PARAMETRIC STUDY FOR SOFT STORY STRUCTURAL MODELS SUBJECTED TO GROUND MOTIONS TYPICAL OF SOFT SOILS

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Abstract

A parametric study where two-degree of freedom (2DOF) simplified models are used to represent structures likely to develop soft stories is presented. Different stiffness and strength balances were considered to define a realistic range of structures with the potential to develop soft story mechanisms according to recommendations of current seismic building codes. Therefore, 338 models were studied for all the considered stiffness and strength combinations which represent typical buildings structures with soft stories currently built in the lakebed zone of Mexico City. Step by step nonlinear dynamic analyses were conducted using 10 artificial acceleration records generated to be compatible with the design spectrum for zone III-a of 2004 Mexico´s Federal District Code (RCDF-2004), corresponding to soft soil conditions in Mexico City. Peak ductility demands and story drifts were obtained, which were compared with some reference value currently proposed in building codes. The results obtained from this parametric study mostly confirm that a soft story mechanism is triggered or prevented with a right combination of strength and stiffness balances for the structural system, which are close to what it is currently proposed in Mexican seismic building codes.

Keywords: soft story, stiffness and strength balances, ductility demands, story drifts, nonlinear dynamic analyses, soft soil acceleration records.

1. Introduction

Nowadays, it is common to design a large inventory of buildings likely to develop a soft story at urban zones. These buildings, which are primarily structured with reinforced concrete frames with infill walls, have a story, usually the first story, with little presence or absence of infill walls, because it is used for parking or retail stores frequently. In contrast, from the second story to the roof many infill and partition walls are used to carry vertical loads or to divide spaces, as they are used as offices or apartments. Therefore, these structural changes along the height causes that the lateral stiffness and strength are much greater at the upper stories than at the first story, favoring the development of a first soft and weak story (Fig. 1). The soft story is a very harmful vertical irregularity condition: many buildings with these characteristics have collapsed or severely damaged during most major earthquakes worldwide.

Fig. 1 - Example of buildings, structured with reinforced concrete frames and infill masonry walls, where the first story is likely to develop a soft story (www.ingcivil.org)

When buildings with these structural characteristics are founded on soft soils (such as saturated sand, unconsolidated clay, etc., representative soils in Mexico City), demands in columns of the soft story will be greater due to further displacements generated by the large movements in the soft soil transmitted to the structure when a seismic event come. This has been mostly observed in midrise buildings between six to ten levels where first soft story has presented damage.

Also, it is common to find buildings with a soft story condition not only at the first story, but also at intermediate or upper stories, in stories commonly known to possess “a double height”. At this kind of stories, structural elements have a much greater flexibility in comparison to the neighboring stories (Fig. 2).

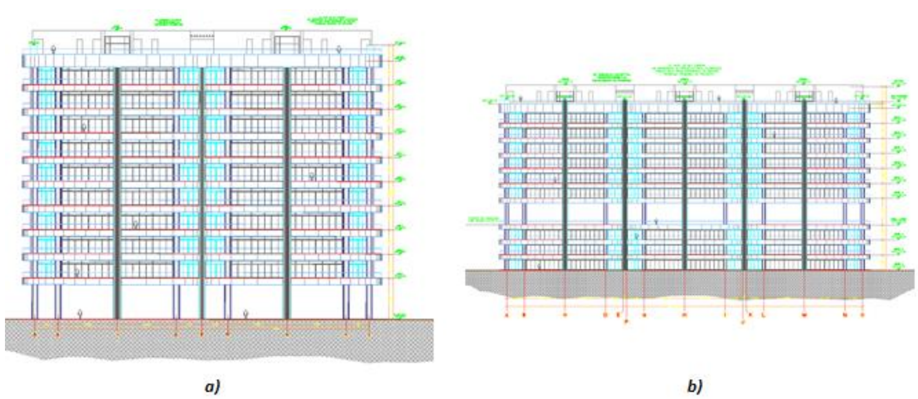


Fig. 2 - Examples of buildings with a double height at the: a) first story and, b) intermediate stories (AHA Universo)

Therefore, there are many reasons that favor the development of a soft story in a structure, such as [1]:

- A height much larger in a given story than the typical story height, which causes a smaller lateral stiffness in the story with the larger height.
- An abrupt change of stiffness between two consecutive stories.
- Discontinuities because of vertical and/or horizontal structural changes.
- Columns interruptions between two consecutive stories.
- Structural walls (shear walls) interruptions between two consecutive stories.
- The use of infilled walls to carry lateral loads and to reduce lateral displacements. In many instances, these walls are erroneously considered as partition walls and are only idealized as loads on frames.

2. State of the Art: Behavior of structures with soft stories in past earthquakes

At a seismic event, displacement demands at the soft story are greater in comparison with neighboring stories due to stiffness and strength contrasts. Also, if the bending moments due to gravitational loads are considered (*P-Δ* effects), the lateral strength of the structural elements could be surpassed or even a structural collapse may be reached [2, 3]. When there is a first soft story irregularity condition, under a dynamic excitation the upper portion of the building tends to move as a rigid body, whereas the columns in the soft story have to resist very large shear forces and bending moments. If the soft story columns have enough strength to bear those demands, then the building will have a reasonable behavior. Otherwise, the building would experience very important damage (flexural or shear hinges at columns), or even a partial or total collapse for the building.

