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# Seismic Design Recommendations for Building Structures in Saudi Arabia

**M.S. Al-Haddad and G.H. Siddiqi***

*Assistant Professor, *Associate Professor*
*Civil Engineering Department, College of Engineering,*
*King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia*

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**Abstract.** The seismic design criteria proposed for the Kingdom of Saudi Arabia (KSA) are presented. For the sake of brevity, the paper presents only specific basic design parameters. However for the sake of completeness, reference is made to appropriate sources, when the issues involved call for more information. The criteria are developed to cover the basic requirements for seismic performance and load calculation, to take care of building and structural system configuration, lay down structural analysis procedure, prescribe design, detailing, good construction practice and quality control requirements for structures, and their structural and non-structural components and foundations.

## Introduction

The Seismic Design Criteria presented in this study are based on outcome of a research project entitled "A Study Leading to Preliminary Seismic Design Criteria in the Kingdom" which was funded by the King Abdulaziz City for Science and Technology (KACST). The three part final report [1] on the study, submitted to KACST, presents the first regionally consistent and systematic treatment of neotectonic and earthquake data in estimating the seismic hazard across the country and the development of seismic design criteria. The major steps involved in the study were:

1) Compilation of earthquake catalog, identification and delineation of the boundaries of seismic sources.
2) Treatment of the seismicity data and preparation of iso-acceleration and seismic zone maps based on probabilistic risk assessment over the Kingdom.

3) Evaluation of the seismic design parameters and development of preliminary seismic design criteria.
4) Prescription and explanation of the detailing requirements.

This paper is solely devoted to the issues involved in development of the tentative preliminary seismic design criteria for the Kingdom of Saudi Arabia. Objectively speaking the criteria were developed to satisfy the following basic seismic design principles:

1) Provision of adequate strength in a structure to sustain the predicted seismic design load with the expectation that some part of the structure may go into inelastic range during a major earthquake.
2) Regulation of the building and structural system configurations to control undesirable torsional effects in the building during an earthquake.
3) Provision of adequate requirements for proportioning and detailing of the structural elements of a building and adequate anchorage of the nonstructural elements.
4) Provision of adequate lateral stiffness in a structure to control the interstory drift and consequently the P-Delta effect.
5) Provision of regulations to enforce good construction practice and quality control.

The seismic design codes, over the past half century, have recognized and rectified the misconceptions and the errors in their earlier versions. The lessons learned from earthquake aftermaths, worldwide, by extensive and in-depth investigations made by qualified research teams, into the response of structures to ground shaking and the reasons which led to their failure have completely changed the philosophy of earthquake resistant design from what it used to be. Any team who are beset with developing a seismic resistant design code cannot afford to neglect such a vast and valuable knowledge base.

It was, therefore, decided to develop the preliminary version of the design criteria for KSA within the framework of a seismic code that is well recognized, updated recently, and accepted nationally and internationally. Based on critical screening and evaluation of worldwide earthquake resistant design codes [2], it was found that the ATC-3-06 amended, "Tentative Provisions for the Development of Seismic Regulations for Buildings", [3], stands out as a unique document on the science and art of earthquake engineering. ATC draws upon knowledge and know-how of a broad spectrum of individuals and/or bodies in professional practice, academic and research groups, and blends it into a meaningful and well knit set of provisions. It may be pointed out that although ATC provisions conform to a general consensus of opinion they do not do so to every school of thought. The recent editions of the most widely used U.S. Official Codes, SEAOC [4] and UBC [5], reflect and incorporate tentative provisions of ATC after due evaluation of the new concepts.

SEAOC and UBC codes were selected as the models for development of seismic design recommendations suitable for and consistent with the type of the building and construction practices in vogue in the KSA. Specifically the manuscript of the criteria follows the SEAOC-format in general and is written in descriptive text. One can go to Ref. [1] for the background and the basis which led to selection and development of the seismic design criteria for the KSA. The global framework of the design criteria is shown in the flow diagram of Fig. 1. This paper emphasizes the specific issues involved in the development of the criteria. For the sake of brevity only the basic requirements which led to development of the code are described and the reference to appropriate sources is made to maintain completeness of the text.

## The Proposed Design Criteria

### Scope of coverage

The criteria were developed for the new building structures. However, the seismic load parameters required for the design of special structures by the professional engineers and the code promulgating authorities are provided in Ref. [1].

### Basic design requirements

The procedures and limitations for the design of structures are based on seismic zoning, soil type, occupancy, structure configuration in plan and elevation, structural systems and height considerations on these systems.

#### *Seismic zone and Zone factor*

Each site is assigned to a seismic zone in accordance with zoning map of Fig. 2. The seismic zone number (SZN) and seismic zone factor, Z, for a structure in a particular zone can be determined from Table 1.

#### *Occupancy categories*

For the purpose of earthquake resistant design, each structure is placed in one of the occupancy categories listed in Table 2. Associated with each category is an important factor, I, which are also listed there.

