17th World Conference on Earthquake Engineering, 17WCEE

Sendai, Japan - September 13th to 18th 2020

MONITORING OF TWO REHABILITATED BUILDINGS AND THEIR STRUCTURAL RESPONSE DURING THE 2017 MEXICO EARTHQUAKES

D. Murià-Vila(1), B.D. Aldama Sánchez(2), M.A. García-Illescas(3), and G. Rodríguez Gutiérrez(4)

(1) *Professor, Instituto de Ingeniería, Universidad Nacional Autónoma de México, dmv@pumas.ii.unam.mx*
(2) *Assistant Professor, Instituto de Ingeniería, Universidad Nacional Autónoma de México, aldamasanchez1@hotmail.com*
(3) *Postdoctoral Student, Instituto de Ingeniería, Universidad Nacional Autónoma de México, illescasmg@gmail.com*
(4) *Assistant Professor, Instituto de Ingeniería, Universidad Nacional Autónoma de México, grog@pumas.ii.unam.mx*

Abstract

Before 2018, there were a few dozen seismically instrumented buildings in Mexico. Two of them, identified as PC and CCUT building, founded in the soft soil of Mexico City, were selected for this paper because the structural response to an earthquake of great intensity of September 19, 2017 was recorded. These buildings are one of the several damaged structures during the Michoacán 1985 earthquake and that were later retrofitted.

The PC building is a 17-story reinforced concrete structure. Since 1990 an accelerometer network is operating in the building, this was a year after its rehabilitation. During 30 years of the continuous monitoring, a large number of seismic events have been recorded, and the 31 most significant ones have been analyzed. The maximum responses recorded in the building until 2019 in terms of acceleration and displacement have been 571 Gal and 35 cm. Seismic records analyses from 1990 to 2019 have shown a decrease of the fundamental vibration frequencies of the building. On the other hand, an increase of dominant vibration frequencies of the site has been observed; this is mainly caused by the great exploitation of the underground aquifers in Mexico City, originating soil consolidation and the modification of the subsoil properties.

The CCUT building is a reinforced concrete structure consisting of a tower of 22-story and three low-rise structures with a basement in common. From the beginning of its construction, the tower presented differential settlement and tilting. In order to control these problems, there have been four underpinnings in different years and the reinforcement of the tower structure in 2011. With the purpose of monitoring the structural response of the building, a seismic instrumentation was installed and is operational since 2008; the instrumentation consists in accelerometers located at strategic points of the building and the ground, as well as a high-resolution GPS system to measure the relative displacements between the roof and the base. More than 25 seismic events of small, moderate and high intensity have been recorded and analyzed. The acceleration and maximum relative displacements were 359 Gal and 35 cm during the 2017 earthquake.

The objective of this paper is to present the performance evaluation of the rehabilitated buildings to the effects of the earthquake on September 19, 2017, in terms of recorded accelerations, variations of its vibration frequencies during a seismic event, as well as its displacements. It is commented if the last rehabilitation in the CCUT building has contributed to the control of its verticality. The analyses of the records are studied with a simplified model and by using a system identification technique based on the modal minimization and N4SID subspace methods.

Keywords: structural damage, rehabilitated buildings, structural monitoring, earthquake records, system identification.

1. Introduction

In 1988, experimental studies on the long-term response of permanently instrumented buildings or for several years to register their movements against earthquakes were formally started in Mexico [1-4]. The purpose of the studies is to contribute to a better understanding of the dynamic response of buildings to earthquakes of great intensity. Among the priority goals, it is possible to determine the forces and damping that occur during intense earthquakes, in order to compare their values with those used in design. Also, to analyze the evolution of the damage and its influence on the dynamic properties and the soil-structure interaction effects during the period that they are instrumented. It took 32 years for Mexico City to be affected by another earthquake of great intensity, the September 19, 2017 Puebla-Morelos earthquake (Mw 7.1). In the two instrumented buildings in Mexico City and one in Acapulco in charge of the Engineering Institute of UNAM (IIUNAM), records of this event were achieved. In addition, the earthquakes of September 7 and 23, 2017, were also recorded for the first two buildings. The effects of these two events were of moderate and small intensity in Mexico City. The two buildings of Mexico City, called PC and CCUT, are located in the soft soil zone, and both were rehabilitated after the effects of the 1985 earthquakes. The other building located in Acapulco, for now, has only been affected by earthquakes of small and moderate intensity with satisfactory performance [5, 6]. This paper presents several of the most interesting data of the response of the PC and CCUT buildings to the effects of the earthquake of September 19, 2017. These results are compared with the data of some previous and subsequent events.

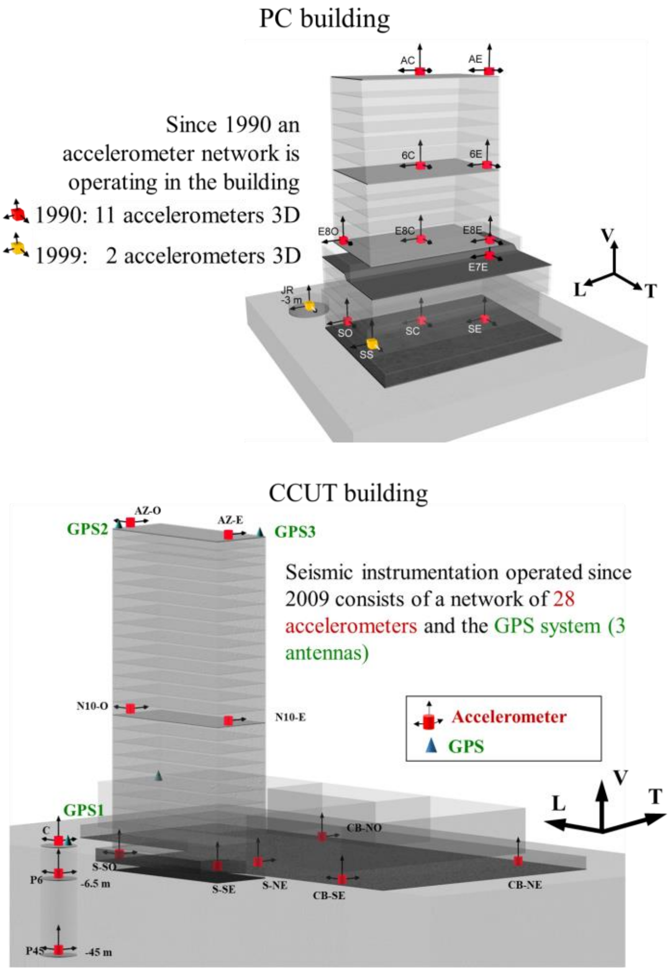
2. Description of the PC and CCUT buildings

The PC building was erected in the eighties and finished just before the great earthquake of September 1985. It is an irregular structure of reinforced concrete of 17-storey. The first levels are parking (plant dimensions 38 by 54 m) and the other 12 levels are destined to offices (plant dimensions 22 by 40 m). The foundation consists of a reinforced concrete box and supported by 266 piles. The building suffered moderate damage during the September 1985 earthquakes, mainly in the transition between parking levels and offices. These damages were repaired and, additionally, the structure was strengthened by replacing the masonry walls along its height for reinforced concrete ones. On April 25, 1989 an earthquake, whose on-site effects were of moderate intensity, caused some damage to the building, producing a decrease in the frequencies of vibration of the building, which becomes evident over time [7]. In September of the same year, the building was instrumented with servoaccelerometers with a 12-bit record system [8] (Fig.1).