Failures and collapses at buildings with soft stories have occurred and documented in strong earthquakes for more than fifty years ago. Some strong earthquakes where soft stories have been documented are [4]: 1967 at Caracas, Venezuela (July); 1971 at San Fernando, California (February); 1972 at Managua, Nicaragua (December); 1985 at Viña del Mar, Chile (March); 1985 at Mexico City, Mexico (September); 1989 at Loma Prieta, California (October); 1994 at Northridge, California (January); 1995 at Kobe, Japan (January); 1999 at Puebla, Mexico (June); 1999 at Taipei, Taiwan (September); 1999 at Izmit, Turkey (October); 2006 at Jakarta, Indonesia (May); 2007 at Pisco, Peru (August); 2008 at Wenchuan, China (May); 2009 at L'Aquila, Italy (April); 2010 at Port of Prince, Haiti (January); 2010 at Concepcion, Chile (February), etc. During the September 19, 1985 earthquake at Mexico City, it was reported that about 8% of the total building collapses were related to a soft story irregularity condition [4, 5]. Buildings with structural failures due to a soft story condition at the first story after an earthquake are shown at Fig. 3.

Fig. 3 - Structural failures at the first story columns due to a soft story configuration [6]

2.1. Mexican seismic code provisions

Some countries consider the soft and weak story phenomena as an irregularity condition at their current seismic codes. The soft story irregularity condition was introduced in Mexico´s Federal District Code (RCDF) since its 1987 edition, being one of the pioneering seismic codes worldwide on defining conditions of structural irregularities. At present, in the current seismic design guidelines (NTCS-2004) of RCDF [7] it is established that the lateral shear stiffness or strength of any story shall not exceed by more than 50 percent the shear stiffness or strength of the story below the one in consideration, i.e. (Eq. 1):

$$\begin{cases} K_{i+1} \leq 1.5K_i \\ V_{i+1} \leq 1.5V_i \end{cases} \tag{1}$$

Otherwise, it should be applied a reduction factor for structural irregularity at the design process, this is, the irregular soft story building should be design for higher lateral forces with respect to a counterpart regular building.

3. Parametric study using two-degree of freedom (2dof) models

In order to evaluate the adequacy of the proposed limits in NTCS-2004 (Eq. 1), a parametric study was performed using simplified two-degree of freedom systems (2dof, Fig. 4) considering an elastic perfectly-plastic behavior. The relations k_2/k_1 and V_2/V_1 were varied, where k_2 and k_1 are the lateral stiffness for the second and the first stories respectively, whereas V_2 and V_1 are the lateral strength for the second and the first stories respectively (Fig. 4).

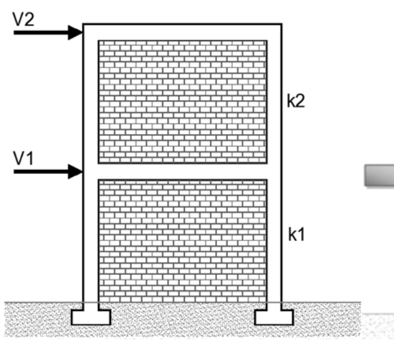
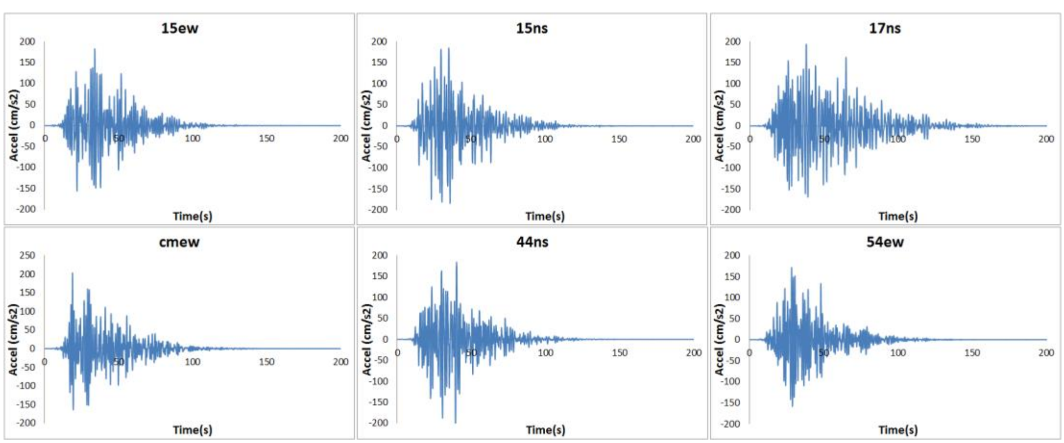


Fig. 4 – 2DOF system used in the parametric study

Step by step nonlinear dynamic analyses using the 2dof systems were performed using Drain-2dx [8] considering typical ground motions of the lakebed zone of Mexico City (zone III-a of NTCS-2004) represented through 10 artificial acceleration records (Fig. 5). These records were generated by Godínez [9] and Pérez-Rocha [10] to match the design spectrum of Appendix A of NTCS-2004 for a site with a period T_s=1.4s (Fig. 6), according to the methodology reported elsewhere [11].



