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DAMAGING CAPACITY OF CASCADIA SUBDUCTION EARTHQUAKES COMPARED WITH CHILEAN SUBDUCTION

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SUMMARY

The study of all accelerograms recorded for Cascadia subduction zone earthquakes, Olympia 1949, Puget Sound 1965 and Nisqually 2001, is done and compared with observed Modified Mercalli Intensities (MMI) at accelerographic stations. These three studied earthquakes are inslab or intraplate type. For this zone thrust earthquake accelerograms have not been recorded yet. Study of damaging capacity of accelerograms is done by using the destructiveness potential factor P_D. Estimated P_D values indicate that none of accelerograms of the three earthquakes was recorded at damaging area, which is in agreement with reported MMI values.

Recorded horizontal peak acceleration of Cascadia inslab earthquakes are systematically lower than the corresponding one for Chile. Comparison of Nisqually 2001 and Central Chile 1981 inslab earthquake accelerograms is also done for these two M = 6.8 earthquakes. Accelerograms characteristics of both subduction zones are markedly different.

Comparison of Chile and Mexico 1985 thrust earthquake accelerograms shows a light level of damage for a future Cascadia thrust earthquake in case to be similar to Mexico subduction.

INTRODUCTION

A comparative study of the damaging capacity of earthquakes of Cascadia and Chile subduction zones will be done by considering the instrumental damaging capacity measured through recorded accelerograms.

The western margin of North American plate from the north of California state, passing by Oregon and Washington states, up to Vancouver island at the south of British Columbia, Canada, is characterized by a convergent tectonics known as the Cascadia subduction zone. In this zone, the small Juan de Fuca plate is born at the Pacific Ocean at 300 [km] west from the North American plate and subducts under it.

The Juan de Fuca plate is a young plate with an estimated age of 10 to 15 million years, similar to the Nazca plate of the Chilean subduction, however the velocity of convergence of Nazca plate is extraordinary higher, 8.3 [cm/year], than Juan de Fuca with 3.0 to 4.6 [cm/year] (Wilson [1]).

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Cascadia subduction zone, similar to Chilean subduction, produces three types of earthquakes, shallow crustal, intraplate or inslab of intermediate depth and thrust interplate, which are shown in Fig. 1.

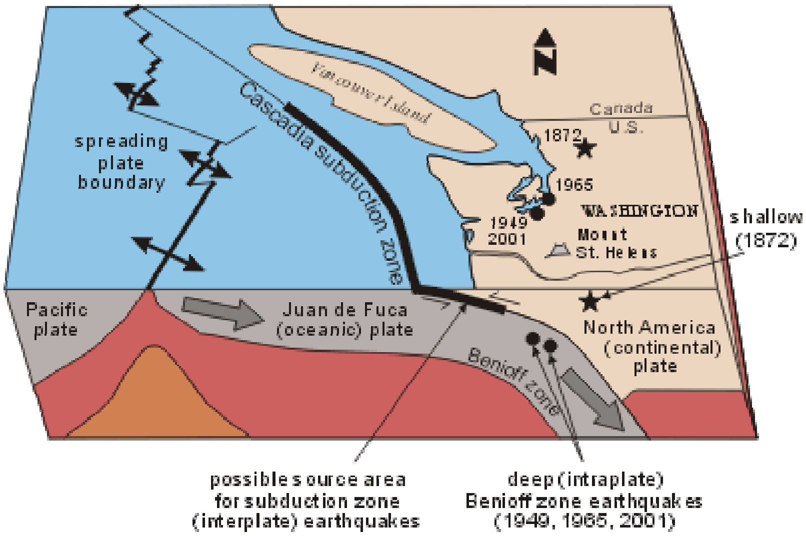

Figure 1. Cascadia subduction diagram showing the three types of earthquakes of the region (Walsh [2]).

EARTHQUAKE TYPES OF CASCADIA SUBDUCTION ZONE

Shallow Crustal Earthquakes.

These events are associated to surface faults in the American continental plate with magnitude Mw larger than 7.0 and hypocenter depth less than 30 [km].

The largest event of this type happened in the Washington and Oregon region was the North Cascadia 1872 earthquake (Fig.1), of estimated magnitude 7.4 and with a large number of aftershocks.

Researches done in the last decade have estimated the possible event of a large shallow earthquake in the region associated to the activity of the Seattle fault. Bucknam [3], [4] estimate the magnitude of this earthquake to be M > 7.0, the earthquake happened before 900 A.D and it was associated to a tsunami in Puget Sound (Atwater [5]).

Thrust Interplate Earthquakes.

These earthquakes are due to differential motion (co-seismic slip) in the interface between the oceanic Juan de Fuca and the continental North American plates. These events happen offshore with surface hypocenter, generally with depth less than 30 [km] and can have large magnitudes. Thrust earthquakes are due to the instant release of large tensions generated by the stick of the oceanic crust when it is pushed under the continent, showing a stick-slip behavior.

These types of earthquakes generally have long duration, more than one minute, and go with destructive tsunamis and large number of aftershocks.

Despite of soil subsidence evidences, uplift and tsunami effects (Satake [6]) showing the Cascadia zone capacity to produce large thrust earthquakes, there are not historical record of event of this type with magnitude larger than 6.0.

Late studies show that most recent thrust earthquake happened around 1700, from evidences of Washington coast change of levels and radio carbon dating of trunks of death trees. In addition in Japan exist an historical record of a tsunami on January 26, 1700 at 9.0 A.M.

Nevertheless this zone has not recorded large thrust earthquakes in the last 300 years, Heaton [7] have study the potential to happen one. They defined the following equation to estimate the maximum moment magnitude Mw of the maximum possible earthquake for the subduction zone:

$$Mw = -0.00889 \cdot T + 0.134 \cdot V + 7.96 \qquad (1)$$

Where T is the age of the subduction plate measured in millions years and V is the convergence velocity in cm/year.

Heaton [7] estimate the maximum magnitude of the earthquake in $Mw = 8.3 \pm 0.5$ by considering for Cascadia T = 10 to 15 million years and V = 3 to 4 cm/year. In addition, Uyeda [8] notice the large coupling between Juan de Fuca and North American plates. They also observed the absence of seismicity for depth larger than 100 [km] and that the subduction angle under Puget Sound is between 10º to 15º, both facts are characteristic of a high coupled subduction zone.

