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SEISMIC MONITORING OF TWO ISOLATED HOSPITALS SUBJECTED TO THE ILLAPEL 2015 EARTHQUAKE

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Abstract

Critical buildings must be able to operate immediately after an earthquake and structural information must be readily available to evaluate its status. Seismic monitoring systems are very valuable in that respect as they can provide information such as: (i) actual seismic demand; and (ii) information on the response of critical components of the structure. This information can be used to give instructions immediately after an earthquake; indications of potential damage and/or allow for detailed post-event analysis of the buildings to assess the structural status of the building and its components. In this article, records from monitoring systems are presented for two seismically isolated projects. The monitoring system is composed of accelerometers and scratch plates. The sensors are positioned at key locations to extract valuable information, such as: (i) accelerations at the foundation of the structure representing the seismic input to the building that can be later used to compute response spectra and compare it with the design spectrum; (ii) accelerations below and above the seismic isolation system in order to validate its mechanical behavior during the earthquake and obtain the real response reductions obtained by the system for this input; and (iii) maximum displacement of the seismic isolation system which can be compared with the maximum allowable design displacement. Responses of the seismic monitoring systems are presented for the Sept. 16th, Illapel earthquake (Chile, 2015). The measured results show that the isolation system reduced the acceleration on the superstructure by 70% in the El Carmen Hospital and by 35% in the La Florida Hospital.

Keywords: Seismic Monitoring System; Hospitals.

1. Introduction

Several seismic protection technologies have been successfully implemented in buildings worldwide [1, 2], especially in lifeline structures such as hospitals, schools, and other institutional buildings [1]. One of the most used technology is the seismic isolation system. These systems are capable of reducing the structure interstory drifts between 2 and 7 times and the floor accelerations between 1.5 and 4 times during a strong earthquake [3]. Moreover, the seismic isolation system is extremely effective, avoiding damage of sensitive equipment, high risk elements, and non-structural contents, allowing a continuous fully operational use of the critical facilities.

Seismic isolation has become increasingly common in Chile. Thirteen structures with true[1] seismic isolation were present at the time of the Maule earthquake in 2010. All system worked flawlessly allowing the structures to remain fully operational after the earthquake. Since the 2010 Chilean earthquake, more than 80 new structures have also incorporated isolation systems. Several of those buildings are hospitals where seismic isolation has become a standard.

Prior to the 2010 earthquake, only two structures had incorporated seismic monitoring systems to capture the real-life behavior of seismic isolation systems. One project was the Andalucía Community Building [4,5,7], a shear wall structure built in 1992 with a plan of 10x6m and four stories. The second structure is the Marga Marga Bridge [6], which was built in 1996 with a total length of 383m. In 2013, two hospitals, the El Carmen Hospital (ECH) and the La Florida Hospital (LFH), both located in Santiago, Chile, were instrumented with accelerometers and scratch plates. These two new hospitals are representative of several hospital projects under construction in Chile. This paper presents the measured response for both projects to the Mw=8.3 Sept. 16th Illapel earthquake (Chile). Particular attention is given to the behavior of their seismic isolation system.

2. Hospitals and Isolation Systems

The El Carmen Hospital (ECH) is operational since 2013. It is located in the Maipu neighborhood of Santiago (Chile), which according to the Chilean specification NCh433 D61 corresponds to a seismic zone 2. It was built on a soil classified as D (NCh433 D61) and has two buildings: Main and North Building. The Main Building has 6 stories and 2 basements, and is seismically isolated with 278 high damping elastomeric bearings. The North Building has 4 stories and no basement. The isolation system is composed of a total of 69 bearings: 51 high damping elastomeric bearings and 18 high damping elastomeric bearings with lead core. The fundamental periods of both structures are slightly above 3 seconds. The Main Building has its isolation system interface above the first basement and the North Building at the foundation level. The main features of both buildings and isolation systems are presented in the Table 1, and the bearings main characteristics in Table 2.