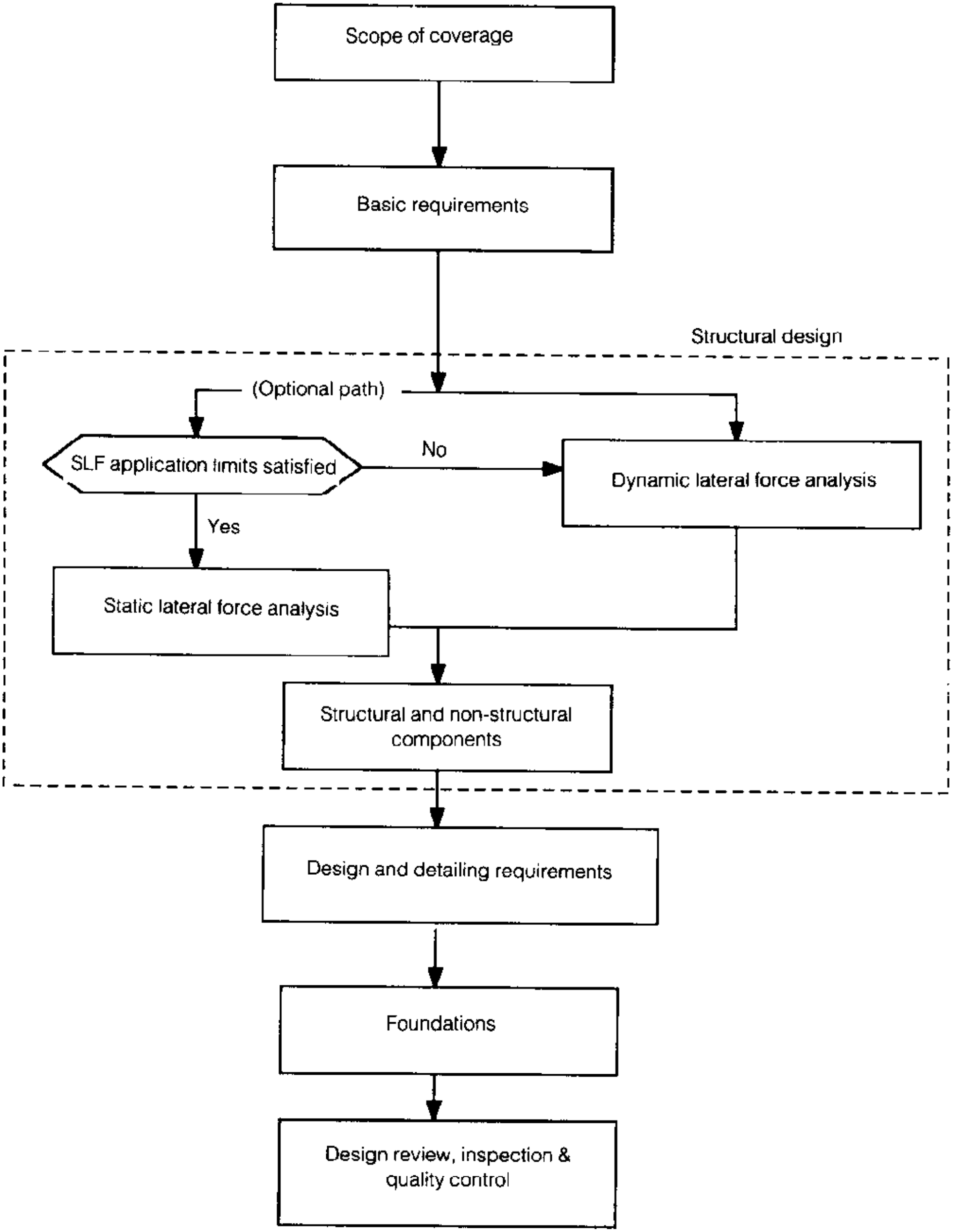


**Fig. 1. Overall framework of the design criteria.**

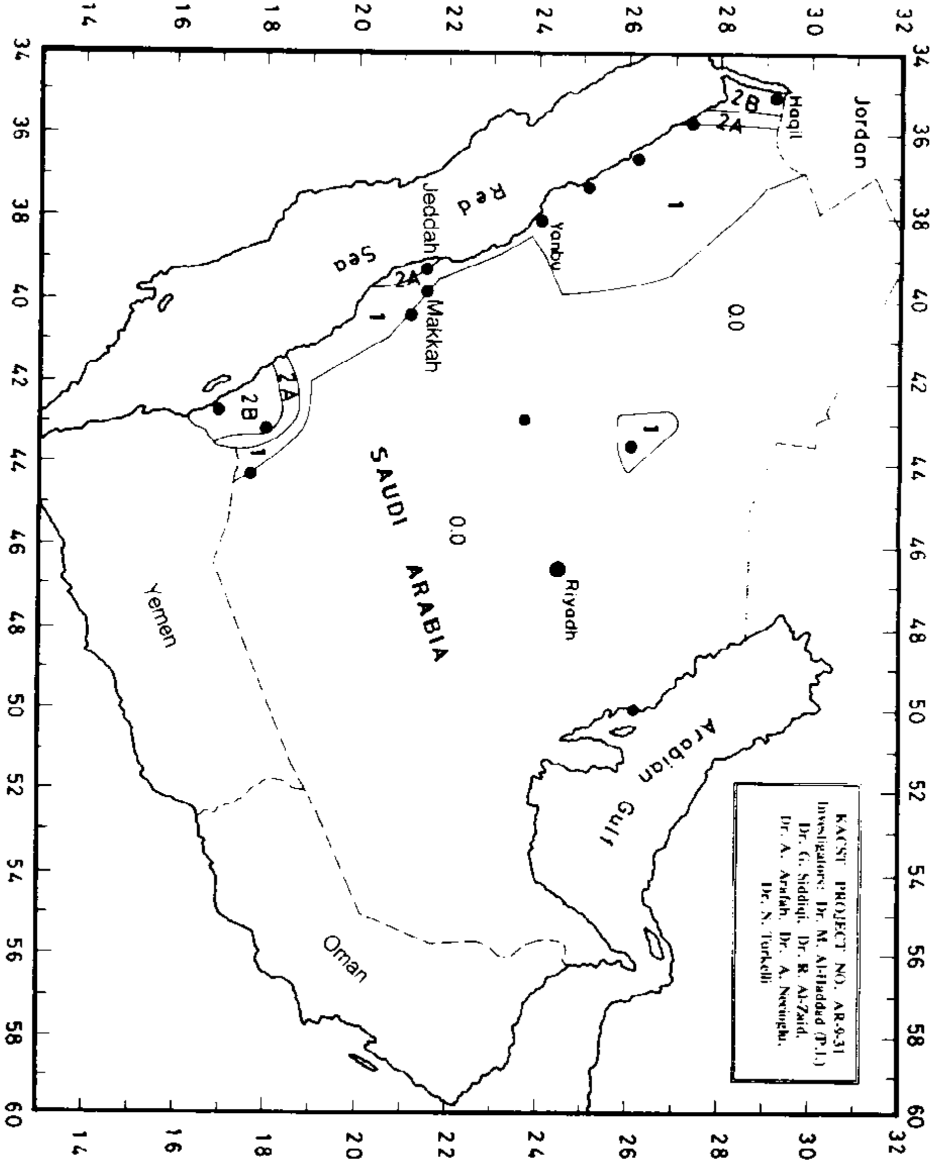


**Fig. 2.** Seismic zonation map.

**Table 1. Seismic Zone Number (SZN) and Seismic Zone Factor, Z**

| SZN | 0 | 1 | 2A | 2B |
|---|---|---|---|---|
| Z | 0.05 | 0.075 | 0.15 | 0.2 |

**Table 2. Occupancy category**

| Occupancy designation | Category description | Occupancy type or function of structure |
|---|---|---|
| ES | Essential | Hospitals and other medical facilities having surgery, and emergency treatment areas. |
| | | Fire and police stations. |
| | | Tanks or other structures containing housing, or supporting water or other fire-suppression materials or equipment required for the protection of essential or hazardous facilities, or special occupancy structures. |
| | | Emergency vehicle and equipment shelters and garages. |
| I = 1.25 | | Structures and equipment in emergency preparedness centers. |
| | | Stand-by power generating equipment for essential facilities. |
| | | Structures and equipment in communication centers and other facilities required for emergency response. |
| | | Structures housing, supporting or containing sufficient quantities of toxic or explosive substances to be dangerous to the safety of the general public if released. |
| SP | Special | Mosques |
| | | Covered structures whose primary occupancy is public assembly capacity more than 300 persons. |
| | | Buildings for schools (through secondary) or daycare centers capacity more than 250 students. |
| | | Buildings for colleges or adults education schools capacity more than 500 students. |
