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Code seismic design criteria for emergency buildings

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ABSTRACT: Current code earthquake-resistant design criteria are oriented to minimize the probability of building collapse and generally fall short to fulfil serviceability requirements under strong shaking. For emergency buildings, design loads are increased by an importance factor which typically ranges between 1.2 to 1.6. Experience gained in real earthquakes and theoretical considerations proove that this criteria does not warrant the expected performance of essential facilities. In this paper a multilevel earthquake resistant design procedure is proposed based upon the probabilistic evaluation of the seismic hazard of the site, the explicit compliance of four performance levels associated to given probabilities of exceedence and allowable spectral reduction factors, this being a further step towards uniform reliability building design in earthquake prone areas.

1 STATEMENT OF THE PROBLEM

1.1 Introduction

According to the basic concepts for the development of seismic design methods of engineered constructions, the safety and serviceability requirements are called Design Criteria (IAEE 1982). Due to the wide margins of uncertainty involved they are treated in probabilistic terms, though usually replaced with a set of practical rules in order to facilitate design applications.

Early code requirements intended to provide minimum design criteria in order to make buildings earthquake-resistive, did not differentiate current buildings from emergency or essential facilities (IAEE 1960; Blume 1961). In the early sixties, structures or buildings which were supposed to be safe and usable for emergency purposes such as hospitals and other medical facilities having surgery or emergency treatement areas, police stations, museums, fire stations, and the like, began to be classified as "essential facilities" (IAEE 1973). For these, an importance or use factor α larger than unity, was imposed as multiplier of seismic loads, maintaining essentially the same design strategy as for current buildings. Namely: buildings designed to resist the prescribed motions may suffer damage, but should have a low probability of collapse minimizing the hazard to life. A sample of α values is given in Table 1.

Experience has shown however, that the above criteria does not necessarily convey to adecuate safety nor reliable serviceability (Bertero 1991; Sauter 1989). An example of this, is the performance of health care facilities that during the last two decades have gone through seismic shaking in the american continent, in 22 earthquakes. Over 126 of those facilities in 13 countries, have suffered some degree of damage; a fifth of them collapsed or were damaged beyond repair (see Table 2). An unknown number of facilities have surely gone undamaged through the refered events; on the other hand,there are no precise statistics about the design criteria of the heavily damaged or collapsed buildings. It is known however, that many of them were built in the last decades according to standards that still are, or until recently have been, enforced.

1.2 Sources of Damage

In the last thirty years or so, codes

TABLE 1: Importance or use factor for essential facilities. A sample.

COUNTRY	YEAR OF CODE	IMPORTANCE FACTOR	REFERENCE
Cuba	1964 1984	1.3 1.6	IAEE, 1973 CEN , 1984
México	1957 1977 1987	1.3 1.3 1.5	IAEE, 1960 RCDF, 1977 RCDF, 1987
USA	1959 - 1966 1970 1979	1.0 (no distinction) 1.0 (no distinction) 1.5	IAEE, 1969 IAEE, 1973 ICBO, 1979
Venezuela	Up to 1955 1967 1982	1.0 (no distinction) 1.25 - 1.33 1.25	MOP , 1959 MOP , 1967 COVENIN, 1982

have incorporated more stringent design criteria and/or enlarged the total areas of seismic hazard. For instance, the percentage of the total venezuelan territory associated to the highest seismic hazard in building code zonation maps, increased from 0.9% in 1947, to 5.3% in 1955, to 8.5% in 1967 and finally to 13.1% in 1982. Therefore building seismic design loads might have been too low in many instances.

In at least three cases, the site seismic hazard was also inadecuately evaluated in terms of local soil conditions and other local geological seismic related threats, leading to malfunction of essential facilities. This has shown that they deserve a proper, detailed and reliable, seismic hazard evaluation.

Performance expectancies were not reached in many cases due to functional vulnerability, mainly as a consequence of limited consideration to actual dynamic characteristics and expected response of the various systems conforming the installation, excesive ductility demands and non-structural related damage. Experience has taught that in essential facilities, functional reliability - normally not verified - is as important as structural reliability.

