Comparison of Recent U.S. Seismic Codes

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Abstract: This paper compares National Earthquake Hazards Reduction Program (NEHRP), Structural Engineers Association of California (SEAOC), ASCE 7, and *Uniform Building Code* (UBC) seismic design provisions to address the differences in their philosophies and applicabilities. These documents are compared by focusing on issues such as (1) purpose of earthquake codes; (2) type of document and target audience; (3) lateral forces; and (4) analysis provisions. NEHRP and ASCE 7 documents are based on strength design while UBC and SEAOC are based on allowable or working stress design. There are other fundamental differences among these documents such as the required methods of analysis, building importance, detailing requirements, soil amplification factors, drift control and P-delta amplification, and the method of assigning an importance factor. Several tables and graphs are presented to illustrate the similarities and differences among these codes.

INTRODUCTION

This paper presents a comparison of the seismic design provisions in documents published by four organizations—Building Seismic Safety Council, Structural Engineers Association of California (SEAOC), ASCE, and International Conference of Building Officials. The documents are (1) *NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings* (1992, 1995) 1991 and 1994 editions; (2) *ASCE 7-95*, "Minimum Design Loads for Buildings and Other Structures," (1995); (3) *Uniform Building Code, Volume 2, Structural Engineering Design Provisions* (1994); and (4) *SEAOC Recommended Lateral Force Requirements and Commentary* (1990). Throughout the remainder of this paper the foregoing documents shall be referenced as NEHRP, ASCE, UBC, and SEAOC, respectively. The comparisons here will focus on the differences in the philosophies and applicabilities of these documents.

The organization of this paper will follow the format and periodically reference a paper by Luft (1989). The reader should refer to the Luft paper for a brief history of the development of the current earthquake codes and to see how the evolution of seismic design provisions has accelerated since 1989 when the paper was published.

PURPOSE OF EARTHQUAKE CODES

It is important to understand the expressed or implied purpose of a particular design document in order to fully understand its provisions. Of course the primary purpose of any earthquake code is to protect life. However, the way that this purpose, as well as any additional purposes, is presented can provide additional insight into the reasons for the presence of specific provisions in the body of the document and its intended audience.

The 1994 edition of NEHRP (1995) (hereafter referred to as NEHRP-94) clearly states that it is intended as a reference document and not a model code. It states that the provisions present criteria for the design and construction of buildings and nonbuilding structures subject to earthquake ground motions. The purpose is to minimize the hazard to life for all buildings and nonbuilding structures, to enhance the expected performance of higher occupancy structures as compared to normal occupancy structures, and to improve the expected capability of essential facilities to function during and following an earthquake. The purpose also states that because of the complexity and the great number of variables involved in seismic design (e.g., as the variability in ground motion, soil types, dynamic characteristics of the structure, material strength properties, quality assurance and control, and construction practices), the provisions provide minimum criteria that are considered prudent and economically practical for the protection of life in buildings subject to seismic ground motions anywhere in the United States. The provisions also clearly state that the ground motions of the specified "design earthquake" may result in both structural and nonstructural damage. It states that for most structures designed and constructed according to these provisions, it is expected that structural damage from a major earthquake may be repairable but might not be economical. For ground motions in excess of the design level specified, a low probability of building collapse is intended.

ASCE 7-95 ("Minimum" 1995), in its scope statement, states that the standard provides minimum load requirements for the design of buildings and other structures that are subject to building code requirements. It further states that the loads specified are suitable for use with the stresses and load factors specified by the current material design specifications for steel, concrete, masonry, wood, and any other conventional structural material used to construct buildings. The purpose stated in "Section 9—Earthquake Loads" indicates that the criteria presented are for the design and construction of buildings and other similar structures subject to earthquake ground motions. It also states that since the specified earthquake loads are based on postelastic energy dissipation in the structure, the provisions for design, detailing, and construction shall be satisfied even if the controlling load combination does not include the earthquake effect. The commentary for "Section 9.1.1 Purpose" repeats the purpose from NEHRP-94 virtually unchanged. The criteria in "Section 9" of ASCE 7-95 are taken from NEHRP-94.

The *Uniform Building Code* (UBC) is a complete model building code. The purpose as stated in "Part I" is to provide minimum standards to safeguard life or limb, health, property, and the public welfare by regulating and controlling the design, construction, quality of materials, use and occupancy, location, and maintenance of all buildings and structures (UBC 1994). No supplementary purpose is stated in the earthquake design provisions. The UBC document is written and organized to be adopted in its entirety by a legal or other type of entity. Therefore, stating an overall purpose to safeguard property and the public welfare indicates that some degree of damage control for seismic events is relevant.

