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Earthquake hazard mapping for seismic design codes: A new approach

J.Grases
Universidad Central de Venezuela, Venezuela
G.Cascante & E.Gajardo
INTEVEP, Venezuela

ABSTRACT: Results of probabilistic hazard evaluations performed in different sites are analysed. They show that within their ranges of usual seismic design exceedences, obtained results can be properly described by a linear variation between the logarithm of the mean rate of exceedence λ and the logarithm of ground motion X: i.e. $\mathrm{Ln}\ \lambda = q - \beta\ \mathrm{Ln}\ x$ or $\lambda = (x/x^*)^{-\beta}$ with $x^* = \exp(q/\beta)$. Iso x^* and iso β maps already prepared for Venezuela retain far more information than normally given in zonation maps, since they allow the reconstruction of cumulative distribution functions for design purposes. Zero period spectral acceleration values at any site can be directly related to service life and established exceedences based on expected performance, this being a further step towards controlled reliability earthquake resistant design.

1. INTRODUCTION

Code seismic design spectra are obtained multiplying normalized soil dependent spectra by zero period spectral acceleration values Xo and an importance factor alpha: further they can be reduced according to global structural ductility and redundancy of the selected structural system.

Even if this approach has limitations, it benefits of the uniqueness of the solution for a given site and has been widely adopted as a practical code format. Notwithstanding, the convenience of maintaining uniform structural reliability requires bridging some code-traditions steming from the very beginning of the earthquake resistant design, such as generalized zonation maps -nowadays with fixed probabilities of exceedence- 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 design values on the basis of expected performance, linked to selected annual probabilities of failure and optimization decisions.

This paper presents an alternate procedure which synthesises hazard evaluations by means of hazard maps. The selection of design ground motions can be linked to service life and acceptable excedences to be selected in accordance to expected consequences of eventual failure or malfunctioning.

2. HAZARD EVALUATIONS

2.1 Previous zonation Maps

Since 1947 Venezuela has had several zonation maps for engineering purposes (MOP, 1947). Until 1982, seismic zonation was esentially based on the known effects of past events, with generalizations proper of isoseismal mapping. Presently enforced earthquake resistant design code (COVENIN, 1982), was approved in 1982 following the suggested ATC-3 (1978) code format; for the first time seismic zonation was presented in terms of expected maximum ground accelerations, nominaly associated to 10% exceedence for a service life of 50 years, on the basis of probabilistic earthquake hazard evaluations performed during 1979-1980 (Grases, 1985).

2.2 Seismotectonic modeling

Improvements since the original study was made more than a decade ago in: (i) the past seismicity of the country; (ii) an improved field identification and understanding of active faults; and (iii) better geophysical data, called for a review and potential revision of the present earthquake zonation map. Seismotectonic models used in several site studies performed during this last ten years have progressively incorporated the refered improvements and have been essentially based on the observed seismicity distribution as well as on tectonic similarity; each source has been defined in terms of: geometry, individual recurrence parameters and relative confidence levels (Fig. 1 and 2).

Ground motion attenuation in firm grounds was redeveloped, adding the available local strong motion records. Near field ground motion leves have been modelled according to values observed in other areas of the world. The attenuation laws used were of the form:

$$\mathrm{Ln}x = C1+C2.M_s-C3.\mathrm{Ln}\ (R+C4) \qquad (1)$$

where M is Richter magnitude and R is focal distance in Km; C1 to C4 are regional regresion constants with differences between the east and the west of the country as given in Table 1 (INTEVEP 1990). The ratio R between the predicted west and east ground motions, reflect known geophysical data:

$$R = 5{,}2\ e^{-0{,}106Ms}(R+10)^{-0{,}29} \qquad (2)$$

For small magnitudes, R tends to 1,0 at large distances and to 1,25 at small distances; for large magnitudes, R tends to 1,0 at short distances and to 0,4 at large distances.

TABLE 1. Coeficients of Eq. (1) for Maximum Ground Accelerations.

