Response of Essential Facilities Under Narrow-Band Mainshock-Aftershock Seismic Sequences

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SUMMARY
The actual value of the importance factor that promotes acceptable performance of structures built in soft soils exhibits significant dependence with respect to the dynamic characteristics of the structural system. The current use given to the importance factor may result in conservative or unsafe design of essential facilities built in soft soils and, because of this, a displacement-based methodology that aims at controlling simultaneously the level of structural and non-structural damage on essential facilities has been recently proposed. Nevertheless, the response of essential facilities under narrow-band mainshock-aftershock seismic sequences has not been properly studied. To help understand the effects of aftershocks in structures built in soft soils, the seismic performance of regular frames is estimated through the use of an equivalent single-degree-of-freedom system. A discussion is offered in terms of the range of structural properties that make the frames vulnerable to the effect of aftershocks. Finally, the performance of a building designed according to the displacement-based methodology is studied when subjected to mainshock-aftershock sequences.

Keywords: Essential facility, Importance Factor, Mainshock-aftershock Seismic Sequences

1. INTRODUCTION

Man-made structures located in seismic regions are not exposed to a single seismic event (i.e. mainshock), but to a sequence consisting of foreshocks, mainshock and aftershocks. Under some circumstances, aftershocks could trigger larger peak lateral displacement demands and larger permanent displacements than those experienced by the structure during the mainshock. As a consequence, aftershocks could increase the structural damage or, even, drive a structure without major damage to demolition due to excessive permanent displacements. A clear example of this scenario was observed in Mexico City after the September 19, 1985 Michoacan earthquake (M_w = 8.0) and its aftershock that occurred on September 20 (M_w = 7.6). It is well documented that medium-rise buildings located in the old bed-lake zone of Mexico City, mainly reinforced concrete buildings with frame-based structural systems suffered moderate-to-severe structural damage as a consequence of the mainshock (Rosenblueth and Meli 1986). Since a strong aftershock shook the city the following day, many buildings increased their state of damage, and suffered excessive permanent displacements and collapse. Several dozen damaged reinforced concrete buildings with large permanent drifts had to be demolished after the earthquakes because of the technical difficulties to straighten and repair them.

There is an urgent need to understand the response of structures subjected to a seismic sequence of mainshock-aftershocks. There have been several investigations aimed at studying the effect of seismic sequences on the response of civil engineering structures. While some of these have been focused on the nonlinear response of single-degree-of-freedom (SDOF) systems (Amadio et al 2003, Hatzigeorgiou and Beskos 2009, Hatzigeorgiou 2010), others have concentrated in the response of multiple-degree-of-freedom (MDOF) systems (Ruiz-Garcia et al 2008, Hatzigeorgiou and Liolios 2010, Ruiz-Garcia and Negrete-Manriquez 2011). Most previous studies employed artificial seismic sequences instead of real (i.e. as-recorded) mainshock-aftershocks sequences. Particularly, they have employed artificial sequences using the mainshock acceleration time-history as a seed for simulating the aftershocks using the following approaches: 1) back-to back, or repeated, approach (Amadio et al 2003, Hatzigeorgiou 2010), and 2) randomized approach (Hatzigeorgiou and Liolios 2010). The first approach consists on repeating the as-recorded mainshock as an artificial aftershock, which assumes that the ground motion features such as amplitude, frequency content, and strong motion duration of the mainshock and aftershock(s) are the same. The second approach consists on selecting a set of as-recorded mainshocks, and generating artificial sequences by selecting a mainshock and using the remaining mainshocks, once at a time, as an artificial aftershock. It should be noted that although previous studies developed extensive analytical information on the effect of seismic sequences on the response of structures, those studies only employed seismic sequences for firm soil sites.

The main purpose of this paper is to gain further understanding on the effects of mainshock-aftershock seismic sequences in the response of essential buildings located in soft soil sites. Particular objectives of the investigation reported in this paper are: a) to study the influence of the ground motion features of artificial seismic sequences on the response of constant-ductility SDOF systems, b) to evaluate the benefit of using an importance factor of 1.5 in the design of the lateral strength of constant-ductility single-degree-of-freedom (SDOF) systems subjected to narrow-band seismic sequences, and c) to assess the response of an essential building designed with a displacement-based methodology under artificial seismic sequences.

