

SEISMIC PERFORMANCE OF BUILDINGS UNDER OCCASIONAL EARTHQUAKE IN PERU

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Abstract

In performance based design multiple design level earthquakes are required as well as structural performance levels and design objectives. To apply these criteria both various earthquake levels and limit design parameters for each level has to be used. Main objective of this work was to determine occasional earthquake level for design of buildings in Peru. Buildings were analyzed subjected to these occasional movements in order to evaluate response (damage) and evaluate various proposals of design parameters for this seismic level.

Working with the performance based approach, maximum firm ground accelerations, elastic design spectrum and uniform hazard spectrum were obtained for a 72 years return period, considered occasional (ATC-40) and service earthquake (Vision 2000). What is remarkable is that very high acceleration levels were found for occasional earthquake (half of severe earthquake) based on Peru's seismicity as compared to ISO 3010 specification (one fifth of severe earthquake for 20 year return period). On the other hand maximum ground acceleration was used for scaling the most significant earthquake records in Peru. Uniform hazard spectrum was considered as the objective design spectrum, in such a way that spectra for the records considered be compatible with this objective spectrum.

Additionally a summary of analytical and experimental work on reinforced concrete, masonry and steel building response when subjected to lateral loads were revised in detail. Cracking is used as elements damage indicator and drift as damage level indicator on the structural system. Emphasis was made on damage under occasional level earthquakes.

Conceptual and methodological aspects relating evaluation of seismic damage on buildings have been analyzed. For this purpose incremental nonlinear static analysis and elastic time history analyses were used.

Damage evaluation was applied to an eight story shear wall building designed for strength according to Peruvian seismic standard (E030). Time history elastic analyses were performed using parameters of the occasional earthquake and to determine maximum demands in the nonlinear range and nonlinear incremental static analysis (pushover) was used. Response was acceptable within range of "immediate occupancy"

Keywords: Performance based design, occasional seismic level, limit states



1. Introduction

Performance based design requires that buildings and other structures be designed and evaluated for different levels of seismic hazard. In accordance with their return period seismic action can be defined as frequent, occasional, rare and very rare earthquakes, corresponding to return periods of 43, 72, 475 and 970 years. To verify the behavior of a structure under occasional seismic events is necessary to define the parameters of this seismic event. The maximum acceleration on firm ground (PGA) is one of the required parameters. To verify design or evaluation of a building by multiple demands, it is necessary to have a design spectrum for each level of seismic hazard. Therefore, by using statistical analysis with seismic records selected based on the characteristics of the terrain, magnitude, and distance from the source, the elastic design spectrum is built for a return period of 72 years.

In addition, interstory distortions for limit state of immediate occupation (IO) by non-linear incremental analysis and elastic time history analysis were verified and also it was checked that the building designed by resistance using Peruvian reinforced concrete standards (E-060) and seismic resistant standard (E.030) does not reach non-linear range

2. Design earthquake movement

In this work design earthquake motion is defined as ground shaking with 50% probability of exceedance in 50 years with a return period of 72 years, considered as occasional earthquake by the ATC-40 (1996) and service earthquake by Vision 2000.





The return period of 72 years is an expression of the average time expressed in years, between the occurrence of an earthquake causing damage of a severity equal to or greater than the one given. The probability of exceedance of 50% in 50 years is a statistical representation of the possibility that the effect of an earthquake to exceed a certain severity over a period of time, expressed in years. For structures that should remain operational after an occasional earthquake, 50 percent of probability of exceedance in 50 years seems reasonable, as shown in Table 1.

For the occasional level earthquake performance is considered as operational according to VISION 2000 and immediate occupation according to the ATC-40. Therefore, the response of the building under the design earthquake level considered will be defined by the following matrix of performance.

		Structural performance level	Damage level
hquake gn level	Occasional	Immediate Occupancy	hairline cracks, between light and moderate damage
Eartl	Tr=72 years 50% in 50 years		elements

Table	1:	Performance	matrix
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For the occasional earthquake level an immediate occupancy performance limit, interstory distortions and maximum roof displacement will be considered as structural performance index.

3. Seismic hazard for occasional earthquake

This work has used the probabilistic method proposed by (Cornell, 1968) and from existing seismicity data such as seismic sources, magnitudes and using seismic catalogues of historical and recorded [3], laws of attenuation for spectral accelerations [4,5] and computational tools [6] parameters of the movement of the ground have been obtained such as the peak ground acceleration (PGA) on firm ground for the regional capital cities of Peru.