Area of the country	C1	C2	C3	C4	σ lnx
East	3,75	0,47	0,57	10	0,66
West	5,40	0,36	0,86	10	0,66

2.3 Modelling and Uncertainties

For the quantitative hazard evaluation, the following parameters were incorporated as random variables: fault rupture length (log-normal distribution), Richter M_s magnitude (exponential distribution), geographical coordinates for lineal or superficial sources (uniform distribution), Poisson distribution for time of occurrences, and a conditional log-normal distribution for maximum ground motions given the magnitude and focal distance. Additionally, fault geometries and its associated maximum M_s were modelled as discrete random variables. Annual mean rates and b values, characterizing source seismicity, were considered deterministic.

2.4 Hazard evaluations and typical outputs

The results of site hazard evaluations following the previous modelling, show that within the ranges of interest the annual rate of exceedence of maximum ground motions x for a given location satisfies the following relation:

$$\mathrm{Ln}\ \lambda = q - \beta\ \mathrm{Ln}\ x \qquad (3)$$

where q and β are constants of the location. Equation (3) can be rewritten in the form:

$$\lambda = (x\ /\ x*)^{-\beta} \qquad (4)$$

where x* is a characteristic value equal to exp (q/β).

3 NEW CODE GROUND MOTION SELECTION APPROACH

3.1 Hazard Maps

From what has been said in Section 2.4, the values of x* and betha are characteristic hazard parameters, which can be obtained in as many points as necessary assuming uniform firm soil conditions. Figures 3 and 4 give the seismic hazard maps for Venezuela, in terms of x* and betha. Observe that for any location, Eq (4) can be readily obtained reading x* and betha from the refered maps. Singularities in points near or over active faults have not appeared due to the particular shape of the attenuation laws used (See Eq. 1 and Table 1).

3.2 Cumulative distribution function

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

$$P = \exp(-\lambda t) \qquad (5)$$

This can be rewritten as:

$$P = P[X \leq x;\, t] = \exp(-t(x/x^*)^{-\beta}) \qquad (6)$$

which has the same form as a Gumbel Type II extreme value distribution. This type of functions also arises as the limiting distribution of the largest value of many independent identically distributed random variables (Benjamin and Cornell, 1970). The mode ($\tilde{x}$), mean ($\bar{x}$) and standard deviation (σ_x) yield:

$$\tilde{x} = x^* [\beta/(\beta+1)]^{1/\beta} \qquad (7)$$

$$\bar{x} = x^* \Gamma(1-1/\beta) \qquad (8)$$

$$\sigma_x = x^*[\Gamma(1-2/\beta) - \Gamma^2(1-1/\beta)]^{0,5} \qquad (9)$$

wer Γ is the gamma function; note that the validity of eq (8) and eq (9) requires $\beta > 1$ and $\beta > 2$ respectively. The coefficient of variation is only dependent of β and is larger than 100% for values smaller than about 2,5. Table 2 gives representative values for maximum ground acceleration distributions for Venezuela (see Figures 3 and 4).

TABLE 2. Maximum ground acceleration distributions. Representative values for Venezuela.

Hazard area	a* (gal)	β	ã (gal)	ā (gal)	σa (gal)	Coef. of variation
High	55	3,6	51	70	33	0,47
Moderate	40	3,8	38	49	22	0,45
Low	30	4,0	28	37	16	0,43

For practical porposes, tail values (small probabilities of exceedence) of maximum ground motions obtained from hazard analysis, have also been modeled as log-normal distributions. In those cases, the standard deviation of the variate X has been obtained as:

$$\sigma_x = 0,39\,(\text{Ln}\, X_{90} - \text{Ln}\, X_{10}) \qquad (10)$$

in which X_i is the ith percentile value of X (see: Bea, 1980).