The SEAOC *Blue Book* does not state a purpose in the body of the *Recommendations*. However, there is a statement of pur-

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pose in the *Commentary.* There it is stated that the function of the *Recommendations* is to provide minimum standards for use in building design regulation to maintain public safety in extreme earthquakes likely to occur at the building's site. Further, the *Commentary* states that the recommendations are intended to safeguard against major failures and loss of life, not to limit damage, maintain functions, or to provide for easy repair. It is also emphasized that buildings designed and constructed using the recommended design procedures are expected to meet the life safety objective. Structures designed in conformance with the *Recommendations* should be expected to (1) resist a minor level earthquake ground motion without damage; (2) resist a moderate level earthquake ground motion without structural damage but with some possible nonstructural damage; and (3) resist a major earthquake ground motion having an intensity equal to the strongest experienced or forecast for the building site, without collapse, but with some possible structural damage as well as nonstructural damage (*SEAOC* 1990).

TYPE OF DOCUMENT AND TARGET AUDIENCE

Another consideration when comparing documents such as these is who is the target audience or expected end user. As mentioned UBC is a model building code. It is written and formatted to be adopted as the required building code for a legal entity. As such it must address in some manner all facets of design and construction requirements that are necessary to provide the guidelines to achieve its stated purpose. The UBC has been adopted by most of the states in the western half of the United States. Two other primary model building codes are used by a majority of the remaining states. The National Building Code by Building Officials and Code Administrators International (BOCA) code is used in the East and Midwest and the Standard Building Code is adopted by much of the South. The earthquake provisions in each of the model codes are written for national coverage. The latest editions of the BOCA code and the Standard Building Code have developed their seismic design provisions using NEHRP-91.

The other three documents studied here are standards or reference documents. SEAOC's *Blue Book* only covers seismic analysis and design. However, the document has been widely used by others in different areas of the country. The early editions were particularly useful since they usually represented current state-of-the-art knowledge that was not available in the model building codes. The fourth edition (1978) and the Applied Technology Council (ATC) document *ATC 3-06* ("Tentative" 1978) provided the foundation upon which all current earthquake codes were built. SEAOC-90 does not include seismic zone maps for any areas other than California. SEAOC-90 forms the basis of the seismic design provisions of UBC (1994). For this reason alone, the *Blue Book* provisions do have a significant impact on the seismic design of buildings outside of California.

NEHRP-94 and its predecessors are documents with national exposure. They were developed from *ATC 3-06*, which was developed as a design source for use in all areas subject to earthquakes in the United States. It was the first document to address the variation in needs of the different seismic zones in the country. By defining seismic performance categories depending on both the seismic hazard exposure group and the value of the velocity-related ground acceleration, NEHRP-91 defines zone-specific forces, zone-specific methods of analysis, and zone-specific material detailing requirements. The acceptance of this approach is evident by the fact that both BOCA and Southern Building Codes Congress International (SBCCI) have incorporated NEHRP-91 provisions into the latest editions of their model codes.

ASCE 7-95 is a reference document with an intended national audience. It covers load requirements including seismic provisions for buildings and other structures. Editions prior to ASCE-93 did not contain any material-specific design requirements. ASCE 7-93 first added a section on reference documents for wood, steel, reinforced concrete, and masonry. An appendix of supplemental provisions was added that contains material-specific design provisions that are "deemed essential for satisfactory performance in an earthquake when designing with loads determined from Section 9, due to the substantial cyclic inelastic strain capacity assumed to exist by the load procedures in Section 9." It also stated that the supplemental provisions form an integral part of the load provisions. The commentary explains that the "nonload" provisions are necessary since it is difficult to separate the design provisions for loads from those for resistance of materials for a design limit state based on system performance.

LATERAL FORCES

There is a major fundamental difference in design approach between NEHRP-94 and ASCE 7-95 as compared to UBC-94 and SEAOC-90. The provisions of the former two are based on strength or limit state design while those of the latter two are based on working stress design. This difference will be apparent in the level of the calculated lateral loads and the load factors applied to the various load combinations including earthquake forces. Therefore when comparing the base shears calculated one must adjust the values of base shear from the codes using the strength approach by a factor of 1.4 to 1.5 to achieve equivalent values for comparison.

