Application of Hirosawa Method to Compare Seismic Performance of Reinforced Concrete Buildings during the Earthquake of 2010 in Chile

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***Abstract*—The Hirosawa Method is used by the Pan American Health Organization to evaluate the structural vulnerability of Health Facilities in Latin America and the Caribbean. In this study, this method has been addressed to evaluate the structural vulnerability of reinforced concrete buildings in Chile during the 2010 Earthquake. A sample of 116 buildings of medium height (between four and ten floor height) were analyzed to compare their real behaviour during the earthquake with the seismic performance given by the Modified Hirosawa Method, in order to determinate if this method can be used to evaluate the structural vulnerability of these type of structures in Chile. According to the results of this investigation, the Hirosawa Method is useful to establish trends in seismic behavior for the analyzed buildings, since of the 26 buildings defined with a safe performance against a seismic event by the Hirosawa Method, only one suffered severe damage and none suffered serious damage during the 2010 Earthquake.**

***Index Terms*—structural vulnerability, Hirosawa method, seismic performance, Chilean earthquake**

I. Introduction

The Hirosawa Method, or "Standard for Seismic Evaluation of Existing Reinforced Concrete Buildings", is used by the Ministry of Construction in Japan to evaluate the seismic safety of reinforced concrete buildings [1]. This method was modified by the Pan American Health Organization to evaluate the structural vulnerability of Health Facilities in Latin America and the Caribbean according to the materials and building typology existing in these countries.

The Hirosawa Method is based on the analysis of the seismic behavior of each floor of the building in the main directions of the structure floor. It is recommended to use this method in reinforced concrete buildings structured with frames or walls and of medium height (not higher than 6 floors) [2] [3].

The modified Hirosawa Method, used in countries like Chile, Mexico, Peru and Ecuador, define the structural vulnerability considering the resistant capacity, geometry and maintenance of the building, with the level of solicitation demanded by the earthquakes that represent the seismic risk and the local conditions of the site where the building is located [4]. This study analyzed reinforced concrete buildings, however, the modified method contemplates other materiality of buildings that can be addressed.

Although the modified method focuses in health facilities, other types of structures were not addressed, which narrows the use of the method. Some studies, have been used the Modified Hirosawa Method [5] [6], but mainly focused in Health Facilities. This study analyzed the modified Hirosawa Method in reinforced concrete buildings of up to 10 floors and compares the performance given by the method with the real behavior of the structure during the 2010 earthquake in Chile

II. Methodology

The current investigation involved analysing a sample of buildings with the Modified Hirosawa Method to compare the real behaviour of these during the 2010 earthquake in Chile. The buildings were selected from the Concepción central area, where the level of damage of each structure was determined by a previous research [7], and structural information of each building was available. Table I shows the level of damage of the buildings that were analysed, which was considering the categories indicated by Montalva, and were also determined by the author by visual inspection days after the seismic event. These represent the real damage suffered by the structure during the 2010 earthquake.

TABLE I. Level of Damage of Analyzed Buildings

Level of damage	None	Light	Severe	Serious
Number of buildings	41	60	14	1

A total of 116 reinforced concrete buildings located in the city center of Concepción were analysed. Their structure is mainly wall based, although there are a few exceptions which are frame structured. The buildings analysed have four to ten floors height. Table II shows the floor distribution for the building sample.

TABLE II. Building Floors

Number of floors	4	5	6	7	8	9	10
Number of buildings	1	50	21	5	14	10	15

The Hirosawa Method is recommended to buildings up to six floors height, however, in this study were analysed

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buildings up to ten floors since many of the buildings with severe or serious damage had more than six floors, therefore, the sample were more representative in damage level.

All the buildings were built between 1951 and 2009. Of the 116 structures, 6 buildings were constructed between 1951 and 1959, 14 between 1960 and 1969, 12 between 1970 and 1979, 9 between 1980 and 1989, 52 between 1990 and 1999, and 23 buildings were built between 2000 and 2009,

The Hirosawa Method is based in the analysis of the seismic behaviour of each floor of the building in their main plan directions. Using the structural and construction information of each building, the Hirosawa parameters were calculated as indicated in the method described by Boroschek in the "Principles of Disaster Mitigation in Health Facilities of Pan American Health Organization" (2000), which describes a "Method for the Analysis of Structural Vulnerability" using the Hirosawa Method as reference.