The second hospital (LFH) was also constructed in 2013, in the La Florida neighborhood of Santiago. It was built on a soil classified as C (NCh433 D61). The building has 5 stories and 2 basements, and has 224 high damping elastomeric isolator bearings above the first basement. The fundamental period of the isolated structure is again slightly above 3 seconds. The main features of the building and isolation system are also presented in the Table 1, and the bearings main characteristics in Table 2.

[1] Vibration reduction obtained from bridges supported on reinforced neoprene pads with small thickness are not considered as true isolation system as they cannot maintain its flexibility through the complete seismic displacement demand of a severe earthquake.

Table 1 – Buildings and Isolation Systems Characteristics.

	El Carmen Hospital (ECH)		La Florida Hospital (LFH)
	Main Building	North Building	
Soil Classification (NCh433 D61)	D		C
Zone Classification (NCh433 D61)	2		2
Stories/Basements	6/2	4/0	5/2
Base Isolation Fundamental Period	3.29 s	3.19 s	3.07 s
Total Surface	60,141m^2	16,616m^2	84,972 m^2
Seismic Weight	72,812 tonf	16,733 tonf	68,322 tonf
Type of Bearings	High damping elastomeric bearings		
Quantity of Bearings	278	69	224
H5-70 Bearings	212	51	
H5-70L Bearings		18	
H5-85 Bearings	66		
H5-75 Bearings			224
Isolators design displacement	317 mm	306 mm	275 mm

Table 2 – Bearings Main Characteristics.

Bearing Type	Diameter (cm)	Total Height (cm)	Rubber Height (cm)	Lead Core Diameter (cm)	Damping @DD
H5-70	70	34.3	20.4	N/A	11%
H5-70L	70	34.3	20.4	10	20%
H5-85	85	34.3	20.4	N/A	11%
H5-75	75	28.9	16.8	N/A	12%

DD: Design Displacement

3. Seismic Monitoring System

The monitoring system for both hospitals is composed of triaxial accelerometers and scratch plates. For the ECH project, two scratch plates (D1 and D2) were installed in the isolation interface of the Main Building and other two in the North Building (D3 and D4). The exact location and photograph of the scratch plates are shown in Fig.1. Three accelerometers were also installed in the ECH. The first one (A1) is located at the foundation of the North Building and the second and third one (A2 and A3) were located below and above the isolation system interface of the Main Building as shown in the photographs in Fig.1. For the LCH project, two scratch plates were also installed at the isolation system interface (D1 and D2) as shown in Fig.2. Two triaxial accelerometers were installed. The first one (A1) located at the foundation level and the second one (A2) above the isolation system interface as shown again in Fig.2.