Figs. 1–6 show the value of the base shear coefficient, *V/*

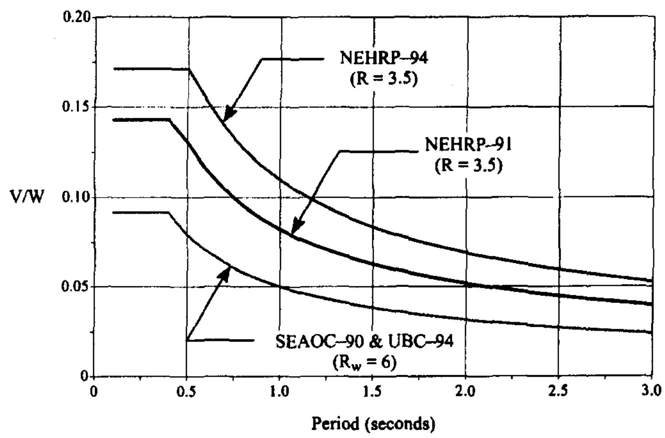

FIG. 1. Bearing Wall System with Reinforced Masonry Considering $A_a = A_v = Z = 0.2$, $S = 1.2$, $C_a = 0.24$, and $C_v = 0.32$

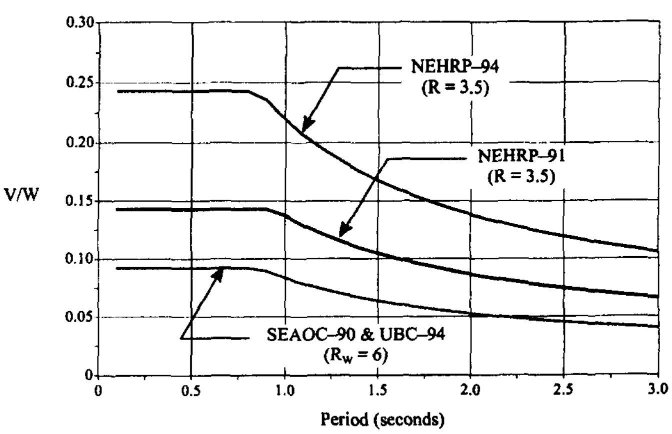

FIG. 2. Bearing Wall System with Reinforced Masonry Considering $A_a = A_v = Z = 0.2$, $S = 2$, $C_a = 0.34$, and $C_v = 0.64$

W, as a function of the period for three different commonly encountered framing systems. The comparisons were made for an ordinary type occupancy structure that might be in the Memphis, Tenn., area. This area was chosen to emphasize the range of values that can be encountered even in areas not subjected to the highest levels of seismicity. Since most data and most comparisons are made based on buildings in regions of highest seismicity, it was deemed appropriate to show a comparison that would apply to greater areas of the country.

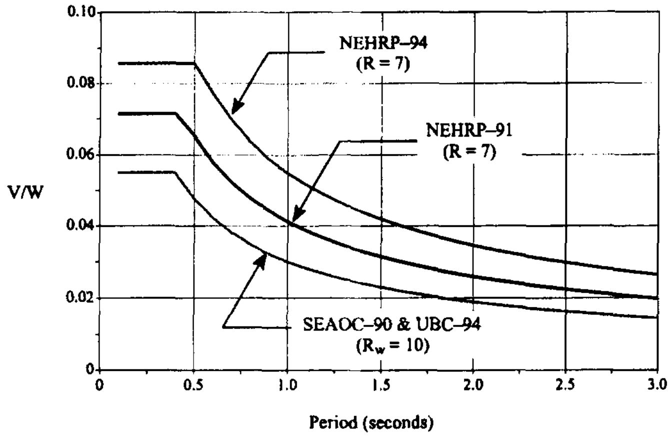

FIG. 3. Eccentrically Braced Steel Frame System with Reinforced Masonry Considering $A_a = A_v = Z = 0.2$, $S = 1.2$, $C_a = 0.24$, and $C_v = 0.32$