Rogers [9] established that one of closest analogs to the Cascadia subduction zone is the Rivera-Cocos plate system in the western coast of Mexico, however this plate, unlike Cascadia case, has produced many thrust earthquakes with magnitudes between 7.0 and 8.0 associated to Cocos plate. Rivera plate also has shown seismicity for depth larger than 40 [km], which can have important consequences for the area of Puget Sound and Vancouver Island (Stanley [10]).

In conclusion, there are not thrust earthquakes accelerograms for Cascadia subduction zone, however this zone has the potential to produce a large event of $Mw = 8.3 \pm 0.5$.

Inslab of Intermediate Depth Earthquakes.

These events are associated to stresses in the Juan de Fuca subducting plate, which are mainly controlled by tension and bending of the subducting plate consequence of the subduction geometry. The plate tension is due to the “slab pull”, consequential of the sinking of the deeper part of the plate into the mantle due to its larger density. In addition the subduction geometry produces, considering the finite thickness of the subducting plate, bending with traction in the upper part of the plate and compression in the lower one.

The last three large earthquakes of the region: Nisqually 2001, (Mw=6.8) with epicenter near Olympia, Puget Sound 1965 (mb=6.5) with epicenter between Tacoma and Seattle and Olympia 1949 (Ms = 7.1) with epicenter also near Olympia, are inslab o intraplate type, (Fig. 1).

All these three earthquakes have accelerograms allowing to study their instrumental damaging capacity and to compare with observed Modified Mercalli Intensities. These earthquakes are characterized to have no aftershocks (1965, 1949) or only four aftershocks for Nisqually 2001. Others inslab of intermediate depth earthquakes are: 1822, 1909, 1939, and 1946 (Ludwin [11]). However since they have not accelerograms they will be not considered in the studies of damage of the next sections.

DAMAGING CHARACTERISTICS OF INSLAB EARTHQUAKES

Main seismic and damaging characteristics of the three inslab of intermediate depth earthquakes with recorded accelerograms are summarized in this section.

Olympia 1949 Earthquake.
On April 13, 1949 the West Side of Washington state was struck by an earthquake of surface magnitude Ms = 7.1, with epicenter at 47.1ºN and 122.7º W, between Olympia and Tacoma. The focal depth was estimated in 54 [km] (Baker [12]). The maximum Modified Mercalli Intensity (MMI) was VIII and the earthquake was felt in an area of approximated 380.800 [km²] including Washington and Oregon and part of Idaho and British Columbia. The maximum ground acceleration was 0.28 [g] recorded at Olympia. Earthquake damage was mainly to low stability soils and old structures, particularly of masonry with mortar of sand and lime. Wood houses were undamaged.

Puget Sound 1965 Earthquake.
On April 29 1965 the largest recorded earthquake since 1833 struck the region of Puget Sound. The epicenter of the event was localized at 47.4ºN and 122.3ºW, with a focal depth estimated in 59 [km] and with body-wave magnitude $m_b = 6.5$.

This earthquake was characterized by a large area of MMI = VII and small pockets at Seattle of MMI = VIII. Nevertheless these pockets, this earthquake is better described as a MMI = VII event, since the VIII effects were difficult to evaluate considering that many building was already damaged by the Olympia 1949 earthquake. The maximum ground acceleration was 0.20 [g] recorded at Olympia Highway Test Laboratory.

Nisqually 2001 Earthquake.
On February 26, 2001 an earthquake with epicenter at the delta of Nisqually River, 47.149ºN and 122.727ºW, struck the Seattle area. The earthquake of Mw = 6.8 had a focal depth of 52 [km]. The observed MMI in most of the region was VII and less; South Seattle had MMI VI-VII while North Seattle had MMI between V and VI.

This earthquake was recorded for many accelerographics stations from the west pacific coast of Olympia peninsula at west, up to Vancouver at north and from Portland at south and Salt Lake City at east. The maximum recorded ground acceleration was 0.68 [g] at Seattle area.

From the analysis of the damage of these three earthquakes, it is concluded that Cascadia subduction zone has not been struck for severe damaging earthquake during the twenty century, situation that makes particularly difficult to estimate the characteristics of a megaevent for this region.

Considering that these three inslab intermediate depth earthquakes are the only ones which has accelerograms, they will be considered for a comparative study of the damaging capacity of Cascadia and Chile subduction zones, by using the instrumental damaging capacity measured through recorded accelerograms.

INSTRUMENTAL DAMAGING CAPACITY

Araya [13], [14] have defined an earthquake destructive instrumental measurement based on the strong nonlinear behavior of simple nonlinear one degree of freedom elastoplastic structures produced by accelerograms. They used the dynamical probabilistic solution of the corresponding Fokker-Planck equation for a wide family of possible accelerograms and elastoplastic structures. From the expected ductilities of the family one-degree of freedom elastoplastic structures, the destructiveness potential factor P_D or the capacity of earthquake ground motion to produce structural and soil damage is defined.

The destructiveness potential factor P_D is:

$$P_D = \frac{\pi}{2\cdot g} \frac{\int_0^{t_0} a^2(t)dt}{\upsilon_0^{\,2}} \qquad (2)$$

Where a(t) is the earthquake ground acceleration, t_o the total duration of the accelerogram, g is the acceleration of gravity and υ_o is the intensity of zero crossings of the accelerograms.

Or

$$P_D = \frac{I_A}{\upsilon_0^{\,2}} \qquad (3)$$

Where I_A is the Arias intensity.

The Arias intensity (Arias [15]) since it was derived from the elastic response of a family of oscillators of one degree of freedom, it is not necessarily related with damage.

The P_D combines simultaneously the effects of amplitude variation with time, frequency content and duration of accelerograms for the measurement of earthquake damage.

Uang [16] verified the capacity of destructiveness potential factor P_D to order recorded damaging accelerograms according to observed damage of large earthquakes.

The destructiveness potential factor P_D allows to compare the destructiveness of different zone of the world through the ductility demand of their accelerograms, property that will be applied to analyze Cascadia accelerograms.