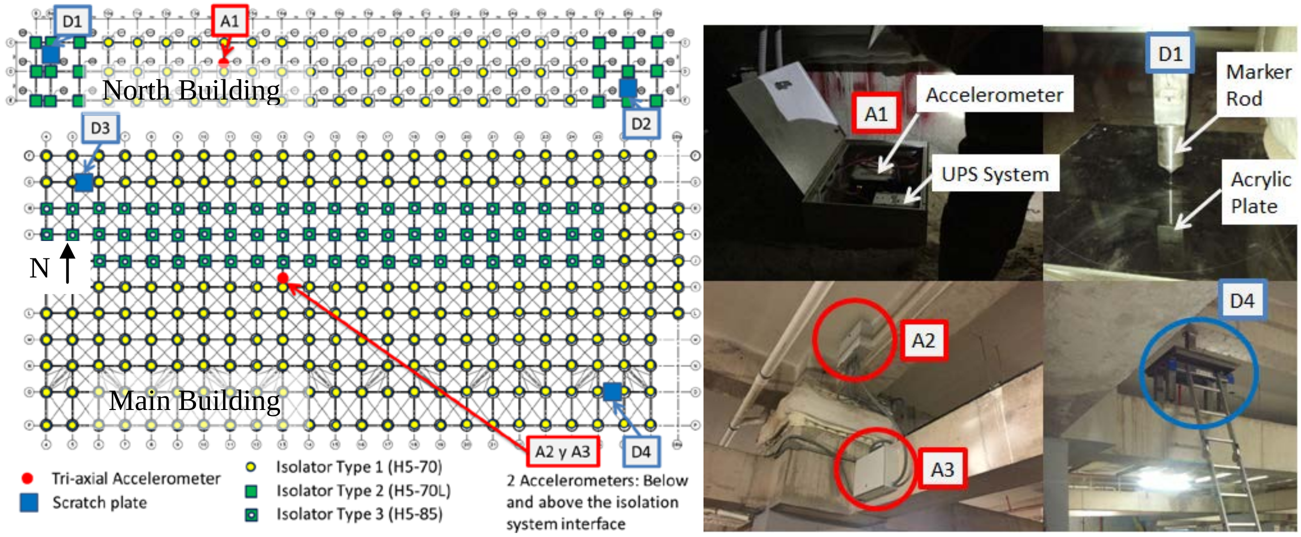


Fig. 1 – Location of the measurement devices for the ECH.

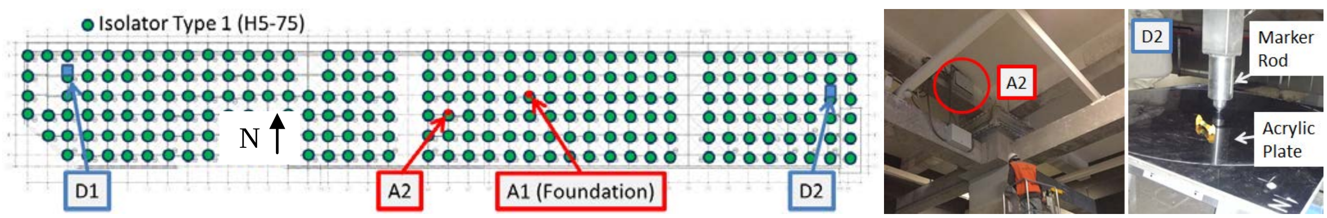
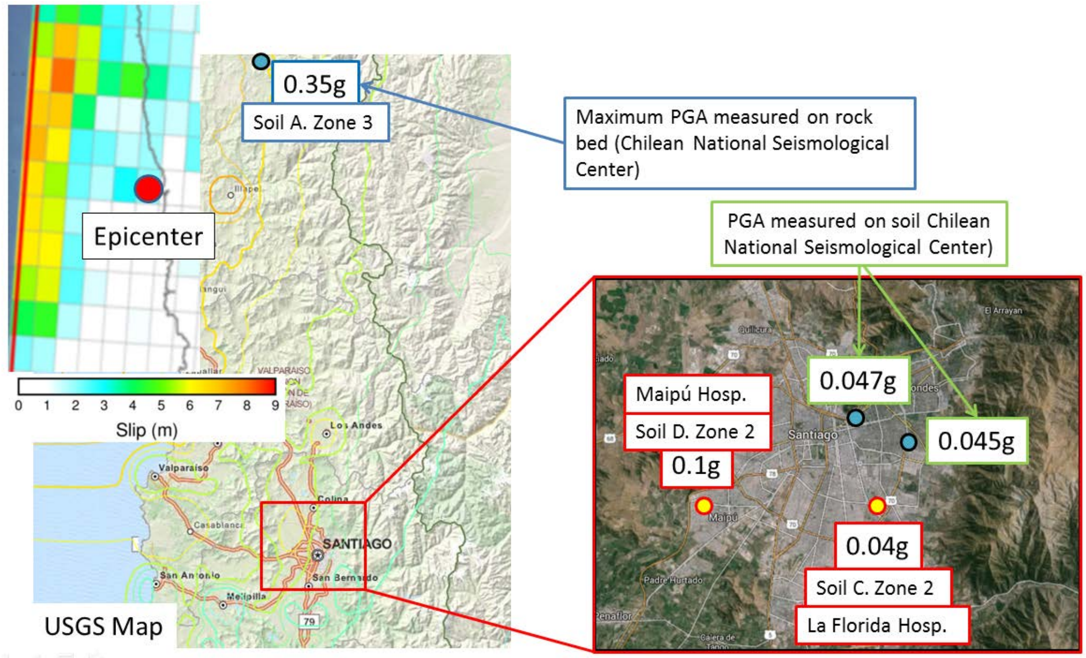