Surely there are unaffected emergency installations in areas shaken by the events listed in Table 2; but, as said, some of the damaged ones were designed with current code strategies. Consequently, the seismic reliability of a possibly large percentage of the existing emergency building stock is doubtful. This paper looks into the design hypothesis of present seismic design codes, recommends new requirements and suggests a methodology for the selection of design ground motions for new and/or the verification of existing buildings. Finaly, it strongly supports a multilevel compliance procedure of expected performance levels.

2 DESIGN CRITERIA OF EXISTING CODES

It must be recognized that even if there are limitations in current code procedures, they have evolved in such a way that tend to explicitize and disagregate parameters paramount for the prediction of the expected seismic demands, as well as for the reliability evaluation.

2.1 General Strategy

Codes for the design of earthquake-resistant buildings, are frequently based upon a general philosophy that can be approximatively described by the following statements: (i) avoid damage under expected motions that may occur frequently during service life; (ii) minimize non-structural damage and prevent structural damage due to ground shaking of occasional occurrence; and (iii) minimize the probability of collapse due to shaking associated to unfrequent events. Current code building design methods are oriented to fulfil the last of the statements independently of the importance or use of the building; therefore, they normally fall short to satisfy the two first statements.

TABLE 2: Health care facilities affected by earthquakes in América (1971 - 1991).

EARTHQUAKE IDENTIFICATION	TOTAL AFFECTED	COLLAPSED OR BEYOND REPAIR	REFERENCE
San Fernando, 1971	9	6	Lew, 1971
Managua, 1972	2	1	EERI, 1973
Antigua, 1974	1	0	Tomblin, 1974
Guatemala, 1976	4	2	Espinosa, 1976
San Juan, 1977	(a)	-	Castano, 1978
Manizales-Charco,1979	8	1	Ramirez, 1980
Cúcuta, 1981	2	0	Malaver, 1982
San Isidro, 1983	1	0	Cruz, 1991
Popayan, 1983	1	0	Sarria, 1985
Mendoza, 1985	10	2	Stein, 1985
Chile, 1985	18	2	Wyllie, 1986
México, 1985	22	6	Rosenblueth, 1989
San Salvador, 1986	9	1	Durkin, 1987
Carúpano, 1986	1	0	Malaver, 1986
Whittier, 1987	18	1	Baird, 1987
Quebec, 1988	2	0	EERI, 1989
Loma Prieta, 1989	7	0	Benuska, 1990
Cóbano-Puriscal,1990	4(b)	-	Santana, 1990
Limón, 1991	6	1	López, 1991
Pochuta, 1991	1	1	Arya, 1991

(a) Health sector losses estimated in several million US \$.
(b) One of them under retrofiting at the time of the quake.

2.2 Code Format

Code formats have evolved and no doubt will continue to do so. In Venezuela, formal consideration of earthquake loads started in 1947; up to 1955 the seismic coefficient C was a constant for each of the three seismic zones. Between 1955 and 1967, C was dependent on the number of stories N. After the 1967 Caracas earthquake, explicit consideration was given to local soil conditions, structural system type and 1.25 to 1.33 increased design loads for essential facilities; dynamic properties were only required for buildings taller than 60 m or 20 stories. Since 1982 the code followed very much the ATC-3 format, with α = 1.25.

For comparison purposes, seismic base coefficient C can be related to design response spectra in the form:

$$Co = \frac{a.\alpha.\beta.\mu}{g.R} \qquad T \leq T* \qquad (1a)$$

$$C = Co\ (T*/T)^{p} \qquad T > T* \qquad (1b)$$

where: a = spectral acceleration for T = 0 sec; α = importance factor; β = soil dependent mean dynamic amplification factor; μ = higher modes base shear modification factor (here assumed as a constant); R = reduction factor; T* and p, soil dependent values; T = natural period (sec); g = acceleration of gravity. The zero period spectral acceleration a is usually refered to zonation maps, which may relay upon probabilistic hazard assessments. In the vast majority of current codes, the distinction for the design of essential facilities is limited to the factor $\alpha > 1$. Before analysing it, we will discuss the factor R.