These parameters were calculated to determinate the structural vulnerability of each building comparing their resistant capacity, form ratios, maintenance and previous damages in the building, and therefore an index was calculated for each building which was compared with its local conditions and the level of solicitation demanded by the earthquakes that represent the seismic risk of the area [4]. This index is called Index of Seismic Behaviour (I_s), and it is calculated at each floor in each main plan direction of the building using (1):

$$I_s = E_0 \cdot S_D \cdot T \quad (1)$$

where

E_0: Basic seismic index of the structural behaviour (defined in [2])

S_D: Irregularity index (defined in [2])

T: Time index of the building (defined in [2])

The methodology also calculates another index, called Index of Seismic Judgment, to stablish the conditions where the structure is located. This index is calculated following (2):

$$I_{so} = E_{so} \cdot Z \cdot G \cdot U \quad (2)$$

where:

E_{so}: Required basic seismic design resistance (defined in [2])

Z: Index of Seismic Zone (its depends on building location, $0.5 \leq Z \leq 1$)

G: Index of topographical and geotechnical conditions (defined in [2])

U: Index of building importance (defined in [2])

The structural vulnerability is established from the comparison between the Index of Seismic Behaviour (I_s), or Hirosawa Index, with the Index of Seismic Judgment (I_{so}) [2] [4]:

i) If $I_s > I_{so}$; the structure can be considered to have a safe seismic performance in case of a seismic event and it is catalogue as "Safe"

ii) If $I_s < I_{so}$; the structure can be considered to have an uncertain performance in case of a seismic event, and therefore it is considered as "Insecure".

The Seismic Chilean Code [8] was used to determine the seismic zone, and to establish the type of soil where each building is located it were used the studies of Galli and Latini regarding the soil conditions in the studied area, and where it was determined that the soil of Concepcion belongs to the classification of soft soils [9] [10].

To those buildings where it was a lack of structural information, it was assumed that their concrete quality was H25, that is a reinforce concrete with a compression strength of 20 MPa [11]. This assumption is rather low comparing with other reinforced concrete studies made in Chile [12] [13].

The Modified Hirosawa Method described by Borocheck has demonstrated to be accurately to evaluate the structural vulnerability of health facilities up to six floors in Latin American. In this study it is analysed if this methodology can be used in any reinforced concrete structure up to ten floors height.

III. Results and Discussion

The parameters of the Modified Hirosawa Method, as described by Boroschek [4], gives the Index of Seismic Behaviour (I_s) which is compared with the Index of Seismic Jugdment (I_{so}) to know if the performance of the building would be "Safe" or "Insecure" during a seismic event. If I_s is higher than I_{so}, then the performance of the building is catalogued as "Safe" and on the other case (I_s lower than I_{so}) the building is catalogued as having an "Insecure" performance during a seismic event.

In this study, a sample of 116 catalogued buildings performances according to the Modified Hirosawa Method (also known as "Standard for Seismic Evaluation of Existing Reinforced Concrete Buildings" [1]) were compared with their real behaviour during the seismic event of 2010 in Concepcion, Chile. Table III summarized the results obtained for I_s, I_{so}, the seismic behaviour according to the Hirosawa Methodology and the real behaviour of the structure during the earthquake of 2010 in Chile.

TABLE III. Results of the Hirosawa Method

N° Building	I_s	I_{so}	Hirosawa Building Behaviour	Real Performance in earthquake
1	0,556	0,550	Safe	Severe
2	0,490	0,550	Insecure	None
3	0,643	0,550	Safe	None
4	0,418	0,550	Insecure	Light
5	0,286	0,550	Insecure	Severe
6	0,246	0,550	Insecure	Severe
7	0,434	0,550	Insecure	Light
8	0,350	0,550	Insecure	Light