Fig. 2 – Location of the measurement devices for the LFH

All acceleration sensors are strong motion EQMET's TSA-SMA systems which integrates triaxial low noise accelerometers with a 24bit data acquisition unit and local recording capability and battery autonomy. They have a range of +- 4g over a frequency bandwidth of DC to 200 Hz. The scratch plates were provided by SIRVE S.A. They have a displacement range of 35cm, and incorporate a spring system to maintain contact of the marker rod to the acrylic plate (Fig.1).

4. Illapel Earthquake description

The Illapel Earthquake stroke Central Chile on September 16th, 2015. Its magnitude reached MW = 8.3 and its epicenter was located near the coast of the Coquimbo region. The rupture propagated to the north reaching a peak slip of 6m [8] as shown in the Fig. 3 a). The Chilean National Seismological Center, registered a maximum PGA of 0.350g near the fault and a maximum PGA of 0.047g in Santiago (www.sismologia.cl). The PGAs measured in the ECH and LFH were 0.100g and 0.040g, respectively. Both values are consistent with the National Seismological Centre figures.



(a) (b)

Fig. 3 – Fault slip profile and PGA levels for the Sep 16, 2015 Mw 8.3 earthquake [9]. (a) PGA near the epicenter (b) PGA levels at different locations in Santiago (Chile).

5. Results

Fig.4a presents the displacement measured by the scratch plates for both hospitals. Largest displacements were obtained for the Main Building of the ECH with maximum range values varying from 14mm to 21mm in the E-W direction, and 16 to 18mm in the N-S direction. These results are far lower than the allowable design displacement for the isolation bearings (317 mm), which indicates that the isolation system was barely activated. Furthermore, the difference in the E-W and N-S direction displacement results do not suggest any significant rotation of the building.

In comparison, the North Building of the ECH experienced smaller maximum horizontal displacement, with maximum values varying between 7 and 9 mm in the E-W direction and between 9 and 15mm in the N-S direction. Largest displacement ranges were observed in the N-S or Y direction which may indicate some rotation of the building. This result would not be surprising given the large aspect ratio of the North Building which makes it prone to rotation.

Results for the LFH are presented in Fig.4b. Maximum range values are around 14mm in the E-W direction and vary between 5 and 10mm in the N-S direction. The displacements are even smaller than those of the ECH. The stiffer soil certainly explains part of this result. It is notable that the results are much larger in the E-W direction. In particular, displacements for the D2 scratch plate are not typical of a seismic event. This result may be explained by concrete retraction prior to the earthquake, especially since the E-W direction coincides with the longest direction of the building.

