SEISMIC HAZARD, ZONATION AND IMPORTANCE FACTORS. A PROPOSAL FOR SELECTING DESIGN GROUND MOTIONS

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ABSTRACT

In current codes seismic design forces for buildings and/or installations are based on design spectra. These are obtained multiplying normalized soil dependent spectra by the maximum ground accelerations Ao and by the importance factor O. The value of Ao is given in generalized seismic zonation maps, reaching maximum ground accelerations in the order of 0,4g: the value of O, being as large as 1,6 in certain codes, is choosen independently of the seismic zone and eventually catastrophic consequences of possibles failures. In this paper it is shown that, should the structural reliability for the same building or installation be a constant in any of the seismic zones, the importance factor should vary from zone to zone. Based on the results of probabilistic hazard evaluations performed in different sites and countries, its has been found that the logarithm of the mean rate of maximum ground motions x, varies linearly with x within the ranges of seismic design values. This permits the use of a uniform procedure for the stablishment of code seismic hazard maps that can be applied in a very general way in the selection of design ground motions on a probabilistic basis. The explicit incorporation in the proposed procedure of the expected performance of the building or installation under earthquake loading, as well as the associated reduction factors, is illustrated for hospital buildings seismic design.

INTRODUCTION

Seismic design forces for buildings and/or installations are currently based on desing spectra. They are obtained by multiplying normalized soil depend spectra by the maximum ground accelerations Ao and by the importance factor α; taking into account global structural ductility and redundancy of given structural systems, they are further divided by reduction factors larger than 1,0.

Even if this approach has some limitations, it benefits of the uniqueness of the solution for a given site. In this paper, some of the limitations of the current approach are discussed and a more general procedure is presented which takes into account the convenience of maintaining uniform structural reliability. The suggested approach bridges problems steming from the very beginning of earthquake resistant design, such as the necessity of having zonation maps, fixed probabilities of excedence for design ground motions, the importance factor and the absence of rudiments of structural reliability. Modern codes should increasingly offer the user, the possibility of selecting

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design values on the basis of reliability expected performance, expressed as maximum annual probabilities of failure and optimization decisions.

This paper has the intention to reflect issues of present code formats for seismic design, which are common in the vast majority of American countries, letalone of practicing engineers; therefore, the following commentaries do not preclude the existence, elsewhere, of different code design formats and/or strategies.

CURRENT CODE SEISMIC DESIGN APPROACH

Normalized Soil Dependent Spectra

The effects of local site conditions on ground motion characteristics have been incorporated in the codes by means of normalized spectra shapes. According to statistical analysis of strong motion records, grouped in up to four different local soil conditions, smoothed mean spectral shapes are given; elastic spectra are obtained by multiplying their normalized ordinates by maximum ground acceleration. ATC-3 {1} introduced the well known effective peak acceleration (EPA) and effective peak velocity related acceleration (EPV), to be understood by considering them as normalizing factors for construction of elastic spectra following the same general procedure. The use of EPV seeks to take into account the effect believed to be representative of motion from distant sources.

Maximum Ground Acceleration

Values of Ao (or EPA and EPV) are selected in generalized code seismic zonations maps, reaching maximum ground accelerations in the order of 0,4g. Usually, those maps are based on probabilistic seismic hazard evaluations, retaining ground motion value associated to say: 10% of exceedence in 50 year (1) or other combinations (3). this technique has at least the two following limitations: (i) within the same seismic hazard depending on the dimensions of the zone and and nearness to seismic sources (8): (ii) these type of seismic zonation maps only retain a minimal fraction of the seismic hazard information from the avaluation performe. Therefore, one of the main code principles, wich is to reach the same reliability whatever the site, will not be fulfilled, and the possibility to choose different exceedences is not offered.

Importance Factor

The above limitations tend to be overcomed by the introduction of the so called importance or use factor α, which typically varies from 1,2 {2} up to 1,6 {5}. When explicitly given, the α value is dependent of the seismic zone. This simplification leads to a nonuniform reliability design, since in order to maintain the same probability of exceedence for α Ao, the α values must be larger in areas of lower hazard as shown in figure 1.

