites are summarized below.

Site 3.1: 19.2982 , -99.0339

Description of Structure: The viaduct superstructure is composed of simply supported steel girders supporting a concrete deck. The wide deck carries two sets of tracks and an occasional train station. The substructure is 7’ diameter, single column bents and big hammerhead bent caps, supported on hollow floating foundations to protect the structure from sinking. The columns have a 5” notch for a drainage pipe that prevents rainwater from accumulating on the roadway. This detail is considered poor since it requires at least 5 inch of concrete cover to provide increased column stiffness. Support spacing varies around an average of 60 ft.

Description of Damage: Severe cracking in the road indicated the columns rocking during the earthquake (see Figure A22 below). Rocking is considered a good phenomenon since it protects the columns from more serious damage during an earthquake. Shear Key Damage was observed on the west side of Juan de Dios Peza (19.2982, -99.0339), as well as damage to the bent caps. In addition, minor damage cracks and spalls from the spans banging together at expansion joints was noticed (19.2982, -99.0339).

Description of Response: No interruption of traffic and Metro Service, engineering assessment of road cracking and superstructure damage underway during visit.

Follow-Up: Given the unique foundation system of the bridge pier (Floating foundations), it would be of interest to gather information of potential foundation damage. Furthermore, the available amount of bridge seat the ends of the girders would be of interest to assess if the girders have any restraint (or enough seat) left to prevent them from falling.

Figure A20. Photo showing ‘S’ shaped viaduct (19.2982, -99.0339)

Figure A21. Roadway cracks as a result of column rocking during the earthquake (19.2982, -99.0339)

Figure A22. Damage to the bent cap due to shear plate movement during the earthquake (left) and spalling at expansion joints (right) (19.2982, -99.0339)

Site 3.2: Severe Damage at Column Base on west side of Amado Nervo (19.3017, -99.0520)

Description of Damage: Cracks and spalls at the base of the column exposed the reinforcement, removed the cover concrete and penetrated deeply into the core. The main reinforcement was coupled in the plastic hinge zone, which meant it had very little strain capacity. Almost no transverse reinforcement was visible at the column, isolated hoops were loosely wrapped around the column.

Description of Response: The bridge is currently supported by a very large steel frame until repair measures have been identified. Local information hinted a similar construction issues in the adjacent columns of the bridge segment. X-ray measurements are anticipated to ensure this column is an anomaly and not typical along the viaduct.

Follow-Up: X-Ray results are of interest and whether this is a localized construction issue or a repeated construction error along the metro line.

Figure A23. Cracks extending into the column core (shown on top) and superstructure shoring with tubular steel frame sections (shown on bottom). (19.3017, -99.0520).

A5. Puebla and Epicentral Region

The city of Puebla is located approximate 150 km southeast of Mexico City. A walking survey around the the city center revealed several buildings had been damaged by the earthquake. A drive south from Puebla toward the epicenter revealed the roads changed from asphalt to gravel, shepherds driving their livestock, and groups of people walked along the side of the road dressed in holiday attire. We stopped in Chiautla near the epicenter, where President Nieto had given a speech after the earthquake but we saw few signs of damage. We drove through many rural towns but we didn't see much damage until we arrive in San Juan Pilcaya. 30 miles southwest of the epicenter.