The CCUT building is composed of a 22-story tower and three low-rise structures with a basement in common. Since 1964, when its construction finished, the tower has presented differential settlements and tiltings in the southwest direction and the low-rise structures uplifting [9]. To control these problems, four underpinnings and two rehabilitations have been done in different years. The last rehabilitation was concluded in 2009, it consisted of the stiffening of the tower by using steel diagonal elements in transversal direction (T), X-type steel bracings at three different levels, and the several coupling beams strengthened at their ends with carbon fiber-reinforced polymer strips (L and T directions). Additionally, in the south side of the base of the tower, expanded in 1987, 36 control piles were added, and concrete reinforced walls in T direction were built between the basement of the tower and the north side low-rise structure. To monitor the structural response and evaluate the performance of the building, an instrumentation was installed in December 2008 consisting of a servoaccelerometric network with a 19-bit record system and a GPS antenna system [10, 11] (Fig.1).

3. Monitoring of the seismic response

The study of the set of records of the buildings, obtained from the seismic events, is firstly done with the structural health monitoring system "AlertaE" [12], developed at IIUNAM to estimate the possible physical condition of the buildings. The seismic events are analyzed with a structural health monitoring system “AlertaE” to estimate the possible global damage of the building. The system is based on two indicators of severity (peak ground acceleration-PGA and Arias Intensity-I_{Arias} [13]) and three structural performance indicators (seismic coefficient-Cs, interstory drift-SD and variation of fundamental horizontal translation frequencies –VF. The vibration frequencies are obtained from the spectral analysis in the final phase of the acceleration records registered in the building [12]). The possible structural condition of the building is established by weighting criterion developed by the five indicators, based on four colors: Green-slight damage, Yellow-intermediate damage, Orange-severe damage (urgent need to inspect the building) and Red is assigned when the inspection suggests evacuating the building.


PC building

Since 1990 an accelerometer network is operating in the building

1990: 11 accelerometers 3D

1999: 2 accelerometers 3D

CCUT building

Seismic instrumentation operated since 2009 consists of a network of 28 accelerometers and the GPS system (3 antennas)

Fig. 1 – Schematic of the PC and CCUT buildings, and its instrumentations

PC building

By applying the “AlertaE” system to the 31 registered events, between 1990 and 2017, it is determined that 11 of the them were classified as Yellow and one as Orange (Table 1). It is worth mentioning that the initial physical state of the building was established at a Yellow level due to the damages of April 1989 earthquake that occurred prior to its instrumentation [8]. The September 7, 2017 earthquake (event 17-1) has been the largest recorded but its intensity at the building site was moderate and similar to the most severe events that affected Mexico City in 1995, 1999, 2007, 2012 and 2014 (events 95-1, 95-2, 99-1, 99-3, 07-1, 12-1, 14-1 and 14-2). Inspections after these events of moderate intensity revealed damage to non-structural elements, and reopening cracks in original structural elements. In addition, cracks were found in the concrete walls built to reinforce the structure.

The September 19, 2017 earthquake (event 17-2) has been the one with the highest intensity recorded. The PGA was 98 cm/s^2. When compared with the maximum registered in Mexico City (168 cm/s^2, SCT station) during the September 19, 1985 earthquake it turns out that the September 19, 2017 earthquake was 42% lower. The maximum accelerations and displacements on the roof of the building were 571 cm/s^2 and 35 cm. The maximum interstory drift was 0.62%, exceeding permissible values according to the building codes of Mexico City (0.60%). The greatest interstory drift of previous events occurred during the 95-1 event whose value was 0.55%. In event 17-2, Table 1, observe that the VF reached 18.5 % with respect to the value of the fundamental vibration frequency of the event 90-1. The 95-1, 99-1, 99-3, 12-1, 14-1, 17-1, 17-2 and 18-1 events caused damage to non-structural elements in facades and finishes, as well as the reopening of cracks in original structural elements and rehabilitated with widths less than 1 mm in walls, and up to 1.2 mm in some columns.

Table 1 – Characteristics of the seismic events recorded and identified physical state of the PC building