2. SEISMIC SEQUENCES CONSIDERED IN THIS STUDY

This study is focused at the effects of aftershocks on the inter-story drift demands of regular frames located in soft soil sites. For this purpose, real (i.e. as-recorded) mainshock-aftershock acceleration time histories (hereafter denoted *seismic sequences*) are needed to perform nonlinear dynamic analyses and subsequent statistical studies. However, it was found that only two real mainshock-aftershock acceleration time-histories recorded at the Central de Abastos (CDAF) station during the September 19 and 20, 1985 earthquakes were available from the Mexican Database of Strong Motions (SMIS 1999). Therefore, this investigation employed a set of artificial seismic sequences as a representation of the seismic environment of the lake-bed zone of Mexico City. For this purpose, the seven earthquake ground motions included in Table 2.1 and recorded during two historical earthquakes were selected from the Mexican Database for Strong Motions. Note that all motions have a dominant period of motion (T_g) close to two seconds. Before generating the sequences, all mainshock accelerograms were scaled to reach the maximum peak ground velocity of the EW component of the motion recorded at the *Secretaria de Comunicaciones y Transportes* during the mainshock of the 1985 events (MX08). Thirty-five artificial sequences having T_{ga}/T_{gm} values of 1.2, 1.0, 0.9, 0.8 and 0.7, were generated by modifying the frequency content of some records. Within this context, T_{ga} is the dominant period of the aftershock, and T_{gm} that of the mainshock. Table 2.2 summarizes the value of dominant period of motion under consideration for the seismic sequences. Another parameter under consideration for the studies was the ratio of the peak ground acceleration of the aftershock, A_{ma}, and that of the mainshock, A_{mm}. Within this context, A_{ma}/A_{mm} ratios of 1.0, 0.9, 0.8 and 0.7 were considered for each artificial sequence with a given T_{ga}/T_{gm} ratio. Thus, a total of 140 artificial seismic sequences were considered in this study. Figure 2.1 shows one of the artificial seismic sequences used herein.

Table 2.1 Earthquake Ground Motions Considered In This Study

No.	Record	Date	Component	T_g (sec)	Nomenclature	A_{max} *(cm/sec^2)*
1	Alameda	04/25/89	NS	2.1	MX01	45.83
2	Alameda	04/25/89	EO	2.1	MX02	37.25
3	Garibaldi	04/25/89	NS	1.9	MX03	52.24
4	Tlahuac	09/19/85	EO	2.0	MX04	117.63
5	Tlahuac	09/21/85	NS	2.0	MX06	49.26
6	Tlahuac	09/21/85	EO	1.9	MX07	51.47
7	SCT	09/19/85	EO	2.0	MX08	167.26

Table 2.2 Artificial Seismic Sequences

Sequence	T_{gm}(sec)	T_{ga}(sec)	T_{ga}(sec)	T_{ga}(sec)	T_{ga}(sec)	T_{ga}(sec)
MX01_03	2.1	2.5	2.1	1.9	1.7	1.5
MX01_07	2.1	2.5	2.1	1.9	1.7	1.5
MX02_03	2.1	2.5	2.1	1.9	1.7	1.5
MX02_07	2.1	2.5	2.1	1.9	1.7	1.5
MX04_02	2.1	2.5	2.1	1.9	1.7	1.5
MX06_04	2.1	2.5	2.1	1.9	1.7	1.5
MX08_06	2.1	2.5	2.1	1.9	1.7	1.5