9	0,538	0,550	Insecure	None
10	0,449	0,550	Insecure	Light
11	0,284	0,550	Insecure	Severe
12	0,239	0,550	Insecure	Light
13	0,162	0,550	Insecure	Severe
14	0,317	0,550	Insecure	Serious
15	0,297	0,550	Insecure	Light
16	0,127	0,550	Insecure	Light
17	0,180	0,550	Insecure	Light
18	0,672	0,550	Safe	None
19	0,432	0,550	Insecure	None
20	0,783	0,550	Safe	None
21	0,299	0,550	Insecure	Light
22	0,259	0,550	Insecure	None
23	0,155	0,550	Insecure	Light
24	0,327	0,550	Insecure	Light
25	0,252	0,550	Insecure	Light
26	0,948	0,550	Safe	None
27	0,024	0,550	Insecure	Light
28	0,378	0,550	Insecure	Light
29	0,333	0,550	Insecure	None
30	0,632	0,550	Safe	Light
31	0,340	0,550	Insecure	Light
32	0,187	0,550	Insecure	Severe
33	0,421	0,550	Insecure	Light
34	0,505	0,550	Insecure	Light
35	0,338	0,550	Insecure	Light
36	0,628	0,550	Safe	None
37	0,300	0,550	Insecure	Light
38	0,237	0,550	Insecure	Severe
39	0,426	0,550	Insecure	None
40	0,498	0,550	Insecure	None
N° Building	**I_s**	**I_{so}**	**Hirosawa Building Behaviour**	**Real Performance in earthquake**
41	1,320	0,550	Safe	None
42	0,520	0,550	Insecure	Light
43	0,865	0,550	Safe	None
44	0,456	0,550	Insecure	Light
45	0,704	0,550	Safe	None
46	0,479	0,550	Insecure	None
47	0,218	0,550	Insecure	Light
48	0,258	0,550	Insecure	None
49	0,258	0,550	Insecure	None
50	0,184	0,550	Insecure	Light
51	0,347	0,550	Insecure	None

52	0,961	0,550	Safe	Light
53	0,659	0,550	Safe	Light
54	0,526	0,550	Insecure	None
55	0,299	0,550	Insecure	Light
56	0,256	0,550	Insecure	Light
57	0,312	0,550	Insecure	Severe
58	0,336	0,550	Insecure	Light
59	0,505	0,550	Insecure	Light
60	0,329	0,550	Insecure	None
61	0,417	0,550	Insecure	Light
62	0,443	0,550	Insecure	Light
63	0,627	0,550	Safe	Light
64	0,524	0,550	Insecure	Light
65	0,536	0,550	Insecure	Light
66	0,390	0,550	Insecure	None
67	0,420	0,550	Insecure	Light
68	0,601	0,550	Safe	Light
69	0,804	0,550	Safe	None
70	0,684	0,550	Safe	None
71	0,247	0,550	Insecure	Light
72	0,660	0,550	Safe	None
73	0,454	0,550	Insecure	None
74	0,696	0,550	Safe	Light
75	0,163	0,550	Insecure	Severe
76	0,456	0,550	Insecure	Light
77	0,292	0,550	Insecure	Severe
78	0,264	0,550	Insecure	Light
79	0,213	0,550	Insecure	Light
80	0,204	0,550	Insecure	Severe
81	0,655	0,550	Safe	Light
82	0,271	0,550	Insecure	None
83	0,480	0,550	Insecure	None
N° Building	**I_s**	**I_{so}**	**Hirosawa Building Behaviour**	**Real Performance in earthquake**
84	0,977	0,550	Safe	Light
85	0,276	0,550	Insecure	None
86	0,277	0,550	Insecure	Light
87	0,400	0,550	Insecure	None
88	0,486	0,550	Insecure	Light
89	0,415	0,550	Insecure	Light
90	0,505	0,550	Insecure	Light
91	0,732	0,550	Safe	None
92	0,680	0,550	Safe	Light
93	0,456	0,550	Insecure	None
94	0,312	0,550	Insecure	None

95	0,453	0,550	Insecure	None
96	0,142	0,550	Insecure	Light
97	0,171	0,550	Insecure	Severe
98	0,242	0,550	Insecure	Severe
99	0,149	0,550	Insecure	None
100	0,473	0,550	Insecure	Light
101	0,243	0,550	Insecure	Light
102	0,242	0,550	Insecure	Light
103	0,333	0,550	Insecure	Light
104	0,248	0,550	Insecure	Light
105	0,361	0,550	Insecure	Light
106	0,320	0,550	Insecure	Light
107	0,494	0,550	Insecure	None
108	1,080	0,550	Safe	None
109	0,353	0,550	Insecure	None
110	0,393	0,550	Insecure	Light
111	0,567	0,550	Safe	None
112	0,656	0,550	Safe	Light
113	0,441	0,550	Insecure	Light
114	0,343	0,550	Insecure	None
115	0,278	0,550	Insecure	Severe
116	0,729	0,550	Safe	None

From all the analysed buildings, a 22% were catalogued with a "Safe" performance in case of a seismic event, and 78% were catalogued as "Insecure", as it can be seen in Fig. 1 where it is displayed the percentage difference between the buildings catalogued as having a "Safe" performance and those catalogued as having an "Insecure" behaviour during a seismic event.

