PERFIL BÍO-SÍSMICO DE EDIFICIOS 3.0
Un instrumento para la calificación sísmica de edificios de hormigón armado. La experiencia chilena

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RESUMEN

El desempeño de los edificios chilenos en eventos sísmicos severos ocurridos en el país, ha tenido reconocimiento nacional e internacional (Ref. 1), lo que gatilló el desarrollo del trabajo denominado "Perfil Bío-Sísmico de Edificios" (Ref. 2), primera versión, utilizando una base de datos de 585 edificios, analizados en dos direcciones.
Dicho procedimiento concluye con un instrumento que registra los valores de indicadores sísmicos que se podrían relacionar con un buen desempeño, lo que permite su posterior aplicación en proyectos en desarrollo, para calificar su eventual comportamiento en futuros eventos sísmicos.
La segunda versión del Perfil Bío-Sísmico de Edificios (Ref. 3), fue publicada en 2010, utilizando la misma base de datos e incorporando 6 edificios de gran altura, lo que permitió extender la validez del procedimiento más allá de los 30 pisos del primer estudio.
Se presenta, en esta ocasión, una versión actualizada, denominada "Perfil Bío-Sísmico de Edificios 3.0", que ha incrementado de 13 a 21 el número de indicadores, y ampliado la base de datos a 4105 edificios construidos entre 1993 y 2017, analizados en dos direcciones, conformando así 8210 casos de análisis.
El texto de este trabajo está en inglés, debido a que será parte de una versión ampliada del mismo que se publicará en 2018 en una revista internacional indexada (Ref. 9).

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I. INDICATORS

I.1 STIFFNESS INDICATORS

One of the most important indicators to define the stiffness characteristic of chilean buildings is the ratio of Height, in meters, divided by the fundamental translational Period of vibration, in seconds. Three indicators have been considered for such evaluation:

(1) H/T (m/s): total height of the building divided by the dominant translational period of vibration.

This indicator is used to control the code analysis (use of a linear elastic system and a reduced seismic action).

(2) H_o/T (m/s): total height of the building, measured for the stories above soil level divided by the dominant translational period of vibration.

This indicator is alternative to number 1, to be used when the stiffness of the structural elements belonging to the underground stories are large enough as to have the most significative vibration of the building taking place above ground level.

(3) H_o/T_{cr} (m/s): total height of the building, measured for the stories above soil level divided by the dominant translational period of vibration with cracked reinforced concrete elements (T_{cr}). The Chilean Code allows to use T_{cr}=1.5T.

This indicator is important to determine the residual stiffness of the building after a severe earthquake. In this case, cracked reinforced concrete elements are considered.

(4) $M_{P\text{-}\Delta}/M_{base}$: base overturning moment due to P-Δ effect divided by the base overturning moment due to the seismic action.

(5) δ/H: building roof displacement resulting from the code analysis, divided by the total height of the building. Depending on the date of the analysis, the code used was either NCh433.Of96 (Ref. 4), NCh433.Of96-modif.2009 (Ref. 5), NCh433.Of96-modif.2009 complemented with Supreme Decree N°117 (Ref. 6), or with the Supreme Decree N°61 (Refs. 7 and 8).

(6) δ/H_o: building roof displacement resulting from the analysis divided by the total height of the building, measured for the stories above soil level.

***(7)* δ_u/H_o:** building roof displacement for cracked reinforced concrete members, divided by the total height of the building, measured for the stories above soil level.

$$\delta_u = 1.3 S_{de}(T_{cr})$$

$$S_{de}(T_n) = \frac{T_n^2}{4\pi^2} \alpha A_0 C^*_d$$

evaluated for $T_n = T_{cr}$

factor C_d^* is given in the next table:

Soil Type	C_d^*	Period Range
A	*1.0*	$T_n \leq 0.23$ s
	$-0.055T_n^2 + 0.36T_n + 0.92$	0.23 s $< T_n \leq 2.52$ s
	$0.08T_n^2 - 0.9T_n + 3.24$	2.52 s $< T_n \leq 5.00$ s
B	*1.0*	$T_n \leq 0.47$ s
	$0.95T_n + 0.55$	0.47 s $< T_n \leq 2.02$ s
	$0.065T_n^2 - 0.75T_n + 3.72$	2.02 s $< T_n \leq 5.00$ s
C	*1.0*	$T_n \leq 0.65$ s
	$0.57T_n + 0.63$	0.65 s $< T_n \leq 2.02$ s
	$0.055T_n^2 - 0.63T_n + 2.83$	2.02 s $< T_n \leq 5.00$ s
D	*1.0*	$T_n \leq 0.90$ s
	$1.1T_n$	0.90 s $< T_n \leq 1.75$ s
	1.93	1.75 s $< T_n \leq 5.00$ s

(8) **δ center of gravity /h:** inter-story drift at center of gravity, resulting from the code analysis. h is the story height.