3.3 Maximum ground accelerations

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

$$x = x^*[(-\text{Ln}\, P)/t]^{-1/\beta} \qquad (11)$$

In this format, the ATC-3 (1978) criteria for the selection of maximum ground accelerations for building design (P=0,90 and t=50 years) would be:

$$a = x^*\,(0,002107)^{-1/\beta} = x^*\,(474,6)^{1/\beta} \qquad (12)$$

Figure 5 gives the isoaceleration map. Other representative values of P and t are given in Table 3.

TABLE 3. Representative values of exceedence probabilities in given life spans used in the selection of design ground motions.

Building or installation	t (years)	1-P (%)	Mean return period (years)
Offshore manned platforms	25	0,01	2490
Dams	100	0,05	1950
Fuel storage tanks	30	0,05	590
Temporary constructions	15	0,30	40

It is easy to prove that if maximum ground accelerations are multiplied by the importance factor α, the probability of not exceeding that motion increased by the exponent $\alpha^{-\beta}$. Given that typical α values range between 1,2 and 1,6, for the β values given in Fig. 3, the associated mean return periods vary from 1,5 to 6 times the ATC values. This means that the use of a constant α value, as established in current codes, is far from leading to uniform structural reliability.

3.4 Selection of design ground motions and expected performance

Experience has shown that current code strategy is not necessarily adequate for buildings whose serviceability must be 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 after very strong shaking; damage shall not impair emergency services, must be repairable and non lifethreatening; (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 nor hindered.

According to the 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.

4 CONCLUSIONS

The proposed seismic hazard mapping retains far more information than currently used zonation maps. They allow the reconstruction of cumulative distribution functions and some of their properties paramount for seismic reliability analysis, this being a further step towards controlled reliability earthquake resistant design.

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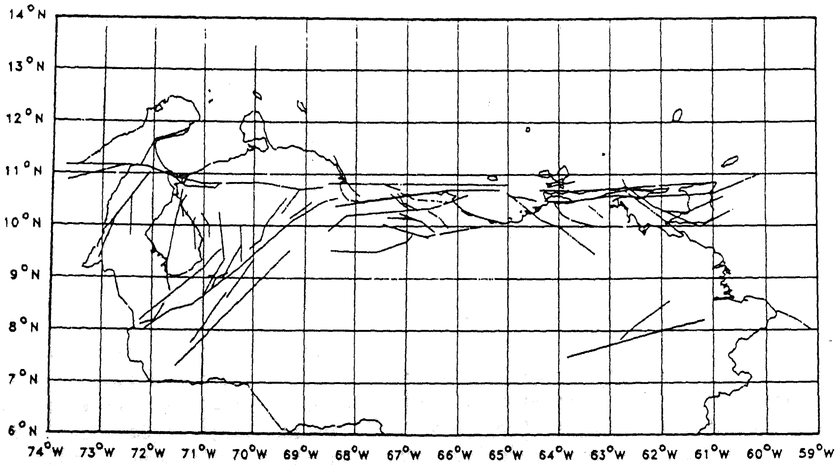

FIGURE 1: MAIN SUPERFICIAL LINEAR SEISMIC SOURCES CONSIDERED: RATE OF DISPLACEMENTS BETWEEN 9 TO 0,01 MM/YEAR; MEAN FOCAL DEPTHS 15-25 KM.