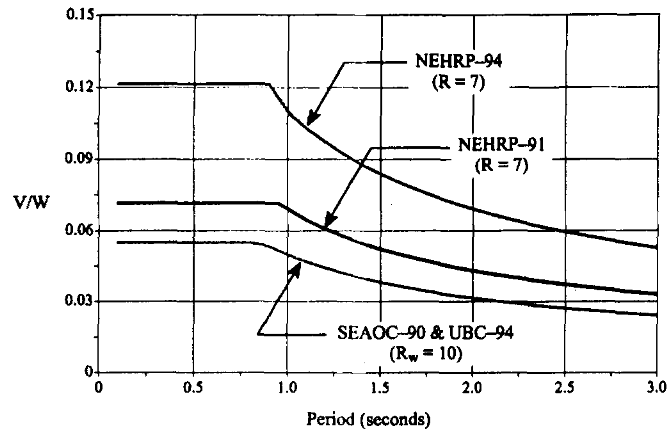

FIG. 4. Eccentrically Braced Steel Frame System with Reinforced Masonry Considering $A_a = A_v = Z = 0.2$, $S = 2$, $C_a = 0.34$, and $C_v = 0.64$

A comparison of the lateral force requirements of the review documents is shown in Table 1. The first line gives the base shear equation for each of the documents. The following paragraphs further describe some of the common parameters that make up the base shear equation.

By scanning Table 1 it is apparent that the review of four seismic codes essentially reduces to the comparison of two: those utilizing the strength approach and those utilizing the working stress approach. The following discussions will make

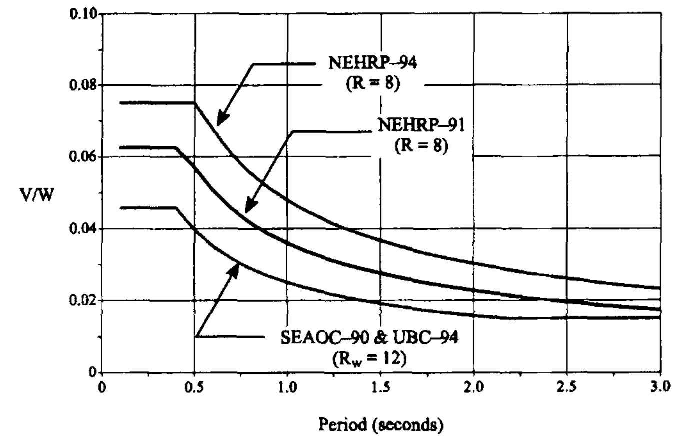

FIG. 5. Special Moment Resisting Reinforced Concrete Frame System and Reinforced Masonry Considering $A_a = A_v = Z = 0.2$, $S = 1.2$, $C_a = 0.24$, and $C_v = 0.32$

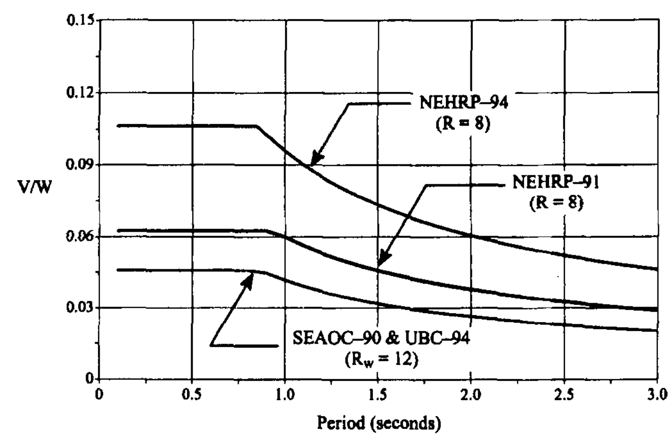

FIG. 6. Special Moment Resisting Reinforced Concrete Frame System and Reinforced Masonry Considering $A_a = A_v = Z = 0.2$, $S = 2$, $C_a = 0.34$, and $C_v = 0.64$