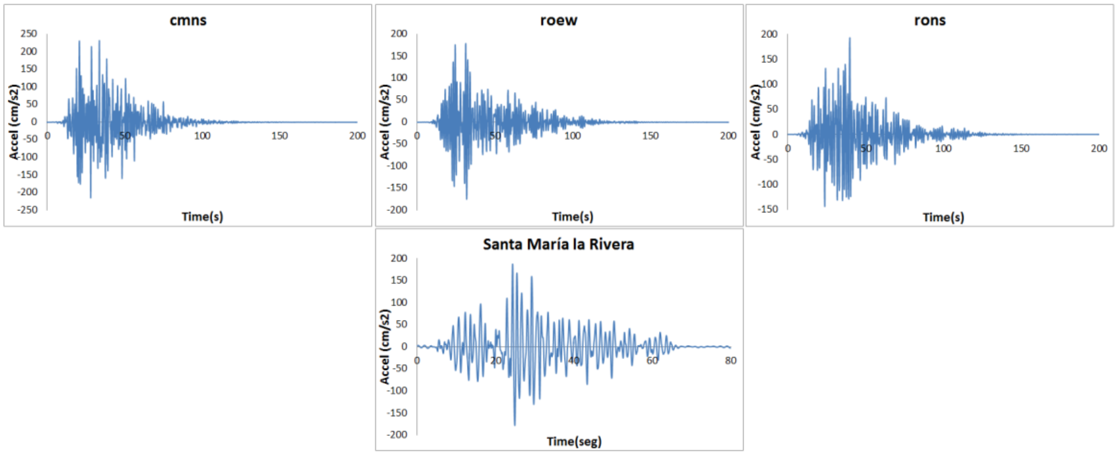


Fig. 5 - Artificial acceleration records for lakebed zone III-a of Mexico City (T_s=1.4s) [9, 10, 11]

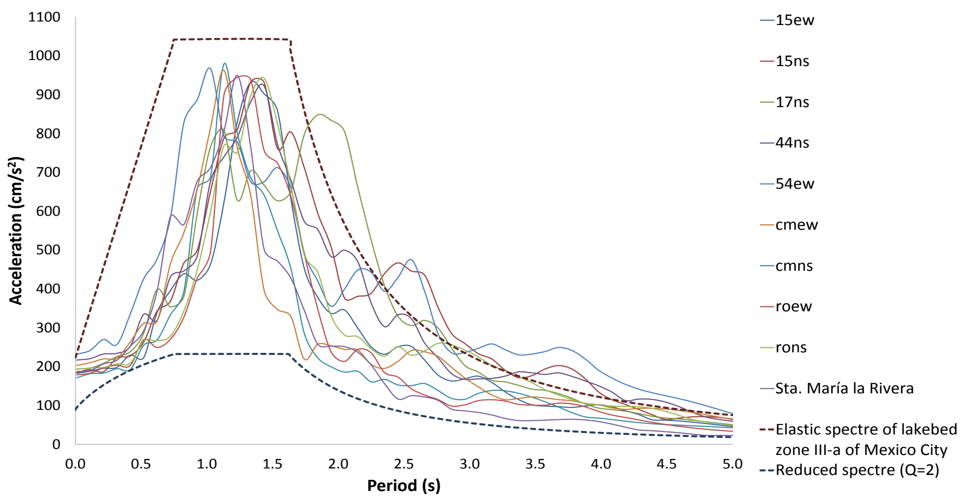


Fig. 6 - Design spectrum and corresponding response spectra for the artificial acceleration records. Design spectra reduced using a seismic response modification factor Q=2 (according to NTCS-2004)

3.1. Definition of dynamic properties for the 2dof models

Miranda [12] proposed an equation (Eq. 2) to compute the fundamental period (T) of structures with a soft story configuration in function of the fundamental period for a regular structure (T_{reg}) and the lateral stiffness ratio k_1/k_2:

$$\frac{T}{T_{reg}} = \frac{1}{-13.62 + 14.6\left(k_1/k_2\right)^{0.015}} \tag{2}$$

Nevertheless, Miranda did not precise about the characteristics of the models he used to define his equation. Then, it was decided to define an equation (Eq. 3) using the results of numerical simulations of prototype structural models considering 2dof systems, estimating in this manner the variation of the fundamental period (T) of structures with a soft story configuration in function of their lateral stiffness ratio (k_2/k_1) and the fundamental period of a regular structure. Therefore, 7600 simulations were done and using a regression based upon least squares method, Eq. 3 was obtained. Miranda´s equation (Eq. 2) and the proposed one (Eq. 3) are compared in Fig. 7 with the medium regression curve obtained from the 2dof data obtained from the numerical simulations. It can be observed from Fig. 7 that, as expected, a better adjustment is obtained with Eq. 3, which it was the one used to define dynamic properties for the 2dof simulations.

$$\frac{T}{T_{reg}} = 0.63205 + \frac{0.32513}{k_2/k_1} \Rightarrow T = \left(0.63205 + \frac{0.32513}{k_2/k_1}\right) T_{Reg} \Leftrightarrow k_2/k_1 = 0.25, 0.50, 0.66, 0.75, ..., 3.0 \tag{3}$$

where $\rightarrow T_{reg} = T_{fun}$

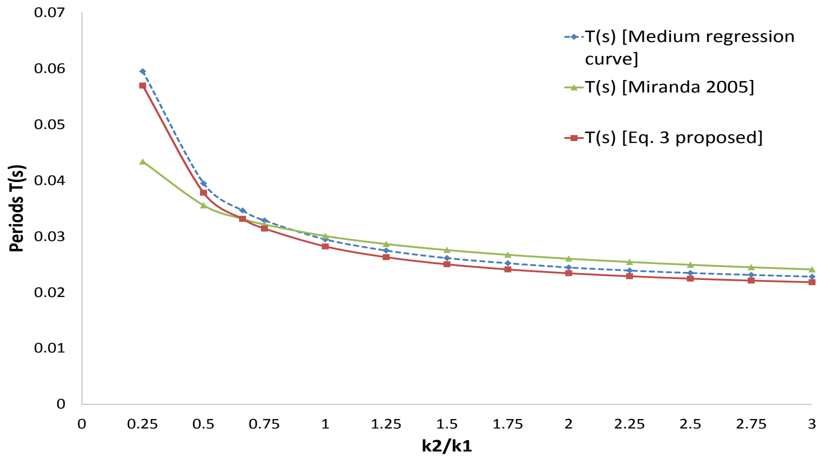


Fig. 7 - Comparison among median curve for 2dof systems (blue line), the equation proposed by Miranda [12] (green line) and Eq. 3 proposed at this study (red line)