(9) **δ_{border}/h:** maximum additional inter-story drift at borders, resulting from the code analysis.

I.2 COUPLING INDICATORS

(10) $T_{rotational}/T_{translational}$:
dominant rotational period of vibration divided by the dominant translational period of vibration.

(11) $T_{translational\ coupled}/T_{translational}$:
coupled dominant translational period of vibration divided by the dominant translational period of vibration.

(12) $Mass_{eq.\ rotational\ coupled}/Mass_{eq.\ translational\ direct}$:
equivalent coupled rotational mass divided by the equivalent translational mass, both for the dominant translational mode.

(13) $Mass_{eq.\ translational\ coupled}/Mass_{eq.\ translational\ direct}$:
equivalent coupled translational mass divided by the equivalent direct translational mass, both for the dominant translational mode.

(14) $Q_{base\ coupled}/Q_{base\ direct}$:
coupled combined base shear divided by the direct combined base shear.

(15) $M_{base\ coupled}/M_{base\ direct}$:
coupled combined base overturning moment divided by the direct combined base overturning moment.

(16) $(M_{base\ direct}/Q_{base\ direct})/H$:
lateral resultant height divided by the total height of the building. Lateral resultant height is the ratio between the combined base overturning moment, divided by the combined base shear.

(17) ($M_{base\ torsional}/Q_{base\ direct}$)/H: dynamic eccentricity divided by the total height of the building. Dynamic eccentricity is defined as the ratio of the torsional combined base moment about the vertical axis, due to an action on the considered direction, divided by the combined base shear.

I.3 REDUNDANCY AND DUCTILITY INDICATORS

(18) Number of resistant lines: number of significant resistant lines (those that individually take more than 10% of the base shear).

(19) R:** Effective Response Modification Factor, given by $R^{**}=R^{*}/(f_{eq}\ f_{min}\ f_{max})$; where f_{min} and f_{max} are factors to allow for minimum and/or maximum base shear. f_{eq} is the earthquake load combination factor, currently 1,4.

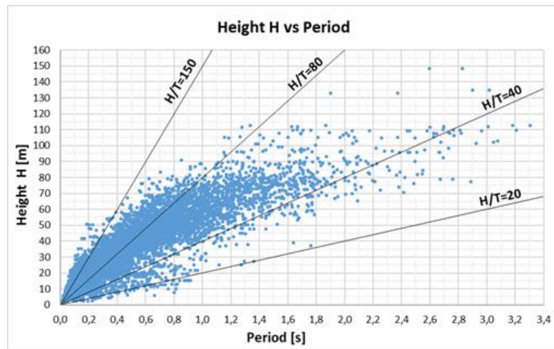
I.4 WALL DENSITY INDICATORS

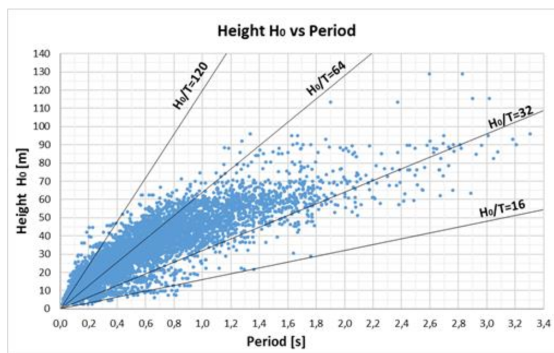
(20) Wall Density for Compression control: cross-sectional area of the resistant elements, at any story, as a percentage of the accumulated slab areas above the corresponding floor. It is recommended to have a wall density equal to or greater than 0,1% of the accumulated slab areas above the corresponding floor.