TABLE 1. Static Lateral Force Criteria

Subject (1)	NEHRP-91 (2)	NEHRP-94 and ASCE 7-95 (3)	UBC-94 (4)	SEAOC-90 and UBC-88 (5)
Base shear	$V = C_sW$	$V = C_sW$	$V = ZICW/R_w$	$V = ZICW/R_w$
Seismic design coefficient C_s or C_{eq}	$C_s = 1.24A_vS/RT^{2/3}$	$C_s = 1.2C_v/RT^{2/3}$	$C_{eq} = 1.25ZIS/R_wT^{2/3}$	$C_{eq} = 1.25ZIS/R_wT^{2/3}$
Upper limit	$C_s = 2.5A_a/R$	$C_s = 2.5C_a/R$	$C_{eq} = 2.75ZI/R_w$	$C_{eq} = 2.75ZI/R_w$
Lower limit	$T \le C_aT_a$	$T \le C_uT_a$	$T_B \le 1.3\ T_A$ zone 4 $T_B \le 1.4\ T_A$ zones 1 to 3 $C/R_W \ge 0.075$ where $3R_w/8$ scaling of forces apply	$C(T_B) \ge 0.8C(T_A)$ $C/R_W \ge 0.075$ where $3R_w/8$ scaling of forces apply
Zone factor	A_a and A_v	A_a and A_v	Z	Z
Importance factor	Seismic hazard exposure group	Seismic hazard exposure group	I	I
Structural system	R	R	R_w	R_w
Soil factor	$S_1 = 1.0$ $S_3 = 1.5$ $S_2 = 1.2$ $S_4 = 2.0$	C_a depends on A_a and soil profile types A, B, C, D, or E C_v depends on A_v and soil profile types A, B, C, D, or E	$S_1 = 1.0$ $S_3 = 1.5$ $S_2 = 1.2$ $S_4 = 2.0$	$S_1 = 1.0$ $S_3 = 1.5$ $S_2 = 1.2$ $S_4 = 2.0$

reference to NEHRP-91/94 and UBC-94 as representing the respective design approaches when comparing and contrasting the two approaches. When significant differences exist between codes using the same approach, these differences will be noted. This procedure will be used throughout the remainder of the paper.

Reviewing the row "seismic design coefficient C_s or C_{eq}" in column 1, Table 1, it is apparent that C_s or C_{eq} are dependent on the T of the structure where T represents the fundamental period of the structure. The C_{eq} term shown for UBC is not a term specifically described in UBC but is used here to provide an equivalent comparison with the C_s term in NEHRP. The proportional dependence on T has varied significantly in previous codes. All of the codes reviewed in this paper have a relationship where C is proportional to $T^{-2/3}$.

The seismic design coefficient shown in the aforementioned row is derived from smoothed earthquake response spectra. The shape of the curves shown in Figs. 1–6 roughly correspond to the general shape of the smoothed response spectra derived from the values of peak ground displacement, peak ground velocity, and peak ground acceleration. NEHRP and UBC put upper limits on C_s and C_{eq} as shown in the "Upper limit" row. The form of the upper limit is similar in both since it is proportional to some measure of the maximum ground acceleration and inversely proportional to the factor related to the type of structural system. NEHRP-91 does not have a lower upper limit for S_3 and S_4 soils in zones of high seismicity, which was changed from the previous edition. As NEHRP-94 states, A_v was used as a "trigger" value throughout NEHRP-91 provisions. The A_v was chosen because it was equal to or greater than A_a in all map areas. The NEHRP-94 provisions introduced new site coefficients, F_a and F_v, to recognize the nonlinearity of the soil factors, and it was concluded that most trigger values should be modified to incorporate these factors. To make the notation easier, NEHRP-94 introduced $C_a = A_aF_a$ and $C_v = A_vF_v$. C_a became the new trigger value for most situations, but A_v remained the trigger for some; most important of all, the seismic performance category is still determined from A_v.

NEHRP and UBC each have a lower limit for C as shown in the "Lower limit" row in Table 1. The lower bound limit for C in NEHRP is established by imposing a maximum value for T. NEHRP-91 requires that the maximum T be less than C_aT_a where T_a is the approximate period computed from one of two equations given in the provisions and C_a is a factor greater than 1.0 that varies depending upon the value of the peak velocity-related acceleration at the site. Similarly, NEHRP-94 requires that the maximum T be less than C_uT_a and C_u is the same factor as C_a of NEHRP-91. UBC requires that the value of T determined by method B, which is any substantiated analytical procedure that considers the structural properties and deformational characteristics of the structure, be less than or equal to the value 1.3 T_A for zone 4 and 1.4 T_A for zones 1–3. T_A is the approximate period computed from code equations. SEAOC's lower limit on C is not zone-dependent. C as calculated using a T determined from method B must be greater than or equal to 80% of C calculated using a T determined from method A. UBC requires an additional lower limit of $C \geq 0.075\ R_w$ to calculate base shear for use in satisfying special provisions where 3 $R_w/8$ scaling of earthquake forces apply. In other words, except for those provisions where code-prescribed forces are scaled up by 3 $R_w/8$, the minimum value of the ratio C/R_w shall be 0.075.