| I = 1.1 | | Medical facilities with 50 or more resident incapacitated patients, but not included above. |
| | | Jails and detention facilities. |
| | | All structures with occupancy more than 5000 persons. |
| | | Structures and equipment in power generating stations and other public utility facilities not included above, and required for continued operation |
| ST<br>I = 1.0 | Standard | All structures having occupancies or function not listed above. |

Note: I = Important factor

The requirements of Table 2 are intended to be the minimums. Additional levels of protection may be provided by increasing design force level, energy absorbing capacity, redundancy in lateral force resisting systems and construction quality assurance. However, sole reliance on increased design force level is not desirable.

## Seismic performance categories (SPC)

Seismic zone number and occupancy category of a building help determine the seismic performance category assigned to the building in accordance with Table 3. SPC of C requires the highest performance level to be built into a structure and that of A, the lowest.

**Table 3. Seismic performance category**

| OC<br>SZN | ES | SP | ST |
|---|---|---|---|
| 2B | C | C | B |
| 2A | B | B | A |
| 1 | B | A | A |
| 0 | No seismic requirement on the structures in this zone | | |

| Notes: | | |
|---|---|---|
| | OC | Occupancy Category |
| | SZN | Seismic Zone Number |
| | ES | Essential OC |
| | SP | Special OC |
| | ST | Standard OC |

## Soil profile coefficient

The soil profile type and the site coefficient, S, associated with the profile are produced in Table 4.