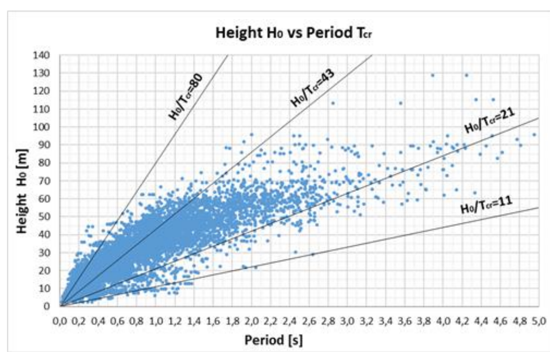
(21) Wall Density for Shear control: cross-sectional area of the resistant elements, at any story, as a percentage of the corresponding floor slab area. It is recommended to have a wall density equal to or greater than 2,0 % of the corresponding floor slab area.

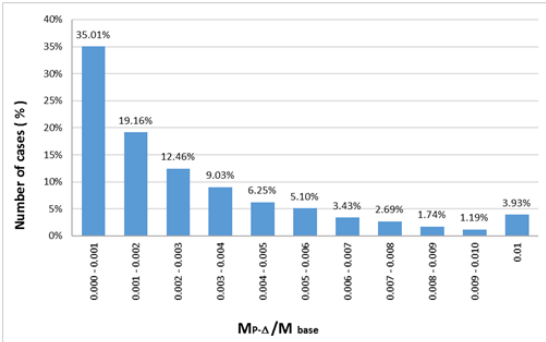
II. ANALYSIS AND RESULTS

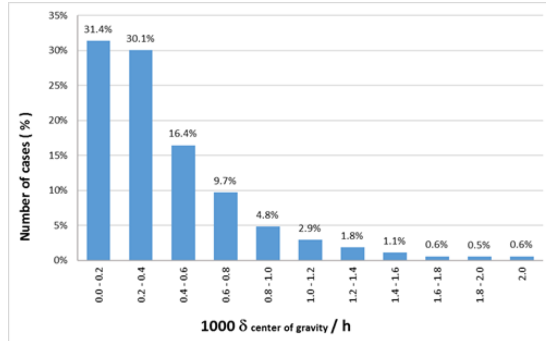
The following figures show histograms and tendency relationship among some indicators. From these figures, it is possible to conclude recommended ranges for the different indicators previously described.