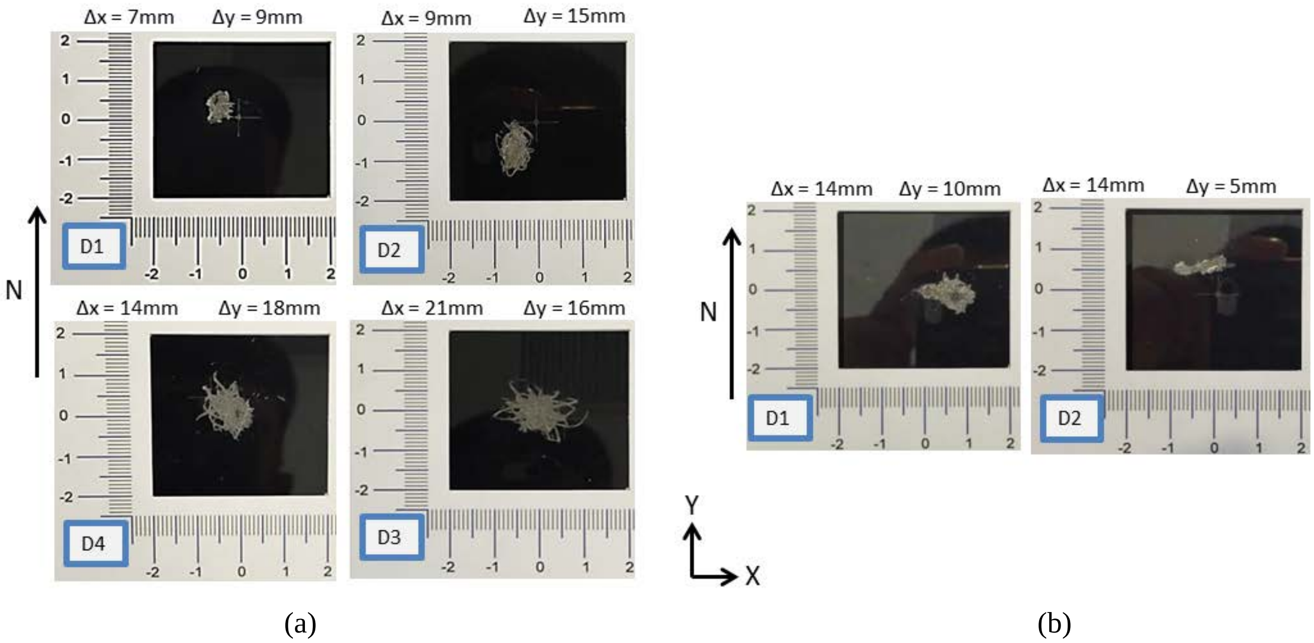
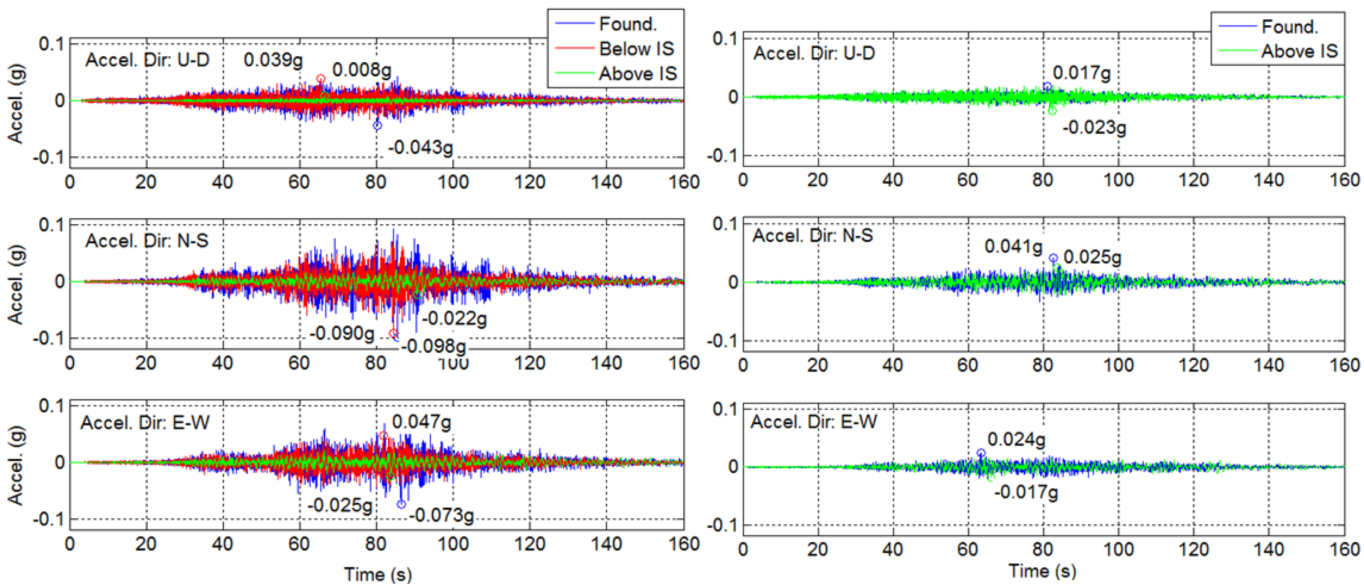


Fig. 4 – Scratch plate displacement results a) El Carmen Hospital b) La Florida Hospital

Fig.5 presents the acceleration records obtained from the monitoring system for both projects. Peak ground accelerations are below 0.1g, which is indicative of a moderated earthquake. For the ECH, similar accelerations were measured by the sensors located at the foundation and below the isolation system. However, a strong reduction is observed for the sensor located above the isolation system. Table 3 indicates that the isolation system provides a reduction of the maximum response between 66 and 80%. It is interesting to note that the largest reduction was obtained along the vertical direction.