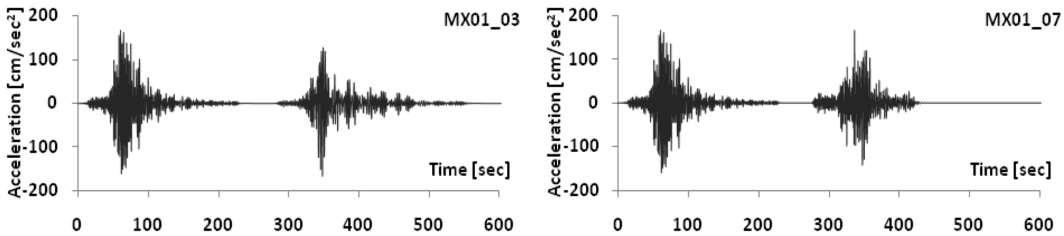

Figure 2.1. Artificial seismic sequences used in this study for a specific case of A_{ma}/A_{mm} = 1.0 and T_{ma}/T_{mm} = 1.2

3. INTER-STORY DRIFT DEMANDS IN SDOF SYSTEMS SUBJECTED TO SEISMIC SEQUENCES

A parametric study was performed to assess the effects of seismic sequences and, in particular, of aftershocks, in the response of SDOF systems that model the response of standard and essential frames. It should be noted that for regular frames that develop a weak beam/strong column mechanism and whose dynamic response is dominated by its first mode of vibration, the response of SDOF systems provide useful information about their roof displacement demand (δ_{max}), maximum inter-story drift index (IDI_{max}), plastic component of inter-story drift index (IDI^{p}_{max}), and other relevant seismic demands. An estimation of the aforementioned demands implies the use of some modification factors that transform the SDOF demands into MDOF demands (Terán-Gilmore 2004, Diaz et al. 2012).

Constant-ductility SDOF systems having 5% of critical damping and an elastoplastic behavior were subjected to the set of artificial sequences under consideration herein. The following relationship was used to characterize the lateral stiffness of the regular frames modeled through SDOF systems:

$$T = \beta N \tag{3.1}$$

where T is the fundamental period of vibration, N the number of stories of the regular frame, and β a dimensionless coefficient. Frames having from 1 to 50 stories were considered in this study.

Figure 3.1 shows mean-plus-one-standard deviation constant-ductility lateral strength spectra, S_a/g, corresponding to displacement ductilities (μ) of 2 and 4. These spectra were computed for systems subjected to the mainshocks listed in Table 3.1. Two sets of structural systems will be considered next: A) *Standard systems*, with a lateral strength that is established by considering directly the spectral ordinates shown in Figure 3.1, and B) *Essential systems*, with a lateral strength capacity that is 50% larger than that under consideration for the standard systems. These levels of lateral strength were assigned to the SDOF systems with the purpose of estimating and comparing interstory drift index demands on standard and essential frames. In consistency with the statistical characterization of the spectra shown in Figure 3.1, the mean-plus-one-standard deviation IDI_{max} demands will be considered next.

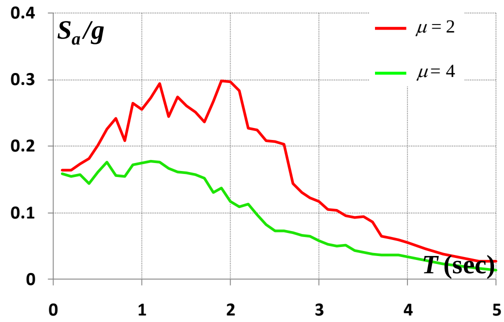

Figure 3.1. 5% damped pseudo-acceleration spectra for mainshocks recorded in soft soils

IDI_{max} spectra corresponding to the set of *standard and essential systems* subjected to the artificial sequences with A_{mm}/A_{ma} = 1.0 and three T_{ga}/T_{gm} ratios are shown in Figure 3.2. In general, the influence of the aftershocks tends to increase with an increase in the values of T_{ga}/T_{gm} and μ. Note that the effect of the aftershocks in terms of IDI_{max} is larger for a ductility of 4 than that for a ductility of 2; fact that can be explained by the smaller levels of lateral strength assigned to the former ductility level. The spectral region where aftershocks affect in a significant manner the seismic response of the SDOF systems starts at about 1.0 and 0.3 seconds for displacement ductilities of 2 and 4, respectively.