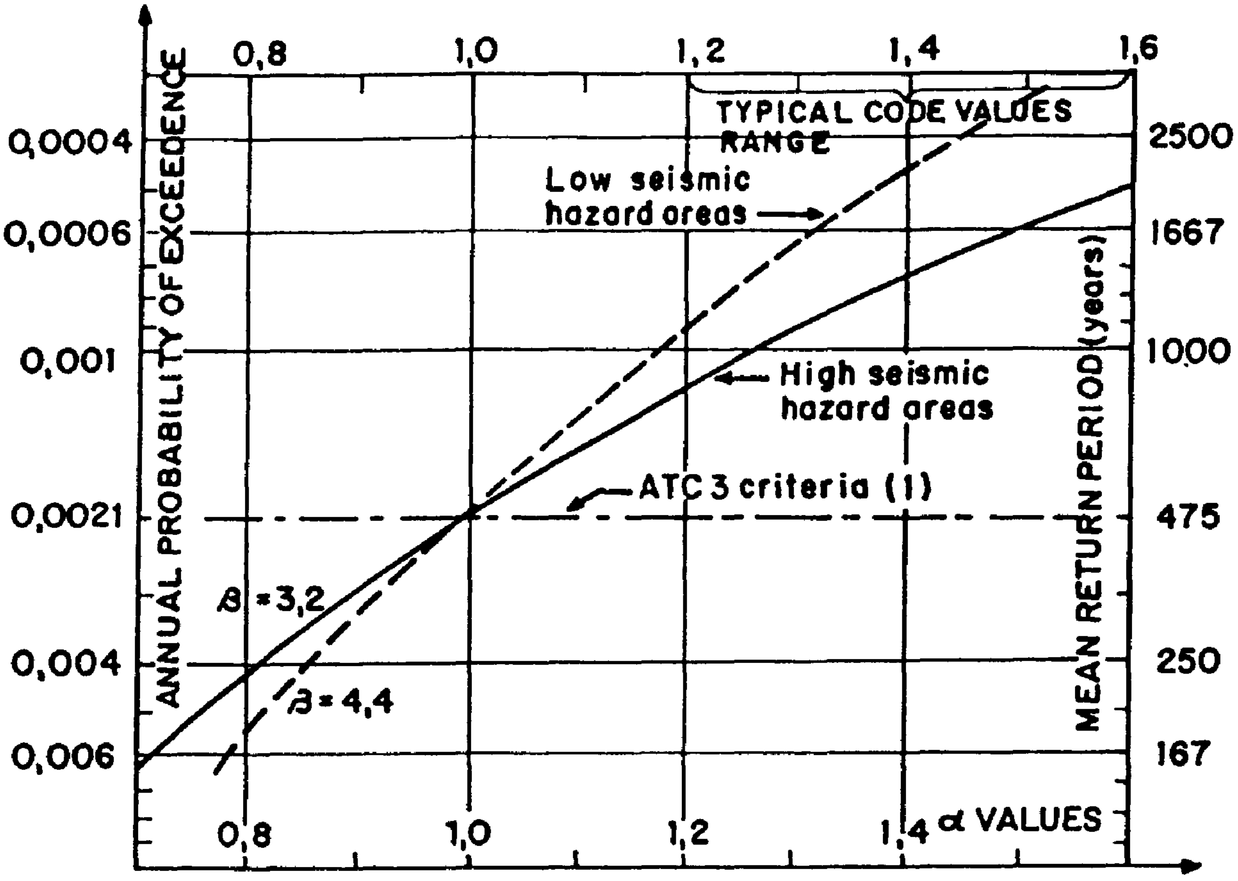

FIGURE 1. Importance factor α vs seismic hazard in Venezuelan areas {8}.

Reduction Factor R

Normally called ductility reduction factor, the larger the R value, the larger will be the expected nonelastic incursions associated to structural and nonstructural damage. Even if the importance factor is understood as a reduction of the inelastic incursion, as R/α , typical code adopted R values may be associated to nonelastic displacements that can severely impair the operational conditions of emergency installations.