2.3 Reduction Factor R

Ideally, the response of essential facilities to seismic actions should remain in the so-called linear elastic range; moderate inelastic demands might be allowed for very intense, highly improbable shaking. Therefore, the idealised allowable ratio between maximum response displacement and yield displacement D will be limited to small values; such allowable ductility demands DA are linked to the design and detailing criteria of members and joints. The reduction factor R is related to DA by means of relations such as those given in Figure 1.

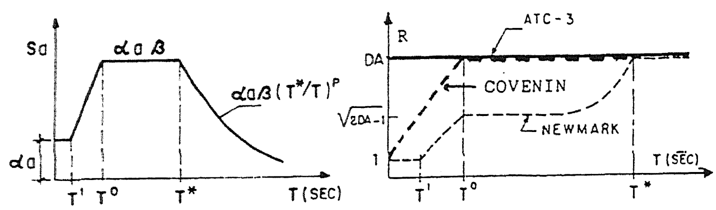

Figure 1. Elastic spectrum Sa and Reduction Factor R; typical code shapes.

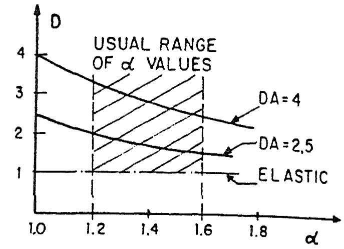

Figure 2. Reduction of ductility demand.

Note that the ATC-3 reduction criterion does not depend on T. Results presented by Riddell et al (1989) strongly support the use of smaller R values for structures with natural periods comparable to the durations of predominant ground motions and shorter.

2.4 The Importance Factor α

For a given design ground motion a, the use of $\alpha > 1$ as established in present codes, can be interpreted as a procedure to reduce the ductility demand. That is:

$$SD = \alpha\, SA / R = SA / (R / \alpha) \qquad (2)$$

where: SA = elastic spectral ordinates; SD = design spectral ordinates. Following the idealizations of the adopted format, Figure 2 shows that the reduction on ductility demands for $T > T^*$ are still important.

A different interpretation of the incorporation of the factor α, is that it reduces the probability of exceeding the allowable ductility DA. This means that, other things being equal, the increase of design ground accelerations by a factor of α will reduce the annual probability of exceedence in the proportion:

$$\Omega = \frac{1 - e^{-(\alpha a/a^*)^{-\delta}}}{1 - e^{-(a/a^*)^{-\delta}}} \qquad (3)$$

where: a^* and δ are characteristic values of the site seismic hazard. Figure 3 illustrates the variation of Ω for typical venezuelan sites. For α values equal to 1.25 , exceedences are reduced to about a half and for α = 1.6 exceedences are 5 times smaller, reductions being larger for lower hazard.

2.5 Comparison of Code Requirements

Comparison of present code requirements for the seismic design of hospital and health care installations of eleven Latin American countries was presented in a previous paper (Grases 1990). The following three conclusions stand out of that exercise: (a) seismic design forces required for the design of a given hospital building, in similar soil conditions and in the most hazardous seismic zones, differ by a factor as large as 4.1; it is not known how much of this differences are attributable to seismic hazardousness; (b) the importance factor ranges from 1.2 to 1.6, and the factorized maximum design ground accelerations αa ranges between 0.26g and 0.84g; probabilistic implications are not given; (c) the code authorized or infered ductility reduction factors R are large enough to be associated to structural damage under strong shaking.