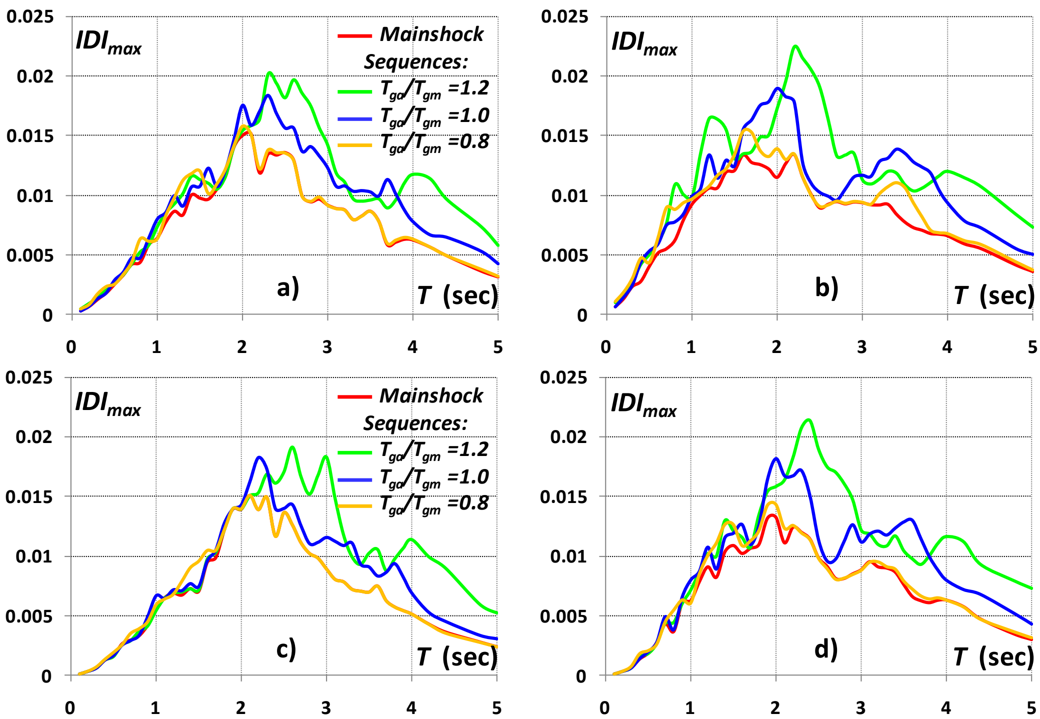

Figure 3.2. IDI_{max} demands for systems (standard group) subjected to artificial seismic sequences with A_{mm}/A_{ma} = 1.0, β = 0.10: a) Standard facilities, μ = 2, b) Standard facilities, μ = 4, c) Essential facilities, μ = 2, d) Essential, μ = 4

Figure 3.2 shows IDI_{max} spectra corresponding to standard and essential systems with μ = 4 and subjected to the set of sequences having T_{ga}/T_{gm} of 0.9 and three values of A_{mm}/A_{ma}. This case was considered relevant since most real mainshock-aftershock seismic sequences exhibit smaller predominant periods for their aftershocks (Ruiz-García 2012). In general, the A_{mm}/A_{ma} ratio does not have a significant influence in the response of the systems under consideration. Note that the use of an importance factor of 1.5 tends to better constraint the increments in the IDI_{max} demands in the essential facilities.