The horizontal destructiveness potential factor P_{DH} includes the simultaneous effect of both orthogonal horizontal accelerograms recorded respectively in directions XX and YY:

$$P_{DH} = P_{DXX} + P_{DYY} \qquad (4)$$

Where P_{DXX} and P_{DYY} represent respectively the P_D of the accelerograms recorded in XX and YY directions.

This instrumental damaging measurement is related with the observed damage measured by Modified Mercalli Intensities MMI, in no instrumental way, through the following relation due to Saragoni [17].

$$MMI = 4.56 + 1.50\cdot Log(P_{DH}) \qquad (5)$$

Where P_{DH} is measured in $10^{-4}\cdot g\cdot sec^3$. The correlation coefficient obtained for Eq. (5) was 0.798.

Considering a damage threshold of MMI = 6.5, corresponding to verifiable damage, a value of $P_{DH} = 20\cdot 10^{-4}$ [g·sec³] = 1.96 [cm·sec] is obtained.

The importance of Eq. (5) is due to the link between the instrumental damage measurement done by accelerograms and the observed damage estimated by MMI. Therefore in the next section this equation will be used to verify if P_{DH} values of recorded Cascadia accelerograms of the three studied inslab earthquakes correlates with reported MMI.

DESTRUCTIVENESS POTENTIAL FACTORS FOR CASCADIA EARTHQUAKES

In this section the PD values estimated by Concha (18) for the three inslab Cascadia earthquakes: Olympia 1949, Puget Sound 1965 and Nisqually 2001 are summarized.

Olympia 1949 Earthquake.

Table 1 indicates the calculated PD and PDH values for the accelerograms of the Olympia 1949, Ms = 7.1, earthquake.

Table 1. Destructiveness Potential Factors for Olympia 1949 Earthquake Accelerograms.

STATION	COMPONENT	DISTANCE [km]	PGA [cm/sec²]	I_A [cm/sec]	ν_0 [crossings/sec]	P_D [cm·sec]	$P_{D H}$ [cm·sec]
Olympia Hwy Test Lab (OHTL)	N86E	39	274.6	112.57	5.59	3.60	6.13
	N04W		161.6	75.31	5.46	2.53	
	Vertical		90.6	18.24	5.46	0.61	
Seattle Dist Engr Off (SDE)	N02W	36	66.5	20.53	4.24	1.14	1.83
	N88W		65.9	14.05	4.51	0.69	
	Vertical		22.0	1.92	5.90	0.05	

This table also includes epicentral distance, peak ground acceleration PGA, Arias intensity I_A and intensity of zero crossing ν_0.

Considering the value of P_{DH} = 6.13 [cm·sec] of Olympia station of Table 1, MMI value of 7.25 is obtained, which is in agreement with the VII-VIII value reported for that station (Stover [19]).

Puget Sound 1965 Earthquake.

Table 2 indicates the calculated PD and PDH values for the accelerograms of the Puget Sound 1965, mb = 6.5 earthquake.

Table 2. Destructiveness Potential Factors for Puget Sound 1965 Earthquake Accelerograms.

STATION	COMPONENT	DISTANCE [km]	PGA [cm/sec²]	I_A [cm/sec]	ν_0 [crossing/sec	P_D [cm-sec]	$P_{D H}$ [cm-sec]
Olympia Hwy Test Lab (OHTL)	176	89	134.2	30.35	6.26	0.78	1.97
	266		194.3	45.04	5.70	1.39	
	Vertical		59.9	7.65	5.09	0.30	
Seattle Federal Bldg (SFB)	148	22	52.2	7.93	4.66	0.36	1.12
	238		77.6	12.44	4.33	0.66	
	Vertical		32.1	3.08	4.68	0.14	

In this case the largest P_{DH} correspond to station OHTL with 1.97 [cm·sec], which is the value corresponding to the damage threshold MMI = 6.5 according to Eq. (5). This value is in agreement with the MMI = VII reported for the area of the accelerographics stations (Ludwin [11]).

Nisqually 2001 Earthquake.

Table 3 indicates P_D and P_{DH} values obtained from the set of 100 components of the accelerograms of the Nisqually 2001, Mw = 6.8, earthquake, recorded by the general array. All PDH values are under 1.96 cm·sec, with the exception of station SP2, P_{DH} =3.93 [cm·sec], station TBPA, P_{DH} = 3.64 [cm·sec] and station PCEP, P_{DH} = 2.22 [cm·sec]. Thus MMI are under the threshold of verifiable damage MMI = 6.5, confirming that Nisqually 2001 is only a MMI VI – VII earthquake. Stations SP2 and TBPA according to

Eq. (5) should be MMI = VII, the MMI values reported for these two station was VI – VII, which can be considered in agreement.

Table 3. Destructiveness Potential Factors for Nisqually 2001 Earthquake Accelerograms. General Array.