Local geology and soil characteristics influence the ground motion at a site. Significance of this influence varies from none to a very large value. This was amply demonstrated by September, 85 Mexico City earthquake.

## Structural systems

Observations made in the aftermath of numerous earthquakes over a long period of time indicate that irregularities in load paths and in structural configuration are major contributors to structural damage and failure due to strong motion.

**Table 4. Site profile and site factor[1], S**

| Profile type | Profile description | S |
|---|---|---|
| S1 | A soil profile with either:<br>(a) A rock-like material characterized by a shear-wave velocity greater than 760 m/s or by other suitable means of classification,<br>or<br>(b) Stiff or dense soil condition where the soil depth is less than 60 m. | 1.0 |
| S2 | A profile with dense or stiff soil conditions, where the soil depth exceeds 60 m or more. | 1.2 |
| S3 | A soil profile 12 m or more in depth and containing more than 6 m of soft to medium stiff clay but not more than 12 m of soft clay. | 1.5 |
| S4 | A soil profile containing more than 12 m of soft clay. | 2.0 |

[1] The site factor shall be established from properly substantiated geotechnical data. In locations where the soil properties are not know in sufficient detail to determine the soil profile type, soil profile S3 shall be used. Soil profile S4 need not be used unless the building official determines that soil profile S4 may be present at the site, or in the event that soil profile S4 is established by geotechnical data, in which case soil profile S4 will be used.

Structures are considered to be structurally regular when they have no significant physical discontinuities in a) plan, b) elevation, and c) in their lateral force resisting systems. The irregular structures have significant physical discontinuities in all or either of the above aspects.

Table 5 lists irregularities in vertical direction and a structure having one or more of these features is designated as having a vertical irregularity. Table 6 does the same for a structure having irregularities in plan.

Structural systems are classified as one of the types listed in Table 7. The table also lists the maximum value of structural system quality factor, $R_w$, and the limiting value of height for a structural system. Building systems, are assigned a $R_w$ value which accounts for their overstrength and the energy absorption capacity, in the inelastic range. As shown in Table 7, the design criteria prohibit use of certain structural types for situations which call for heigher seismic performance.

Height limits on various structural systems in seismic performance category C are also given in Table 7. The height limits are principally provided to meet the fire protection requirements. In general, the ductile systems have no limits, while the dual systems have 50 m or no limit depending upon the system combination involved.

**Table 5. Vertical structural irregularities**

| Type | Irregularity definition |
|---|---|
| A[1] | **Stiffness irregularity – soft story**<br>A soft story is one in which the lateral stiffness is less than 70 percent of that in the story immediately above or less than 40 percent of the combined stiffness of the three stories above. |
| B[2] | **Weight (mass) irregularity**<br>Mass irregularity shall be considered to exist where the effective mass of any story is more than 150 percent of the effective mass of an adjacent story. A roof which is lighter than the floor below need not be considered a mass irregularity. |
| C[2] | **Vertical geometric irregularity**<br>Vertical geometric irregularity shall be considered to exist where the horizontal dimension of the lateral force resisting system in any story is more than 130 percent of that in an adjacent story. One story penthouse need not be considered. |
| D | **In-plane discontinuity in vertical lateral force resisting element.**<br>An in-plane offset of the lateral load resisting elements greater than the length of those elements. |
| E | **Discontinuity in capacity – weak story**<br>A weak story is one in which the story strength is less than 80 percent of that in the story above. The story strength is the total strength of all seismic resisting elements sharing the story shear for the direction under consideration. |

[1] Reference is made to UBC for system limitations, more severe requirements for overturning.

[2] Dynamic lateral load procedure of Section 6.3 of Ref. [1] shall be used.

**Table 6. Plan structural irregularities**

| Type | Irregularity definition |
|---|---|
| A | **Torsional irregularity, to be considered when diaphragms are not flexible**<br>Torsional irregularity shall be considered to exist when the maximum story drift, computed including accidential torsion, at one end of the structure transverse to an axis is more than 1.2 times the average of the story drifts of the two ends of the structure. |
| B | **Reentrat corners**<br>Plan configurations of a structure and its lateral force resisting system contain reentrant corners, where both projections of the structure beyond a reentrant corner are greater than fifteen percent of the plan dimension of the structure in the given direction. |
| C | **Diaphragm discontinuity**<br>Diaphragms with abrupt discontinuities or variations in stiffness, including those having cutout or open areas greater than fifty percent of the gross enclosed area of the diaphragms. |
| D | **Out-of-plane offsets**<br>Discontinuities in a lateral force path, such as out-of-plane offsets of the vertical elements. |
| E | **Nonparallel systems**<br>The vertical lateral load resisting elements are not parallel to or symmetric about the major orthogonal axes of the lateral force resisting system. |

(1) Reference is made to UBC for more severe requirements for torsion, overturning and orthogonal effects.