The result of the probabilistic seismic hazard analysis is a curve of risk that represents the hazard for a site, generated by the occurrence of all earthquakes in all possible locations within a seismic source.





Fig. 2 - Seismic hazard curve for major Peruvian cities located in seismic zones 3 and 2, firm ground.

Fig. 4 - Seismic hazard for representative Peruvian cities, firm ground.

Moyobamb

Tr=72 year

Fig. 3 - Seismic hazard for the city of Iquitos, located in the seismic zone 1, firm ground.



Annual rate of occurrance

0.1

0.01

0.001

0.0001

0.00001

Table 2 - Probabilistic seismic hazard analysis results

Earthquake	Return period	Maximum acceleration on firm ground PGA (g)					
design level	(years)	Seismic zone 3	Seismic zone 2	Seismic zone 1			
Occasional	72	0.293	0.265	0.1			

The level of acceleration for occasional earthquake of 0.29 g obtained from the seismic hazard analysis is larger than the acceleration for the service earthquake established in ISO3010 and greater than acceleration for the occasional earthquake in recent work by Taipe [9]. This level of acceleration has increased by the use of new attenuation laws [4,5] as compared with those used by Casaverde, 1. and Vargas, J. [11]. Consequently the level of seismic hazard due to occasional level earthquakes would be direct contribution of seismic sources surrounding the site. In case of Lima (F3, F4) sources are subduction interfaces, sources of subduction intraplate (F8, F9, F12, F13, F14) and continental sources (F15, F16, F18, F19, F20) [3].



4. Spectral scaling and adjustment for occasional earthquake

In seismic evaluation and design, records readily available are required which represent seismic hazard for the earthquake level under consideration and that describe accurately ground motion parameters (acceleration, velocity and displacement), frequency content and duration. Therefore, when seismic action in terms of acceleration is required there are three ways to obtain records: artificial records generated so that their response spectra are compatible with design spectra; synthetic records obtain from seismological models, and real records obtained from actual historical earthquakes. Due to the fact that actual records contain abundant information about the nature of ground motions and carry all the characteristics of the movement (amplitude frequency content and duration) they reflect all factors influencing the accelerograph (magnitude, source characteristics, trajectory, distance and site effects) this study focuses on ways of spectral scaling and adjustment of actual records

Event	Station name	Component	Epic loc	center ation	Focal depth	Epicentral distance	Hypocentral distance	Magnitude	Site	PGA	PGV	PGD
	~		Latitud (S)	Longitud (W)	events (Km)	(Km)	(Km)	(Mw)	Characteristics	(cm/s2)	(cm/s)	(cm)
21/05/1070	Estacion Parque	N82W	0.26	79 97	64	261	367	6.6	Coarse Cravel	-104.80	4.71	1.60
51/05/19/0	de la reserva	N08E	9.30	/0.0/	04	501		0.0	Coarse Graver	-97.70	6.98	2.60
03/10/1074	Estacion Parque	N08E	12.5	77 08	13	114	115	81	Coarse Gravel	179.00	10.30	-5.30
03/10/17/4	de la reserva	N82W	12.5	11.90	15	114	115	0.1	Coarse Graver	-192.50	14.50	6.40
02/10/1074	Estacion Surgo	L 12 270 77 52(21.2	21.2	(2.80	(7.22)	69	Dense Gravel	192.35	-20.50	7.90		
03/10/19/4	Estacion Suico	Т	12.279	2.219 11.550	21.2	03.89	07.52	0.8	and Boulder	-207.12	16.90	8.00
00/11/1074	Estacion Parque	L	12.52	77 502	12.8	70.05	80.08	7.2	Dense Gravel	46.21	-3.60	1.80
07/11/19/4	de la reserva	Т	12.32	11.392	12.0	79.05	00.08	1.2	and Boulder	-69.21	-4.91	-1.80

Tabla 3: Seismic events, selected for scaling and spectral adjustment.

4.1 Scaling to the maximum ground acceleration (PGA)

According to this approach a seismic record is simply multiplied by a constant. This means that multiplying all record values by a scalar factor, these values are the only ones scaled remaining unchanged frequency content and duration. The scalar factor k is obtained by $k = \frac{PGA_{ground}}{PGA_{record}}$ where PGA ground is the maximum

ground acceleration for the occasional earthquake obtained from the seismic hazard analysis, PGA_{record} is the maximum acceleration of each record.