In Table 1, maximum allowed R values of several American country codes for the seismic design of reinforced concrete hospital buildings, are given; design ground accelerations (α Ao) for rock or firm soils, correspond to the highest seismic zones. The fact that present codes don't explicitly incorporate the expected performance --serviceability-- of the building or installations in the selection of the R value can, as said, impair the operational conditions of the building.

TABLE 1.
Maximum ground accelerations (rock or firm soils), importance factor and largest allowed reduction factor, for seismic design of reinforced concrete hospital buildings, in highest seismic zones.

Country Code and Year	Importance Factor α	α Ao (g)	Largest R value	Ref.
CHILE, 1989	1,25	0,40	8(2;3)	(11)
COLOMBIA, 1984	1,2	0,36	7	(2)
MEXICO D.F, 1987	1,5	0,06(4) 0,15	4(3)	(14)
USA(1), 1988	1,25	0,50	8	(12)
VENEZUELA, 1982	1,25	0,375	6	(4)

(1) SEAOC, Recommendation;
(2) depends on soil type and natural period;
(3) also valid for steel structures;
(4) noncompressive soils.

Expected Performance

In a general way, the design strategy of current building seismic design codes is to provide minimum standards in order that structures design in conformance with them safeguard lifes and considerably reduces the probability of major failures. As the 1988 SEAOC Commentary to Chapter 1 states{12}, structures so designed should be able to resist minor levels of earthquake ground motions without damage, resist moderate ground motions without structural damage but some nonstructural damage, and resist major levels of earthquake motions without collapse, but possibly with some structural as well as nonstructural damage. This type of statements are not followed by deterministic nor probabilistic linkage to allowed reduction factors.

NEW SEISMIC DESIGN CODE APPROACH

Seismic Hazard Maps

Quantitative evaluation of seismic hazard, accumulates the contribution of identified seismic sources to the annual rate of exceedence λ of given levels of ground motion. The results show that, within the ranges of interest, the rate of excedence of maximum ground motions x for a given location satisfies the following relation:

$$\mathrm{Ln}\,\lambda = q - \beta\,\mathrm{Ln}x \qquad (1)$$

where q and ß are constants of the location. Table 2 {8} gives values inferred from results of seismic hazard evaluations in terms of maximum ground acceleration on firm soils; they are normally given for λ values between at least 0,1 (1/year) to 0,001 (1/year) and represent the probabilistic prediction of future ground motions in given sites. Equation 1 can be rewritten in the form:

$$\lambda = (x/xc)^{-\beta} \qquad (2)$$

where xc is a characteristic value equal to: exp (q/ß). For maximum ground accelerations, typical characteristic values of ac are given in Table 2.

From what has been said, given a seismotectonic model, the values of ac and ß are characteristic hazard parameters, which can be obtained in as many points as necesary assuming uniform firm soil conditions. Figures 2a and 2b show the general shape of seismic hazard maps for Venezuela; tentative values are given. Observe that for any given location, Eq.2 is readily obtained reading ac and ß from the previously referred figures. Singularities in points near active faults have not appeared due to the particular shape of the attenuation laws used, which are of the form:

$$\mathrm{Ln}x = C1 + C2.M - C3.\mathrm{Ln}(R+C4) \qquad (3)$$

where x represents some ground motion parameter, M is Richter magnitude, R is focal distance, and Ci (i=1,2,3,4) are regional regression constants, typically C4 is in the order of 5 to 10 kilometers.