**Table 7. Structural system, $R_w$ and height limits**

| BSS(1) | | Lateral load resisting system description | $R_w$[5] | H[2] meters(7) |
|---|---|---|---|---|
| A. Moment Resisting Frame | 1- | Special Moment Resisting Space Frames (SMRSF) | | |
| | | Steel | 8 | N.L. |
| | | Reinforced Concrete | 8 | N.L. |
| | 2- | Concrete Intermediate Moment Resisting Frames (IMRSF)[6] | 5 | |
| | 3- | Ordinary Moment Resisting Space Frames | | |
| | | Space Frames | | |
| | | Steel(6) | 6 | |
| | | Reinforced Concrete(3) | 2 | |
| B. Building Frame System | 1- | Steel Eccentric Braced Frame (EBF) | 8 | 75 |
| | 2- | Shear walls | | |
| | | Reinforced Concrete | 6 | 75 |
| | | Reinforced Masonry | 4 | 50 |
| | 3- | Steel Concentric Braced Frames | 6 | 50 |
| C. Dual System | 1- | Shear Walls | | |
| | | Concrete with SMRSF | 8 | N.L. |
| | | Concrete with Concrete IMRSF(6) | 5 | 160 |
| | 2- | Steel EBF with Steel SMRSF | 8 | N.L. |
| | 3- | Concrete Braced Frames | | |
| | | Steel with Steel SMRSF | 8 | N.L. |
| | | Steel with Concrete SMRSF | 6 | 50 |
| D. Bearing Wall System | 1- | Shear Walls | | |
| | | Reinforced Concrete | 4 | 50 |
| | | Reinforced Masonry | 3 | 35 |
| E. Undefined System | | Inverted Pendulum Structures | 3 | |
| | | Tanks, Vessels, Trussed Towers | 3 | |

Notes:
[1] BSS = Basic Structural Systems are defined in Section 5.5, Ref. [1]
[2] H = Height Limit applicable to Seismic Performance Category C
[3] Prohibited in Seismic Performance Category C and B
[4] N.L. = No Limit
[5] See Ref. [1] for combination of Structural System
[6] Prohibited in Seismic Performance Category C
[7] See Ref. [1] for height limitations in Seismic Performance Category B

## Structural design

Static and dynamic lateral force procedures are available for evaluation of seismic forces and their distribution on a building. The dynamic lateral force (DLF) procedure can always be applied. However, the static lateral force (SLF) procedure can be employed subject to conditions of regularity, occupancy and height of a building.

### Static lateral force procedure

The static lateral force procedure may be used for the following structures except when they are built with irregularity types A, B and C given in Table 5:

1) All structures, regular or irregular for SPC A.
2) Regular structures under 75m in height with lateral force resistance provided by systems listed in Table 7, except those structures which are located on soil profile S4 and have a period greater than 0.7 second.
3) Irregular structure not more than 5 stories nor 20m in height.

### Base shear and its distribution

The Seismic Design Criteria [1] adopted the SLF procedure provided by SEAOC-1988 and UBC-1991. The procedure follows the recent state-of-the-art which was originally recommended by ATC. It involves the following steps.

1) The total base shear, V, is estimated by:

$$V = \overline{C} \; . \; W \tag{1}$$

where, W is the total seismic dead load, and C is given by:

$$\overline{C} = \left( \frac{ZIC}{R_w} \right) \tag{2}$$

where,

$$C = \frac{1.25\,S}{T^{2/3}} \leq 2.75 \tag{3}$$

where T, is the fundamental period of vibration in seconds determined approximately by,

$$T = 2.44\, C_t\, (H)^{3/4} \tag{4}$$

where,

$$C_t = \begin{cases} 0.035 \text{ for steel moment resisting space frames} \\ 0.030 \text{ for reinforced concrete moment resisting space frames and eccentric braced frames} \\ 0.020 \text{ for all other structures} \end{cases}$$

H = height in meters above the base to the upper most level.

2) Part of the base shear equal to $F_t$ is assumed to be concentrated at the level of the roof (n-th level) of the building, and the remaining portion of the base shear $(V\text{-}F_t)$ is distributed over the height as follows:

$$V_x = (V\text{-}F_t) \cdot \frac{w_x\, h_x}{\sum_{i=1}^{n} w_i\, h_i} \tag{5}$$

where,

$V_x$ = Concentrated load at designated level-x applied over the area of the building in accordance with the mass distributed at that level,

$w_i$ or $w_x$ = the portion of w which is located at or assigned to level i or x, respectively and

$F_t$ = $0.07\,T\,V \leq 0.25V$ when $T > 0.7$ second
0.00, when $T \leq 0.7$ second.

3) $V_x$ is distributed to various elements of the vertical lateral force resisting system in proportion to the rigidities when the diaphragms are considered to be rigid.