Lakebed zone III-a was among the most severely punished regions in Mexico City during the 1985 Michoacán earthquake. Many apartment buildings and condos with soft first stories collapsed at the times. Nowadays, there are still too many apartment buildings with soft first stories. Typical soft-story buildings have a total height ranged from six (6N) to eight (8N) stories, particularly at neighborhoods of zone III-a. Therefore, the soft-story, 2dof systems were defined in terms of benchmark 3D, regular building models: a six (6N) and eight (8N) story buildings modeled and designed with the structural program ETABS (Fig. 8). The considered structural system for the building models is reinforced concrete frames with masonry infill walls, which it is the most commonly used in Mexico City for buildings with soft story potential. Both models are regular in terms of stiffness and strength ($k_{n+1}=k_n$ and $V_{n+1}=V_n$ at all levels) having the same plan distribution, story heights and structural elements geometries (Fig. 8).

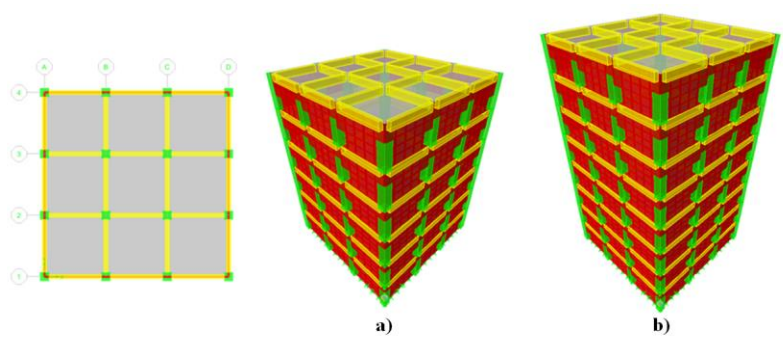


Fig. 8 - Plan and 3D views of models: a) 6N with fundamental period T=0.328s and, b) 8N with fundamental period T=0.452s

Therefore, the natural periods for the 2dof systems representing the soft story models were determined in function of the fundamental periods for the 6N (T=0.328s) and 8N (T=0.452s) regular models and the stiffness ratio k_2/k_1 using Eq. 3, in a range $0.25 \leq k_2/k_1 \leq 3.0$ at *0.25* increments considering also the ratio $k_2/k_1=0.66$. Then, estimating the natural periods for the 2dof soft story models with Eq. 3, assuming a uniform mass distribution ($m=m_1=m_2$), and solving the 2dof eigenvalue problem in terms of k_1 (as k_2 is defined as $k_2=nk_1$), Eq. 4 was obtained to compute the story lateral stiffness the 2dof systems:

$$k = k_1 = \frac{10.472\pi^2 m}{T_{fun}^2} \Rightarrow k_2 = nk_1 \rightarrow n = 0.25, 0.50, 0.66, 0.75, 1.0, ..., 3.0 \quad (4)$$

Similarly, the uniform mass for the given stiffness ratio $n= k_2/k_1$, m_n is computed as (Eq. 5):

$$m_n = \frac{T^2\left(k_1 + 2k_2 - \sqrt{(k_1+2k_2)^2 - 4k_1k_2}\right)}{8\pi^2} \Leftrightarrow n = 0.25, 0.50, 0.66, 0.75, 1.0, ..., 3.0 \quad (5)$$

Since Drain-2dx software was used for the nonlinear dynamic simulations, a calibration was done between the fundamental periods obtained with this software (using the lateral stiffness and masses computed in Eqs. 4 and 5) by comparing with those obtained with Eq. 3. A perfect match was obtained for most k_2/k_1 ratios and small differences (less than 5 percent) were only observed when $k_2/k_1=0.25$ and $k_2/k_1=0.50$ (Fig. 9), so for practical purposes, the calibration was correct.

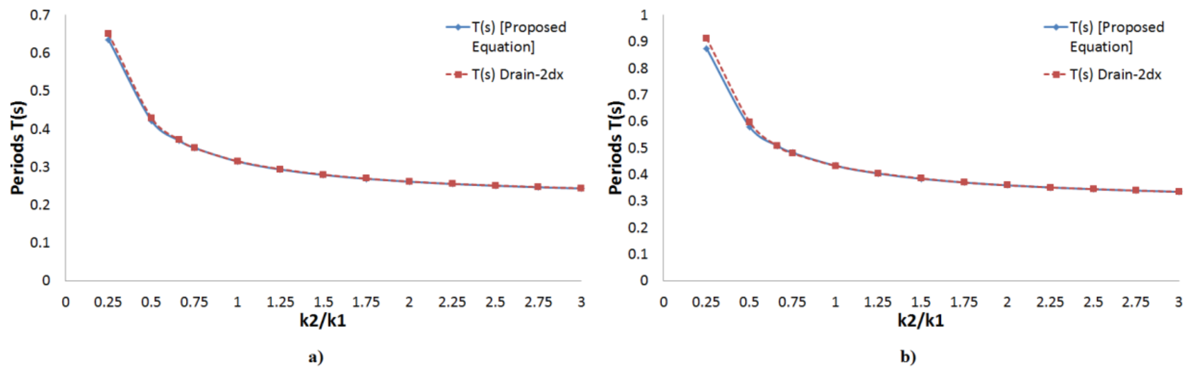


Fig. 9 – Period calibration of the 2dof systems representing the models: a) 6N (T_{fun}=0.328s) and b) 8N (T_{fun}=0.452s)

The lateral base shear (V_n) for the 2dof systems was assessed from the pseudo-accelerations of the design spectrum for zone III-a (Fig. 10) in function of the computed fundamental periods (Eq. 3) and using a seismic response modification factor Q=2 specified in Mexico´s Federal District Code [7] for reinforced concrete frames with infill walls, which it is the most common structural system used in buildings with soft stories. The story shear strength for each model was defined considering the following strength variations: at $0.25 \leq V_2/V_1 \leq 3.0$ at 0.25 increments including $V_2/V_1=0.66$ also.