Similar results were obtained for the LFH, showing the effectiveness of the isolation system. However, there are some notable differences. First, the accelerations at the foundation are approximately half of the ones measured for the ECH. As mentioned before, this result is explained by the stiffer soil on which the LFH is built. Second, the reduction provided by the isolation system is not as good as for the ECH with values ranging from 27 to 40% in the horizontal direction. The smaller seismic demand implies that the isolation system did not fully activate and thus didn't reach its best performance. Hence, a smaller reduction was observed. Finally, contrary to what was observed for the ECH, the isolation system did not provide any reduction of the accelerations in the vertical direction. Maximum acceleration was actually increased by about 30%.



(a) (b)

Fig. 5 – Measured accelerations for all sensors and all directions (a) ECH project (b) LFH project.

Table 3 - Maximum acceleration and isolation system reduction.

	El Carmen Hospital (ECH)			La Florida Hospital (LFH)		
	Max. Accel. U-D	Max. Accel. N-S	Max. Accel. E-W	Max. Accel. U-D	Max. Accel. N-S	Max. Accel. E-W
Foundation Level	0.039g	0.098g	0.073g	0.017g	0.041g	0.024g
Above Isolation Interface	0.008g	0.022g	0.025g	0.023g	0.025g	0.017g
Reduction	80.9%	77.4%	66.2%	-32.7%	40.4%	27.3%

Fig.6 presents the elastic spectra along with the design spectrum for the ECH. Isolated buildings in Chile are designed using the NCh 2745 code and fixed base structures with NCh 433 code. For reference, both design spectra are shown here. It can be first observed that all responses are significantly smaller than the design spectrum. For the vertical direction (U-D), similar elastic spectra are obtained from processing the measurements of sensors located at foundation and below IS. The elastic spectrum obtained from the sensor above IS presents a similar response in frequency but with different amplitude. The IS provided significant damping in the vertical direction, without affecting the general vertical stiffness of the interface. For the horizontal responses, the elastic spectra calculated from the records of the sensors at the foundation and below IS are again similar. However, the spectrum along N-S for the sensor above IS shows a shift in frequency, from 0.35s at the foundation to 1.74s. Similar results were obtained from the E-W direction with a frequency shift from 0.35s to 1.38s.