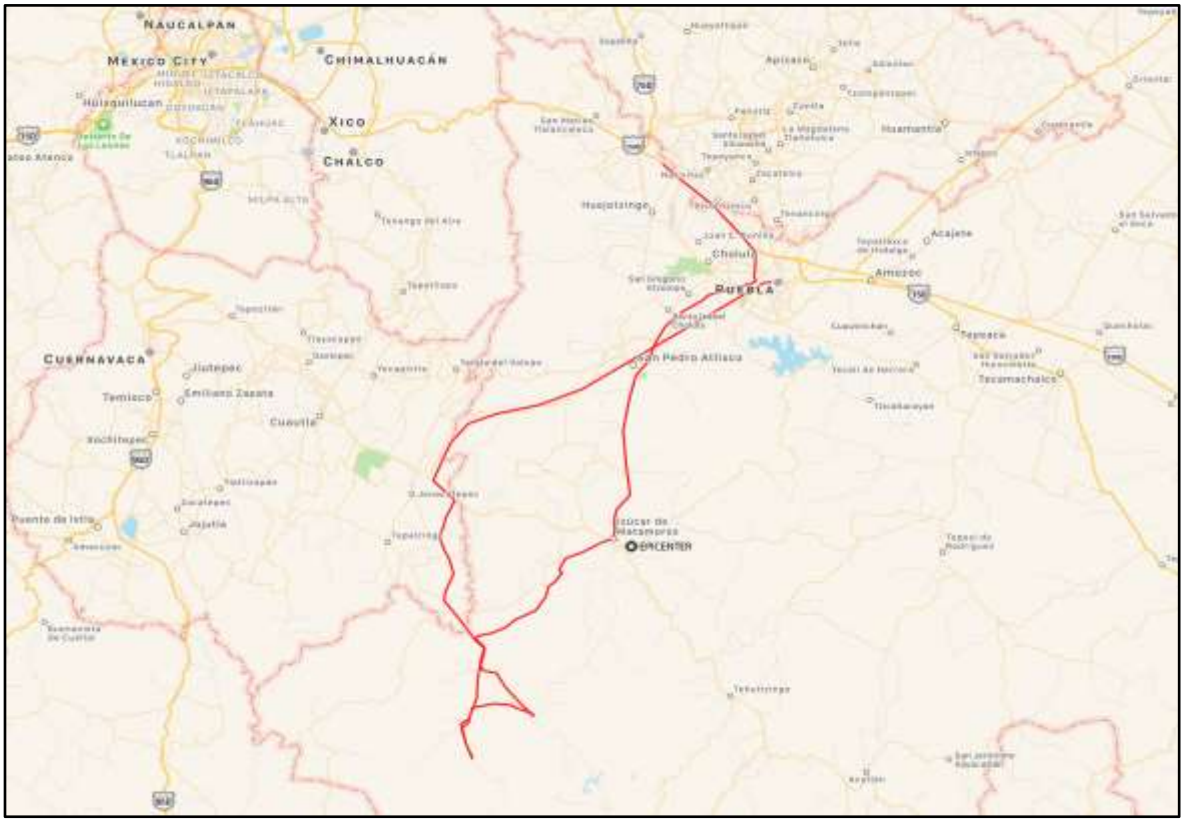

Figure A24. Travel from Puebla to the Epicentral Area and to San Juan Pilcaya.

A.5.1. Site 1: Downtown Puebla (19.0429, -98.1975)

Puebla is a beautiful city which was designed to resemble Paris. Walking around the Parque Centro we were disappointed to see shoring, yellow tape, and damaged roofs on several buildings. Even the Catedral de Puebla had shoring on the gables facing the square. This was the only damage we saw in Puebla.

Figure A25. This restaurant (Portal Morales) has signboard covering its damaged roof and shoring supporting its windows, doors, and balconies, all suggesting severe damage (19.0429, -99.1975).

Figure A26. The building next door, the Periodicos El Sol (The Sun Newspaper) had yellow tape around the exterior and signs posted on the doors suggesting damage inside (19.0429, -99.1975).

A5.2. Site 2: San Juan Pilcaya (18.2330, -98.7050)

Description of Town: Thirty miles southwest of the epicenter and several miles south of Chiautla is the ancient village of San Juan Pilcaya built from adobe bricks. The main streets in the center of town are cobblestone and there is a beautiful 400 year old church surrounded by homes and businesses.

Description of Damage: The church was severely damaged and most of the walls of the houses and stores were crumbling after the earthquake. Fortunately, there were no casualties. The bridge leading into the hills behind the town had pier damage and people were being cautioned not to use it. We were told that the town of Palantar was also seriously damaged but we didn't have time to visit.