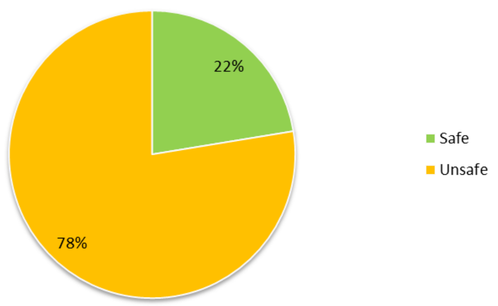

Figure 1. Percentage of buildings with "Safe" and "Insecure" Performance according to the Hirosawa Method

For the studied sample, the buildings that were catalogued as having a "safe" performance during a seismic event were more consistent with their real damage suffered during the eartquake, therefore these type of response it is going to be analysed first.

As can be seen in Fig. 2, more than 95% of those buildings catalogued as having a "safe" performance do not suffer much damage during the earthquake of 2010 in Chile. Only 4% of the "safe" buildings experienced severe damage during the earthquake, which demonstrated that the Modified Hirosawa Method is successful when compare with real behaviour during an earthquake for buildings catalogued as having a "safe" performance.

Moreover, when compared the floor distribution for buildings with "safe" performance, as illustrated in Fig. 3, it can be seen that the results from the Hirosawa Method are generally consistent with their real damage during the earthquake. For buildings up to seven floor height all the analized buildings had none or light damage during the earthquake. On the other hand, when the results from the Hirosawa Method are compared with real performance of buildings of eight to ten floors height, it can be seen that the methodology is less accurate when real behaviour of the building is compared with their catalogued performance, as more damaged buildings appear with a catalogued "safe" performance.

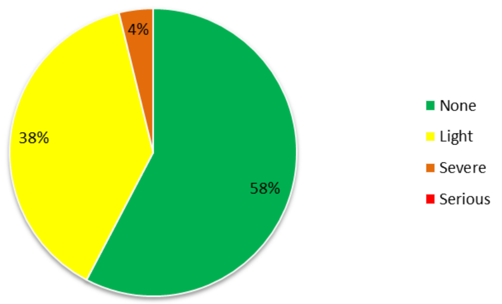

Figure 2. Percentage of buildings with "Safe" Performance and their relationship with real damage during the 2010 Earthquake in Chile

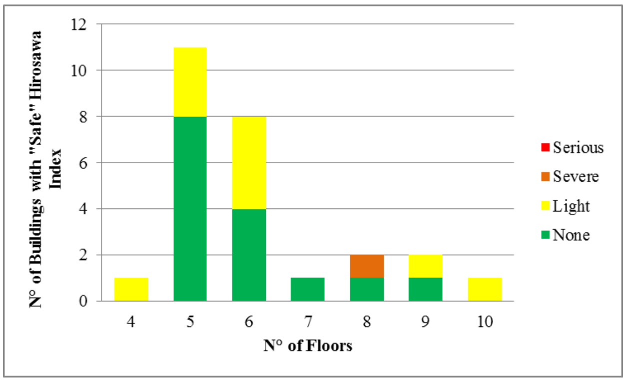

Figure 3. Buildings with "Safe" Performance in relation with their real damage and number of floors

However, the results are less representative with the real behaviour of buildings during the earthquake of 2010 for those buildings catalogued as having an "insecure" performance. As can be seen in Fig. 4, where it is displayed the comparison between the buildings catalogued as "insecure" with the Hirosawa Method and their real performance during the earthquake of 2010, a 56% of buildings catalogued as "insecure" performance suffered light damage during the earthquake, which is not associated with an insecure behaviour. On the other hand 29% of buildings that were catalogued as "insecure" had no damage during the earthquake, which indicates that the methodology is not representative in some cases when the building is catalogued as “insecure”. Nevertheless, as much as 71% of buildings that were catalogued as having an “insecure” performance during a seismic event had some extent of damage during the earthquake (from light to serious), which suggest that being catalogued as “insecure” leads to some extent of damage which not nessesary means a higher level of damage in the structure. This can be due that the described methodology is recommended to use it in buildings up to six floors height, however, the analized sample has buildings up to ten floors height.