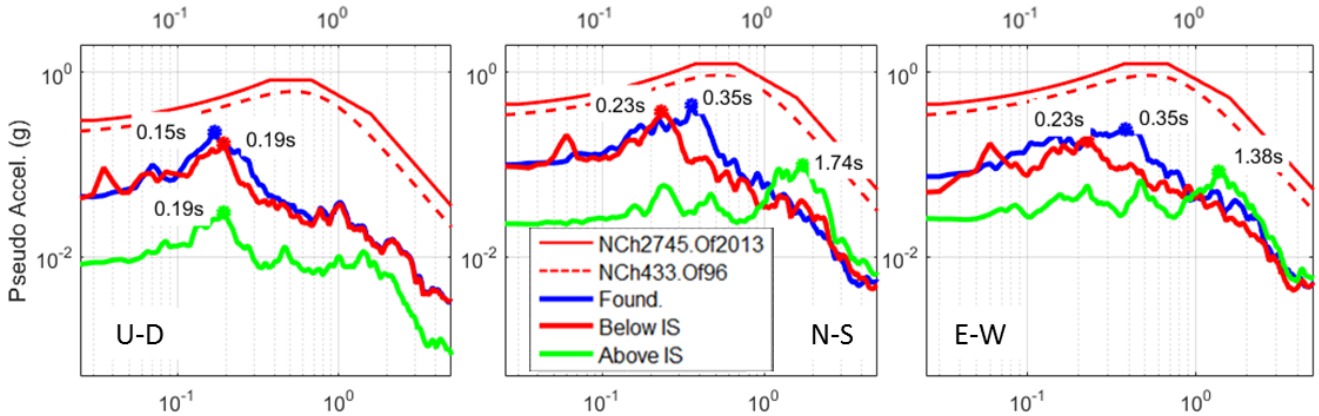


Fig. 6 - Elastic Spectra obtained using the measured accelerations in the El Carmen Hospital, the NCh433 D61 spectrum and the NCh2756 Spectrum. (IS: Isolation System)

Fig. 7 presents the elastic spectra for the LCH. In the horizontal direction, results were similar to the ECH results. Due to the IS, the horizontal period shifted from 0.28s to 1.44s (N-S) and from 0.34s to 1.22s (E-W). In the vertical direction, both the spectra from the sensor at foundation and above IS present a very similar response for periods longer than 0.2s. For shorter periods, the response from the above IS sensor is larger.

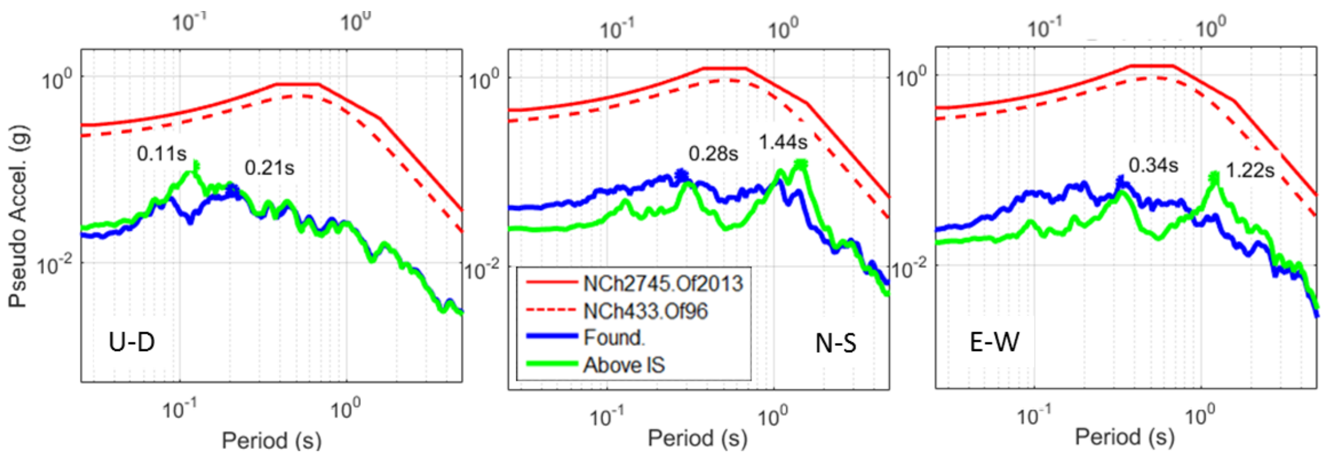


Fig. 7 - Elastic Spectra obtained using the measured accelerations in the La Florida, the NCh433 D61 spectrum and the NCh2756 Spectrum. (IS: Isolation System)

Discussion

The results along horizontal directions are generally similar for both projects. Both systems show a shift in the fundamental period and a significant reduction of the response above IS. This result is interesting as it shows that even with a moderate demand (<0.1g PGA), the IS with high damping elastomeric bearings activates and provides added protection and comfort.

The main difference between projects along the horizontal direction is the shift in the fundamental period, which is greater for the ECH especially in the N-S direction. As in every hysteretic system, as the deformation increases beyond the yield point the secant stiffness deviates from the initial stiffness, tending towards the tangent stiffness. In the ECH, lateral deformation were approximately twice those measured at the LFH, therefore the secant stiffness of the IS in the ECH is closer to the tangent stiffness, i.e. the overall system is softer and the fundamental period is longer.