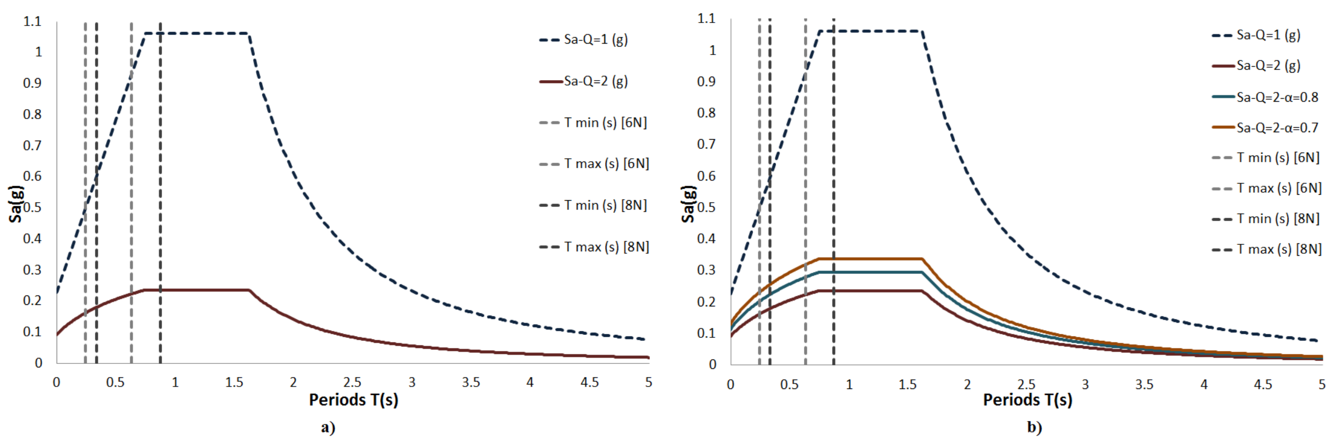


Fig. 10 - Period ranges for the 2dof systems representing the 6N and 8N models and their corresponding design spectrum: a) regular buildings and, b) irregular buildings (using α correction factors)

For regular buildings, the resulting design spectrum is the one identified in Fig 10a as S_a Q=2. According to Mexican seismic codes, a correction factor for structural irregularity (identified in this paper as α) must be applied when important k_2/k_1 and V_2/V_1 ratios exist and define a soft or weak story, modifying the design spectrum and resulting higher design spectral ordinates (Fig. 10b). Therefore, in NTCS-2004 [7] it is proposed to use the following correction factors: a) for irregular structures α=0.8 when $1.5 \leq k_2/k_1 \leq 2.0$ or $0.5 \leq k_2/k_1 \leq 0.667$ or $1.5 \leq V_2/V_1 \leq 2.0$ or $0.5 \leq V_2/V_1 \leq 0.667$; b) for strongly irregular structures α=0.7 when $k_2/k_1 > 2.0$ or $0.5 < k_2/k_1$ or $V_2/V_1 > 2.0$ or $0.5 < V_2/V_1$. Formerly, in RCDF-1987 [3] it was proposed to use a general correction factor for structural irregularity α=0.8 when $k_2/k_1 > 2.0$ or $0.5 < k_2/k_1$ or $V_2/V_1 > 2.0$ or $0.5 < V_2/V_1$.

3.2. Average responses from nonlinear dynamic analyses

Nonlinear dynamic analyses were conducted for the 2dof systems under the action of 10 artificial acceleration records which were obtained as explained elsewhere [9-11] and are fully compatible to the design spectrum for zone III-a (Fig. 3), as mentioned before. Among the processed results, peak global and story ductility demands were obtained, computed from the ultimate and yield displacement demands obtained from Drain-2dx analyses, for each 2dof system for each record. Then, mean responses were obtained and peak response envelope curves were defined. Some of these envelope curves are depicted in Figs. 11 to 15, with or without using the correction factors for structural irregularity α.

The average peak global ductility curves representing the 6N model are depicted in Fig. 11, for each considered stiffness (k_2/k_1) and strength (V_2/V_1) ratio. It can be observed in Fig. 11 that unreasonable peak ductility demands were obtained for all k_2/k_1 values when $V_2/V_1=0.25$, representing a theoretic numerical collapse for the 2dof system. In fact, very similar peak responses were obtained for the 8N model for $V_2/V_1=0.25$. The very large ductility demands were also obtained for the 2dof systems with $V_2/V_1=0.25$ when applying the correction factors for structural irregularity α. Therefore, it was confirmed that weak and soft stories structural collapses are prone in zone III-a for buildings from 6 to 8 stories when $V_2/V_1=0.25$, even if they are designed according to the guidelines of a modern building code.