Fig. 5 - Original and scaled to maximum ground acceleration (PGA) seismic records for occasional earthquake level.



4.2 Adjusting an earthquake record to an objective spectrum

This procedure aims to modify frequency content of each seismic record so that spectrum fits the objective spectrum in the whole range of periods or frequencies. In this procedure records are adjusted in time domain adding waves to the reference record.

Accelerographs have been generated by means of a spectral adjustment procedure to a uniform hazard spectrum of 72 years return period (occasional earthquake). Seismo Match [14] was used, which is a program design based on theories proposed by Abrahamson (2009) y Hancock et al. (2006) [15]. The objective spectrum and adjusted spectrum of the selected records are shown in figure 6.



Fig.6 - Response spectra before and after adjustment to the uniform hazard spectrum for occasional earthquake (return period 72 years).

When this adjustment of response spectra to the uniform hazard spectrum as objective spectrum is made, there is a real change in frequency content, as shown in records and Fourier spectra (Fig. 7)



Fig. 7 - Accelerographs and Fourier Spectra generated before and after spectral adjustment method.



5. Elastic design spectrum for occasional earthquake

Design spectra are obtained through statistical procedures representing the probable seismicity of the site. For development of the elastic design spectrum for occasional earthquake level seismic acceleration records displayed in Table 4 are used and following the process of Newmark-Hall-1982, Ridel-Newmark-1979 and Mohraz-1976 [8,9] the curves of the spectrum of elastic design for a site are established, using the following steps.

1. Maximum acceleration on firm ground is determined for the level of occasional earthquake with a return period of 72 years, through a probabilistic seismic hazard analysis (PSHA). Where a = 0.293g, for T = 0s.

2. Maximum ground motions are determined using the following relations, $v = c_1 \frac{a}{g}$, $d = c_2 \frac{v^2}{a}$, [13], where

a, is the maximum acceleration obtained on firm ground, v, maximum ground speed and *d* is the maximum displacement of the ground; g is acceleration of gravity; the constants c_1 and c_2 are selected appropriately for the condition of the site, based on the results of statistical analysis of numerous seismic records, giving preference to those records obtained in the local regions of the site. Because values of maximum displacement and velocity of ground movement are not available, through statistical analysis of log-normal distribution of selected records the constants c1 and c_2 are obtained, where: $c_1 = 87.8$ cm/s, $c_2 = 9.5$. From the mentioned relations maximum values of ground velocity and displacement are obtained, as shown in Table 4.

$$v = 25.72 \text{ cm/s}$$
 y d = 21.79 cm.

				Ground motion parameters				
Front	Event Station Name Component Site Characteristics		PGA	PGV	PGD	ad/v2	v/a	
Ewent	Station Name	Component	Site Characteristics	cm/s2	cm/s	cm		cm/s
31/01/1951	Parque de la recerva	N82W	Dense Gravel and Boulder	60.44	1.65	0.31	6.882	26.781
51/01/1951	r alque de la leserva	N08E	Dense Graver and Boulder	45.70	0.92	0.15	8.099	19.749
17/10/1966	Parque de la reserva	N82W	Coarse Gravel	180.60	13.20	7.30	7.566	71.701
17/10/1900	r alque de la leselva	N08E	Coarse Graver	269.30	21.60	16.60	9.582	78.684
31/05/1970	Parque de la recerva	N82W	N08E Coarse Gravel	104.80	4.71	1.60	7.559	44.089
51/05/17/0	31/05/19/0 Parque de la reserv	N08E	Coarse Graver	97.70	6.98	2.60	5.214	70.086
29/11/1971	29/11/1971 Parque de la reserva	N82W	Dense Gravel and Boulder	53.55	4.08	1.70	5.469	74.743
20/11/17/1		N08E	Dense Graver and Doulder	86.54	4.22	1.20	5.831	47.837
05/01/1974	074 Z arate	L	A lluvium sediment	139.59	3.23	1.30	17.394	22.699
05/01/17/4	Zarate	Т	Andvium sedinem	156.18	4.40	1.10	8.874	27.638
03/10/1974	Parque de la reserva	N08E	Coarso Graval	179.00	10.30	5.30	8.942	56.449
03/10/17/4	Talque de la leserva	N82W	Coarse Graver	192.50	14.50	6.40	5.860	73.894
03/10/1974	Surco	L	Dense Gravel and Boulder	192.35	20.50	7.90	3.616	104.554
03/10/17/4	Suico	Т	Dense Graver and Doulder	207.12	16.90	8.00	5.802	80.045
00/11/1074	Parqua da la racorra	L	Donso Gravel and Roulder	46.21	3.60	1.80	6.418	76.425
09/11/1974	r alque de la leserva	Т	Delise Glaver and Boulder	69.21	4.91	1.80	5.167	69.596
00/11/1074	La Molina	L	Clavov Silt	116.79	7.89	2.40	4.502	66.276
09/11/1974		Т	Clayey Silt	93.71	5.35	1.30	4.256	56.006
							a(% g)	0.293
							v(cm/s)	25.72
							d(cm)	21.79