### Horizontal torsional moments

Additional shears in the vertical elements induced by horizontal torsional moments are accounted for as follows:

1) To account for uncertainties in locations of lateral loads, the mass at each level shall be assumed to be displaced from the calculated center of mass in each direction by a distance equal to five percent of the building dimension, at that level, perpendicular to the direction of the force under consideration.
2) where the diaphragms are "rigid", torsional design moment due to the eccentricities between the center of the applied lateral forces and the center of rigidities of the vertical resisting elements should be accounted for in the analysis.

For more information on the effect of the torsional moment and the special cases in which irregularity induces severe loading SEAOC or UBC CODE may be referred to.

### Overturning

At any level, the overturning moments to be resisted are determined using those seismic forces ($F_t$ and $F_x$) which act on levels above the level under consideration. At any level, the incremental changes of the design overturning moment is distributed to the vertical resisting elements in the manner similar to the distribution of $V_x$ mentioned earlier.

### Story drift limitation

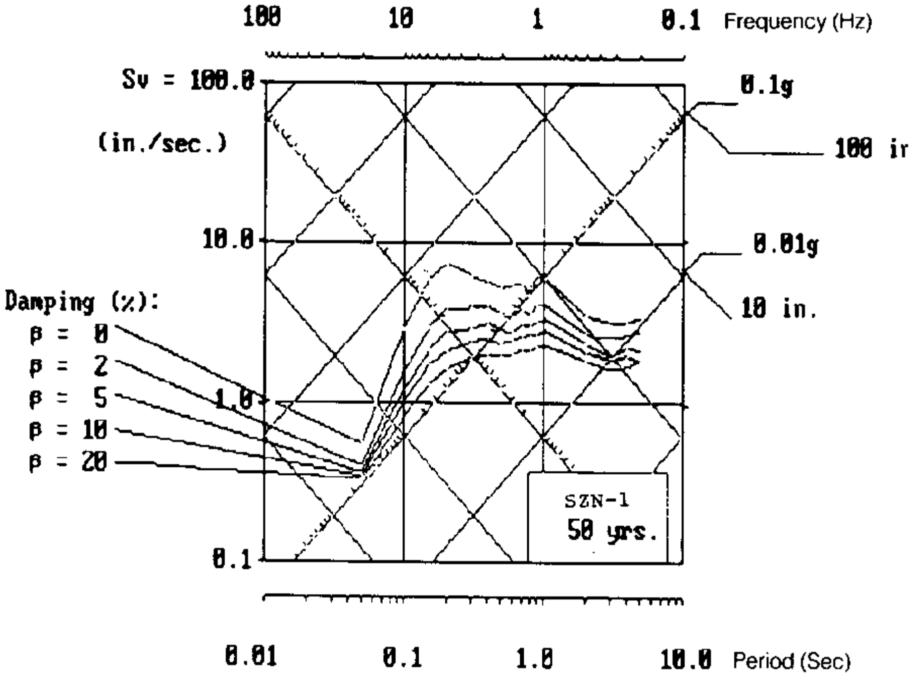
The displacement of a floor level relative to the level above or below (story drift) due to the design lateral forces is required not to exceed $0.03/R_w$ nor 0.005 times the story height in case of structures having a fundamental period of less than 0.7 second. For structures having a fundamental period of 0.7 second or greater, the calculated story drift shall not exceed $.02/R_w$ nor .004 times the story height.

### P-delta effect

When the story drfit exceed $.01/R_w$ times the story height, the member forces and moments, and the story drifts induced by P-delta effect shall be considered in the evaluation of overall structural stability.

## Dynamic lateral force procedure

Dynamic lateral force procedure is always acceptable for seismic design. For thc cases, where the conditions qualifying application of the SLF are not justified, the design criteria suggest using the response spectrum analysis. This procedure should be applied by a professional engineer who is familiar with the concept of the dynamic analysis. The principles of structural dynamics are used for computation of the period and the shape of selected modes of vibration. The seismic force is generated with the help of response spectra of a site. The design forces are scaled, according to a prescribed procedure, to reflect the ductility and energy absorbing characteristics and maintain a minimum design strength of a structure. The spectra for various zones of the Kingdom are produced in Figs. 3,4 and 5. The spectra are developed at the site in a given zone where the peak ground acceleration obtained had the highest value. The smooth response spectra for 5% damping for a zone, normalized for Z = 1.0, are produced in Fig. 6. For a specific site, the spectral acceleration is equal to the ordinate times the Z-value of the site.