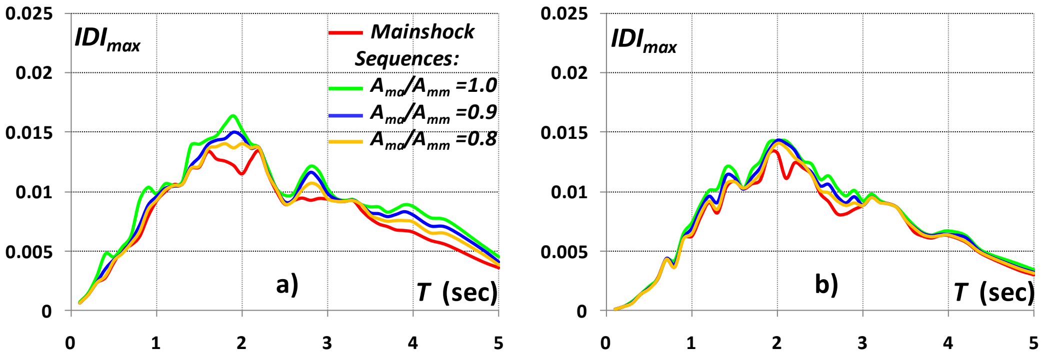

Figure 3.3. IDI_{max} demands for systems subjected to seismic sequences, T_{mm}/T_{ma} = 0.9, β = 0.10, μ = 4, a) Standard facilities, b) Essential facilities

Figure 3.4 shows IDI_{max} spectra corresponding to standard and essential systems with μ = 4 and fundamental periods established according to β = 0.08 (see Equation 3.1), when subjected to the set of sequences having A_{mm}/A_{ma} = 0.8 and three levels of T_{ga}/T_{gm}. A β of 0.08 implies that the structural systems are stiffer than those analyzed for the case of β = 0.1. In spite of their increased lateral stiffness and strength, seismic sequences still have the potential to trigger large IDI_{max} demands on essential systems having periods of vibration longer than two seconds. Once again, it can be observed that the T_{ga}/T_{gm} ratio has an important influence in the response of systems located in soft soil. Particularly, seismic sequences having a predominant period of the aftershock larger than that of the mainshock have an increased damage potential for the frames vulnerable to aftershocks.

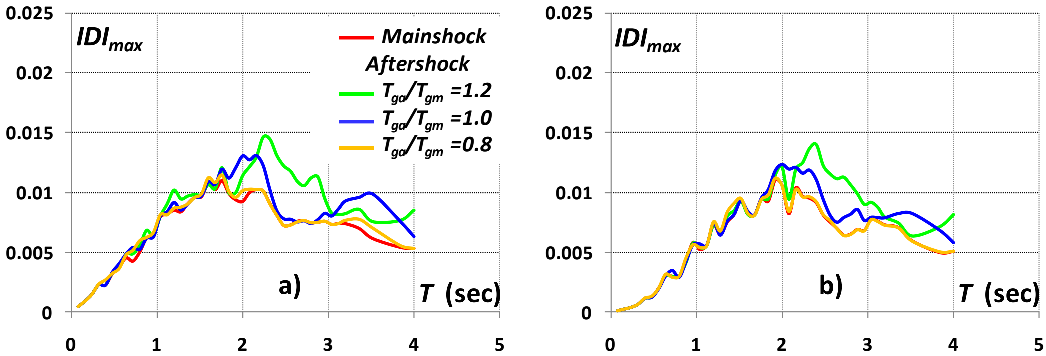

Figure 3.4. IDI_{max} demands for systems subjected to seismic sequences, A_{mm}/A_{ma} = 0.8, β = 0.08, μ = 4, a) Standard facilities, b) Essential facilities

Figure 3.5 shows IDI^{P}_{max} spectra for standard systems subjected to seismic sequences having T_{ma}/T_{mm} of 1.2 and A_{ma}/A_{mm} of 1.0. It can be seen that this response parameter is strongly influenced by the occurrence of an aftershock. Similar to other study-cases, the IDI^{P}_{max} demands tend to increase when the allowed displacement ductility increases. The levels of plastic interstory drift under consideration in Figure 3.5 illustrate the potential of aftershocks to induce larger plastic rotation demands, and thus structural damage and permanent drift, in regular frames.