Event	**Date**	**M**	**D epic, in km**	**PGA in cm/s^2**	**$I_{h\text{-Arias}}$, in cm/s**	**Cs**	**SD in %**		**VF in %**		**Damage level of the event**	**Damage level from event 1989**
							L	**T**	**L**	**T**		
90-1	31/05/1990	5.3	319	7	0.8	0.01	0.08	0.15	0.0	0.0	Light	Intermediate
91-1	01/04/1991	5.4	381	3	0.2	<0.01	0.04	0.03	-0.9	0.9	Light	Intermediate
93-4	15/05/1993	6.1	332	10	1.5	<0.01	0.05	0.04	-0.6	-0.6	Light	Intermediate
93-11	24/10/1993	6.7	317	13	2.9	0.02	0.16	0.17	2.0	1.1	Light	Intermediate
94-1	23/05/1994	6.3	219	6	0.5	<0.01	0.03	0.02	-0.8	-0.8	Light	Intermediate
94-3	10/12/1994	6.5	307	17	6.9	0.03	0.20	0.34	6.3	6.6	Intermediate	Intermediate
95-1	14/09/1995	7.5	343	30	21.4	0.04	0.36	0.55	10.9	10.0	Intermediate	Intermediate
95-2	09/10/1995	7.9	572	17	9.8	0.04	0.19	0.27	8.4	5.6	Intermediate	Intermediate
97-1	11/01/1997	7.1	459	18	8.2	0.05	0.39	0.29	12.7	11.5	Intermediate	Intermediate
97-2	22/05/1997	6.5	313	5	0.4	<0.01	0.07	0.07	4.6	3.6	Light	Intermediate
99-1	15/06/1999	6.7	226	28	17.6	0.03	0.20	0.42	7.3	5.9	Intermediate	Intermediate
99-2	21/06/1999	5.8	324	6	0.7	0.01	0.05	0.06	4.8	6.1	Light	Intermediate
99-3	30/09/1999	7.4	447	27	20.9	0.03	0.26	0.47	9.4	8.2	Intermediate	Intermediate
99-4	29/12/1999	5.9	318	6	0.7	<0.01	0.08	0.07	3.3	3.6	Light	Intermediate
07-1	13/04/2007	6.3	293	14	2.4	0.01	0.07	0.08	1.1	3.3	Light	Intermediate
11-3	10/12/2011	6.5	196	21	4.6	0.03	0.08	0.12	1.9	0.9	Light	Intermediate
12-1	20/03/2012	7.4	355	43	29.0	0.05	0.30	0.30	7.4	5.7	Intermediate	Intermediate
13-2	16/06/2013	5.8	152	25	6.4	0.03	0.11	0.12	2.2	3.6	Intermediate	Intermediate
13-3	21/08/2013	6	293	10	1.5	0.01	0.06	0.07	2.4	5.0	Light	Intermediate
14-1	18/04/2014	7.2	333	47	30.9	0.05	0.23	0.38	7.0	11.6	Intermediate	Intermediate
14-2	08/05/2014	6.4	317	37	14.5	0.05	0.20	0.39	6.6	6.8	Intermediate	Intermediate
14-3	10/05/2014	6.1	326	10	1.6	0.02	0.07	0.11	9.6	13.3	Light	Intermediate
14-4	07/07/2014	6.9	883	6	0.8	<0.01	0.06	0.05	7.3	5.1	Light	Intermediate
14-5	29/07/2014	6.4	432	5	0.2	<0.01	0.03	0.04	7.3	0.0	Light	Intermediate
15-1	20/03/2015	5.4	173	5	0.3	<0.01	0.01	0.02	7.3	6.2	Light	Intermediate
17-1	07/09/2017	8.2	749	31	32.2	0.05	0.27	0.26	9.9	8.5	Intermediate	Intermediate
17-2	19/09/2017	7.1	122	98	179.1	0.07	0.62	0.54	7.3	18.5	Severe	Intermediate
17-3	23/09/2017	6.1	569	3	0.2	<0.01	0.02	0.02	3.8	10.0	Light	Intermediate
18-1	16/02/2018	7.2	370	30	15.4	0.02	0.31	0.12	11.6	8.6	Intermediate	Intermediate
18-2	17/02/2018	5.9	406	3	0.2	0.00	0.01	0.02	8.1	5.4	Light	Intermediate
18-3	19/02/2018	6	381	5	0.5	0.00	0.02	0.03	5.8	9.2	Light	Intermediate

The PC building and the SCT station are located in the same soft soil zone. Then, the response spectra is calculated with the ground motion records at the SCT station for earthquake events of September 19, 1985 (85-1), 99-3 and 17-2 are compared with those recorded at the building field station. It is observed that for the event 17-2 the spectral amplitudes in the SCT and the PC sites are 585 and 388 cm/s^2, respectively. In Fig.2, it can be seen that the maximum response of 1985 was approximately 1.6 and 2.4 times greater than that recorded during the 17-2 event, registered in both, the SCT and in the building site, respectively. One can also note the difference between a moderate earthquake (event 99-3) and high intensity earthquakes (events 85-1 and 17-2) for this site. An interesting aspect that can be seen, when comparing the response spectra of the SCT station and the building site, is that the amplitudes of the moderate intensity event 99-3 are similar; in contrast with the high intensity event 17-2 where there are significant differences. The response spectra calculated with the basement records show that the significant amplitudes of the horizontal components are between 0.4 and 2.9 s of period. The greatest spectral amplitudes for the events prior to 2000 are concentrated between 2.1 and 2.9 s of period, while for events after 2007 they are between 1.9 and 2.4 s of period. This is mainly caused by the great exploitation of the underground aquifers in Mexico City, originating soil consolidation, and the modification of the static and dynamic subsoil properties [8].

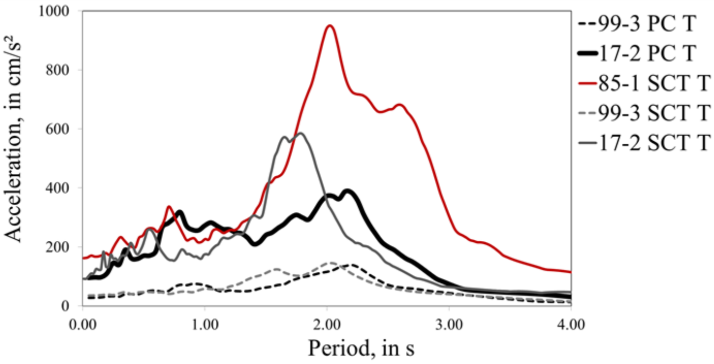


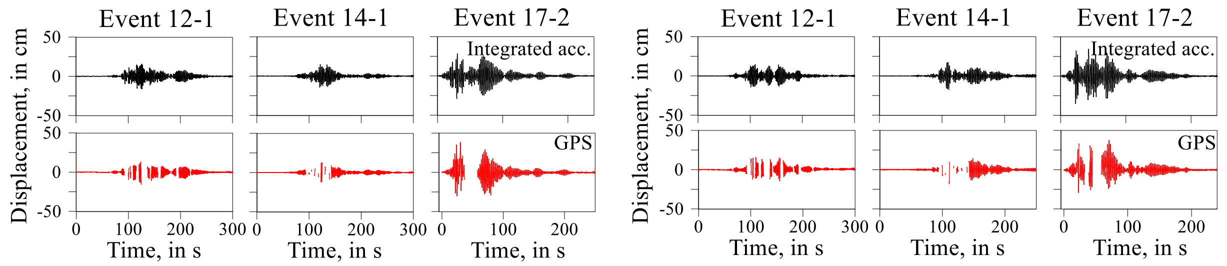
Fig. 2 – Comparison of the response spectra calculated with the events 99-3, 17-2 and the September 19, 1985 (85-1) earthquake of the PC (T component) and the SCT field-surface stations (EW component).