Description of Response: Food and other goods were being distributed in a big outdoor shelter that had previously been built next to the church.

Follow-Up: Was the extensive damage simply due to adobe construction or were there site effects that contributed to the damage?

Figure A27. Damaged church (left) (18.2330, -98.7050), and typical adobe damage from earthquake (right) (18.2334, -98.7055).

Figure A28. Building Damage (left) (18.2286, -98.7045) and damage observed at center pier of the bridge (right) (photo taken while standing on the bridge) (18.2335, -98.7040).

A6. Morelos State

Morelos is a 1884 sq mile large state with a population of about 1.777 million people. Given its proximity to the epicenter, significant damage was observed and reported throughout the entire state. Two UNAM-GEER teams visited the eastern and western regions of the state (i.e., along highways #950 and 1150/160 respectively) to document structural, geotechnical and infrastructure damage.

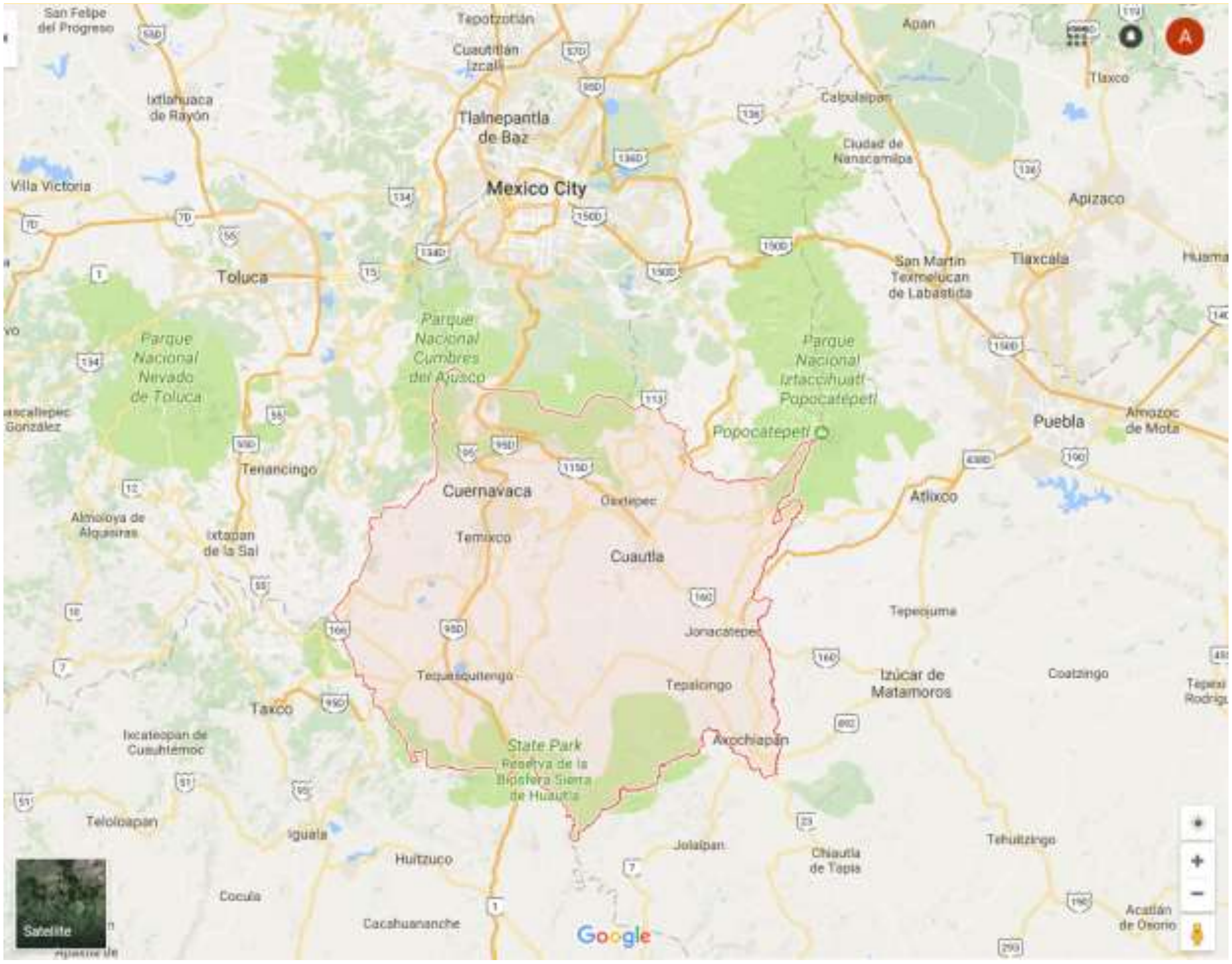

Figure A29. Map showing the state of Morelos

A6.1. Site 1: Tlayacapan Rockslide (18.9486, -98.9837)

Description of Damage: Rockslide with houses right below it. The path of the boulders is visible in the vegetation; boulders were slowed down due to (1) the vegetation above the houses, (2) the soft soil conditions and (3) existing boulder from previous events. Imprints from tumbling boulders were visible in the soft soils along the slide path. Only damage to the one residential house was observed, this structure was unoccupied. Preliminary UAV flight performed.