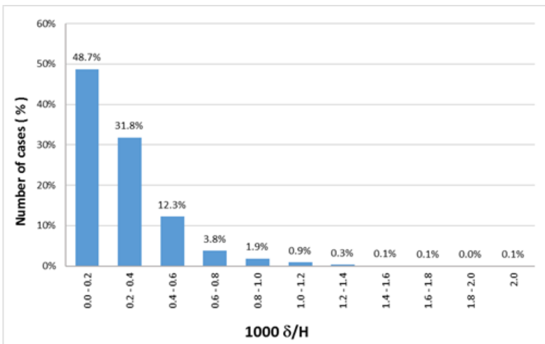


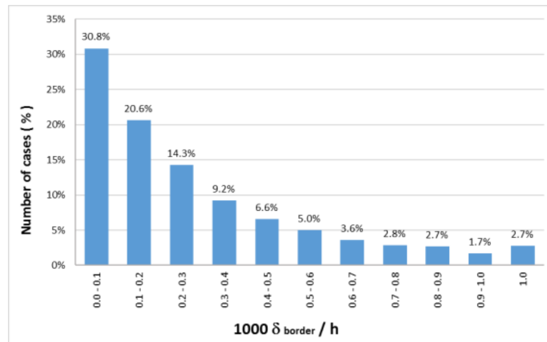


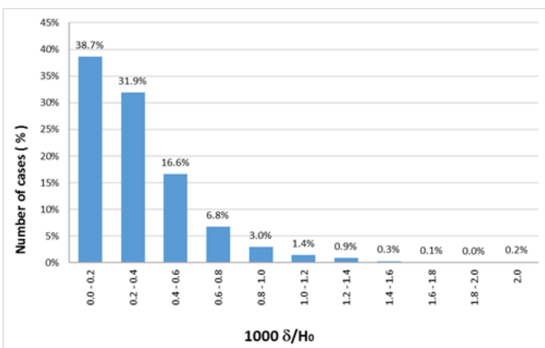


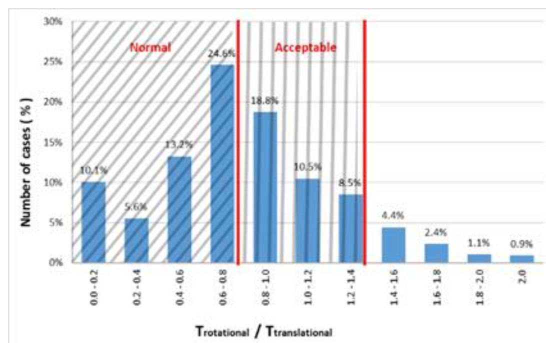

Number of cases (%)
35.01%
19.16%
12.46%
9.03%
6.25%
5.10%
3.43%
2.69%
1.74%
1.19%
3.93%
0.000 - 0.001
0.001 - 0.002
0.002 - 0.003
0.003 - 0.004
0.004 - 0.005
0.005 - 0.006
0.006 - 0.007
0.007 - 0.008
0.008 - 0.009
0.009 - 0.010
0.01
MP-Δ /M base

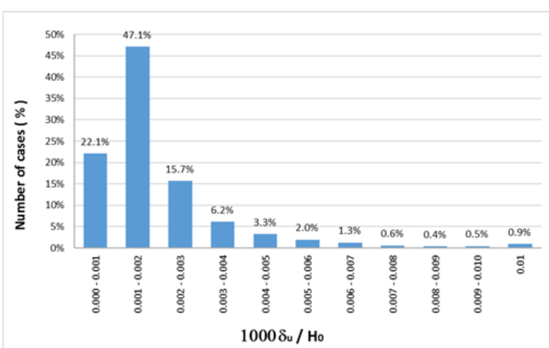

Number of cases (%)
31.4%
30.1%
16.4%
9.7%
4.8%
2.9%
1.8%
1.1%
0.6%
0.5%
0.6%
0.0 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 1.0
1.0 - 1.2
1.2 - 1.4
1.4 - 1.6
1.6 - 1.8
1.8 - 2.0
2.0
1000 δ center of gravity / h

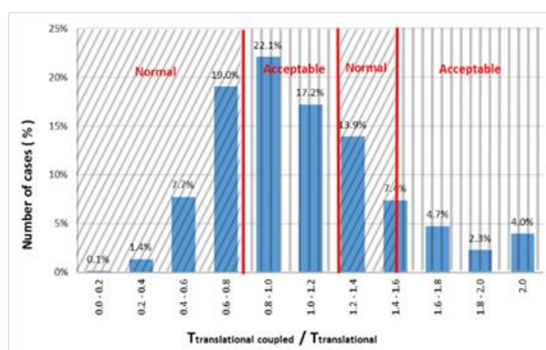

Number of cases (%)
48.7%
31.8%
12.3%
3.8%
1.9%
0.9%
0.3%
0.1%
0.1%
0.0%
0.1%
0.0 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 1.0
1.0 - 1.2
1.2 - 1.4
1.4 - 1.6
1.6 - 1.8
1.8 - 2.0
2.0
1000 δ/H

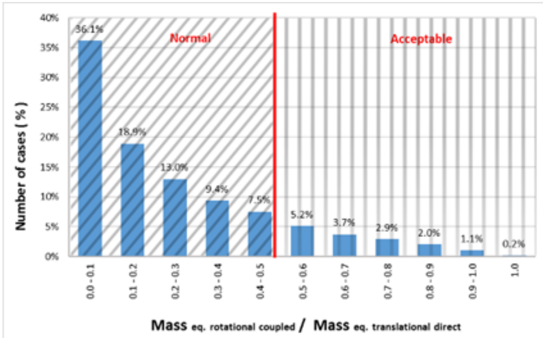

Number of cases (%)
30.8%
20.6%
14.3%
9.2%
6.6%
5.0%
3.6%
2.8%
2.7%
1.7%
2.7%
0.0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1.0
1.0
1000 δ border / h

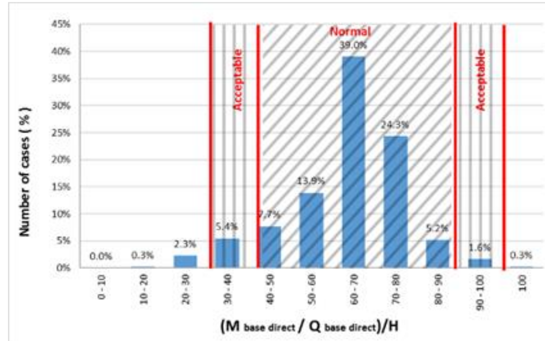

Number of cases (%)
38.7%
31.9%
16.6%
6.8%
3.0%
1.4%
0.9%
0.3%
0.1%
0.0%
0.2%
0.0 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 1.0
1.0 - 1.2
1.2 - 1.4
1.4 - 1.6
1.6 - 1.8
1.8 - 2.0
2.0
1000 δ/H0