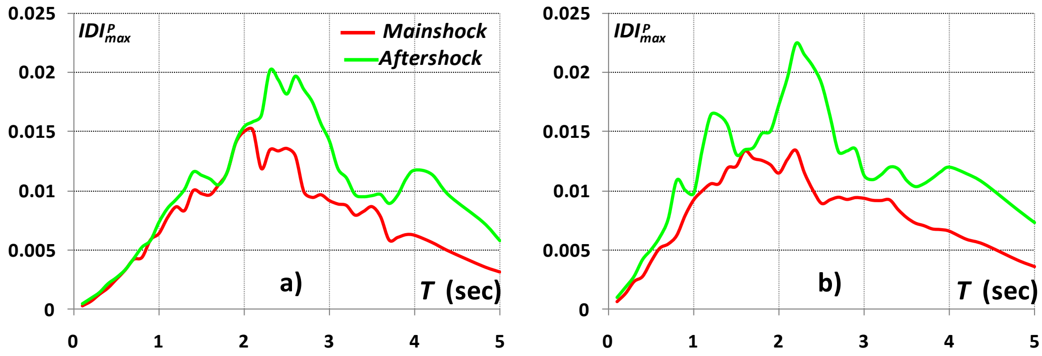

Figure 3.5. IDI^p_{max} demands for systems subjected to seismic sequences, T_{ma}/T_{mm} = 1.2, A_{ma}/A_{mm} = 1.0, β = 0.10, Standard facilities, a) μ = 2, b) μ = 4

From the results under consideration in this paper, it can be concluded in a preliminary manner that narrow-band seismic sequences can affect the dynamic response of standard and essential structures. In general terms, it can be said that as the value of T_{gm}/T_{ga} and A_{mm}/A_{ma} increase, the larger is the effect of the aftershock in the seismic response of regular frames. Nevertheless, it is possible to say that the effect of T_{gm}/T_{ga} is larger than that of any other parameter under consideration. Figure 3.6 schematically illustrates the effect of T_{gm}/T_{ga} and A_{mm}/A_{ma} in the response of regular frames subjected to the action of seismic sequences generated in soft soil. It should be emphasized that the importance factor used during the strength-based design of the systems under consideration has less effect on the dynamic response of the systems under consideration than the value of T_{gm}/T_{ga}, and A_{mm}/A_{ma}. Note that the worst case scenario is represented by the dark red color, while green represents cases in which an aftershock has no significant influence in the response of the structural systems.

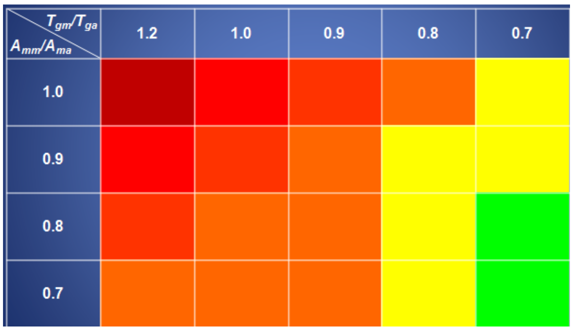

Figure 3.6. Color diagram representing influence of parameters T_{mm}/T_{ma} and A_{mm}/A_{ma} on response of systems studied herein when subjected to seismic sequences

4. EFFECT OF NARROW-BAND SEISMIC SEQUENCES IN INTER-STORY DRIFT DEMANDS OF AN ESSENTIAL BUILDING

The effect of narrow-band seismic sequences in the response of an essential steel building was studied in the second stage of this investigation. A displacement based-design methodology (Diaz et al. 2012) was used for determining the required lateral stiffness and strength of the steel framing system shown in Figure 4.1, which is assumed to be located in the Lake-bed Zone of Mexico City. The frame was designed through the consideration of a threshold value of 0.010 for its inter-story drift index demand (IDI^{IO}_{NS}) and a threshold value of 0.005 for the maximum plastic rotation demand allowed in the structural members of the frames. The former thresholds are assumed to allow for an essential facility capable of satisfying the immediate occupancy performance level in non-structural and structural terms, respectively. In addition, the frame was designed to meet a weak-beam/strong-column criterion according to a capacity design approach. A detailed description of the design process can be found in (Diaz et al. 2012).