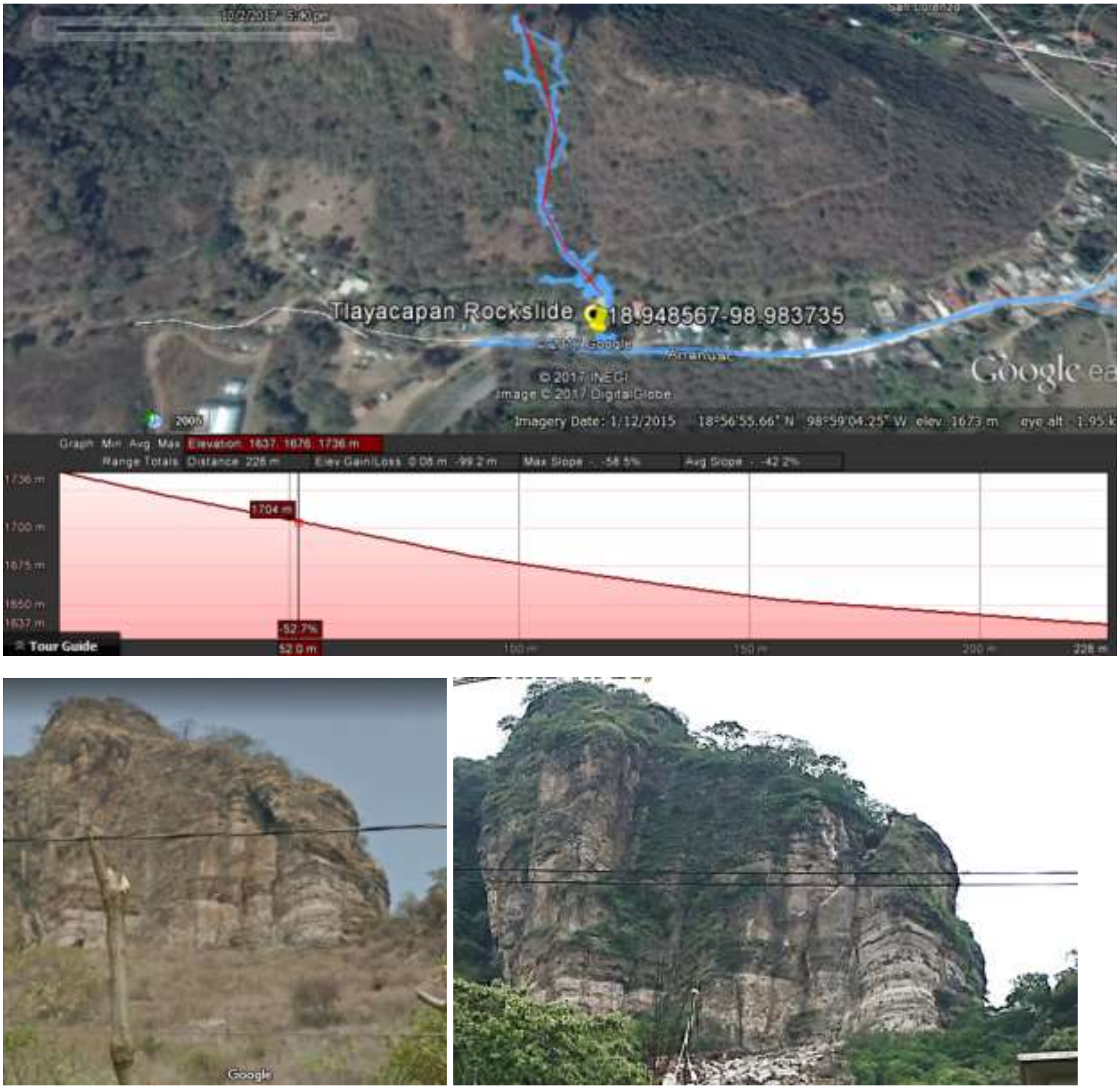

Figure A30. Top: Location and profile of rockfall slide, Left: 'Before" view from Google and Right: current view after earthquake (18.9486, -98.9837)

Figure A31. Photographs from main highway (left) and UAV (right) (18.9486, -98.9837)

Figure A32. Damage to a resident under construction by massive boulder (~9 m^3) from rockfall (18.9488, -98.9840)

<u>A6.2. Site 2: Totolapan Landslide (18.9816, -98.9246)</u>

This site is an old lava rock (Tezontle) quarry which is currently being used as landfill. The cuts of the quarry are overly steep and possibly undercut. Aerial imagery shows an existing cut area where previous landslides might have occurred (on the left - Source: Google Earth). Given the quarry geometry, the new landslide (triggered by the earthquake) was somewhat anticipated. New material covered about half of the landfill (i.e., waste) area and left nearby houses unstable. The instability of the slope is clearly observed by extension cracks meters north of the houses and a medium size failure during the reconnaissance team visit to the site. Short duration rain storms can potentially produce more failures in the site, substantial cracking was identified via aerial photographs. Soil type: clay and lava material.

Figure A33. Google earth before shots of Totolapan Landslide (18.9816, -98.9246)

Figure A34. Photographs showing slope failure after the earthquake (18.9816, -98.9246)

A6.3. Site 3:Atlatlahucan Landslides (18.9378, -98.8784)

Over six “landslides” were observed along the hills that run parallel to Route 115, to the SE, over a distance of about 2 km. These slides were associated with old mining quarries, according to google earth images from 2011 – 2017. Open cut mining activities did not seem to be continuous. A comparison of “before and after” imagery indicated potential for additional slide movement at all individual mines. In addition to individual slides, substantial cracking of the surface at the top plateau of the landslides was observed. This was not as extensive in previous years based on google earth observations.