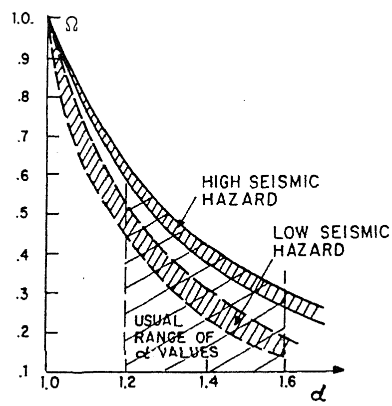

Figure 3. Typical Ω values for Venezuela.

3 ESSENTIAL FACILITIES

A number of reliability limitations of current code criteria related to the expected performance of essential facilities have been presented in the two previous Sections. To overcome those code limitations, some basic requirements must be incorporated.

3.1 Seismic Hazard Site Evaluations

In the selection of sites for new essential facilities or in the evaluation of existing ones with retrofit purposes, reliable hazard assessments are necessary. This requires the explicit consideration of historical damaging earthquakes, location of main active faults, probabilistic distribution of maximum ground motions, local soil and topographic effects, ground stability and landslide risk, tsunamie risk and effects due to possible malfunction of nearby installations.

Lack of local or regional information has obliged to rely upon statistics from better known regions, with limited analytically based extrapolations; better understanding of earthquake hazards and progress in its assessment is reflected in the recognition of associated uncertainties, although gauging the probability of such hazards fall outside the scope of current codes.

3.2 Distribution Functions of Maximum Ground Motions (DFMGM)

From what has been said, probabilistic distribution functions should be incorporated in the design methodology and used within a explicit strategy based in possible exceedences associated to preestablished performance levels. For all practical purposes DFMGM's at given sites can be properly described as Gumbel Type II extreme value distributions. Namely:

$$P = P\,[A \leq a; t] = e^{-t(a/a*)^{-\delta}} \qquad (4)$$

where: t= service life; a* (gal) and δ are site hazard values given in code maps (Grases et al 1992). It is known, that the use of a single parameter that multiplies normalized soil-dependent spectra has limitations (Bertero 1991); at present it represents a trade off between predictability limitations and practice.

3.3 Evaluation of Dynamic Properties

Seismic response depends on the dynamic properties of the whole structural system: structural and non-structural elements, as well as soil-foundation interaction. Given the possibilities of present computer programs, code requirements for essential facilities must call for detailed analytical studies in order to determine seismic demands and identify critical regions; several models can be considered in the dynamic analysis, including basic equipments if necessary. Simplified methods should only be allowed in particular cases.

3.4 Functional Reliability

In order to assure functional reliability, particularities of essential facilities deserve full attention from the designer and user (PAHO 1992; Stewart 1989). Those can be exemplified by typical features of health care facilities; i.e.: (i) occupancy: hospitals house permanently a large number of persons (patients, visitors, medical and service staff, as well as suppliers) and many patients must be surrounded by delicate equipments; (ii) complexity: health instalations combine hotel and office services with laboratory, equipments and storage, often in internal areas without natural light; (iii) dependence of vital services: power supply, water and communications are vital. Those particularities mark definite differences from usual buildings; ignoring them has often been the cause of functional vulnerability and poor seismic performance. In order to reduce non-structural damage, allowable drift should be limited to less than about 0.008 of the interstory height.

4 PROPOSED METHODOLOGY

In addition to the requirements established in Section 3 a multilevel earthquake resistant design as proposed by Bertero (1991), is strongly supported.

TABLE 3: Proposed performance levels: expected performance, ground motions, selection criteria and R values for compliance verification.

PERFORMANCE LEVEL	EXPECTED PERFORMANCE	GROUND MOTION (a)	R (b)
PL1	Essentialy elastic response; no damage. Fully operational facility.	*Highly probable during service life.* (1-P)>0.60	1.0
PL2	Minor to no damage to structural elements; scattered non-structural reparable damage. Fully operational facility.	Probable events during service life. (1-P) ranges: 0.30-0.40.	0.3R≥1.0
PL3	Limited structural damage; facility may be partly affected, but emergency services shall remain operational.	Intense shaking associated to a low probability of ocurrence. (1-P) ranges: 0.1-0.15.	0.5R≥1.0
PL4	Heavy structural damage but small probability of collapse. Non operational installation. Rescue warranted.	Very strong possible shaking though highly improbable. (1 - P) ≤ 0.04.	R

(a) (1-P) = Probability of excedence (see Ec. 4).
(b) Tentative values.