Fig. 5 summarize the distribution of number of floors with buildings with “insecure” performance. This figure shows that for buildings up to six floors height the real damage sufered by the structure is rather low despite being catagorized as “insecure” by the method. On the other hand, the higher damages are concentrated in buildings with seven or more floors, which is consistent with being catagorized as “insecure” structures during a seismic event. The higher level of real damage suffered by the structures during the earthquake its distribuited in buildings with seven or more floors, which demonstrated that taller buildings experienced more damage that those of five and six floors during the earthquake of 2010.

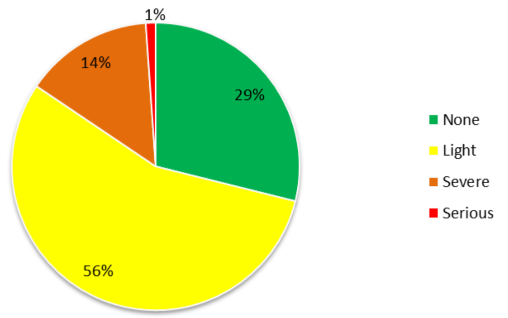

Figure 4. Percentage of buildings with “Insecure” Performance and their relationship with real damage

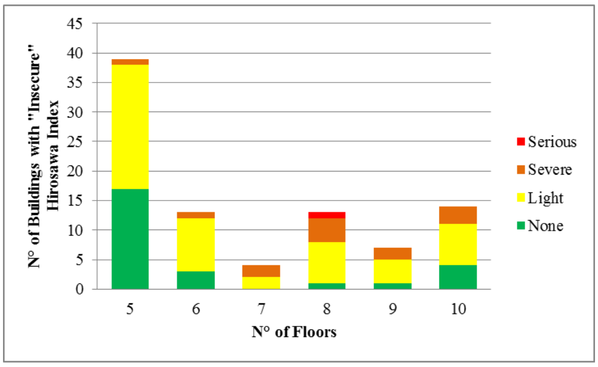

Figure 5. Buildings with “Insecure” Performance in relation with their real damage and number of floors

Fig. 6 and 7 illustrated the results obtained with the methodology considering the floor height of the analysed buildings. As can be seen from these figures, for buildings with seven or more floors the methodology indicates that is more likely that those buildings have an “insecure” performance than a “safe” one. Of all the 44 buildings analized that had between seven to ten floor floors, only 14% were catalogued as safe, while the rest 86% were considered as insecure. For buildings with four to six floors height, the results are less severe than for higher floors, where more than a fourth of the sample was catalogued as having a “safe” performance.