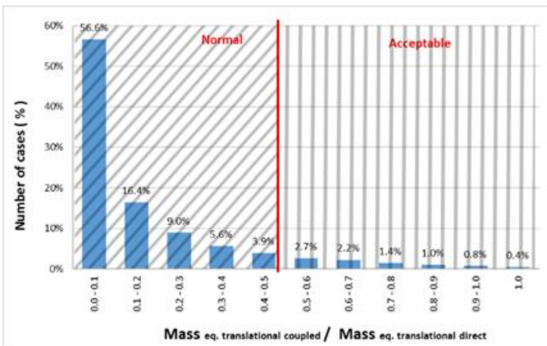

Normal
Acceptable
Number of cases (%)
10.1%
5.6%
13.2%
24.6%
18.8%
10.5%
8.5%
4.4%
2.4%
1.1%
0.9%
0.0 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 1.0
1.0 - 1.2
1.2 - 1.4
1.4 - 1.6
1.6 - 1.8
1.8 - 2.0
2.0
Trotational / Ttranslational

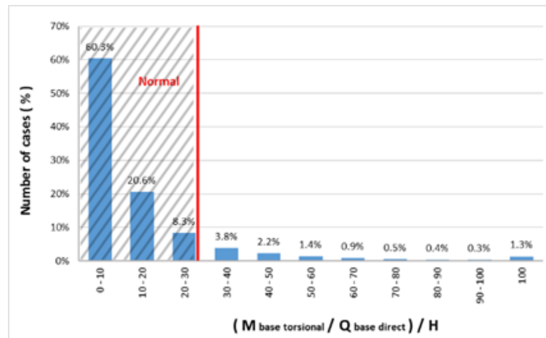

Number of cases (%)
22.1%
47.1%
15.7%
6.2%
3.3%
2.0%
1.3%
0.6%
0.4%
0.5%
0.9%
0.000 - 0.001
0.001 - 0.002
0.002 - 0.003
0.003 - 0.004
0.004 - 0.005
0.005 - 0.006
0.006 - 0.007
0.007 - 0.008
0.008 - 0.009
0.009 - 0.010
0.01
1000 δu / H0

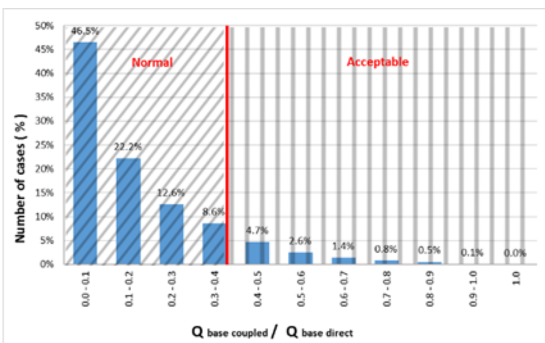

Normal
Acceptable
Normal
Acceptable
Number of cases (%)
0.1%
1.4%
7.7%
19.0%
22.1%
17.2%
13.9%
7.4%
4.7%
2.3%
4.0%
0.0 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 1.0
1.0 - 1.2
1.2 - 1.4
1.4 - 1.6
1.6 - 1.8
1.8 - 2.0
2.0
Ttranslational coupled / Ttranslational

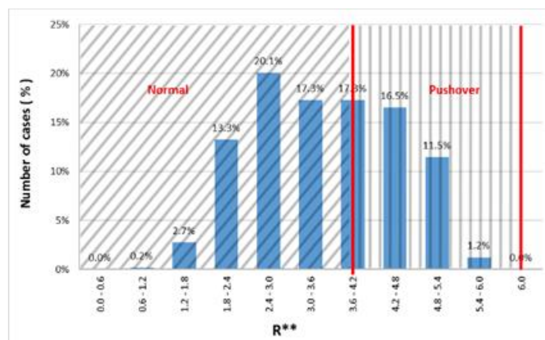

Normal
Acceptable
Number of cases (%)
Mass eq. rotational coupled / Mass eq. translational direct