NUMB	STATION	COMPONENT	PGA [cm/sec²]	I_A [cm/sec]	ν_0 [crossing/sec]	P_D [cm-sec]	P_{DH} [cm-sec]
1	ALST	NS	74.37	11.52	10.59	0.103	0.153
2	ALST	EW	59.72	6.59	11.45	0.050	
3	ALST	UP	23.26	1.44	12.28	0.010	
4	BEVT	NS	48.62	3.39	8.8	0.044	0.084
5	BEVT	EW	47.81	3.33	9.09	0.040	
6	BEVT	UP	22.16	1.78	8.04	0.028	
7	BRKS	NS	101.91	30.05	6.57	0.696	1.13
8	BRKS	EW	75.67	20.29	6.84	0.434	
9	BRKS	UP	44.99	6.77	7.07	0.135	
10	ELW	NS	54.36	5.94	8.77	0.077	0.14
11	ELW	EW	55.31	5.42	9.32	0.063	
12	ELW	UP	34.32	2.27	10.71	0.020	
13	ERW	NS	8.34	0.120	12.75	0.001	0.002
14	ERW	EW	9.29	0.14	12.64	0.001	
15	ERW	UP	8.32	0.080	13.82	0.000	
16	ERW	NS	7.82	0.1038	12.43	0.001	0.002
17	ERW	EW	9.33	0.139	12.59	0.001	
18	ERW	UP	7.85	0.074	14.03	0.000	
19	GNW	NS	79.43	5.94	8.6	0.080	0.23
20	GNW	EW	156.04	11.59	8.8	0.150	
21	GNW	UP	60.75	3.98	8.38	0.057	
22	KEEL	NS	13.38	1.01	12.79	0.006	0.013
23	KEEL	EW	14.16	1.08	12.55	0.007	
24	KEEL	UP	7.06	0.266	12.95	0.002	
25	KIMB	NS	90.74	11.07	5.47	0.370	1.16
26	KIMB	EW	132.74	21.64	5.24	0.790	
27	KIMB	UP	46.23	5.11	5.82	0.151	
28	KIMR	NS	147.37	19.84	7.62	0.340	0.88
29	KIMR	EW	159.78	26.06	6.92	0.540	
30	KIMR	UP	69.15	8.64	7.81	0.142	
31	KINR	NS	48.47	9.27	8.78	0.120	0.236
32	KINR	EW	74.07	8.41	8.51	0.116	
33	KINR	UP	30.85	3.59	11.21	0.029	
34	KITP	NS	48.38	9.38	6.81	0.202	0.425
35	KITP	EW	47.34	8.73	6.26	0.223	
36	KITP	UP	26.19	3.85	7.06	0.044	
37	LAP	NS	99.64	27.84	5.81	0.826	1.355
38	LAP	EW	83.46	20.86	6.28	0.529	
39	LAWT	NS	55.21	9.28	9.47	0.103	0.194
40	LAWT	EW	64.56	9.19	10.06	0.091	
41	LAWT	UP	28.77	2.71	10.39	0.025	
42	LEOT	NS	73.99	7.01	8.33	0.101	0.241
43	LEOT	EW	62.52	8.37	7.72	0.140	
44	LEOT	UP	39.24	4.09	9.03	0.050	
45	MBPA	NS	151.81	19.4	17.89	0.061	0.089
46	MBPA	EW	117.88	13.44	21.80	0.028	
47	MBPA	UP	49.04	3.47	28.66	0.004	
48	MPL	NS	79.72	14.55	4.89	0.608	1.173
49	MPL	EW	95.91	15.46	5.23	0.565	
50	MPL	UP	48.61	4.95	6.04	0.136	
51	PCEP	NS	209.35	50.27	6.88	1.060	2.220
52	PCEP	EW	200.08	50.82	6.63	1.160	
53	PCEP	UP	151.88	36.300	7.53	0.064	
54	PCFR	NS	128.39	31.8	7.14	0.624	1.394
55	PCFR	EW	108.24	34.93	6.73	0.770	
56	PCFR	UP	138.27	31.42	12.79	0.192	
57	PCMD	NS	108.4	24.98	12.43	0.162	0.392
58	PCMD	EW	154.7	30.41	11.50	0.230	
59	PCMD	UP	66.33	11.84	10.64	0.105	
60	QAW	NS	111.91	31.76	6.54	0.740	1.330
61	QAW	EW	102.72	25.24	6.54	0.590	
62	QAW	UP	75.12	19.04	6.43	0.461	
63	RAW	NS	122.38	22.36	6.93	0.466	1.368
64	RAW	EW	169.5	37.05	6.40	0.902	
65	RAW	UP	54.88	7.63	8.62	0.103	
66	RBEN	NS	107.31	13.4	6.17	0.352	0.780
67	RBEN	EW	107.67	11.99	5.29	0.428	
68	RBEN	UP	44.64	5.09	6.61	0.117	

Table 3. Continuation. Destructiveness Potential Factors for Nisqually 2001 Earthquake Accelerograms. General Array.

NUMB	STATION	COMPONENT	PGA [cm/sec²]	I_A [cm/sec]	ν_0 [crossing/sec]	P_D [cm-sec]	P_{DH} [cm-sec]
69	RHAZ	NS	38.61	3.27	6.29	0.083	0.168
70	RHAZ	EW	44.57	3.26	6.19	0.085	
71	RHAZ	UP	35.84	2.17	7.15	0.042	
72	ROSS	NS	24.96	1.17	9.34	0.013	0.023
73	ROSS	EW	18.38	1.06	10.42	0.010	
74	ROSS	UP	13.02	0.48	13.52	0.003	
75	RWW	NS	61.46	12.04	4.56	0.579	1.353
76	RWW	EW	73.82	13.91	4.24	0.775	
77	RWW	UP	42.53	3.70	4.15	0.21	
78	SBES	NS	4.92	0.12	13.65	0.001	0.002
79	SBES	EW	6.18	0.13	13.53	0.001	
80	SBES	UP	4.71	0.06	14.85	0.000	
81	SEW	NS	166.1	23.47	10.08	0.231	0.413
82	SEW	EW	128.69	21.99	11.01	0.182	
83	SP2	NS	186.46	35.53	5.93	1.100	3.930
84	SP2	EW	302.06	83.59	5.35	2.920	
85	SP2	UP	114.87	11.49	6.31	0.289	
86	SQM	NS	4.79	0.05	7.03	0.001	0.004
87	SQM	EW	9.36	0.14	6.39	0.003	
88	SQM	UP	4.79	0.05	7.03	0.001	
89	TBPA	NS	63.69	25.39	3.86	1.700	3.640
90	TBPA	EW	62.72	22.07	3.38	1.940	
91	TBPA	UP	45.71	8.55	5.36	0.297	
92	TKCO	NS	168.22	47.55	10.41	0.439	0.933
93	TKCO	EW	267.49	76.67	12.46	0.494	
94	TKCO	UP	76.17	14.30	14.41	0.069	
95	UPS	NS	59.56	8.44	7.08	0.169	0.313
96	UPS	EW	54.04	7.79	7.34	0.145	
97	UPS	UP	53.84	6.32	5.10	0.243	
98	WISC	NS	92.61	12.18	6.87	0.258	0.577
99	WISC	EW	111.25	17.21	7.35	0.319	
100	WISC	UP	33.81	4.04	7.05	0.082	

Table 4 indicates the P_D and P_{DH} values obtained from the set of 75 components of the accelerograms of the Seattle Urban array, for Nisqually earthquake.