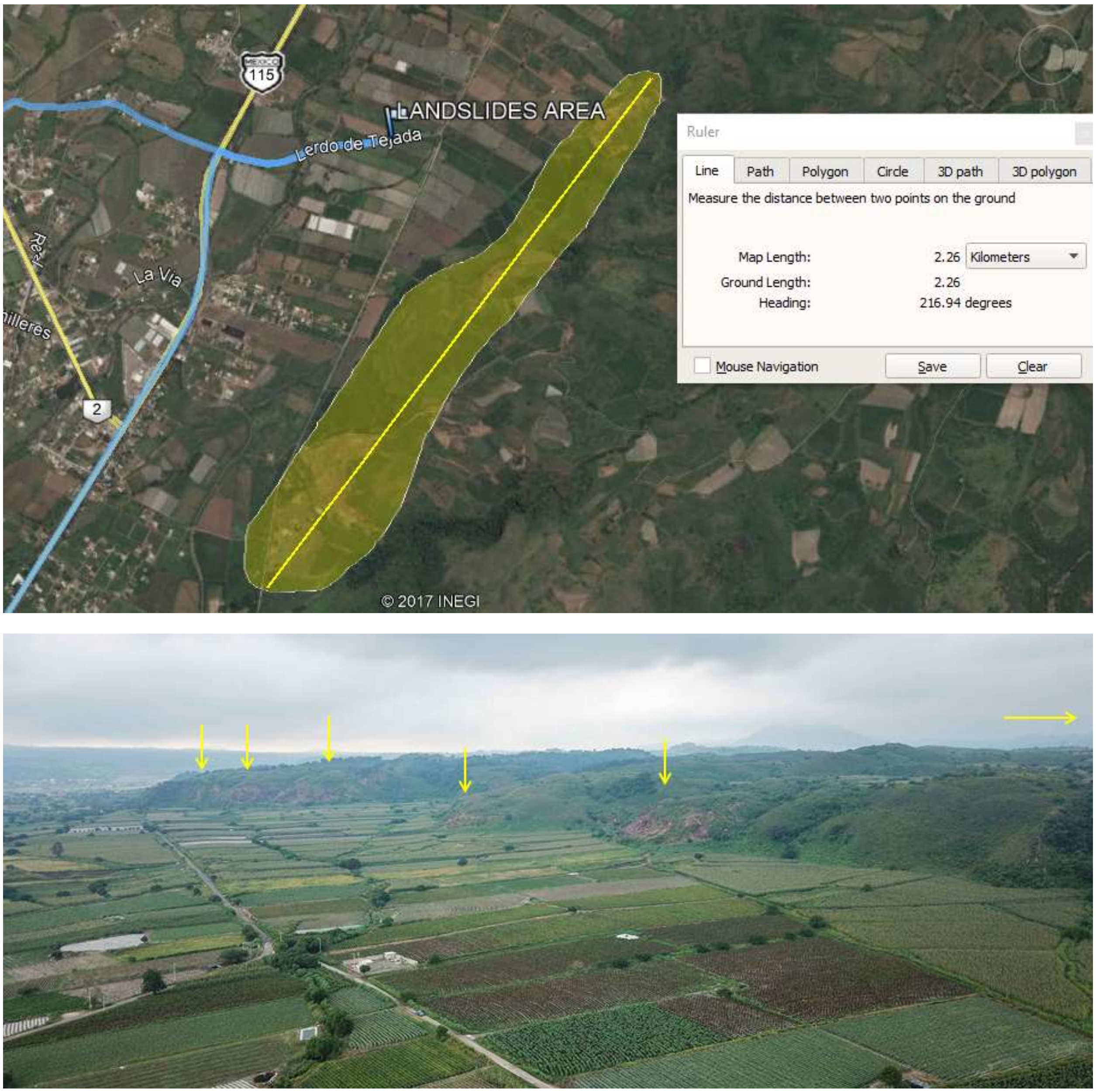

Figure A35. Extent of the observed Atlatlahucan landslides, but it is possible that the slides continue beyond our observation (18.9409, -98.8709)

Figure A36. Aerial UAV images of several of the Atlahuacan landslide and cracking on top of the plateau (18.9409, -98.8709)

A6.4. Site 4: Tetela del Volcán Topographic Effects (18.8949, -98.7279)

The city of Tetela del Volcán was visited. Mostly structural damage and collapse of adobe houses was observed. The entire city is built along a slope, where local site conditions or topographic effects could have contributed to the response behavior. Significant differences in house damage were observed at the upper slope. Multiple collapses observed. Moderate damage was observed at the bottom of the slope. This could be due to better construction (lots of stores and commercial structures were located near the bottom) or also due to better soil conditions. It might be of interest to study the soil conditions and the building performance along the hill site, to see if topographic effects affect the building performance in the city of Tetela del Volcán.

Figure A37. City map (top), structural damage and collapse to residential buildings (middle and bottom; 18.8949, -98.7279)

A6.5. Site 5: Embankment failure in Tejalpa-Zacatepec Highway (18.7146, -99.1835)

Description of Area: Embankment supporting part of the highway.