Table 4: Accelerograms recorded at seismic stations of the city of Lima

In Fig. 9, a comparison between Peruvian standard (E.030) spectrum adjusted for occasional earthquake (doted red) for a common building on firm ground and the spectrum from this study is presented. Spectral acceleration is larger in the area of constant acceleration (between T = 0s and 0. 4s). For longer periods, spectral curves are similar but E.030 shows increasing acceleration. The spectrum of this study can be used to verify the design of the structure so that response lies in the elastic range, that is within boundaries of the immediate occupancy performance.



Fig. 8 - Straight lines and periods identifying regions of acceleration, velocity, displacement and tripartite elastic design spectrum.



Fig. 9 - Elastic design spectrum for occasional earthquakes with return period of 72 years

6. Damage evaluation for occasional earthquake

Nonlinear static procedure, where a model of the structure is built explicitly considering non-linear behavior of the elements is used to estimate damage of a building due to the occasional earthquake. Then the model is loaded with a set of prescribed lateral forces monotonically incremented until the control displacement of a joint (for example the center of mass of the roof of the building) exceeds a pre-set displacement (objective) or the collapse of the structure.

To verify the structural performance of the building due to the occasional level earthquake, displacements obtained from the performance point with displacement limits for immediate occupancy performance level after ATC-40 and FEMA 273 are compared. Also to verify displacements through a the time history elastic analysis and to compare them with the allowable displacement of standard E.030 and acceptability criteria scaled and adjusted records for occasional earthquake records are used.

Performance level	ATC-40	FEMA 273	Vision 2000	
Immediate occupancy	0.01	0.01	0.002-0.005	

Table 5 - Limit drift for Immediate occupancy performance level



					SCALED		ADJUSTED
Event	Station name	Component	Magnitude (Mw)	PGA (cm/s2)	SCALE	PGA (cm/s2)	PGA (cm/s2)
17/10/1966	Parque de la reserva	N82W	8.1	180.60	1.59	287.43	326.858
17/10/1966	Parque de la reserva	N08E	8.1	269.30	1.067	287.38	272.132
31/05/1970	Parque de la reserva	N82W	6.6	104.80	2.74	287.43	211.08
31/05/1970	Parque de la reserva	N08E	6.6	97.70	2.94	287.43	234.63
03/10/1974	Parque de la reserva	N08E	8.1	179.00	1.606	287.39	310.039
03/10/1974	Parque de la reserva	N82W	8.1	192.50	1.493	287.38	237.905
03/10/1974	Surco	L	6.8	192.35	1.494	287.36	238.826
03/10/1974	Surco	Т	6.8	207.12	1.387	287.42	218.687

Table 6 - Seismic records parameters for elastic time history analysis

7. Damage evaluation of a model structure

A typical building of eight levels is considered with symmetry both in plant and elevation. Structural system is dual: frames and shear walls. Structural elements were design using Peruvian R.C. standard (E-060). A non-linear incremental static analysis (Pushover) was performed. This allows knowing the response of the structure under the action of the occasional level earthquake.



Fig. 10 - Reinforcement of prototype eight story building

For non-linear static analysis, beams and columns are modeled with a plastic hinge with yield in bending and flexo-compression models located at the ends. Since the behavior of the wall is controlled by bending, hinges having a behavior in flexo-compression are located at the base of the first floor.



Fig. 11 - Model and distribution of plastic hinges in beams, columns and walls for nonlinear analysis.





Fig. 12 - Plastic hinges sequence according to performance level

As can be seen in Figure 12, first yield occurs in three beams when moment reaches nominal yield moment. This corresponds to step 1. Ultimate resistance occurs when moment in the hinge reaches ultimate capacity (yellow hinge), because they reach its rotation limit in collapse prevention (PC)-level, this occurs in step 11.