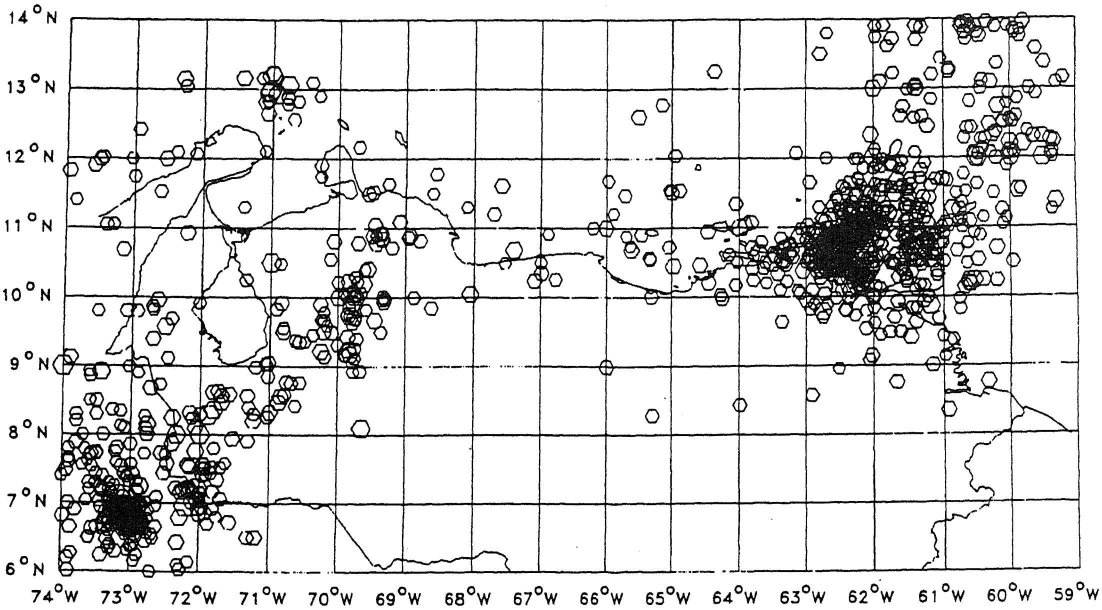

FIGURE 2: MAP OF EPICENTERS. VENEZUELA 1900-1991.
FOCAL DEPTH 0-300 Km. CATALOGUE INTEVEP-FUNVISIS

Symbol	Magnitude
⬡	4.0
⬡	5.0
⬡	6.0
⬡	7.0

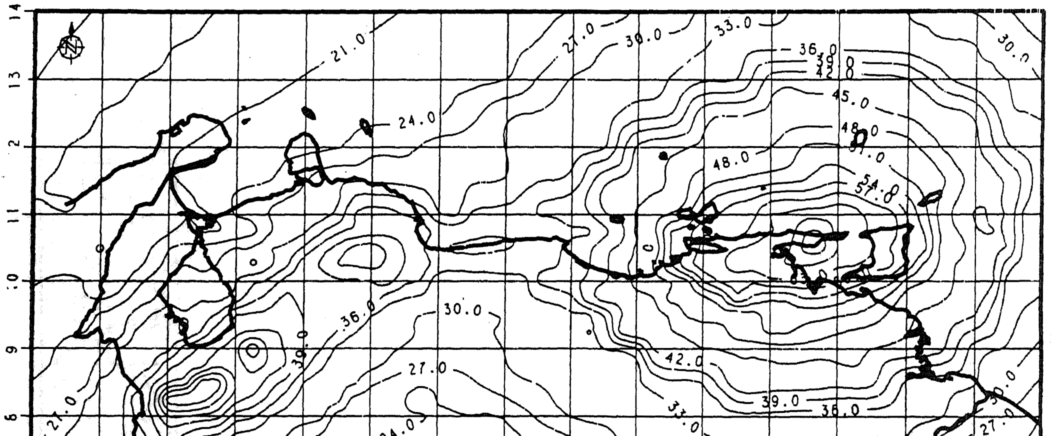

FIGURE 3: PRELIMINARY HAZARD MAP FOR VENEZUELA IN TERMS OF ACCELERATIONS
x* VALUES OF EQUATION 11, IN GALS.