CCUT building

In this building, the records of the 25 seismic events obtained between 2011 and 2018 were studied. When applying the “AlertaE” processing, it was determined that six events reached the Yellow level (Table 2). The first earthquake of moderate intensity recorded after its last rehabilitation was that of March 20, 2012 (event 12-1). In the inspection of the property there were cracks and partial falls of the finish of several concrete and masonry walls, the breakage of a glass and the damage of the mechanism of one of the elevators. The maximum accelerations were 176 and 32 cm/s^2 on the roof and surrounding terrain, respectively. For the earthquakes of April 18 and May 8, 2014 (events 14-1 and 14-2), and September 7, 2017 (event 17-1), all three with an intensity similar to the earthquake of 2012, only slight damage was observed. In the high intensity earthquake of September 19, 2017 (event 17-2), the values of the variation indicator of the fundamental frequencies practically coincided with those established in the threshold between the Yellow and Orange levels. In this event, the damage was essentially reopening of cracks previously consolidated by damage of previous earthquakes in masonry walls, reopening cracks in original structural elements, and appearance of additional cracks in coupling beams and in some connections of the X-type steel bracings with the frame. Relative movements between soil and foundation were evidenced.

During the September 19, 2017 earthquake, the accelerations and maximum displacements on the roof of the building were 359 cm/s^2 and 34.5 cm. In all events, the displacements calculated by double integration procedure of the acceleration records and those measured with the GPS system are similar, verifying that the procedure established in “AlertaE” is valid even for this type of wide band high intensity events (Fig.3). The maximum estimated interstory drift was 0.35%.

Since 2011, there is a GPS system data record at each hour with which it is possible to calculate the tilt [10]. The tilting movements recorded between a period from 2011 to 2018 show a tendency of decrease of the tilt, approximately 0.78 mm per year are observed in L component. While a fluctuation of the tilt in T component is appreciated, apparently correlated with the rainy and summer season. The fluctuation of the tilt in this component is stable and it is around of 1.01 m. The seismic events occurred in this period are indicated and there have been no changes in the measurements between values before and after these events [11].



a) L Component

b) T Component

Fig. 3 – Comparison of time-histories GPS displacements and double-integrated acceleration of events 12-1, 14-1 and 17-2 recorded in the NE corner roof of the CCUT building

Table 2 – Characteristics of the seismic events recorded and identified physical state of the CCUT building

Event	**Date**	**M**	**D epic, in km**	**PGA, in cm/s²**	**$I_{h\text{-Arias}}$, in cm/s**	**Cs**		**SD, in %**		**VF, in %**		**Damage level from event 11-1**
						L	**T**	**L**	**T**	**L**	**T**	
11-1	25-Feb-11	6	473	0.9	0.02	<0.01	<0.01	<0.01	<0.01	0.0	0.0	Light
11-2	7-Apr-11	6.7	586	1.6	0.08	<0.01	<0.01	<0.01	0.01	4.5	1.7	Light
11-3	10-Dec-11	6.5	199	17.2	2.85	0.01	0.01	0.04	0.05	7.5	3.4	Intermediate
11-4	16-Dec-11	4.6	368	0.4	<0.01	<0.01	<0.01	<0.01	<0.01	1.5	1.7	Light
12-1	20-Mar-12	7.4	345	31.8	15.04	0.05	0.03	0.20	0.14	16.4	6.8	Intermediate
12-2	2-Apr-12	6	358	7.9	0.41	<0.01	<0.01	0.03	0.03	16.4	6.8	Intermediate
12-3	11-Apr-12	6.4	463	5	0.42	<0.01	<0.01	0.04	0.03	14.9	6.8	Intermediate
12-4	15-Nov-12	6.1	207	6.1	0.52	<0.01	<0.01	0.02	0.02	13.4	5.1	Intermediate
13-1	21-Apr-13	5.8	378	7.8	0.57	0.01	0.01	0.05	0.06	14.9	6.8	Intermediate
13-2	16-Jun-13	5.8	156	20.6	3.44	0.02	0.02	0.07	0.09	14.9	8.5	Intermediate
13-3	21-Aug-13	6	296	8.9	0.95	<0.01	<0.01	0.04	0.04	19.4	8.5	Intermediate
14-0	9-Mar-14	5.8	408	1.3	0.05	<0.01	<0.01	<0.01	0.02	14.9	6.8	Intermediate
14-1	18-Apr-14	7.2	337	30	12.86	0.03	0.03	0.17	0.18	20.9	10.2	Intermediate
14-2	8-May-14	6.4	320	29.4	8.5	0.02	0.04	0.13	0.19	16.4	10.2	Intermediate
14-3	10-May-14	6.1	330	8.5	0.92	0.01	<0.01	0.05	0.05	16.4	8.5	Intermediate
14-4	7-Jul-14	6.9	883	2.1	0.17	<0.01	<0.01	0.02	0.02	17.9	8.5	Intermediate
14-5	29-Jul-14	6.4	431	3.4	0.16	<0.01	<0.01	0.02	0.02	17.9	6.8	Intermediate
15-1	20-Mar-15	5.4	175	3.8	0.09	<0.01	<0.01	<0.01	<0.01	11.9	5.1	Intermediate
17-1	7-Sep-17	8.2	750	22.3	11.11	0.05	0.02	0.18	0.10	17.6	6.6	Intermediate
17-2	19-Sep-17	7.1	750	85.6	89.26	0.09	0.08	0.35	0.29	24.9	11.7	Intermediate-severe
17-3	23-Sep-17	6.1	569	1.8	0.082	<0.01	<0.01	0.01	0.01	18.1	11.0	Intermediate
17-4	25-Dec-17	5	295	<0.01	0.48	<0.01	<0.01	<0.01	<0.01	18.2	5.3	Intermediate
18-1	16-Feb-18	7.2	372	6.4	20.78	0.03	0.03	0.10	0.12	24.0	11.0	Intermediate
18-2	17-Feb-18	5.9	408	0.1	2.39	<0.01	<0.01	<0.01	<0.01	24.2	12.9	Intermediate
18-3	18-Feb-18	6	383	0.3	4.47	<0.01	<0.01	0.02	0.02	25.1	11.7	Intermediate

The displacements recorded by the GPS are only available after event 11-2. Note that, during events 12-1, 14-1 and 17-2, comparatively with the record obtained through double integration for these three selected events, the GPS unit at the roof NE corner had problems with satellite signals that caused the alteration of amplitude and loss of certain sections of the displacement history, although the maximum amplitudes of displacement were captured in L component and very close to the maximum in T component.