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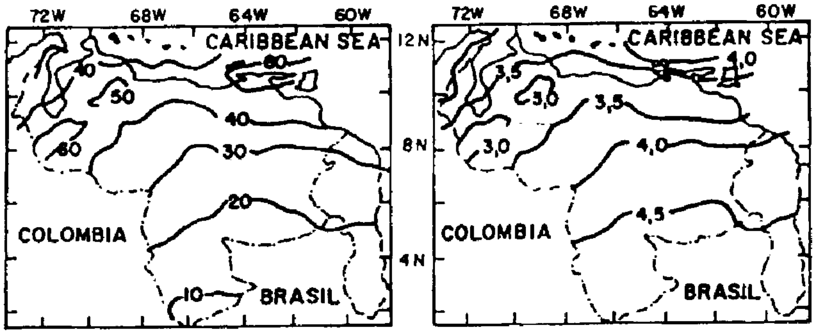

FIGURE 2a. ac (gal)

FIGURE 2b. β

FIGURE 2. Seismic hazard maps for Venezuela. General shape for characteristic parameters ; tentative values from Refs. (4; 7; 8).

TABLE 2.

Characterization of seismic hazard in terms of maximum ground acceleration; Equations 1 , 2 and 6.

Locality	Ln = q-βLnA		ac,j (gal)		T(*) (year)	
	q	-β	j=1year	j=50year	100gal	300gal
10 Km from San Andreas Fault, California (10)	14,19	3,09	99	351	1,1	31
70 Km from San Andreas Fault, California (10)	12,71	3,12	59	218	5,2	160
Venezuelan north east coast (8)	14,49	3,60	56	166	8,1	50
20 Km from Boconó fault Venezuela (8)	12,44	3,27	45	149	14	495
Pasto, Colombia (7)	11,69	3,15	41	142	17	532
Central Venezuelan Coast (8)	11,47	3,20	36	122	26	884
Arauca, Colombia (7)	9,48	3,55	14	43	1075	-
Northern Protugal, 41°N - 7°N (13)	2,86	2,26	3,5	20	1952	-

(*) Mean return period.

Cumulative Distribution Functions

If occurrence time of maximum ground motions is modeled as a Poisson distribution, the probability that ground motions of the class given by λ occurs at least once in t years, is given by:

$$1 - e^{-\lambda t} \qquad (4)$$

These can be rewritten as:

$$P = P\{ x > x ; t \} = 1 - e^{- t\,(x/xc)\,-\,\beta} \qquad (5)$$

which has the same form as a Gumble type II extreme value distribution. In this distribution xc is the most probable annual maximum; the most probable maximum in t years is equal to:

$$xc \,.\, t^{\,1/\beta} \qquad (6)$$

Given the probability of exceedence P and the economic life span t of the building or installation, the value of x is readily obtained as:

$$x = xc \left[\frac{- \mathrm{Ln}\,(1-P)}{t} \right]^{-1/\beta} \qquad (7)$$

In this format, the ATC-3 {1} criteria for maximum ground accelerations would be:

$$a = ac\,(0{,}002107)^{-1/\beta} = ac\,(474{,}6)^{-1/\beta} \qquad (7a)$$

Maximum Ground Acceleration

Zero spectrum acceleration Ao for a given location is obtained from Eq. 7 for accelerations; code seismic hazard maps, Figs. 2a and 2b, give ac and ß. Code sets of P and t values shall be given according to accepted risks as exemplified en Table 3. In this form the importance or use factor α is abolished. Note that the linkage to reliability measurements, such as the annual probability of failure, requires the characterization of several probability distributions functions.

TABLE 3

Representative values of exceedence probabilities in given life spans used in the selection of design ground motions.

Building or Installation	Life Span (years)	Exceedence Probability	Mean return Period (years)
Offshore manned platforms (rare event)	25	> 0,01	< 2490
Dams	100	> 0,05	< 1950
High voltage S/E equip.	50	0,03	1642
Bridges and elev. passes	100	0,10	950
Fuel storage tanks	30	0,05	586
High rise buildings	50	0,10	475
Low rise housing	50	0,20	225
Temporary constructions	15	0,30	43

Expected Performance and Reduction Factors

Experience has shown that current code strategy is not necessarily adequate for buildings whose serviceability must de secured immediately after strong quakes, such as: hospitals, police stations and the like. In those cases earthquake resistant design requirements must explicitly minimize the risk of disruption. Exemplified for hospital installations, that means: (a) the building must remain stable even after very strong shaking; damage shall not impair emergency services, must be repairable and nonlife threatening; (b) medical staff and personnel must remain in reasonable safe conditions; eventual evacuation must be warranted; (c) in extreme cases entrance of rescue teams should not be risky or hindered.