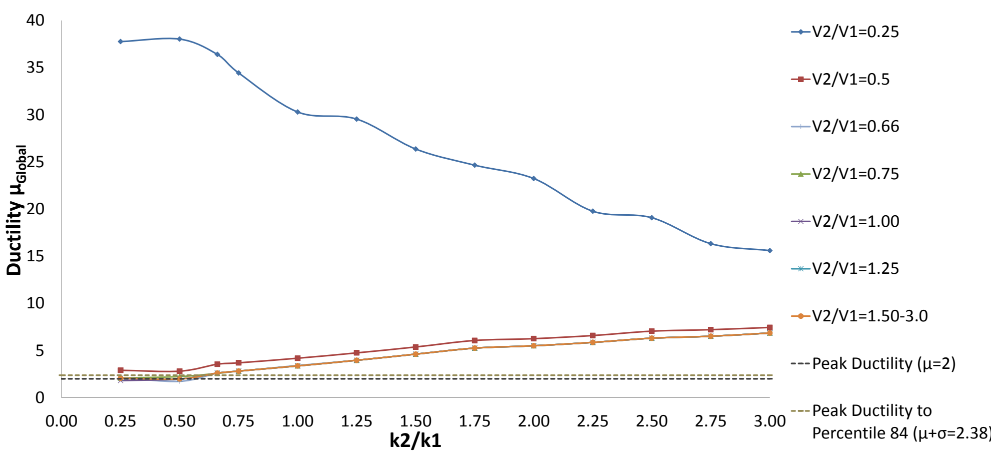


Fig. 11 – Peak global ductility demands vs. stiffness ratios, mean envelope curves corresponding to the 6N model, without using correction factors α

In order to ease the comparison for the remaining strength ratios V_2/V_1, in Figs. 11 to 15 the strength ratio $V_2/V_1=0.25$ is omitted as theoretical weak story collapses are always obtained. Also, in Figs. 12 and 13 two straight lines are used to highlight the following: a) the peak displacement ductility demand μ=2 directly related to the seismic response modification factor Q=2 used for the design of the 2dof models and, b) an statistical limiting value μ=2.38 (Eq. 6), taking into account one standard deviation (σ) related to the uncertainties in the ground motions considered in NTCS-2004 at the time of defining the response spectrum:

$$\bar{\mu} = \mu + \sigma = \mu\left(\frac{1}{0.84}\right) = 2(1.19) = 2.38 \tag{6}$$

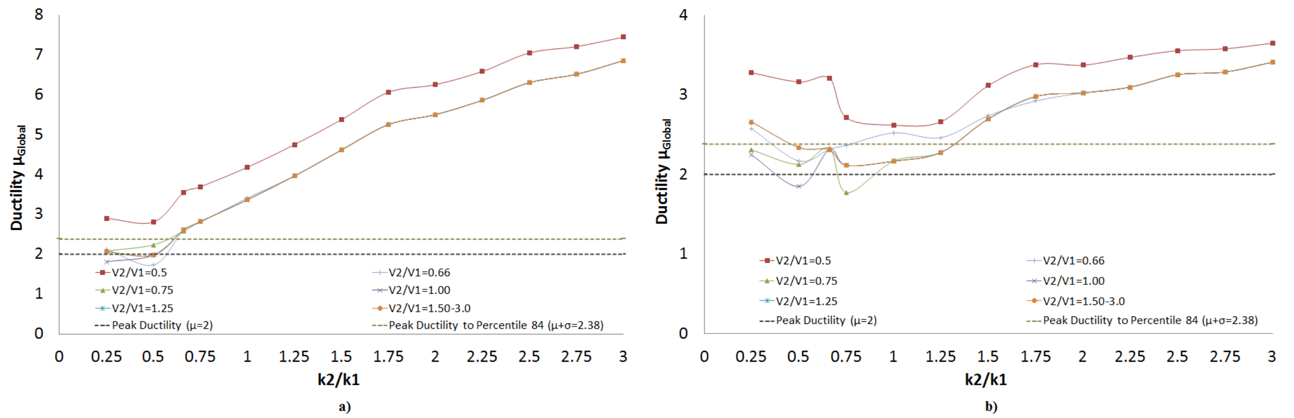


Fig. 12 – Peak global ductility demands vs. stiffness ratios, mean envelope curves without using correction factors α: a) 6N model and, b) 8N model

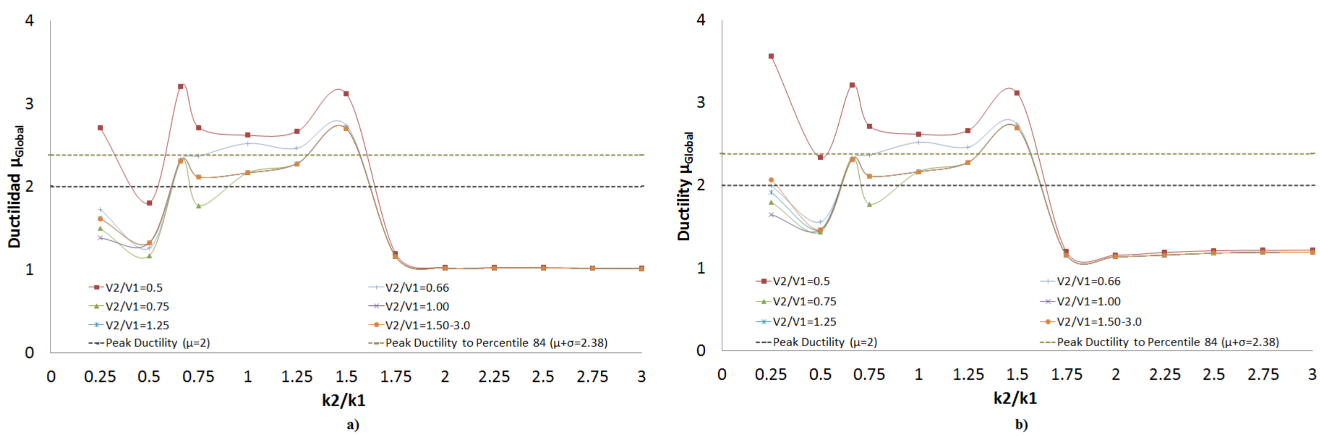


Fig. 13 - Peak global ductility demands vs. stiffness ratios, mean envelope curves for the 8N model: a) using a correction factor α=0.7 and, b) using a correction factor α=0.8