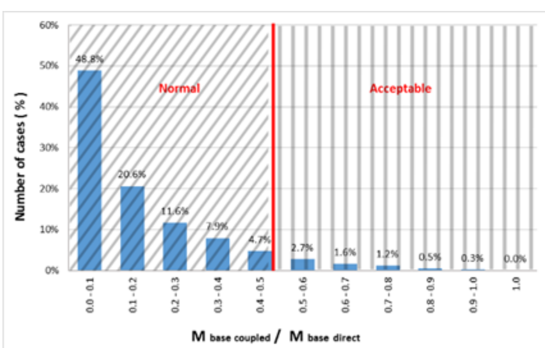

Acceptable
Normal
Acceptable
Number of cases (%)
(M base direct / Q base direct)/H


Normal
Acceptable
Number of cases (%)
Mass eq. translational coupled / Mass eq. translational direct


Normal
Number of cases (%)
(M base torsional / Q base direct) / H


Normal
Acceptable
Number of cases (%)
Q base coupled / Q base direct


Normal
Pushover
Number of cases (%)
R**


Normal
Acceptable
Number of cases (%)
M base coupled / M base direct

III. UPDATED INDICATOR RANGES

INDICATORS	NORMAL RANGE	ACCEPTABLE OUT-OF-RANGE VALUES
STIFFNESS		
1 H / T [m/s]	40 - 80	20 -40 and 80 - 150
2 H_0 / T [m/s]	32 - 64	16 - 32 and 64 - 120
3 H_0 / T_{cr} [m/s]	21 - 43	11 - 21 and 43 - 80
4 $M_{P-\Delta}$ / M_{base}	0 – 0,1	
5 1000 δ / H	≤ 2,0 ‰	
6 1000 δ / H_0	≤ 2,0 ‰	
7 1000 δ_u / H_0	≤ 10,0 ‰	10 ‰ – 15 ‰
8 1000 $\delta_{center\ of\ gravity}$ / h	≤ 2,0 ‰	
9 1000 δ_{border} / h	≤ 1,0 ‰	
COUPLING		
10 $T_{rotational}$ / $T_{translational}$	0 – 0,8	0,8 – 1,4
11 $T_{tanslational\ coupled}$ / $T_{translational}$	0 – 0,8 and 1,2 – 1,5	0,8 – 1,2 and 1,5 – 2,0
12 $Mass_{eq.\ rotational\ coupled}$ / $Mass_{eq.\ translational\ direct}$	0 – 0,5	≤ 1,0
13 $Mass_{eq.\ translational\ coupled}$ / $Mass_{eq.\ translational\ direct}$	0 – 0,5	≤ 1,0
14 $Q_{base\ coupled}$ / $Q_{base\ direct}$	0 – 0,4	≤ 1,0
15 $M_{base\ coupled}$ / $M_{base\ direct}$	0 – 0,5	≤ 1,0
16 ($M_{base\ direct}$ / $Q_{base\ direct}$)/H	40 % - 90 %	20 % - 40 % and 90 % - 100 %
17 ($M_{base\ torsional}$ / $Q_{base\ direct}$)/H	≤ 30 %	
REDUNDANCY AND DUCTILITY		
18 Number of resistant lines	≥ 3	2 – 3
19 R**	≤ 4	4 –6 (pushover) ≥ 6 non linear dyn.
20 Wall Density for Compression control	≥ 0,1 %	
21 Wall Density for Shear control	≥ 2,0 %	

IV. SUMMARY

The main recommendations to be considered in the building design procedure can be summarized as follows:

V.1 STIFFNESS

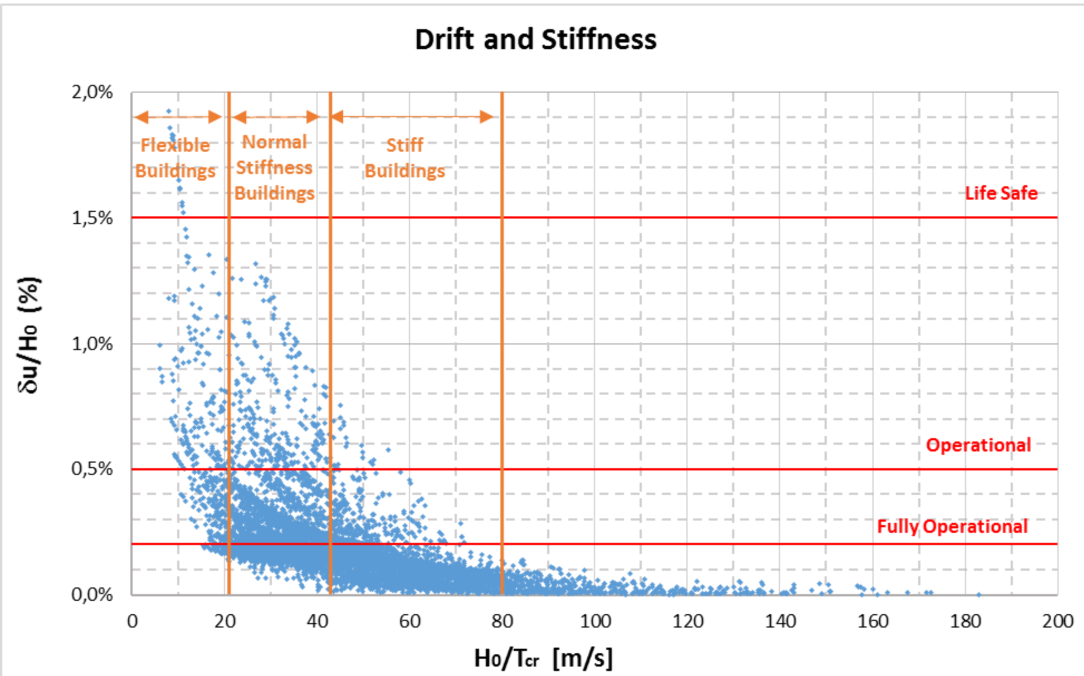
- From the Indicators (1), (2), and (3), it is possible to conclude the following stiffness classification:

CASES \ STIFFNESS	OUT OF RANGE	FLEXIBLE	NORMAL	RIGID	OUT OF RANGE
CASE 1: H/T	H/T<20	H/T: 20 to 40	H/T: 40 to 80	H/T: 80 to 150	H/T > 150
CASE 2: H_o/T	H_0/T<16	H_0/T: 16 to 32	H_0/T: 32 to 64	H_0/T: 64 to 120	H_0/T > 120
CASE 3: H_o/T_{cr}	H_0/T_{cr}<11	H_0/T_{cr}: 11 to 21	H_0/T_{cr}: 21 to 43	H_0/T_{cr}: 43 to 80	H_0/T_{cr} > 80

NUMBER OF STORIES	STIFFNESS CLASSIFICATION	OUT OF RANGE	FLEXIBLE	NORMAL	RIGID	OUT OF RANGE
1-10	Low-Rise Buildings	1.5%	6.6%	24.5%	57.7%	9.7%
11-20	Low to Mid-Rise Buildings	0.0%	1.8%	53.0%	43.7%	1.5%
21-30	Mid-Rise Buildings	0.0%	4.5%	73.7%	21.8%	0.0%
31-40	High-Rise Buildings	0.0%	13.4%	78.7%	7.9%	0.0%
41 +	Skyscrapers	0.0%	25.0%	75.0%	0.0%	0.0%
TOTAL SAMPLE		**0.7%**	**4.9%**	**43.3%**	**45.9%**	**5.2%**

- Overturning moment due to P-Δ effect below 10% of the base overturning moment due to the seismic loads.

- Using this stiffness classification, it is possible to create the overall drift and stiffness relationship shown below:



V.2 COUPLING

- Separate periods of vibration of the fundamental modes by around 20%.
- Try to avoid that the period of the fundamental torsional mode be larger than the period of the translational mode.
- Try to avoid that indirect (coupled) effects (stresses, displacements) be larger than 50% of the direct effects.
- Try to avoid that the dynamic eccentricity measured at the base of the building (torsional moment divided by the shear force), be larger than 30% of the height of the building.

V.3 REDUNDANCY AND DUCTILITY

- Use at least three resistant lines in each direction of analysis, each one apable of taking more than 10% of the shear stresses.
- If values of R** are lower than 4, linear analysis for design may be acceptable.
- If values of R** are between 4 and 6, use equivalent nonlinear static analysis (pushover) for design.
- If values of R** are larger than 6, perform a dynamic nonlinear analysis.

V.4 WALL DENSITY

- Try to have cross-sectional area of the resistant elements, at any story, equal to or greater than 0,1 % of the accumulated slab areas above the corresponding floor.
- Try to have cross-sectional area of the resistant elements, at any story, in each direction, equal to or greater than 2,0 % of the corresponding slab area.

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