Description of Damage: A portion of an embankment partially supported on a retaining wall suffered significant damage manifested as medium to large cracks on the pavement for a length of 70 ft. The failure occurred on the section of the embankment that was not supported by the retaining wall, indicating a failure due to suboptimal design.

Description of Response: The road was closed due to the damages.

Figure A38. Significant deformations along pavement due to embankment deformation (18.7146, -99.1835).

A6.6. Site 6: Transition zone from CDMX to the town of Jojutla & Surrounding areas

Description of Area: Plenty of damages were found in Mexico City on structures on soft lake or transitional sediments. South of Mexico city, up until the town of Emiliano Zapata, there were very few damages observed. However, further south, starting at the Town of Tlaltizapan, damages became more common, with extent of damage increasing as one moves south. Geologic maps of the area revealed a transition from intrusive and extrusive igneous rock and limestone geologic strata in Cuernavaca and Emiliano Zapata where few damages were observed to alluvial soils in Jojutla where widespread damage to 1 to 2 story structures was observed.

Description of Damage: The majority of the damaged structures consisted of 1 to 2 story houses constructed with masonry and reinforced concrete or adobe. Section A6.7 provides further details.

Description of Response: Food and other living supplies were being distributed at various areas. Many partially collapsed buildings were being demolished, and the rubble was being removed.

Follow-Up: Characterize the soil conditions (e.g. shear wave velocity) as one moves from Mexico City to Jojutla with the intention to reveal potential site effects and ground motion amplification that resulted in relatively little damage in the zone in between. This characterization could be completed by taking, for example, shear wave profiles in the following sites: Cuernavaca, Emiliano Zapata, Tlaltizapan, and Jojutla (from North to South)

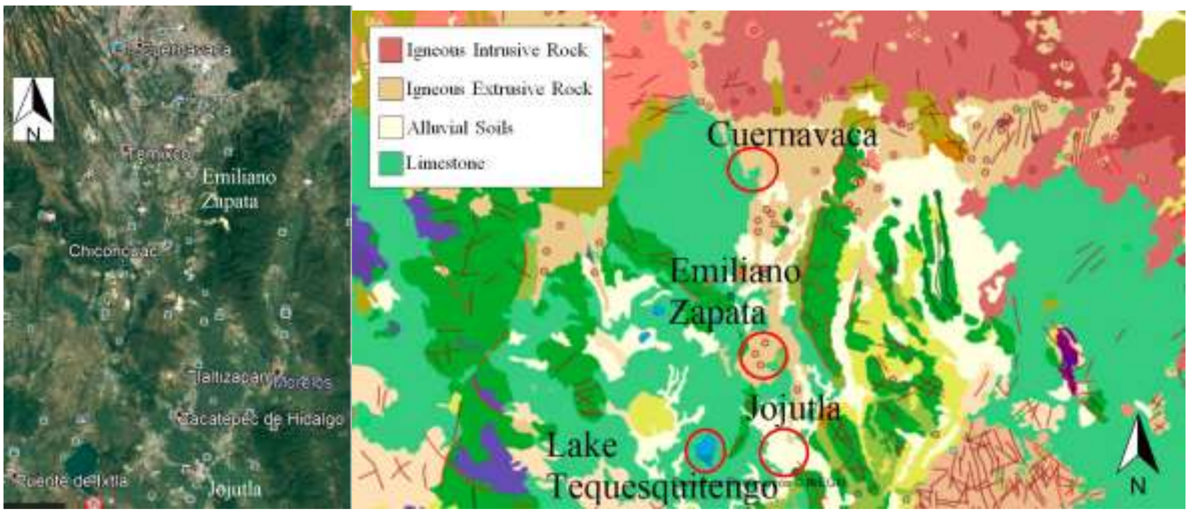

Figure A39. Map of western Morelos (left) and Geologic map of southern Morelos region (from INEGI's website) (right)

A6.7. Site 7: Towns of Jojutla, Tlaquiltenango, Tlaltizapan, and Lake Tequesquitengo

Description of Area: These areas are in the southern part of Morelos. Jojutla has about 53,000 habitants, Tlaquiltenango has about 30,000 habitants, Tlaltizapan has about 45,000 habitants. Lake Tequesquitengo is a manmade lake located to the west of Jojutla.