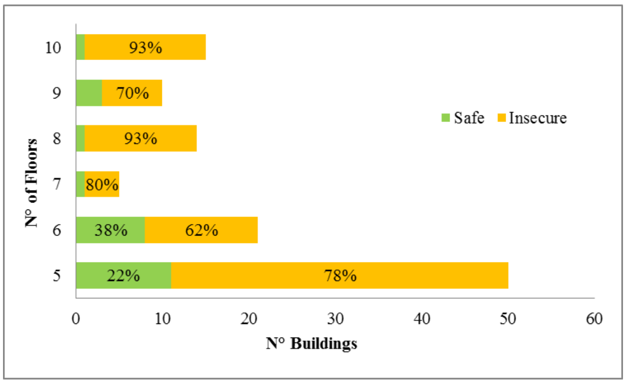

Figure 6. Hirosawa Performance in relation with the number of floors

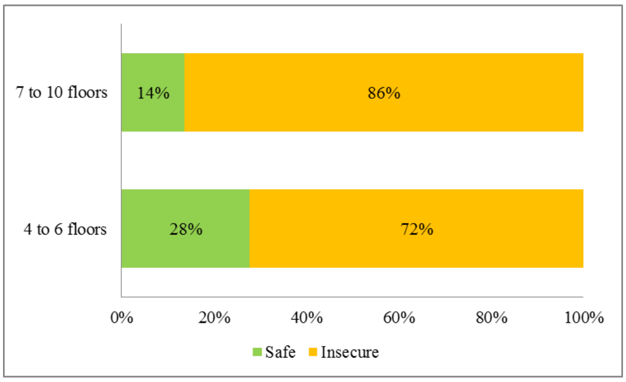

Figure 7. Hirosawa Performance of buildings grouped by floor height

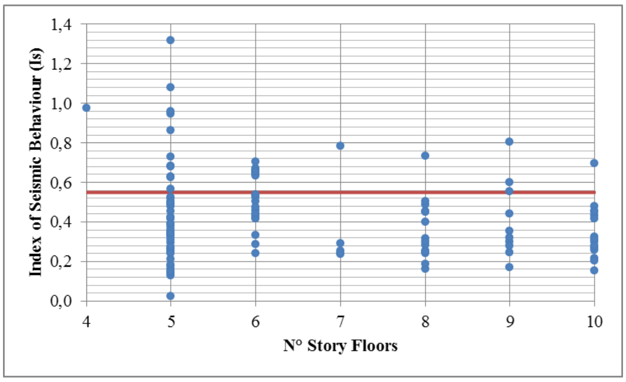

Figure 8. Relation between the Number of floor floors and the index of Seismic Behaviour (Is) of each building.

Particularly, Fig. 8 presents the Index of Seismic Behaviour (I_S) distribution in buildings with different storey floors. The red line represents the index of Seismic Judgment (I_{so}), which is iqual to 0.55 to all cases, as can be seen in Table III. All points lower this line are considered low by the methodology, thus leading to an “insecure” performance. As can be seen, the majority of the analized buildings had five floors, and their index is rather low compared with the index of seismic jugdment.

As can been also seen from Fig. 6, a high percentage (78%) of the buildings with five floors had an index of seismic behaviour under 0.55, and a 61% of buildings with six floors have also an “insecure” performance. And when these low index are compared with real performance, it can be seen from Fig. 3 and 5 that a high percentage of the analized buildings with five and six floors had some damage (light or severe), which is consistent with a lower I_s index.

Likewise Fig. 6 and 8 illustrated a high percentage of low I_s index for buildings with more than six floors height, with percetanges of 80%, 93%, 70% and 93% for buildings with seven, eight, nine and ten floors respectively. And compared with the results shown in Fig. 5, it can be seen that a high percentage of these buildings suffered some damage during the earthquake.

Table IV diplays the number of buildings of each floor catalogued as “safe” and “insecure” by the methodology, and the level of damage to those buildings. Here, the first category of the Hirosawa Method (Safe) are compared with those buildings that had none or light damage during the earthquake of 2010 (and where categorized as safe),

TABLE IV. ASSERTIVENESS RATE OF THE HIROSAWA METHOD

Floors		5	6	7	8	9	10
Hirosawa Method	Safe Buildings	11	8	1	1	3	1
Performance in 2010 Earthquake	None or Light	11	8	1	1	2	1
Assertiveness rate for "Safe" Buildings (%)		100	100	100	100	67	100
Hirosawa Method	Insecure Buildings	39	13	4	13	7	14
Performance in 2010 Earthquake	Severe or Serious	1	1	2	5	2	3
Assertiveness rate for "Insecure" Buildings (%)		3	8	50	38	29	21
Assertiveness rate of the Hirosawa Method (%)		24	43	60	43	40	27

and the second category of the Method (Insecure) are compared with those buildings that actually had greater damage during the earthquake, that is severe or serious damage (and where categorized as insecure). From these results, an overal assertiveness rate of the method is show in the last row for each floor category according to the results of this investigation. This rate was calculated considering both none/light and severe/serious damage in comparison with safe and insecure buildings. Eq. (3) was used to calculate this percentage.

$$\text{Assertiveness rate} = \frac{\text{none/light} + \text{severe/serious}}{\text{Safe} + \text{Insecure}} \cdot 100\% \quad (3)$$

As can be seen in Table IV, the overall assertiveness rate of the method is low to those buildings with five and ten floors, and is more assertive in buildings with seven floors. This table also shows that the assertiveness rate of the Method for buildings catalogued as “Safe” is 100% for all buildings except those of nine floors, where the rate decreases to a 67% of assertiveness. The method is less accuralety when the buildings are catalogued as “Insecure”, since for buildings of five and six storey height the assertiveness rate is less than 10%, and for buildings of seven to ten storeys height this rate increases ranking between 21% and 50% of assertiveness, and reaching its maximum with buildings of seven floors.