In the case of PDH values of Table 4, of the Seattle Seismic Urban array, the largest PDH values correspond to BOE (P_{DH} = 6.118 [cm·sec]) and SDS (P_{DH} =6.361 [cm·sec]) stations.

Considering Eq. (5) a value of MMI = 7.25 is obtained for station SDS, where a MMI = VI –VII was reported. Similar value is obtained for station BOE where a MMI = VII was reported. (See Table 5).

In general the values obtained for P_{DH} are in agreement with the reported MMI.

In Table 5 the PDH values with the corresponding reported MMI for Nisqually earthquake are indicated.

The results of Table 5 are shown in Fig. 2 and compared with the line corresponding to Eq. (5). In this figure the horizontal line represents the threshold of verifiable damage (MMI = 6.5) of $P_{DH} = 20\cdot10^{-4}$ [g·sec³]. In general the P_{DH} values of Nisqually earthquake are higher than estimated P_{DH} values from Eq. (5) in the range of $P_{DH} \geq 20\cdot10^{-4}$ [g·sec³]. It can be also appreciated that larger P_{DH} values of Table 5 correspond to the larger MMI values. For example station BOE located at Boeing Field (King County International Airport), 8 [km] at North of Seattle, in the Valley of the Duwanish river, recorded one of the largest P_{DH} = 6.12 [cm·sec] at a site where liquefaction effects were observed. The stations KDK and NOR recorded respectively P_{DH} of 3.64 [cm·sec] and 5.44 [cm·sec], they are located at Pioneer Square, an area of unreinforced masonry houses of more than one century old, 10 % of these houses had damage. In the area of the Holgate overpass of interstate highway I – 5, where the station SDS, SDN and SDW are located, they respectively have P_{DH} = 6.36, 2.8 and 2.88 [cm·sec]. At this location the column of one bridge showed damage.

Table 4. Destructiveness Potential Factors for Nisqually 2001 Earthquake Accelerograms. Seattle Seismic Urban Array.

NUMB	STATION	COMPONENT [1]	PGA [cm/sec²]	I_A [cm/sec]	ν_0 [crossing/sec]	P_D [cm-sec]	P_{DH} [cm-sec]
1	ALK	0	43.83	3.19	6.74	0.070	0.097
2	ALK	1	24.30	2.27	6.21	0.059	
3	ALK	2	24.28	1.58	6.47	0.038	
4	ALO	0	72.43	13.63	11.15	0.110	0.521
5	ALO	1	100.52	25.35	9.84	0.262	
6	ALO	2	103.37	20.43	8.89	0.259	
7	BHD	0	82.75	20.49	6.98	0.421	2.301
8	BHD	1	139.62	24.74	6.27	0.630	
9	BHD	2	159.91	42.95	5.07	1.671	
10	BOE	0	76.56	7.41	7.29	0.139	6.118
11	BOE	1	185.67	58.26	5.51	1.921	
12	BOE	2	184.53	114.37	5.22	4.198	
13	BRI	0	48.22	4.40	13.74	0.023	0.509
14	BRI	1	89.64	16.54	6.70	0.369	
15	BRI	2	86.37	14.76	10.26	0.140	
16	CRO	0	53.58	13.06	6.83	0.280	0.821
17	CRO	1	115.19	19.26	6.47	0.459	
18	CRO	2	84.05	16.97	6.85	0.361	
19	CTR	0	44.36	6.70	8.74	0.088	0.717
20	CTR	1	75.45	16.14	6.00	0.448	
21	CTR	2	69.17	12.64	6.86	0.269	
22	EVA	0	35.63	5.86	9.22	0.069	0.209
23	EVA	1	52.54	9.39	8.84	0.120	
24	EVA	2	54.35	8.62	9.84	0.089	
25	HAL	0	50.91	9.54	7.43	0.173	0.783
26	HAL	1	94.79	26.16	7.38	0.480	
27	HAL	2	75.18	15.33	7.11	0.303	
28	HAR	0	86.41	22.00	10.17	0.213	2.838
29	HAR	1	211.59	104.93	8.68	1.393	
30	HAR	2	183.26	99.72	8.31	1.445	
31	HIG	0	59.96	11.09	7.05	0.223	1.074
32	HIG	1	127.78	21.31	5.20	0.788	
33	HIG	2	64.06	13.22	6.81	0.285	
34	KDK	0	68.77	9.66	7.24	0.184	3.640
35	KDK	1	183.44	67.74	6.10	1.821	
36	KDK	2	148.73	60.57	5.77	1.819	
37	LAP	0	75.10	18.04	7.38	0.331	1.355
38	LAP	1	99.64	27.84	5.81	0.826	
39	LAP	2	83.46	20.86	6.28	0.529	
40	MAR	0	79.55	11.14	7.59	0.193	1.367
41	MAR	1	125.61	24.32	6.06	0.662	
42	MAR	2	113.59	28.16	6.32	0.705	
43	NOR	0	134.48	35.21	7.12	0.694	5.435
44	NOR	1	192.11	139.44	7.50	2.479	
45	NOR	2	211.23	98.93	5.78	2.957	
46	PIE	0	50.08	6.72	8.38	0.102	1.096
47	PIE	1	126.08	38.98	8.96	0.485	
48	PIE	2	99.38	31.62	7.20	0.611	
49	SDN	0	78.68	16.14	7.53	0.284	2.805
50	SDN	1	161.36	67.49	7.23	1.293	
51	SDN	2	183.96	73.91	6.99	1.512	
52	SDS	0	130.95	29.20	6.16	0.769	6.361
53	SDS	1	276.85	101.94	5.23	3.723	
54	SDS	2	210.68	74.72	5.32	2.638	
55	SDW	0	564.48	31.15	9.34	0.357	2.887
56	SDW	1	215.87	67.14	6.84	1.433	
57	SDW	2	676.16	83.28	7.57	1.454	
58	SEU	0	72.41	9.27	6.57	0.215	0.991
59	SEU	1	96.17	17.35	5.70	0.534	
60	SEU	2	95.42	19.32	6.50	0.457	
61	SEW	0	54.01	3.85	11.42	0.030	0.412
62	SEW	1	166.10	23.47	10.08	0.231	
63	SEW	2	128.69	21.99	11.01	0.182	
64	THO	0	59.99	6.33	6.05	0.173	1.154
65	THO	1	88.75	19.71	6.18	0.515	
66	THO	2	113.84	23.76	6.10	0.639	
67	UNK	0	61.18	8.47	10.16	0.082	0.584
68	UNK	1	112.39	18.67	6.63	0.425	
69	UNK	2	127.40	26.00	12.76	0.160	
70	UNR	0	131.40	43.29	16.55	0.158	1.499
71	UNR	1	212.98	80.05	11.08	0.652	
72	UNR	2	268.70	145.68	13.12	0.847	
73	WEK	0	85.84	17.56	10.93	0.147	0.815
74	WEK	1	176.95	45.71	10.89	0.385	
75	WEK	2	221.87	53.25	11.13	0.430	