Given that the site where the CCUT building and the SCT station are located corresponds to soft soil and to dominant periods of site between 1.3 and 2 s, it is also interesting to compare the response spectra of events recorded in both sites with the spectrum of the record obtained from the earthquake of September 19, 1985 (event 85-1). The PGA at the CCUT field station during the 2017 earthquake was 122 cm/s^2, 27% lower than the PGA recorded during the event 85-1 at the SCT station. Fig.4 compares response spectra of March 20, 2012 (event 12-1, moderate intensity) and September 19, 2017 (event 17-2, high intensity) earthquakes with those of the SCT station. The most significant spectral ordinates correspond to the 85-1 event. It is observed that for the event 17-2 the spectral amplitudes in the SCT station and the CCUT site are

585 and 350 cm/s^2, respectively. The maximum spectral ordinates calculated at the SCT and CCUT sites during the 17-2 event were approximately 1.6 and 2.7 times lower than those recorded during the event 85-1 at the well know SCT station, respectively. As noted in the PC building case (Fig. 2), when comparing the response spectra of the SCT station againts the CCUT building site (Fig. 4), the amplitudes are similar in the moderate intensity event 12-1 contrary to high intensity event 17-2 where there are significant differences. Taking into account that the regional responses of the valley, where Mexico City is located, are quasilinear, the response from one to another site in Mexico City vary depending on the charateristics of the earthquakes.

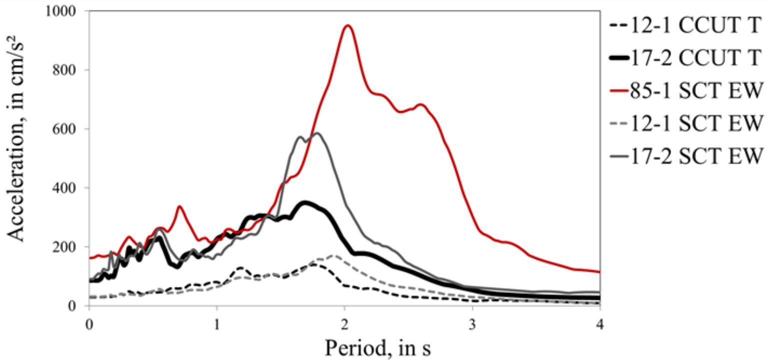


Fig. 4 –Comparison of the response spectra calculated with the events 12-1, 17-2 and the September 19, 1985 (85-1) earthquakes of the CCUT (T component) and the SCT field-surface stations (EW component).

4. Dynamic property variation

In a second stage, the records of the most intense seismic events were studied in order to identify the variation of frequencies and damping fractions throughout the duration of the event. This analysis is performed based on the 3D simplified model and by using a system identification technique based on the modal minimization (MM) and N4SID subspace methods. The MM method is based on the minimization of the differences between the measured acceleration signals and the ones calculated with a simplified modal superposition model [14, 15]. For the identification of the structural parameters, a computer program was used, in which multiple inputs and outputs signals were established based on the seismic records. By means of this technique, sequential analyzes were performed for short duration time windows elapsed (5 to 15 s), allowing the study of the variation of the structural parameters from window to window. The seismic events were divided into several windows, in each one the frequencies, damping and the contribution in the response of the significant modes were identified, with which it is possible to reproduce the measured acceleration response in the building. Results obtained from the records of both buildings from MM method, indicated that with the first two modes of each component it is sufficient to reproduce the acceleration responses recorded in the buildings. In addition, the participation factor of the fundamental modes obtained in the stretch of greater amplitudes was greater than 80%. Also, the records of events have been analyzed with the N4SID subspace method [16, 17, 18] where a discrete state space model is identified recursively; modal parameters are calculated from this model. Order models from 12 to 100 (PC) and from 12 to 150 (CCUT), intervals of two, were identified; as the order model increase, the accuracy in the identified model is improved. The 3D model used for the building with this recursive method was such that it can provide a history of frequencies in intervals of one second or less [19, 20]. A common problem by using subspace identification methods is the presence of spurious modes that appear either by noise sources or by nonlinearities in the system [21, 22]. In the studied case, spurious modes were removed by using criteria based on the identification of pair conjugated eigenvalues and threshold damping values; most of them are removed with simple criteria. Finally, modal average values were calculated in each iteration along the identification process.

In the PC building the variations of the fundamental frequencies calculated with the values of the final phase of small amplitudes of each event with respect to the value of initial phase of the first event recorded in 1990 (which was of low intensity) show reductions of up to 10% for L and T components. In the values between the events of 1995 and 2014 there is a fluctuation and apparent recovery that is partly justified by the regional consolidation process of surrounding soft soil zones. Before the event of September 19, 2017, the frequency reductions are up to 21.6% for L and T components. Fig.5 shows the variations of the frequencies of the first two modes in the T, L and torsion (R) components, obtained for events 90-1, 99-3, and 17-2 by using both MM and N4SID identification methods. Table 3 shows the average frequencies of the fundamental modes in the T, L and R components, obtained with the data estimated with the N4SID method for events 90-1, 95-1, 99-1, 99-3, 12-1, 14- 1, 17-2 and 18-1. These values corresponding to the initial (f_i) and final (f_f) phases of low intensity, and to the phase of high intensity movement (f_s). In the fundamental frequency values, the differences obtained between the MM and N4SID methods, for the intense and final phases, are 2.1-2.7% (L), 3.6-2.4% (T), and 8.9-5.5% (R). Regarding the damping ratio for the first modes it found variations between 0.011 and 0.097 with an average of 0.044, and for the second modes, these values fall between 0.005 and 0.068 with an average of 0.025.