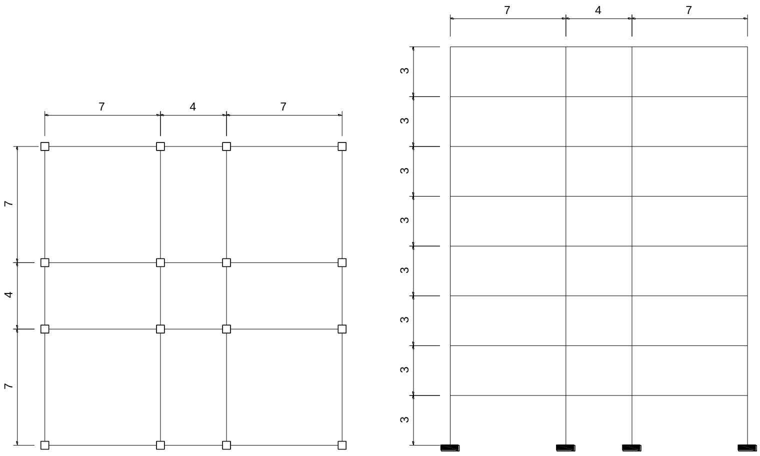

Figure 4.1. Plan and elevation view of building under consideration (dimensions in meters)

For the sizing of the frame, square box sections were considered for the columns and W-shape sections for the beams. In the design process, A36 steel was considered for the structural elements. Table 4.1 summarizes the sizes of beams and columns of the frame. A fundamental period of 0.97 seconds was determined for the frame.

Table 4.1. Cross Sections for Beams and Columns of Both Versions of the Frame

Stories	T = 0.97 sec		
	Columns		Beams
	Side (cm)	Plate thickness (cm)	Section
1-3	60	2.540	W18X86
4-6	55	1.905	W18X76
7-8	50	1.905	W18X60

A detailed two-dimensional non-linear model of the building was prepared to assess its seismic performance with the DRAIN 2DX program (Prakash et al. 1993). While the beams of the frame were assigned a bilinear behavior with 2% strain-hardening, the model of the columns considered the combined effect of bending and axial load and a bilinear behavior with no strain hardening. Expected material strengths were used to estimate the structural properties of beams and columns. Particularly, the expected yield stress of the steel was considered to be 20% larger than its nominal value. P-Δ effects were considered through a geometric stiffness matrix, and the base of the columns on the ground story were assumed to be rotationally fixed. In the case of the dynamic non-linear analyses, the non-linear model of the frames considered 5% of critical damping through a Rayleigh matrix that assigned the indicated damping to the first two modes of vibration.

To help understand the effect of the aftershocks on the response of the framed building under consideration, two sets of artificial seismic sequences were defined. The sequences were characterized by motions having: a) T_{gm}/T_{ga} = 1.2 and A_{mm}/A_{ma} = 0.9; and b) $T_{gm}/\ T_{ga}$ = 1.0 and A_{mm}/A_{ma} = 0.8. Fig. 4.2 shows mean-plus-one-standard deviation inter-story drift index and plastic rotation demands along height for the building. Note that the figure contemplates the demands corresponding to the earthquake ground motions used to establish the design spectra for the frames (i.e., mainshock earthquake ground motions), and those demanded by the seismic sequences under consideration herein. It can be observed that although the frame is able to adequately control its IDI_{max} and maximum plastic rotation demands within its design threshold (0.010) when it is subjected to the set of mainshocks, both demands increase as a consequence of the aftershocks. Under this circumstance, the frame is able to satisfy the performance level of Immediate Occupancy when it is subjected to mainshocks, but it might not perform well if it is subjected to a seismic sequence with the specified ground motion characteristics.