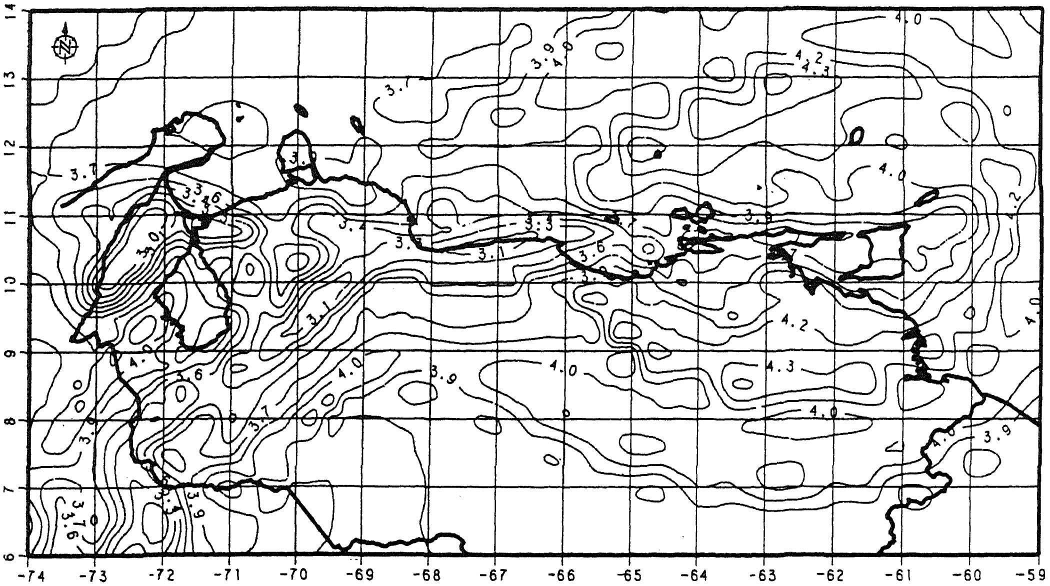

FIGURE 4: PRELIMINARY HAZARD MAP FOR VENEZUELA IN TERMS OF ACCELERATIONS.
β VALUES OF EQUATION 11.

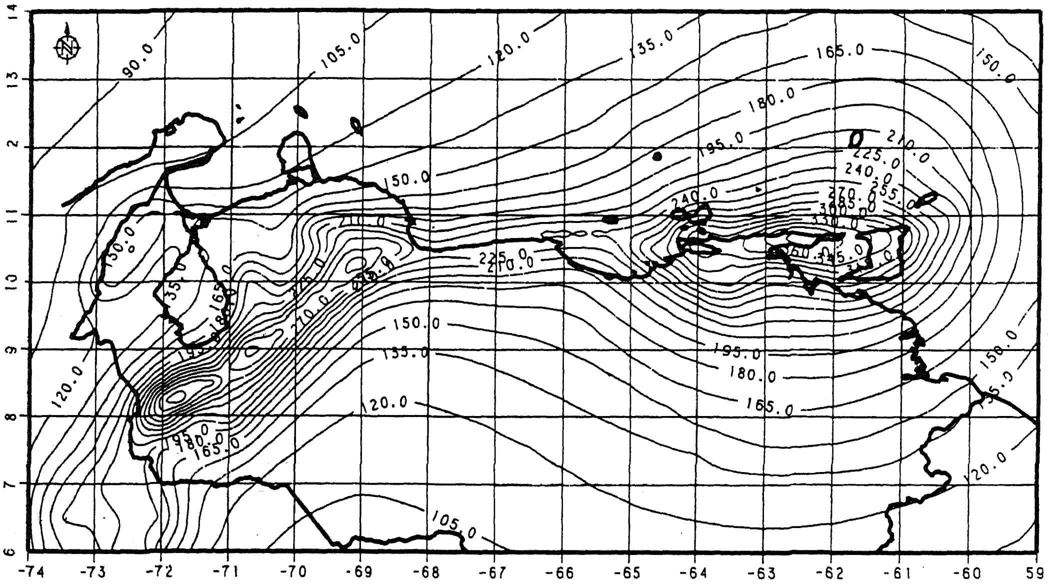

FIGURE 5: ISOACCELERATION MAP, BASED ON VALUES GIVEN IN FIGURES 3 AND 4
10% EXCEEDENCE IN 50 YEARS