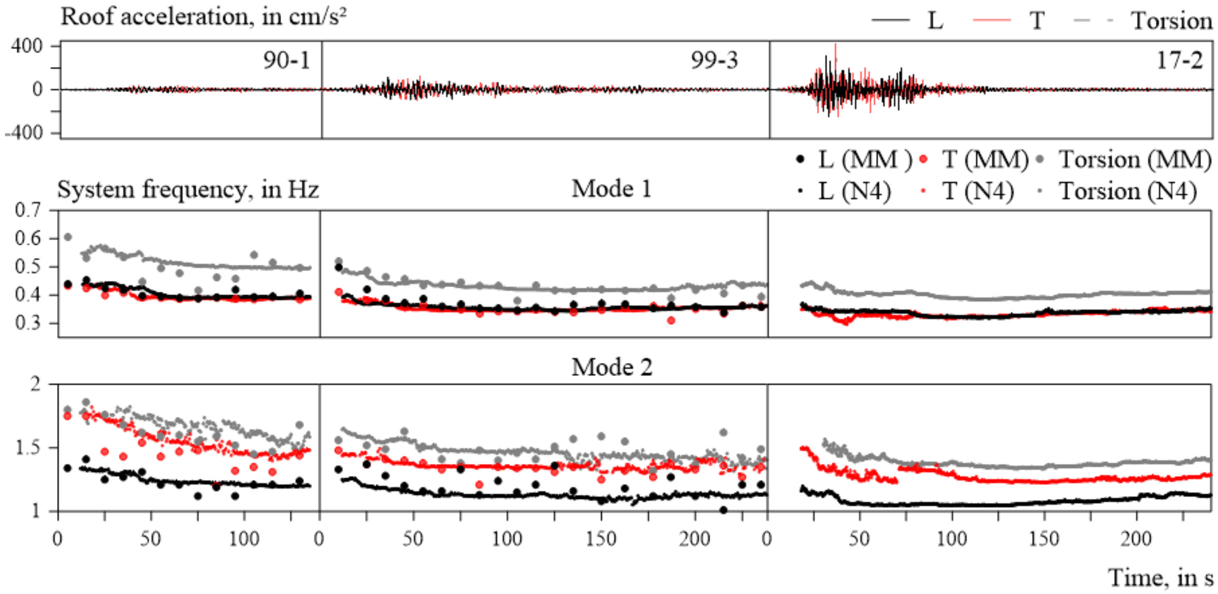


Fig. 5 – Estimated frequencies in L, T and R (torsion) components of the PC building for events 90-1, 99-3 and 17-2.

Regarding the ambient vibration records, the frequencies from measurements after rehabilitation works for the building in January 1989 [7, 8] are available. In addition, frequencies from three tests conducted before the events 99-3 (VA2), 07-1 (VA3) and 17-2 (VA4) were considered, and one other after event 18-1 (VA5). In Table 4 the frequencies obtained from ambient vibration test and the variation of frequencies VA2 to VA5 relative to VA1 are presented. The values decreases are similar and up to 26.8% between VA2 and VA4, despite event 99-3 presented a lower intensity than April 25, 1989 earthquake, suggesting that the structure was damaged prior to its instrumentation in 1989, being the most intense event occurred after rehabilitation. This means that after the earthquake in April 25, 1989 the level of damage in the building is intermediate, according to the classification of system “AlertaE” [12]. After the event 18-1, the values of frequencies drop up to 32.9% and the level of structural condition remains the same.

In the CCUT building, the results based on the six events 12-1, 14-1, 17-1, 17-2, 17-3 and 18-1 are presented, being the most significant events 12-1, 14-1 and 17-2. For the events 12-1 and 14-1, the values are compared using both identification methods. The six events are analyzed using the recursive N4SID subspace identification method. The vibration frequency values of the most significant events, corresponding to the first two modes that define the response in the tower of the CCUT building, are shown in Fig.6. The results for the events analyzed using both identification techniques were proximally similar.

The identified vibration frequencies of the seismic events obtained with N4SID method are shown in Table 5. Decreasing values at the final phase (f_f) of the events 12-1, 14-1 and 17-2 were observed with respect to those identified in the initial phase (f_i), showing a cumulative damage in events 12-1 and 14-1 of moderate intensity as well as event 17-2 of high intensity. At the final phase of high intensity event 17-2, the frequencies associated to the fundamental modes decrease with respect to the values at the start of the movement in 12.4, 6.6 and 11.0 % for the L, T and R components, respectively. The reductions, considering the initial phase of the movement in the event 12-1, were of 19.5, 9.4 and 21.7 %, respectively. Subsequently, for the events 17-3 and 18-1, a partial recovery of the vibration frequencies is evidenced, for the first mode it is 2.1, 1.0 and 4.5% for the L, T and R components, but there is still a drop with respect to the initial phase of the 12-1 event. The decrease in the values of the frequencies shows a process of cumulative damage caused by the effect of successive earthquakes, with major damage detected in event 12-1. In the fundamental frequency values, the differences obtained between the MM and N4SID methods, for the intense and final phases, are 7.2-12.9% (L), 3.1-3.1% (T), and 7.1-11.6% (R). About the damping ratio for the first modes it found variations between 0.002 and 0.140 with an average of 0.024, and for the second modes, these values fall between 0.005 and 0.150 with an average of 0.038.

Table 3 – Identified vibration fundamental frequencies of the seismic events obtained with N4SID method in PC building

Event	**f_i, in Hz**			**f_s, in Hz**			**f_f, in Hz**			**Vf_f, in %**		
	L	**T**	**R**	**L**	**T**	**R**	**L**	**T**	**R**	**L**	**T**	**R**
90-1	0.434	0.431	0.563	0.389	0.381	0.493	0.393	0.388	0.495	-9.4	-10.0	-12.1
95-1	0.464	0.446	0.577	0.349	0.347	0.430	0.366	0.366	0.444	-15.7	-15.0	-21.1
99-1	0.445	0.421	0.549	0.350	0.340	0.421	0.370	0.367	0.446	-14.8	-14.9	-20.9
99-3	0.391	0.376	0.480	0.343	0.343	0.416	0.371	0.364	0.443	-14.6	-15.6	-21.4
12-1	0.421	0.379	0.478	0.341	0.338	0.415	0.379	0.367	0.445	-12.8	-14.9	-21.0
14-1	0.401	0.377	0.469	0.341	0.334	0.408	0.371	0.354	0.431	-14.5	-17.9	-23.5
17-2	0.358	0.353	0.437	0.322	0.308	0.385	0.340	0.347	0.405	-21.6	-19.4	-28.1
18-1	0.396	0.383	0.445	0.310	0.326	0.379	0.344	0.346	0.410	-20.7	-19.6	-27.3

Note: f_i - Frequency of initial phase, f_s - Frequency of intense phase, f_f - Frequency of final phase
Vf - Variation of frequencies f_f of event with respect to the f_i of event 90-1

Table 4 – Ambient vibration frequencies and differences respect to test VA1

Tests	**Date**	**Frequencies, in Hz**			**Variation, in %**		
		L	**T**	**R**	**L**	**T**	**R**
AV1	15/01/1989	0.560	0.560	0.800	0.0	0.0	0.0
AV2	25/06/1999	0.490	0.440	0.590	-12.5	-21.4	-26.3
AV3	04/04/2006	0.475	0.440	0.590	-15.2	-21.4	-26.3
AV4	01/03/2017	0.476	0.439	0.586	-15.0	-21.6	-26.8
AV5	21/03/2018	0.439	0.415	0.537	-21.6	-25.9	-32.9

Table 5 – Identified vibration fundamental frequencies of the seismic events obtained with N4SID method in CCUT building