[1]. 0: Vertical Component, 1: Horizontal Component, 2: Horizontal Component

Table 5. Horizontal Destructiveness Potential Factors P_{DH} and MMI for Nisqually 2001 Earthquake.

General Array		
STATION	**PDH[cm-sec]**	**MMI**
BRKS	1.130	V
GNW	0.230	VI-VII
KIMB	1.160	VI
KIMR	0.880	VI
KINR	0.236	V
KITP	0.425	VI
LEOT	0.241	IV
MPL	1.173	VI
PCEP	2.220	VI
PCFR	1.394	VI
PCMD	0.392	VI
QAW	1.330	VI
RAW	1.368	VI
RBEN	0.780	V
RWW	1.353	VI
SP2	3.930	VI-VII
TBPA	3.640	VI-VII
TKCO	0.933	V
UPS	0.313	V
WISC	0.577	V

Seattle Seismic Urban Array		
STATION	**PDH[cm·sec]**	**MMI**
ALO	0.521	VI
BHD	2.301	VII
BOE	6.118	VII
BRI	0.509	VI
CRO	0.821	VI
CTR	0.717	VI
EVA	0.209	V
HAL	0.783	V
HAR	2.838	VI-VII
HIG	1.074	VI
KDK	3.640	VI-VII
LAP	1.355	V
MAR	1.367	V
NOR	5.435	VI
PIE	1.096	VI
SDN	2.805	VI-VII
SDS	6.361	VI-VII
SDW	2.887	VI-VII
SEU	0.991	VI
SEW	0.412	VI-VII
THO	1.154	VI
UNK	0.584	VI-VII
UNR	1.499	VI-VII
WEK	0.815	VI-VII

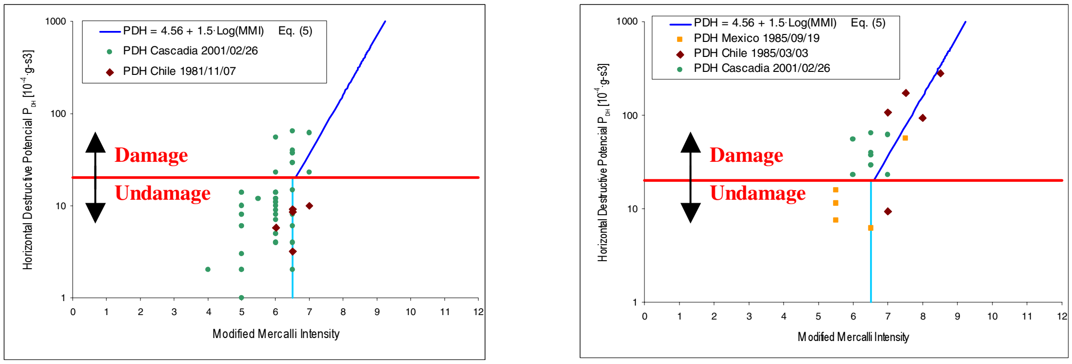

Figure 2. Relation between Horizontal Destructive Potential Factor and Mercalli Modified Intensity for Nisqually 2001 Earthquake. **a)** Comparison with Central Chile 1981 earthquake. **b)** Comparison with Mexico 1985 and Central Chile 1985 thrust earthquakes.

The largest P_{DH} values were obtained at accelerographic stations located on fill, with the exception of Boeing Field located on Holocenic soil. Therefore soil dynamic amplification effect should be expected, however the observed light structural damage does not correlate with the fill foundation soil.

In Table 4, the largest horizontal PGA value correspond to station SDW with 676.16 [cm/sec²], this station is located on fill at an epicentral distance of 55.3 [km]. The P_{DH} for this station was one of the largest 2.88 [cm·sec]. The accelerogram of the 90° component shows only one large spike, in contrast with the rest PGA values recorded on fill which are noticeably lower. This station also recorded the largest vertical PGA 564.48 [cm/sec²], with a value similar to the horizontal PGA, which is characteristic of inslab intermediate depth earthquakes.

In conclusion, estimated destructiveness potential factors for the three studied inslab Cascadia earthquakes indicate that practically none accelerogram was recorded in damaging area, which coincides with reported MMI values for these earthquakes. Since most of estimated P_{DH} are lower than the threshold of damage, P_{DH} do not correlate well, since correspond to elastic response which is not the purpose of P_{DH}, which is to measure damage.

COMPARISON BEETWEEN CASCADIA AND CHILE PGA

Saragoni [20] has demonstrated that Chilean PGA values are systematically higher than the Cascadia subduction zone.

Fig.3 illustrates this situation for Nisqually 2001 (Mw = 6.8) earthquake. In this figure the recorded PGA values are shown, classified by soil type according to NERHP, with the attenuation curves proposed by Saragoni [20], Atkinson [21] and Youngs [22]. The curve of Saragoni [20], corresponds to Chile horizontal PGA attenuation formula for inslab earthquakes recorded only on ‘rock and hard soil’ similar to soil C.