4.1 Expected Performance Levels

Earthquake-resistant design for new or retrofiting requirements to be applied to emergency buildings, must explicitely minimize the risk of disruption. Expressed in a general form, for health care facilities this means: (i) the building must remain stable even after very strong shaking; damage shall not impair emergency services, it must be limited, repairable and non life threatening; (ii) medical personnel and staff, patients and visitors, must remain in reasonable safe conditions during an intense earthquake; eventual evacuation must be warranted; (iii) free entrance to hospital buildings is paramount; in extreme cases, entrance of rescue teams should not be hindered or risky.

In order to establish procedures for their formal compliance, the given requirements can be stated in several performance levels related to increasing intensities of ground motion. Four different levels are proposed in Table 3; the description of the expected performance follows generalized statements related to the structural behaviour under earthquake loading. Their relation to the R values given in column 4, is guided by the present values for the different structural systems of the venezuelan code (COVENIN 1982); i.e., DA = 6 for ductile moment resisting reinforced concrete frames; DA = 5 for the so-called reinforced concrete dual systems; and DA = 4 for bearing wall systems providing support for vertical loads as well as for lateral loads.

The probabilities of exceedence suggested in column 3 have been subjectively choosen.

4.2 Multi-level Earthquake-resistant Design

Design with explicit compliance of several performance levels, is occasionally applied to certain type of structures. It is proposed here as code design criteria for essential facilities; following Bertero (1991), two distinct phases must be considered: i) a preliminary design of the entire facility in order to conform the critical or controlling level design earthquake; ii) in a second phase, the preliminary design would have to be analized and

TABLE 4: Desingn ground motions for two different sites, according to the proposed criteria given in Table 3 (t = 50 years).

PERFORMANCE LEVEL	SELECTED (1-p) VALUE	DESIGN GROUND ACCELERATIONS (gal)	
		High Seismic Hazard Site (1)	Low Seismic Hazard Site (2)
PL1	0.75	129	47
PL2	0.40	585/R	194/R
PL3	0.10	584/R	168/R
PL4	0.01	623/R	145/R

(1) a^{*} = 40 gal; δ = 3.1 (2) a^{*} = 20 gal; δ = 4.3

detailed to ensure the fulfilment of the rest of the performance levels.

4.3 Controlling Levels of Design

The largest design requirements in terms of forces and/ or allowable displacements on the basis of ecuations (1a), (1b) and (4), will control the design. Table 4 gives a comparison between those critical levels for two different hazard sites. Note that for the high hazard site, PL4 is the controlling level of design shears provided that R is less than 623/129=4.8; otherwise PL1 is mandatory. For the low hazard site PL2 is critical if R is less than 4.1; otherwise PL1 is mandatory.

5. CONCLUSIONS AND RECOMMENDATIONS

Idealizations adopted in modern codes can be improved towards controlled and uniform reliability. The importance or use factor prescribed for emergency facilities does not fulfil this objective.

In order to overcome reliability limitations related to the expected performance of new or existing emergency buildings, codes must incorporate requirements to: properly evaluate site seismic hazard, perform detailed dynamic analysis to evaluate seismic demands and identify critical regions. It is proposed that the selection of maximum design ground motions be related to four expected performance levels, associated to given exceedences and allowable spectral reduction factors. The explicit compliance of this performance levels requires a multi-level earthquake-resistant design methodology. The critical or controlling levels depend upon the probability distribution function of the site seismic hazard.

For mitigation purposes the preparation and due publication of updated design criteria, as well as the establishement of guidelines for the qualification and retrofiting of existing emergency facilities, is strongly recommended.

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