Event	**f_i, in Hz**			**f_s, in Hz**			**f_f, in Hz**			**Vf, in %**		
	L	**T**	**R**	**L**	**T**	**R**	**L**	**T**	**R**	**L**	**T**	**R**
12-1	0.678	0.594	1.151	0.514	0.502	0.805	0.592	0.561	0.964	-12.6	-5.7	-16.3
14-1	0.636	0.577	1.030	0.475	0.495	0.778	0.575	0.557	0.947	-15.2	-6.3	-17.7
17-1	0.631	0.585	1.023	0.498	0.501	0.848	0.581	0.560	0.959	-14.2	-5.8	-16.7
17-2	0.623	0.576	1.014	0.464	0.459	0.770	0.545	0.538	0.902	-19.5	-9.4	-21.7
17-3	0.568	0.554	0.940	0.501	0.522	0.848	0.552	0.546	0.909	-18.6	-8.1	-21.1
18-1	0.592	0.561	0.967	0.469	0.490	0.802	0.557	0.544	0.943	-17.8	-8.5	-18.1

Note: f_i - Frequency of initial phase, f_s - Frequency of intense phase, f_f - Frequency of final phase,
Vf - Variation of frequencies f_f of event with respect to the f_i of event 12-1

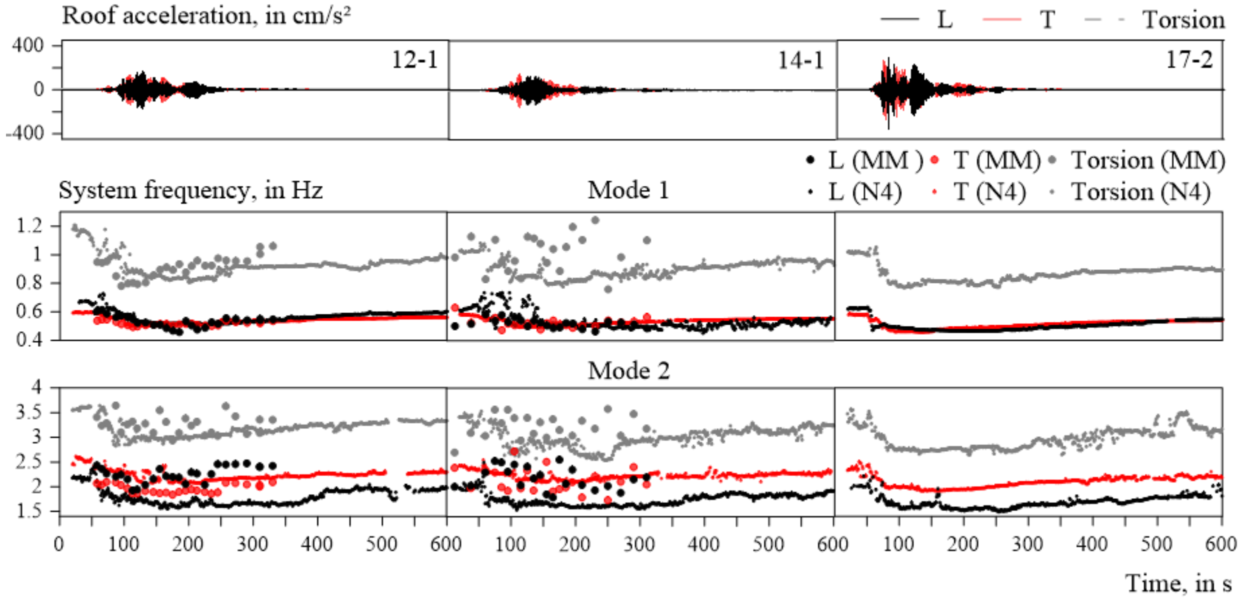


Fig. 6 – Estimated frequencies in L, T and R (torsion) components of the CCUT building for events 12-1,14-1 and 17-2.

5. Conclusions

Results obtained for the events analyzed with both identification methods turned out to be similar. In the first mode, identification results are very close even when the methods operate with different approaches, providing reliable results. In contrast, results based on N4SID method are more consistent in the identification of the second mode with less variation when comparing with MM method. Thus, the estimates with the recursive N4SID method are achieved satisfactorily mainly in the intense and final phases of the records, and for the two modes for each component. During the intense phase of the ground motion, when the response of buildings is predominant, the identification was acceptable in terms of accuracy even the difference in the resolution of the records systems and in terms of coupling effects between modes. Regarding the initial and final phases of the movements, the low resolution of the records in the PC building affects and complicates the correct identification of the modal parameters, mainly in the initial phase.

The structural health monitoring system (AlertaE) has been a valuable tool in the diagnosis of the two buildings studied. The changes in structural performance of the PC building, after its rehabilitation, are due to the main damages caused by the earthquake April 25, 1989, just before its instrumentation. The analysis of the seismic records 1990-2018 shows that the fundamental frequencies of the building in horizontal components have decreased, taking the example of the event 18-1, where these frequencies reduced up 11.6% according to AlertaE assessment and 20.7 % with N4SID estimation. In spite of the soil consolidation, the frequency values for moderate and high intensity events have dropped with respect to the ones in 1990, and the change of the piles tip contact presented between 1991 and 1993 [8]. For CCUT building the effects of the event 12-1 caused a reduction in the fundamental frequency values of horizontal components of the building with respect to the values of the initial phase of the movement until 16.4 % according to AlertaE assessment and 12.6 % with N4SID estimation, and for event 17-2, the maximum cumulative reductions reached are 24.9 % and 19.5 % with AlertaE system and N4SID method, respectively. This suggests that the decreasing trend of the values was caused by the effect of damage accumulation in the structural system. The structural performance of the two rehabilitated buildings, during the high intensity earthquake of September 19, 2017, suggests a Yellow category according to the structural health system. This category remains the same as before this event. Note that the differences observed between variations of frequencies estimated by the two ways, implicitly, include those changes largely attributed to the resolution of the records systems.

The experimental data have been useful to develop representative numerical models of the buildings [23]. Due to the fact that the buildings were affected by a large earthquake, it is convenient to carry out complementary studies about vulnerability to other intense future earthquakes. For the first time in Mexico, we have records of the structural response of a high intensity earthquake which will allow us to accomplish studies of its performance with better estimations.