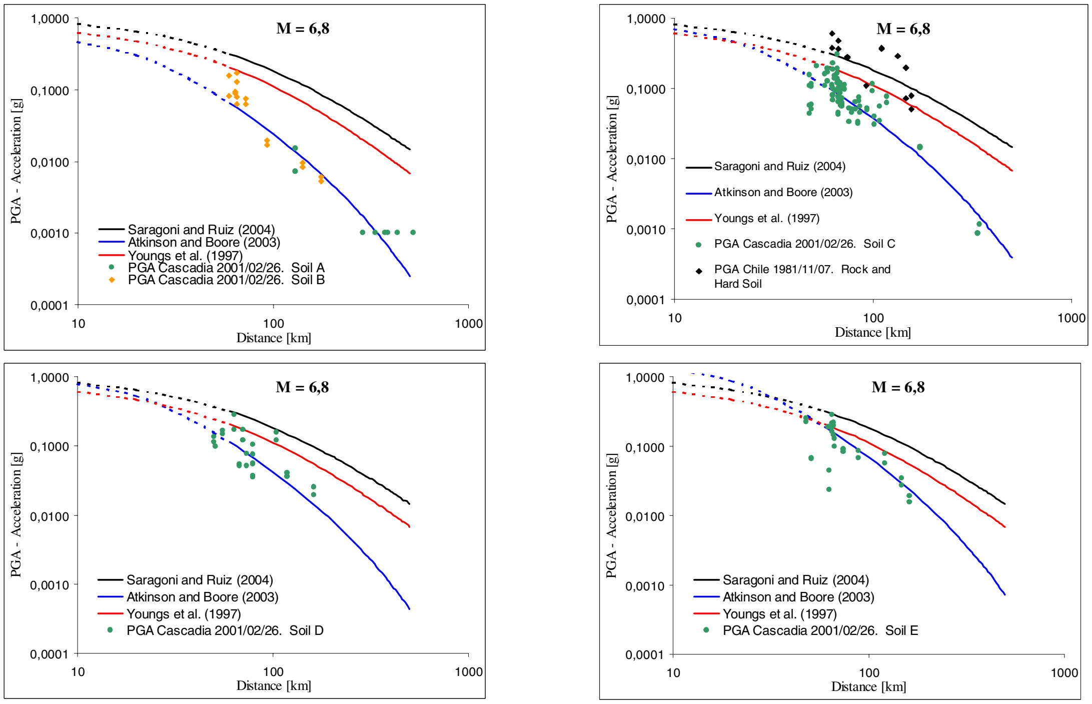

Figure 3. Comparison of Horizontal Peak Ground Acceleration attenuation formulas for M = 6.8 with Nisqually 2001 and Central Chile 1981 PGA values for different soil types. Central Chile 1981 values are only for rock and hard soil.

From this figure it can be appreciated, despite the inclusion of fill soils, where soil amplification should be expected with respect to Chilean rock and hard soil, that all Nisqually PGA values are systematically lower than Saragoni [20] attenuation formula. Youngs [22] also overestimate Nisqually data. Atkinson [21] formula derived for Cascadia PGA database give the best estimate.

However it must keep in mind that despite the large differences in PGA values between Cascadia and Chile, the level of almost damage was similar for the two inslab earthquakes.

In the next section the Central Chile inslab earthquake, Ms = 6.8, of 1981/11/07 will be compared with similar magnitude Nisqually 2001 earthquake.

COMPARISON BETWEEN 2001 NISQUALLY AND 1981 CENTRAL CHILE EARTHQUAKES

On November 7, 1981 an inslab Ms = 6.8 earthquake struck Central Chile, with epicentral 32º 24' S and 71º 47' W, at Papudo town. The focal depth was 56.1 [km]. The maximum PGA was 0.605 [g] in horizontal direction and 0.637 [g] in vertical, recorded at Papudo station. The maximum MMI was VII at Papudo and La Ligua, where accelerograms were recorded (Fresard [23], [24]).

The affected area of Central Chile is highly populated, therefore with good MMI reported information. Since this earthquake is the same inslab type than Nisqually 2001 and has similar magnitude, allows comparing similar earthquakes of Cascadia and Chile subduction zones.

The earthquake was recorded at the eight accelerographics stations indicated in Table 6. This table summarizes the main characteristics of accelerograms: PGA, hypocentral distance, intensity of zero crossing υ_o, Arias Intensity I_A, P_D, P_{DH} and MMI (Fresard [24])

Table 6. Destructiveness Potential Factors for Central Chile 1981 Earthquake Accelerograms

NUMB	STATION	COMPONENT	DISTANCE [KM]	PGA [cm/sec²]	I_A [cm/sec]	ν_0 [crossing/sec]	P_D [cm-sec]	P_{DH} [cm-sec]	MMI
1	PAPUDO	N50E	62	371.4	1.96	24.50	0.325	0.979	7.0
2		S40E		592.9	3.90	24.41	0.654		
3		VERT		624.3	2.62	34.10	0.230		
4	LA LIGUA	N70W	67	358.7	2.06	22.61	0.402	0.895	7.0
5		S20W		462.6	2.52	22.62	0.493		
6		VERT		339.1	1.50	32.87	0.139		
7	SAN FELIPE	S20E	110	368.5	1.91	23.14	0.357	0.573	5.5
8		N70E		363.6	1.65	27.61	0.216		
9		VERT		123.5	0.32	23.64	0.058		
10	VENTANAS	NS	74	264.6	1.48	18.41	0.435	0.843	6.5
11		EW		271.5	1.46	18.86	0.408		
12		VERT		210.7	0.91	26.68	0.128		
13	PELDEHUE	EW	133	284.2	0.99	23.16	0.184		6.0
14	SANTIAGO	NS	156	75.5	0.10	25.74	0.015	0.029	6.0
15		EW		78.4	0.11	27.37	0.014		
16		VERT		50.0	0.06	29.58	0.007		
17	LLOLLEO	S80E	146	193.1	0.46	13.34	0.260	0.316	5.5
18		N10E		71.5	0.11	14.05	0.056		
19	VIÑA DEL MAR	N80E	93	107.8	0.17	21.88	0.036		6.5

The largest P_{DH} is for Papudo station with 0.979[cm·sec]. This station also has the largest PGA, 0.605 [g] and 0.637 [g], in horizontal and vertical directions. These values are similar that the ones obtained for Nisqually earthquake. The main difference is that Chile accelerogram have many pulses of similar amplitude to the PGA value and the Nisqually record has only one pulse.