Prob. of Exceed.: .01 Design Response spectrum Soil class: 1

**Fig. 3. Response spectrum for a site in Zone 1 for probability of exceedance of 10% in 50 years (return period of 475 years).**

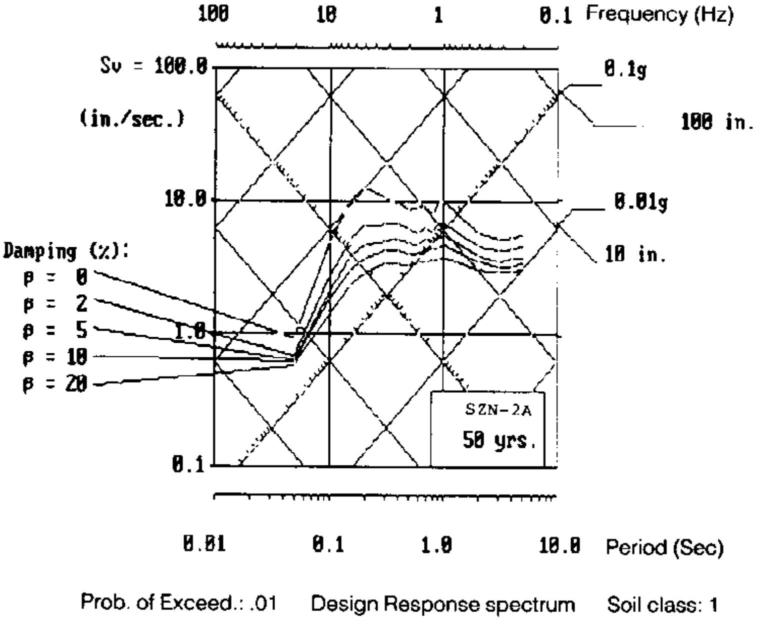


**Fig. 4. Response spectrum for a site in Zone 2A for probability of exceedance of 10% in 50 years (return period of 475 years).**

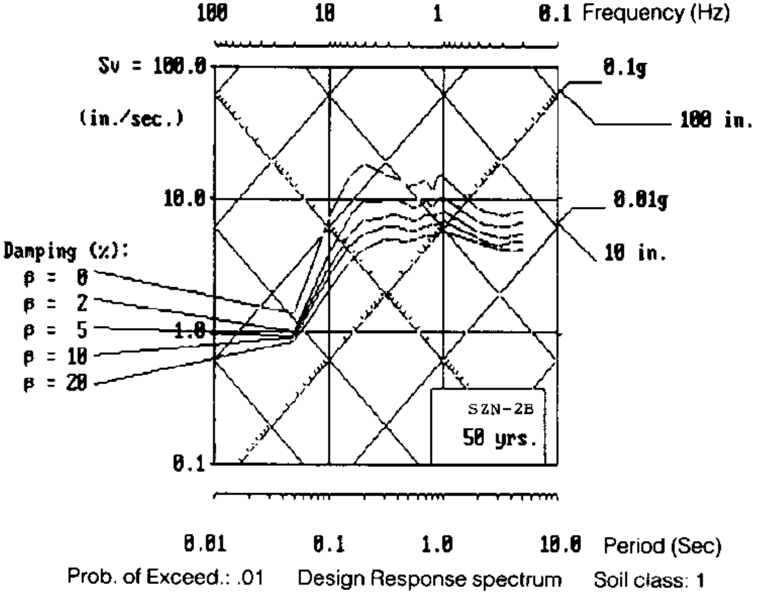


**Fig. 5. Response spectrum for a site in Zone 2B for probability of exceedance of 10% in 50 years (return period of 475 years).**

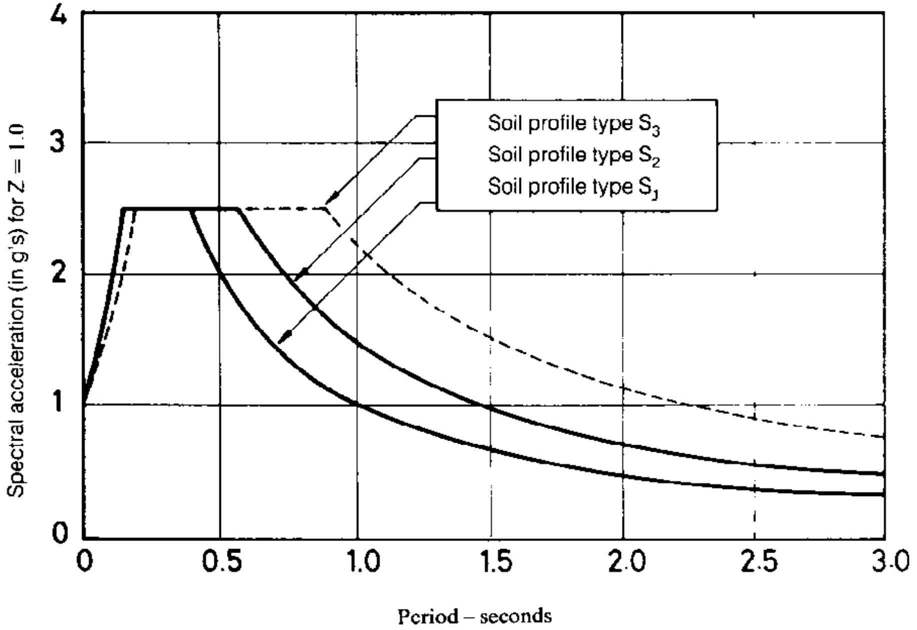


**Fig. 6. Response spectra normalized for Z = 1.0 for 5% damping.**

### Structural and non-structural components supported by structures

Parts and portions of structures, permanent non-structural components and their attachments, and the attachments for permanent equipment supported by a structure shall be designed to resist seismic forces, $F_p$ given by the following formula suggested by SEAOC and UBC codes:

$$F_P = Z\,I\,C_P\,W_P$$

where

$W_p$ = the weight of an element or component

$C_p$ = the coefficient given in Table H of UBC and SEAOC codes.