Fig. 13 - Capacity curve of eight story building in the X-X direction

Performance point is located in the intersection of curves for inelastic demand spectrum and capacity spectrum, as shown in Fig 14



Fig. 14 - Performance point in the X-X direction for occasional earthquake.



Yiel	d point	Performance point			
Sa (g)	0.393	Sa (g)	0.355		
Sd (cm)	3.843	Sd (cm)	4.841		
Dy (cm)	5.556	Du (cm)	6.998		

Table 7 - Yield point values of the bilinear representation of the capacity curve and the performance point.

7.1. Evaluation of global demand of performance point

In global evaluation building drift and interstory drift for occasional earthquake is taken into account. As shown in Table 5.

Table 8 - Global drift obtained from the static nonlinear pushover analysis

Earthquake level	Sd (cm) Sa (g)		T (s)	D (cm)	Global drift (%)	
Occasional	4.84	0.35	0.74	7.00	0.29	

Table 9 - Interstory drifts and drift limit obtained from the static nonlinear pushover analysis.

Earthquake	Interstory drift (%)								
level	1st story	2nd story	3rd story	4th story	5th story	6th story	7th story	8th story	(70)
Occasional	0.039	0.083	0.112	0.129	0.136	0.135	0.131	0.124	1.00

From non-linear incremental analysis for occasional earthquake a displacement on the roof of the building of 7cm or a distortion of 0.0029 is obtained, this value is much lower compared with proposals of ATC-40, FEMA 273 and VISION 2000. Results for interstory displacements are also lower than drift limit of 0.01. Therefore, the building designed for strength will have an elastic behaviour and will remain within the limits of performance of immediate occupancy, as it is to be expected.

7.2. Results from time history elastic analysis

With records generated from adjustment to a design spectrum with a return period of 72 years displacements tend to remain almost constant, while the displacements obtained from records scaled to the maximum ground acceleration for occasional earthquake they increase in the entire height of the building.



Fig. 15 - Displacements obtained from records scaled to the maximum PGA and from adjusted uniform hazard spectrum.





Fig. 16 - Interstory drifts obtained from records scaled to the maximum PGA and adjusted uniform hazard spectrum.

Drift obtained by time history analysis (seismic records adjusted to the design earthquake) do not have much dispersion as compared to those obtained with the scaled records. Maximum drift obtained for the elastic range using seismic records is in the order of 3.5/1000, which is less than allow for reinforced concrete structures en Peruvian Standards (E-030) defined as 7/1000. Drift obtained with the elastic spectrum for occasional earthquake is much less than the drift allowed in standard E-030. They are smaller than distortions limits specified by the FEMA 273 [1] where maximum drift for structural walls for immediate occupancy is 1/200 and for the immediate occupancy is 1/300 and reparability performance level is 1/200 [10].

8. Conclusions

Occasional motion for design seismic considered was the event that produces a maximum horizontal acceleration with 50% probability of exceedence in 50 years; this means a return period for this damage threshold of approximately 72 years.

For Peru seismicity the level of acceleration obtained from the seismic hazard analysis for this occasional earthquake is 0.29g. This is significantly larger than the acceleration for service earthquake established in ISO3010 and larger than acceleration for the occasional earthquake in former work by Taipe [9].

The structural performance level for the earthquake with a return period of 72 years considered is so called "immediate occupancy". For this performance level buildings present cracks in structural elements, mild to moderate damage to contents and architectural elements and will require some minimal repairs to non-structural components.

It is concluded, that the use of attenuation laws that do not included all regional data and do not consider all the seismic activity in this region results in higher PGA values, as compared with attenuation laws developed by Casaverde L. and Vargas, J.[11] used in Earthquake Resistant Standard E-030.[16]

It is concluded that records generated by means of an adjustment to a design spectrum, is more adequate than those generated by simply scaling to a maximum acceleration since those records capture all characteristics of movement, as changes in frequency content. In addition, when used in design and evaluation of buildings they produce more reliable results both in forces as in displacements.

It is concluded that elastic design spectrum developed in this study is a good representation of the characteristics of the terrain of the site and can be used in the evaluation of building design and verification of their behavior for occasional earthquake.



It is concluded that for a typical eight story apartment building in Peru designed with structural walls, drifts and displacements obtained through the incremental static analysis and time history elastic analysis will be within the limit of the immediate occupancy performance level and will be able to withstand lateral loads due to the stiffness of the members. Therefore, when imposing a seismic action with a maximum acceleration of 0. 293g this building will respond within the elastic range, with the accepted damage level (Table 1).

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