This has not been, however, the observed performance of many hospital installations shaken by past quakes in the American hemisphere. In fact, during the last two decades over 100 hospitals attending a total population in the order of 10 to 12 million in 9 different countries have suffered some degree of damage due to earthquakes; about a fifth of them collapsed or were beyond repair (Table 4 {9}).

Even if there are no precise statistics about the design criteria of the heavily damaged or collapsed buildings, many of them were built in the last decades according to standards that still are --or have until recently been-- enforced, strongly supporting the already mentioned limitation of the O factor.

TABLE 4
Hospital installations affected by recent earthquakes in America {9}.

Event	Total Number	Collapsed or demolished
San Fernando, 1971	9	6
Managua, 1972	2	1
Guatemala, 1976	2	2
Cúcuta, 1981	2	-
Popayán, 1983	1	-
Mendoza, 1985	10	2
Chile, 1985	22	2
México, 1985	22	6
San Salvador, 1986	11	1
Whittier, 1987	18	1
Quebec, 1988	2	-
Loma Prieta, 1989	7	-

Selection of Design Ground Motions

According to the here proposed seismic design code approach, the selection of design ground motions should be based on maximum code accepted risk values such as those given in Table 3; design spectrum values should use allowed reduction factors associated to preestablished expected performances. In the case of hospital buildings,four performance level have been proposed for selecting design seismic actions {9} and are reproduced in Table 5; R values have been sligthtly modified and are refered to framed members. The application of the criteria stablished in Table 5 is given in Table 6 for two sites with marked hazardousness differences duly characterized in that table. The results show that in order to fulfil the expected performance, design values are conditioned by performance levels associated to moderate R values.

TABLE 5. Performance levels for selection of design motions, for reinforced concrete hospital buildings; 45 years service life {9}.

Performance Level	Expected Performance	R(*)	Probability of Occurrence	T(**) (years)
PL1	Essentially elastic response; no visible damage. Hospital fully operational.	1,5	Highly probable ground motions; 60% exceedence in 45 years.	< 50
PL2	Minor damage to structural elements; scattered nonstructural reparable damage. Hospital fully operational.	2,0	Probability of exceedence about 20% in 45 years. Intense shaking in highly seismic areas.	200
PL3	Limited structural damage; some installations may be affected; emergency services remain operational.	3,0	Small probability of occurrence; 10% in 45 years.	430
PL4	Heavy structural damage but small probability of collapse. Nonoperational installation.	4,0 to 5,0	Less than 5% in 45 years. May be the most intense in high seismic regions.	Larger than 900

(*) Allowed ductility reduction factor for essentially complete frames.

(**) Mean return period.

TABLE 6. Application of the criteria of Table 5 to two sites with marked hazardousness differences.

Parameters		Site 1: High seismic area; representative of certain locations in the Caribbean.	Site 2: Low seismic hazard; far from active sources.
ac (gal)	Eq. (7)	55	20
β	Eq. (7)	3,1	5
2,2 Ao/R	(gal)*	147	31
PL1; (R=1,5)	2,2.Ao / R (gal.)	284	95**
PL2; (R=2,0)		334**	88
PL3; (R=3,0)		284	75
PL4; (R=4,0)		268	59

(*) ATC-3, 1978 {1} criterion: 10% of exceedence in 50 years; R=6.

(**) Value to be choosed as design ground motion, proportional to design spectrum.

CONCLUSIONS.

The results of quantitative evaluations of earthquake hazard in terms of ground motions can be synthetized by two characteristic hazard parameter maps; their values allow the selection of design ground motions on the basis of maximum code accepted risks, abolishing the need of the importance or use factor. Code reduction factors for the determination of design spectrum ordinates, must be associated to preestabilished expected performance.

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