In general the values of Z and I shall be the values used for the building. The designer shall refer to UBC or SEAOC codes for the exceptional cases such as anchorage of machinery and equipment, and tanks and vessels containing hazardous materials where higher values of I need to be employed.

### Design and Detailing Requirements

All structural framing systems shall comply with the requirements given before. Only the elements of the designed seismic force resisting system can be used to resist the design forces. The individual components shall be designed to resist the prescribed design seismic forces acting on them. The components shall also comply with the applicable requirements for the material properties contained in ACI 318M-89 [6] for reinforced concrete (RC) buildings and Chapters 24 and 27 of UBC for masonry and steel construction respectively. In addition, such framing systems and components shall comply with the detailed system design requirements provided in Section 2337 of UBC. For design and detailing of RC frames, the most widely used structural system in the KSA, the applicable articles in ACI 318M-89 for different performance categories as follows:

#### 1) Seismic Performance Category A

R.C. buildings assigned to Category A shall be designed as per requirements of ACI-318M-89 (ordinary framing system) excluding those prescribed in Chapter 21.

#### 2) Seismic Performance Category B

R.C. buildings assigned to Category B shall be designed as per requirements of ACI 318M-89, including those prescribed in Section 21.9 (requirements for frames in regions of moderate seismic risk).

#### 3) Seismic Performance Category C

R.C. building assigned to Category C shall conform to all the requirements of ACI 318M-89 including those prescribed in Chapter 21.

### Foundations

For the load combination including earthquake, the soil capacity must be sufficient to resist the loads at acceptable strains considering both the short time of loading and the dynamic properties of the soil. Bearing capacity may be increased by 33 percent of the allowable if substantiated by geotechnical data.

The connection of superstructure elements to the foundation shall be adequate to transmit to the foundation the forces for which the elements are required to be designed.

For regular buildings, the force $F_t$ may be omitted when determining the overturning moment to be resisted at the foundation-soil interface.

### Special requirements for SPC C and B

For buildings classified as Categories B and C a separate report shall be prepared and submitted which should comprise of results of investigation conducted on the foundations to determine the potential hazards due to (1) slope-instability, (2) liquefaction and (3) surface rupture due to faulting, as a result of earthquake motions.

The pile and Caisson foundations have to meet special requirements prescribed in Ref [1].

### Design review, inspection and quality control

Quality control as per ACI chapter 3,4,5 are always required. In seismic performance Category C and B special review of the design and construction is required as follows:

1) Design review by an inependent, licensed structural engineer.
2) Specification of an appropriate testing and inspection program by the structural engineer of record.
3) Construction observation by the structural engineer of record consisting of:
    a) Review of testing and inspection reports.
    b) Periodic site visits to observe general compliance with the structural engineering plans and specifications.

## Conclusion

The research project entitled "A Study Leading to Preliminary Seismic Design Criteria for the Kingdom" was completed recently. The project was designed to conduct a systematic investigation leading to the design criteria presented here. The delineation of seismic zones was based on the iso-acceleration map developed during the course of the project and the recent state-of-the-art was employed to evaluate zone factor for various zones. The proposed design requirements are generally formulated within the framework of SEAOC and UBC codes after due consideration and modification of the relevant issues. The paper presents the seismic zonation map and the evaluated values of various seismic design parameters applicable in the KSA. Such information along with the simplified guidance to the appropriate references provided in this paper are essential for seismic design and evaluation of seismic vulnerability of existing buildings.

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# توصيات تصميم المباني المقاومة للزلازل في المملكة

**محمد شاذلي الحداد و غلام حسين صديقي**

*قسم الهندسة المدنيّة، كلية الهندسة، جامعة الملك سعود، ص.ب ٨٠٠،*
*الرياض ١١٤٢١، المملكة العربية السعودية*

(استُلم في ٢٦/١٢/١٩٩٢م؛ قُبل للنشر في ٢٢/٦/١٩٩٣م)

**ملخص البحث.** يعرض هذا البحث أسس التصميم الزلزالي للمباني في المملكة العربية السعودية. ومن أجل الاختصار، يعرض البحث عوامل التصميم الرئيسة فقط مع الإشارة إلى المراجع المناسبة للحصول على المعلومات اللازمة في هذا المجال. وتشمل أسس التصميم المقترحة المتطلّبات الأساسية لتحقيق الأداء الزلزالي المطلوب وكيفية حساب أحمال الزلازل، وكذلك تحديد نوع النظام الإنشائي للمبنى وطريقة التحليل الإنشائي وتسليح عناصر الخرسانة المسلّحة ومستوى مراقبة الجودة المطلوب لتنفيذ العناصر الإنشائية وغير الإنشائية وكذلك أساسات المنشأ.