The measured fundamental periods are smaller than the periods estimated at the design stage (>3.0s). This difference is explained by the small relative displacements observed, indicating that the isolators were not at their maximum deformation capacity, which means that they present a greater secant stiffness than at design stage.

The behavior along the vertical direction is substantially different for each hospital. In the ECH a strong reduction is observed and in the LFH there is no reduction, and the response is even larger for some periods. The response for ECH is particularly interesting as it is typical of a system with added damping. Further research is required however to explain these results.

6. Concluding Remarks

The response of two seismically isolated hospitals in Santiago to the September 16th Illapel earthquake (Chile 2015) were presented and analyzed. The Mw=8.3 earthquake generated a moderate demand in Santiago with PGAs between 0.05g to 0.10g. Even for this moderate demand, the isolation system for both hospitals were activated with measured shifts in fundamental periods of 0.35s to 1.74s (ECH, N-S), and 0.28s to 1.44s (LFH, N-S). The maximum horizontal accelerations were reduced by 70% and 35% respectively.

Small displacement ranges were measured by the scratch plates with values from 10 to 20mm for ECH and 5 to 10mm for LFH. These results are very small compared with the design displacements of the isolators (around 300mm). Therefore, the isolation systems were barely activated, but still performed very well in terms of acceleration reduction, especially for the ECH project.

The response of the isolation systems to vertical acceleration was different between each project. For the ECH, maximum vertical acceleration was reduced by 80%, and the fundamental period remained unchanged. However, for the LFH, an increase of 32% was observed for the maximum vertical acceleration.

7. Acknowledgements

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7. References

[1] Martelli Alessandro, and Forni Massimo (2010): Seismic Isolation and other Antiseismic Systems Recent Applications in Italy and Worldwide. *Seismic Isolation and Protection Seismic*, 1, 75-123; doi: 10.3390/buildings2030300.

[2] Gordon P. Warn, and Keri L. Ryan (2012): A Review of Seismic Isolation for Buildings: Historical Development and Research Needs. *Buildings*, 2, 300-325; doi: 10.3390/buildings2030300.

[3] De la Llera JC, Lüders C, Leigh P, and Sady H (2004): Analysis, testing, and implementation of seismic isolation of buildings in Chile. *Earthquake Engineering and Structural Dynamics*, 33, 543-574; doi: 10.1002/eqe.360.

[4] Rivera R, Masanori I, Morita K (2014): Dynamic behavior under strong motions and structural design procedures of seismically isolated buildings. *Bulletin of the International Institute of Seismology and Earthquake Engineering*, 48, 61-66

[5] Moroni MO, Sarrazin M, Soto P (2012): Behavior of Instrumented Base-Isolated Structures during the 27 February 2010 Chile Earthquake. Earthquake Spectra, 28,S1,S407-S424; doi: 10.1016/j.soildyn.2012.06.019.

[6] Sarrazin M, Moroni O, Neira C, Venegas B (2013): Performance of bridges with seismic isolation bearings during the Maule earthquake, Chile. *Soil Dynamics and Earthquake Engineering*, 47, 117-131, doi: 10.1016/j.soildyn.2012.06.019.

[7] Boroschek R, Retamales R, Aguilar A (2012): Seismic response of isolated structures subjected to Mw 8.8 Chile Earthquake of February 28, 2010. The International Symposium for CISNID 25th Aniversary, Paper No. M-2.

[8] Tilmann, F., Zhang, Y., Moreno, M., Saul, J., Eckelmann, F., Palo, M.,Dahm, T. (2016). The 2015 illapel earthquake, central chile: A type case for a characteristic earthquake? *Geophysical Research Letters*, 43(2), 574-583. doi:http://dx.doi.org/10.1002/2015GL066963

[9] USGS Preliminary Finite Fault Results for the Sep 16, 2015 Mw 8.3 46 km W of Illapel, Chile Earthquake