Comparing the peak global ductility demands with these limiting values, it can be observed in Fig. 12a (6N model results) that they are smaller than the ductility limiting values only when $k_2/k_1=0.50$ for the strength ratio $V_2/V_1 \geq 0.66$, the meaning of which is that the system could develop considerable damage for greater demands. For the 8N model, the range of stiffness ratios where peak responses were smaller than the limiting values was wider ($0.50 \leq k_2/k_1 \leq 1.25$ for the strength ratio $V_2/V_1 \geq 0.75$ and $k_2/k_1=0.50$ to $k_2/k_1=0.75$ for strength ratio $V_2/V_1 \geq 0.66$). It can be also observed from Fig. 12 that the same average peak global ductility demands were obtained for all curves when the strength ratio is $V_2/V_1 \geq 1.25$.

Analyzing the resulting curves obtained using the reduction factors for structural irregularity α=0.7 and α=0.8 (Figs. 13a and 13b, 8N model), it can be observed that the use of this structural irregularity factor is helpful to reduce the global nonlinear system response satisfactorily, decreasing the risk to develop a soft or weak story. Nevertheless, the difference between the obtained results using α=0.7 (Fig. 13a) or α=0.8 (Fig. 13b) is small when $k_2/k_1 \geq 2.0$, so perhaps it might be enough to modify the system response positively to use a correction factor for structural irregularity α=0.8, pending, of course, of more exhaustive series of simulations to corroborate these tendencies for other buildings heights and characteristics for the ground motions.

In order to evaluate the adequacy of the stiffness and strength ratio limits proposed in NTCS-2004, it was analyzed the possibility to develop a soft or weak story in any story for the 2dof systems [13]. For space constraints, only the results obtained for the 8N model are shown in Figs. 14 and 15. Therefore, normalized curves with respect to the demand of the benchmark 2dof "regular system" in stiffness, defined in this work as the 2dof system where $k_2/k_1=1.0$, are presented in Figs. 14 and 15. Dotted lines are used in Figs. 14 and 15 to depict reference limiting values to ease finding a potential soft or weak story response, the meaning of which are:

1) If $\mu/\mu_{reg}=1.0$, the 2dof system responds as a regular structure.
2) If $1.0<\mu/\mu_{reg}\leq 1.5$ or $1.0>\mu/\mu_{reg}\geq 0.66$, the 2dof system may be considered as reasonably regular.
3) If $1.5<\mu/\mu_{reg}\leq 2.0$ or $0.66>\mu/\mu_{reg}\geq 0.50$, the 2dof system develops a soft/weak story condition.
4) If $\mu/\mu_{reg}>2.0$ or $\mu/\mu_{reg}<0.50$, the 2dof system develops a strong soft/weak story condition.

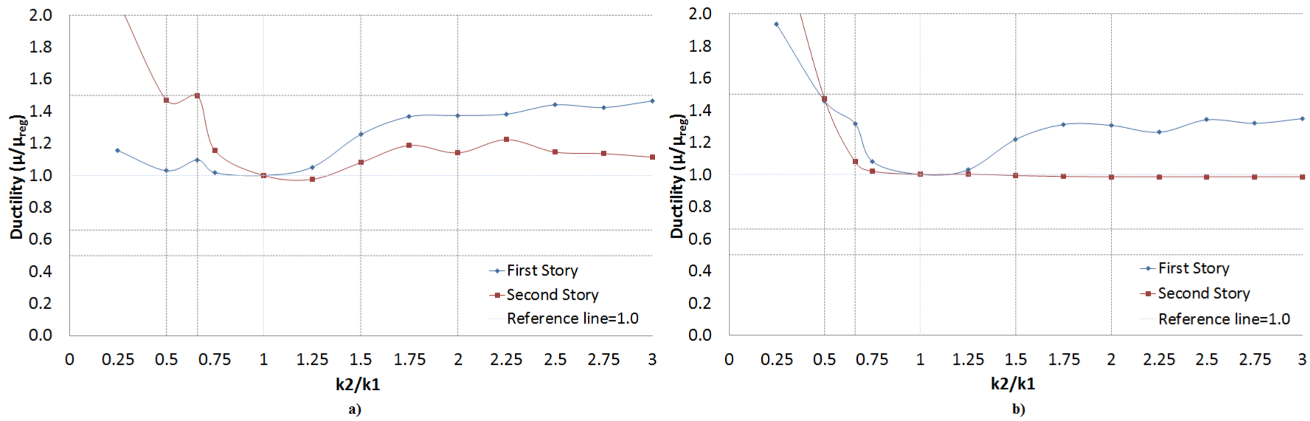


Fig. 14 – Comparison between normalized ductility demands for each story for the 2dof system, representing the 8N model, for: a) $V_2/V_1=0.50$ strength ratio and b) $V_2/V_1=0.66$ strength ratio

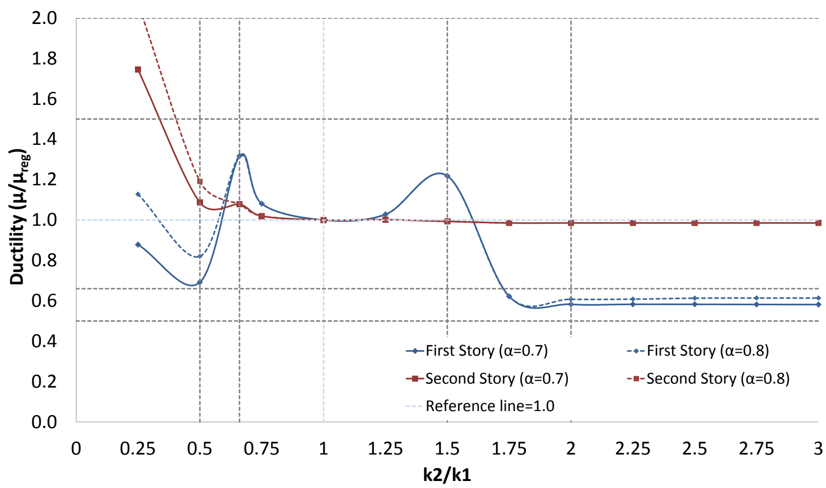


Fig. 15 - Comparison between normalized ductility demand for each story for the 2dof system, representing the 8N model, when $V_2/V_1=0.66$, using correction factors for structural irregularity α=0.7 and α=0.8