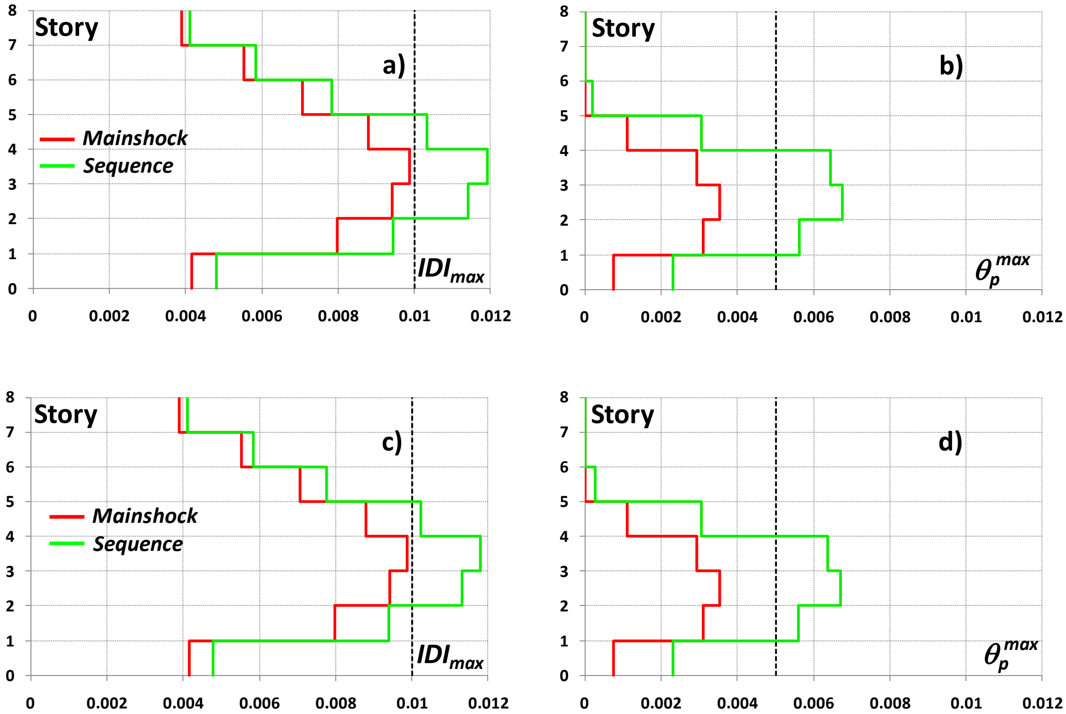

Figure 4.2. Maximum deformation demands along height for building under consideration:
a) IDI_{max}, $T_{gm}/\ T_{ga} = 1.2$, $A_{mm}/A_{ma} = 1.0$; b) θ_p^{max} $T_{gm}/\ T_{ga} = 1.2$, $A_{mm}/A_{ma} = 1.0$;
c) IDI_{max}, $T_{gm}/\ T_{ga} = 0.9$, $A_{mm}/A_{ma} = 0.8$; d) θ_p^{max} , $T_{gm}/\ T_{ga} = 0.9$, $A_{mm}/A_{ma} = 0.8$

6. CONCLUSIONS

Essential buildings are complex systems that exhibit a high vulnerability to the action of earthquakes. To date, the dynamic response of essential facilities located in soft soils and subjected to seismic sequences has not been evaluated. In this work, inter-story drift demands of essential regular frames were estimated through the use of an equivalent SDOF model. Several parameters associated to seismic sequences and models were studied.

The impact that parameters T_{ga}/T_{gm} and A_{mm}/A_{ma} have on the response of the systems under consideration herein was studied. The effect of aftershocks in their dynamic response is greater as the value of these two ratios increase. Nevertheless, the influence of parameter $T_{ga}/\ T_{gm}$ is larger than that of any other parameter under consideration herein. It can be concluded that although the use currently given to the importance factor within strength-based formats may have an important influence in the dynamic response of essential structures, the influence of parameters such as $T_{ga}/\ T_{gm}$ and A_{mm}/A_{ma} may be even larger.

An essential facility designed according to a displacement-based design methodology was subjected to a set of sequences. Inter-story drift demands in a MDOF model of the essential facility corroborate the conclusions previously obtained from the study of SDOF systems, since the response demands are larger when the system is subjected to the mainshock-aftershock seismic sequences with large values of T_{ga}/T_{gm} and A_{mm}/A_m.

AKCNOWLEDGEMENTS

While the first author would like to thank *Universidad Michoacana de San Nicolás de Hidalgo*, the second and third author would like to acknowledge *Universidad Autonoma Metropolitana*. All authors would like to express their gratitude to the *National Council for Science and Technology* (CONACYT) in México for the financial support provided to develop the research reported in this paper.

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