Other interesting seismic records that were obtained during the earthquake of September 19, 2017 were those of roof displacement, captured by the GPS system of the CCUT building and operating in parallel with the accelerometric network. Additionally, this system contributes to the continuous recording of the verticality of the building and when an earthquake occurs to register the displacements. Regarding the tower´s tilt of the building after the last rehabilitation, it shows very small variation and the tendency suggests even a small recovery of verticality which correlates with the seasonal changes of precipitation and temperature. According to these measurements, the tilt values are practically stable in T component and show a slight recovery in L component. It is expected that the monitoring of the verticality in the coming years will confirm the stability of the tower's tilt. The measurements show that the earthquakes have not produced significative changes. Displacements measured with GPS are also available during earthquakes. Thanks to this we have verified that the baseline correction procedure applied to the accelelerograms is correct because when calculating the displacements, these are similar to those recorded by the GPS.

6. Acknowledgements

The study was carried out with the financing provided by the Government of the Mexico City and the National Autonomous University of Mexico. Also the authors wish to thank the support of the Mexican Nacional Council for Science and Technology through FORDECYT 297246 project. UNAM. We thank LA Aguilar, M Ayala, J Camargo, C Pérez, AL Ruiz, R Delgado, GG Aguilar, L Ramírez, PH Galván, MA Macías, D Almora, L Alcántara, JM Velasco, A Mora, H Sandoval, M Torres, G Castro, R Vázquez and I Molina, for the operation and maintenance of the instrumentation of the building, as well as for the collaboration in the pre-processing or analysis of the registers. The authors also thank the valuable comments and recommendations of R Meli, S Loera and S Alcocer.

6. References

[1] Meli R, Faccioli E, Murià-Vila D, Quaas R, Paolucci R (1998): Study of site effects and seismic response of an instrumented building, *Journal of Earthquake Engineering*, **2** (1), 89-111.

[2] Murià-Vila D (2007): Experiencia mexicana sobre la respuesta sísmica de edificios instrumentados. *III Coloquio de Ingreso a la Academia, Academia de Ingeniería, México*

[3] Murià-Vila D, Rodríguez G, Zapata A, Toro AM (2001): Seismic response of a twice-retrofitted building, *ISET Journal of Earthquake Technology*, **38**, (2-4), 67-92.

[4] Rodríguez-Cuevas N (1992): Response measurements of tall building under seismic excitation. *Proceedings of X World Conference Earthquake Engineering*, Madrid, Spain, Balkema, Rótterdam, 2665-2671.

[5] Aldama BD, García MA, Murià-Vila D (2019): Evolución de las propiedades dinámicas de un edificio instrumentado ante sismos de mediana y baja intensidad. *Proceedings of 22 National Congress of Seismic Engineering. SMIS*, Monterrey, México.

[6] Murià-Vila D, Taborda R, Zapata A (2004): Soil structure interaction effects in two instrumented tall buildings. *Proceedings of 13th World Conference on Earthquake Engineering*, Vancouver, Canada.

[7] Rodríguez-Cuevas N, Quass R (1990): Respuesta estructural de un edificio instrumentado en la ciudad de México durante sismos recientes. *Proc. Int. Seminar on Seismic Instrumentation and Use of Energy Dissipators in Structures*. *Mexican Society of Seismic Engineering*, 125-155

[8] Murià-Vila D, Camargo J, Aldama BD (2017): Influence of soil structure interaction and subsoil consolidation in the seismic response of a building. *Proceedings of 16th World Conference on Earthquake Engineering*, Santiago de Chile, Chile.

[9] Rodríguez JF, López NP, Auvinet G (2008): 3D Numerical modeling of the behavior of large buildings founded on Mexico City soft clays. *Proceedings of the 2nd International Workshop on Geotechnics of soft soils- Focus on ground improvement*, Glasgow, UK, 87-94.

[10] Murià-Vila D, Camargo J, Rodríguez G, Aldama BD (2017): Tilt and seismic response monitoring of a rehabilitated building. *Proceedings of 8th International Conference on Structural Health Monitoring of Intelligent Infrastructure*, Brisbane, Australia.

[11] Murià-Vila D, Aldama BD, García-Illescas MA, Rodríguez G (2019): Seven years of Monitoring of a Rehabilitated Building in Soft Soil and Structural Response to the September 2017 Earthquakes in Mexico. *Submitted to Earthquake Spectra.*

[12] Murià-Vila D, Aldama BD, Loera S (2010): Structural warning for instrumented buildings. *Proceedings of 14th European Conference on Earthquake Engineering*, Ohrid, Macedonia.

[13] Arias A (1970): A Measure of Earthquake Intensity. *Seismic Design for Nuclear Power Plants* (R. J. Hansen ed.), MIT Press.

[14] Beck JL, Jennings PC (1980): Structural identification using lineal models and earthquake records. *Earthquake Engineering and Structural Dynamics*, **8**, 145-160.

[15] Camargo J, Murià-Vila D (2011): Implementation of genetic algorithms in a system identification method for instrumented buildings. *Proceedings, 5th International Conference On Structural Health Monitoring of Intelligent Infrastructure*, Cancún, México.

[16] Van Overschee, P., and De Moor, B., 1994. N4SID Subspace algorithms for the identification of combined deterministic-stochastic systems, *Automatica*, **30**, 1, 75-93.

[17] Oku, H., and Kimura, H., 1999. A Recursive 4SID from the Input-Output Point of View, *Asian Journal of Control*, **1**, 4, 258–269.

[18] Peeters, B., and Ventura, C. E., 2003. Comparative study of modal analysis techniques for bridge dynamic characteristics, *Mechanical Systems and Signal Processing*, **17**, 5, 965–988.

[19] García-Illescas M, Murià-Vila D, Alvarez-Icaza L (2019): Monitoring and Identification of Vibration Frequencies on a Portion of Mexico City Metro Line 12. *Advances in Civil Engineering,* Article ID 4128320, doi.org/10.1155/2019/4128320) **2019**,1-13.

[20] García-Illescas MA, Murià-Vila D, Aldama BD, Alvarez-Icaza L (2019): Frequency monitoring in a structure on soft soil by means of n4sid identification method. *8th International Operational Modal Analysis Conference (IOMAC'19)*, Copenhagen.

[21] Marchesiello S, Fasana A, Garibaldi L (2016): Modal contributions and effects of spurious poles in nonlinear subspace identification. *Mechanical Systems and Signal Processing*, **74**, 111-132.

[22] Boroschek RL, Bilbao JA (2019): Interpretation of stabilization diagrams using density-based clustering algorithm. *Engineering Structures*, **178**, 245-257.

[23] Murià-Vila D, Arnau Delgado O, Aguilar Silva GG, Arias Lara D, Pérez-Liévana K (2019). Numerical simulation of the CCUT tower response recorded during March 20th, 2012 and September 19th, 2017 earthquakes. *Submitted to Earthquake Spectra.*