A balanced inelastic behavior in both stories is observed from the curves corresponding to the strength ratio $V_2/V_1=0.50$ (Fig. 14a), averting a soft story mechanism when $k_2/k_1\geq 0.50$. Nevertheless, for this strength ratio, peak ductility demands greater than the limiting values were obtained (Fig. 12), being an undesirable structural behavior. For the curve when $V_2/V_1=0.66$ (Fig. 14b), the 2dof systems apparently respond similar to the benchmark regular structure when $0.50\leq k_2/k_1\leq 3.0$. However, they develop a clear weak/soft first story [13], presenting greater normalized demands at the first story rather than at the second story when $k_2/k_1\geq 1.50$. In fact, from the peak story ductility demand curves (not shown), it is clearly observed that the second story presents an elastic behavior [13]. Similar results were obtained for the 2dof system representing the 6N model [13]. Clear soft first stories are developed when $V_2/V_1\geq 0.75$ for all the stiffness ratios k_2/k_1 under study (not shown, [13]).

A significant reduction of peak first story ductility demands are obtained when using the correction factors for structural irregularity α=0.7 and α=0.8 when $V_2/V_1=0.66$ (Fig. 15), and that it is why the shape of the normalized curve for the first story abruptly changes with respect to the one depicted in Fig. 14b, primarily when $k_2/k_1 \geq 1.50$. Normalized curves for the second story do not change because an elastic behavior is obtained with (Fig. 15) or without (Fig 14b) using the α factor. The results shown in Fig. 15 lead one to conclude that applying the reduction factor α is helpful to minimize considerably the risk of developing a soft/weak story. Likewise, doing a comparison between the results obtained using both reduction factors, α=0.7 and α=0.8, it is observed that the difference is minimal when $k_2/k_1 \geq 1.75$, whereas for $k_2/k_1=0.50$ is slightly larger. For $k_2/k_1=0.25$, a greater reduction of peak ductility demands are obtained when α=0.7. Nevertheless, the 2dof systems still developed very large ductility demands for this stiffness ratio (unrealistic to develop for the considered structural system under study), so perhaps a smaller α factor should be used for such systems. Despite this fact, it seems that for most systems prone to develop a soft/weak story, it may be enough to design them using a correction factor for structural irregularity α=0.8, in order to have a reasonably performance from a collapse prevention mindset under the design earthquake scenario.

3. Concluding remarks

A parametric study where two-degree of freedom (2DOF) simplified models are used to represent structures likely to develop soft stories was presented. Different stiffness (k_2/k_1) and strength (V_2/V_1) ratios were considered to define a realistic range of structures with the potential to develop soft/weak story mechanisms according to recommendations of current Mexican seismic building codes. The 2dof models represent six and eight stories buildings. Also, correction factors for structural irregularity currently proposed in Mexican seismic codes (α=0.7 and α=0.8) were considered in the study.

Step by step nonlinear dynamic analyses were conducted using 10 artificial accelerations records corresponding to soft soil conditions found in the lakebed zone of Mexico City. From the obtained results, it can be concluded that a reasonable regular response was obtained for such records and soil condition when:

$$0.50 \leq \frac{V_{n+1}}{V_n} \leq 1.50 \text{ and } 0.66 \leq \frac{k_{n+1}}{k_n} \leq 1.50$$

These stiffness and strength ratios correspond to values where the studied 2dof systems avert the possible development of a soft/weak story at any level of the structure (six and eight stories) located at zone III-a of Mexico City. However, if peak global ductility demands are compared with the limiting values for the studied structural system ($\mu=2$), the stiffness and strength ratios combinations where the 2dof systems developed an acceptable behavior from a collapse prevention viewpoint are significantly modified and reduced:

$$0.66 \leq \frac{V_{n+1}}{V_n} \leq 1.50 \text{ and } \frac{k_{n+1}}{k_n} = 0.50$$

$$0.75 \leq \frac{V_{n+1}}{V_n} \leq 1.50 \text{ and } 0.66 \leq \frac{k_{n+1}}{k_n} \leq 1.25$$

The results obtained for the 2dof models when $V_2/V_1=0.25$ and $k_2/k_1=0.25$ lead to unrealistically large peak story ductility demands that cannot be developed by any structural system, so they should be regarded as “theoretical numerical” collapses. Therefore, it can be concluded that these stiffness and strength ratios are no suitable, even applying correction factors for structural irregularity α.

The results obtained in this parametric study allows one to conclude that for the considered structural system and ground motions, the soft or weak story is averted or minimized with a good combination of stiffness and lateral strength similar to what it is currently proposed in Mexican seismic codes. Likewise, the use of a correction factor for structural irregularity is helpful to reduce significantly the peak story and global ductility demands, and then preventing the development of an uncontrollable soft/weak story. From the results obtained until now, it seems that using a correction factor for structural irregularity α=0.8 could be enough to control to reasonable bounds peak story and global responses for the studied six and eight stories models at the soft soils of zone III-a of Mexico City.

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5. References

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