Description of Damage:

- Jojutla: Widespread damage to 1 to 2 story structures. In some blocks most of the buildings collapsed or partially collapsed. No drone flights were made at this location to take aerial photographs and map the extent of the damage; however, from ground observations it appeared that the damage was widespread and a relatively large portion of buildings were significantly damaged (about 5 buildings collapsed or partially collapsed per block in the most affected area). Most of the collapsed or partially collapsed structures were either constructed out of masonry with reinforced concrete columns or out of older adobe bricks. It appears that many of the affected structures were originally designed as 1 story structures, and some time later a second story was added. The structural failures indicated shear wall failures and collapse of first story due to buckling of the columns on the first story. Close to the Río Apatlaco, there were about 5 to 10 collapsed buildings on either side of the river (FIG), and the bridge connecting both sides suffered significant damages. One of the banks along the river failed, showing signs of lateral spreading potentially due to loss of strength due to the seismic load. The bank failure damaged a two story structure and a significant portion of the sidewalk leading to this structure.

- Tlaquiltenango: The town of Tlaquiltenango suffered significant damages on many 1 to 3 story buildings, as well as on its main church. Many of the damaged structures had already been demolished, thus it was impossible determining the potential causes for failure. However, several undemolished buildings showed clear signs of failure of the first story, possibly due to failure of the columns of the first story or the connections between the columns and the slab of the second story. In a few places groups of 3 to 4 buildings had collapsed, indicating the possibility of localized weak or soft soils that further amplified the ground motions, poor construction of that group of buildings, or interaction between those buildings. The town's main church exhibited large cracks that extended through its entire height failure. However, it should be noted that on this case the bell tower of the church did not show clear signs of damage, possibly due to its less slender shape as opposed to those of other churches as described above.
- Tlaltizapan: There were several 2 story structures in the town of Tlaltizapan that either completely or partially collapsed. The structural failures indicated shear wall failures and collapse due to buckling of columns, most likely because of inappropriate design or poor construction. A different structure suffered significant damage on its second story while its first story remained relatively intact.
- Lake Tequesquitengo: Along the northeast shore of Lake Tequesquitengo there was a failure on the road caused by failure and lateral spreading of the lake bank, shown as large cracks and significant displacement of the road. The side of the road closer to the lake settled about 2 feet, and its horizontal displacement was of about 1 foot. The length of the failure, as measured from the cracks on the pavement's surface, was of about 170 feet.

Description of Response: Food and other living supplies were being distributed at various areas. Many partially collapsed buildings were being demolished, and the rubble was being removed.

Follow-Up: UAV flight over the towns of Jojutla and Tlaquiltenango to map the extent of the damage to structures as well as other ground deformations along Río Apatlaco.

Figure A40. Group of partially collapsed and undamaged buildings in Jojutla (18.6176; -99.1775)

Figure A41. Partially collapsed building (18.6176; -99.1775)

Figure A42. Block with several collapsed buildings (rubble already removed) (18.6153; -99.1744), and and collapsed building with second story on ground after first story collapsed (18.6154, -99.1746)

Figure A43. Map of Jojutla with heavily affected area by Rio Apatlaco highlighted in red (top), partially collapsed buildings close to Rio Apatlaco (middle, 18.6123, -99.1817), structure with failed first story and second story fallen on top (bottom left, 18.6113, -99.1821), and Apatlaco River bank failure and affected structures.

Figure A44. Cracks along pavement on Lake Tequesquitengo (top left), vertical displacement of road (top right), (c) and (d) large cracks opened on pavement (bottom, 18.8313, -99.2538).