A zone factor is used to numerically indicate the expected range of ground motions for the various areas of the country. The factor is related to the design ground acceleration. The zone factor is shown in the "Zone factor" in row Table 1. NEHRP uses two values to define the zone effect. The numerical coefficients are A_v, effective peak velocity-related acceleration, and A_a, the effective peak acceleration. For most areas of the country the two values are identical or vary only slightly. The values of A_v and A_a enter into the calculation of the seismic design coefficient, C_s, and are part of the controlling criteria for other provisions. ASCE 7-95 modified the maps from NEHRP-94 slightly to include point values in areas bounded by a single contour to aid interpolation. The contours in the Pacific Northwest and Alaska were also adjusted slightly to reflect the revised assessment of the overall seismicity of the region (see "Section 9.1.4.1" of ASCE 7-95). UBC uses a zone factor, Z, which is a numerical value that varies from 0.075 for zone 1 to 0.40 for zone 4. The Z value is a major component in the calculation of the base shear as shown in the "Base Shear" row. The maps that both approaches use are based upon the work of Algermissen and Perkins (1976). The values of peak acceleration shown on the map by Algermissen and Perkins have a 90% probability of not being exceeded in a 50-year period. The map in SEAOC covers only California and indicates some regions of the state in zone 2. The UBC map does not show any zone 2 for California.

The "Importance factor" row in Table 1 is related to the occupancy or function of the building. The principle that both code approaches use is that a structure housing essential facilities that are required for postearthquake recovery, hazardous materials, or large populations will get treatment to enhance its survivability over ordinary or standard structures. The method that each approach uses to achieve this is substantially different. UBC uses a value greater than 1.0 assigned to the importance factor as a direct multiplier of the lateral forces. Therefore, UBC attempts to provide a greater level of safety for more important structures by requiring larger design forces. In the method used by NEHRP the structure is assigned to a seismic performance category based upon its seismic hazard exposure group classification and the value of A_v at the site. The seismic performance category determines the level of sophistication in the method of analysis, which provides restrictions on the type and height of framing systems permitted, and indicates when more restrictive detailing is required. ASCE has defined four building categories that correspond to the seismic hazard exposure groups of NEHRP. Categories I and II of ASCE 7-95 are equivalent to group I in NEHRP and categories III and IV closely correspond to NEHRP categories II and III, respectively. Also, the seismic hazard exposure classification requires more restrictive drift limitations for the more essential facilities designated as group II or III. ASCE relaxed some of the drift provisions in NEHRP for masonry cantilever shear wall and masonry wall frame buildings because the current reference standard for masonry does not include the necessary definitions of the systems. Thus, NEHRP attempts to increase the level of safety in an essential facility by requiring more rigorus design and construction requirements.

The structural framing system is incorporated into the analysis through the R and R_w factors of NEHRP and UBC, respectively. The two factors are used similarly in each document to adjust the base shear for the capacity of a particular framing system for energy absorption and energy dissipation. Both factors represent the ratio of forces that would develop under the design ground motion if the structure's response was entirely elastic to the code-prescribed design forces. This explains why, for a given structural system, R_w should always be larger than R. The ratio of R_w to R is typically on the order of 1.3:1.7, reflecting the approximate difference between the service load and ultimate load approach.

The "Soil factor" row is also shown in Table 1. The numerical values and written descriptions of the four soil types are essentially identical, i.e., the factor is a direct multiplier greater than 1.0 in the base shear equations, in all approaches except NEHRP-94. All approaches except NEHRP-94 use a soil factor S that, as the material beneath the site becomes softer, increases from 1.0 for a S_1 shallow stiff or dense soil or rock to 2.0 for a S_4 soil consisting of more than 40 ft of soft clay. However, post–Loma Prieta studies resulted in considerable modification of the soil profile types in the NEHRP-94 provisions. NEHRP-94 defines five soil profile types as A for hard rock with a measured shear wave velocity greater than 5,000 ft/set (1,500 m/s); soil profile type B for rock with a shear wave velocity between 2,500 ft/s (760 m/s) and 5,000 ft/s (1,500 m/s); soil profile type C for very dense soil and soft rock with a shear wave velocity between 1,200 ft/s (360 m/s) and 2,500 ft/sec (760 m/s) or with $\bar{N}$ over 50 or $\bar{S}_u$ greater or equal to 2,000 psf (100 kPa); soil profile type D for stiff soil profile with a shear wave velocity between 600 ft/s (180 m/s) and 1,200 ft/s (360 m/s), or with the standard penetration resistance $\bar{N}$ less than or equal to 50, or the undrained shear strength $\bar{S}_u$ between 1,000 psf (50 kPa) and 2,000 psf (100 kPa); soil profile type E for soil profile with a shear wave velocity less than 600 ft/s (180 m/s) or any profile with more than 10 ft (3 m) of soft clay defined as soil with plasticity index (PI) greater than 20, water content greater than 20%, and S_u less than 500 psf (25 kPa); and soil profile type F for soils requiring site-specific evaluations.