These evidence points to the likelihood that although in some cases the methodologhy is not accurately when catalogued as “insecure”, the Hirosawa Method could be applied to reinforced concrete buildings up to ten floors height with similar characteristics as the analized sample (building resistance, soil conditions, seismic zone, etc), since in most cases the results of the Hirosawa Method when the buildings are catalogued as “Safe” are very much consistent with the real behaviour of the analized buildings during the earthquake of 2010 in Chile.

IV. CONCLUSIONS

The Modified Hirosawa Method, as described by Boroschek in “Principles of Disaster Mitigation in Health Facilities of Pan American Health Organization” (2000), was applied to a sample of Chilean buildings and the results of the method were compared with the behaviour of these structures during the earthquake of 2010 in Concepcion, Chile.

From an analysed sample of 116 buildings, the majority of those catalogued as “safe” for the method endure the forces from the 2010 earthquake in Chile and had none to light damage in their structure, which indicated that the methodology is effective when the index of seismic behaviour is higher than the index of seismic jugdment for the analized sample.

For those buildigns catalogued as “insecure” by the methodology, a high percentage of structures suffered some extent of damage. However, more than half suffered only light damage, which is not considered as an “insecure” structure when enduring eathquake forces. Thus, when the index of seismic behaviour is lower than the index of seismic jugdment it could be interpreted as the structure will suffer some damage during the earthquake, which is not neccesary a severe damage that leads to an “insecure” performance.

In order to verify the applicability of the method more studies should be conducted, which have to include type of structure, soil conditions and different reinforced concrete resistances.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] JBDPA Japan Building Disaster Prevention Association, "Standard for seismic evaluation of existing reinforced concrete buildings" (in Japanese), JBDPA, 2001.

[2] M. Hirosawa, “Retrofitting and restoration of buildings in Japan,” IISEE Lecture Note, Seminar Course, Tsukuba, Japan, 1992. presented at the IEEE Summer Power Meeting, Dallas, TX, June 22-27, 1992.

[3] A. Hiroyuki, "A method for the evaluation of the seismic capacity of existing reinforced concrete buildings in Japan," *Bulletin of the*

New Zealand National Society for Earthquake Engineering, vol. 14, no. 3, pp. 105-130, 1981.

[4] R. Boroschek, M. Astroza, E. Kausel, and C. Osorio, "Methods for the analysis of structural vulnerability in principles of disaster mitigation in health facilities," Pan American Health Organization, Disaster Mitigation Series, 1 st ed. Washington D.C., 2000, Appendix, pp. 117-128.

[5] P. Albuquerque, "Seismic vulnerability assessment of medium-rise buildings using the Index Method: the case of block #22 of Santa Maria Hospital," 2008, unpublished

[6] A. Takahashi, S. Tago, A. Ilki, and T. Okada, "Seismic capacity evaluation of existing reinforced concrete buildings in turkey (effect of retrofit)," presented at the 13th World Conference on Earthquake Engineering, Vancouver, Canada, August 1-6, 2004.

[7] G. Montalva, N. Bastias, and A. Rodriguez-Marek, "Ground-motion prediction equation for the Chilean subdction zone," *Bulletin of the Seismological Society of America*, vol. 107, pp. 2541-2541, Oct. 2017.

[8] INN "Seismic Design of Buildings NCh 433 OF. 1996", Instituto de Normalización Nacional, Santiago, Chile, 1996.

[9] C. Galli, "Urban geology and soil foundation of concepción and talcahuano," Final research report of Project N°75 of the Commission of Scientific Research of The University of Concepcion, Concepción, Chile, 1967

[10] G. Latini, "Seismic classification of the subsoil of the Concepcion-Talcahuano interzone. Application to Nch 433," Civil Engineering Undergraduate Thesis, Dept. Civil Engineering, University of Concepcion, Concepción, Chile, 1999

[11] INN "Concrete – General Requirements NCh 170 OF. 1985", Instituto de Normalización Nacional, Santiago, Chile, 1985.

[12] L. Rojas, "Durability Study of Old Reinforced Concrete Structures, with Emphasis on the Corrosion of the Reinforcements," Civil Engineering Undergraduate Thesis, Dept. Civil Engineering, University of Chile, Santiago, Chile, 2006

[13] D. Ugalde and D. Lopez-Garcia, "Elastic overstrength of reinforced concrete shear wall buildings in Chile," presented at the 16th World Conference on Earthquake Engineering, Santiago, Chile, January 9-13, 2017