The PGA of 1981 Chile earthquake recorded on rock and hard soil, are compared in Fig. 3, for Soil C according to NEHRP classification, with the values recorded for Nisqually 2001 earthquake. From this comparison is clear that Central Chile 1981 PGA are significantly higher than Nisqually 2001 ones, confirming that Chile PGA are higher than Cascadia ones (Saragoni [20]).

The P_{DH} values obtained for Central Chile 1981 earthquakes are compared in Fig. 2a with the P_{DH} values for Nisqually 2001 earthquake. From this comparison is clear that Chile 1981 P_{DH} value are significantly lower or similar to Nisqually 2001 due specially to the remarkably higher zero crossing values of Table 6. The υ_o values of 1981 Chile earthquake are in the range of 20 zero crossings/sec and the Nisqually 2001 are in the order of 10 or less.

On the other hand the higher values of υ_o of Chile earthquake explain the larger PGA values compared with Nisqually values.

In conclusion the comparison of both earthquakes shows that even they are inslab type and of similar magnitude, they have significant differences in PGA, P_{DH} and υ_o values, confirming they belongs to two different types of subduction zone. Both earthquakes are characterized to be almost of undamaging effect, which characterize this type of subduction earthquakes of this magnitude.

CASCADIA THRUST EARTHQUAKE

As it was commented in a previous section, the Cascadia subduction zone has not recorded accelerograms of thrust interplate earthquake, since the largest event of this type is estimated to happen around 1700. Due to this lack of information it is interesting to study the characteristics of thrust accelerograms recorded in similar subduction zones. Heaton [7], as it was mentioned previously, estimated the maximum magnitude for the Cascadia thrust earthquake to be $Mw = 8.3 \pm 0.5$. A comparison will be done with the epicentral accelerograms of the thrust earthquakes of Central Chile, 1985, $Ms = 7.8$ and Michoacan, Mexico, 1985, $Mw = 8.1$.

In Table 7 the P_{DH} and MMI values from Saragoni [25] are indicated for the 5 Pacific coast accelerographic stations of the Michoacan, Mexico 1985 earthquake. These are the nearest station to the epicenter. In this Table are also included the corresponding MMI values estimated by Astroza [26]. In general the P_{DH} values for this $Mw = 8.1$ earthquake are under the threshold of damage, with the exception of Zacatula station with $P_{DH} = 57.0$ [10^{-4}g·sec^3]. These values are shown in Fig. 2b, where the P_{DH} value of Zacatula, follows the trend of Eq. (5) and correspond to the largest MMI value of only 7.5. The epicentral area of this earthquake was characterized by light damage. The accelerographic stations of Mexico City are not included in this study since they are more than 400 [km] away from the epicenter on very soft volcanic clay.

The P_{DH} and MMI values from Saragoni [26], for the 5 most important epicentral accelerographic stations of the Central Chile, 1985 earthquake, are indicated in Table 8. In general these P_{DH} values for this $Ms = 7.8$ earthquake are over the threshold of damage, with the exception of UTFSM station with $P_{DH} = 9.3$ [10^{-4}g·sec^3]. These values are also shown in Fig. 2b where P_{DH} values follow the trend of Eq. (5).

Table 7. Horizontal Destructiveness Potential Factors and MMI Values for Epicentral Accelerograms of Mexico 1985 Earthquake

STATION	DISTANCE [km]	P_{DH} [10-4·g·seg^3]	MMI
Zacatula	48	57.0	7.5
Caleta de Campos	52	7.6	5.5
La Villita	43	11.3	5.5
La Union	72	16.0	5.5
Zihuatanejo	100	6.2	6.5

Table 8. Horizontal Destructiveness Potential Factors and MMI Values for Epicentral Accelerograms of Central Chile 1985 Earthquake

STATION	DISTANCE [km]	P_{DH} [10-4·g·seg^3]	MMI
Ventanas	58	106.6	7.0
Viña del Mar	47	173.4	7.5
Almendral	43	94.0	8.0
UTFSM	43	9.3	7.0
Llolleo	64	281.9	8.5

In general the Chile P_{DH} values are significantly larger than Mexico P_{DH} values, showing that Chile thrust earthquake was more damaging at the epicentral area than Mexico earthquake (Saragoni [25]).

Saragoni [20] shows that PGA values for Chile subduction zone are quite different from Mexico subduction, therefore the use of Chile thrust accelerogram data to forecast thrust Cascadia earthquake seams to be on the conservative side.

In the same Fig. 2b the 2001 Nisqually earthquake P_{DH} values are included and compared with Mexico and Chile earthquake P_{DH} values. From this comparison appears that 2001 Nisqually values are similar to 1985 Mexico, showing the light damage of both earthquakes.

Since some researchers consider Mexico Rivera-Cocos plate system to be closest analogs to the Cascadia subduction zone, the damaging capacity of Cascadia thrust accelerograms should be similar to Michoacan, Mexico 1985 earthquake with a little larger magnitude Mw = 8.3. In consequence with rather light damage at the epicentral area, similar to 2001 Nisqually earthquake. Therefore the similitude between both plates requires more studies to support this conclusion for future engineering design in Cascadia zone.

COMMENTARIES AND CONCLUSIONS

The estimation of P_{DH} values from accelerograms for the three available inslab Cascadia earthquakes shows that these earthquake produce light damage, which are in agreement with reported MMI values.

Comparison of horizontal PGA for Cascadia and Chile subduction zones show that Chilean values are systematically higher that the Cascadia zone.

Comparison of two similar magnitude, M = 6.8, inslab earthquakes of Cascadia and Chile shows that their accelerograms are quite different but produce similar level of damage. Differences are essentially due to the higher intensity of zero crossings per second of Chilean earthquakes.

Estimated Mw = 8.3 thrust earthquake for Cascadia zone being similar to Mexico, Michoacan 1985, Mw = 8.1 earthquake would produce light damage at epicentral zone. Therefore more researches will be required in the future to understand similarity between Juan de Fuca and Rivera-Cocos system plates. Chilean subduction accelerograms appears to be different than Cascadia zone accelerograms.

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