The last factor to be discussed in the base shear equation is the W factor. This factor represents the total dead load plus applicable portions of other loads. In both NEHRP and UBC the total dead load plus 25% of the floor live load in storage occupancies must be included. UBC also requires inclusion of 25% of the floor live load in warehouse occupancies. NEHRP and UBC require that when the partition load is included in the floor design loads, the actual weight of partitions be included but not less than 10 psf (500 Pa). NEHRP specifies that the total operating weight of permanent equipment be included. ASCE expands that provision to include the effective contents of all vessels. UBC specifies that the total weight of permanent equipment be included. Snow loads in excess of 30 psf (1.5 kPa) must be included. However, both codes allow a significant reduction when conditions warrant and when approved by the building code enforcement authority. NEHRP allows a reduction up to 80% by allowing a 0.2 load factor on the snow load. A maximum reduction up to 75% is allowed by UBC.

ANALYSIS PROVISIONS

A comparison of the main elements of the analysis provisions of the two approaches is summarized in Table 2. The following paragraphs will expand on the information presented in it.

Both code approaches require different types of analysis procedures depending on other circumstances. In NEHRP the type of analysis required is determined by the seismic performance category (SPC), as stated in the discussion of the importance factor, and the configuration of the building. UBC uses zone, height, and irregularities as the main parameters determining the required analysis procedure. Both approaches permit a simplified static equivalent lateral force (ELF) procedure for many conditions. NEHRP has no analysis requirements for all buildings assigned to SPC A. However, some specific construction and detailing requirements must be met. All buildings in SPC B and C can be analyzed using the ELF procedure. Buildings in SPC D and E must be regular buildings less than 240 ft (70 m) in height or have only type 1, 2, or 3 vertical irregularity, have five stories or less, and be less than 65 ft in height to qualify for the ELF analysis. UBC has no requirements for zone zero. Furthermore, UBC permits ELF for all regular buildings less than 240 ft (70 m) tall. All irregular buildings in zone 1 and irregular buildings in zone 2 if defined as "occupancy catetory IV" can be designed using ELF. Other irregular buildings that have five stories and are shorter than 65 ft (20 m) high can be analyzed using ELF. A regular tower supported on a regular rigid lower platform can be designed using ELF if certain stiffness requirements are met.

Some form of dynamic analysis is required for all other building types not described as qualifying for the ELF procedure. NEHRP provides specific design provisions for a one degree of freedom per level modal analysis, which is permitted for regular buildings taller than 240 ft (70 m) and irregular buildings with only type 1, 2 or 3 vertical irregularity, which are taller than five stories or 65 ft. For all other irregular buildings not qualifying for the ELF or the modal analysis methods, NEHRP requires a dynamic analysis that gives special consideration to the dynamic characteristics of the building. The commentary suggests a three-dimensional (3D) response spectrum analysis or its equivalent to meet this requirement. NEHRP has two exceptions to the ELF and the dynamic analysis presented earlier for buildings in SPC D and E. First, for buildings in seismic hazard exposure groups II and III with A_a greater than 0.4 and within 6 mi of a fault with the capacity for a magnitude 7 or greater quake, a site-specific response spectrum is required. Second, any building (SPC D or E) located on S_4 soil (NEHRP-91) or soil profile type E (NEHRP-94) in areas of A_v greater than 0.2 and with a fundamental period greater than or equal to 0.7 s, also requires a site-specific response spectrum.

In zones 2, 3, and 4, UBC requires a dynamic analysis for all buildings exceeding 240 ft (70 m) in height and any building not qualifying for the ELF procedure. Also, in a manner similar to NEHRP all regular and irregular buildings must be designed using a dynamic analysis that includes the effects of the soils at the site if the structure is located on a type S_4 soil in NEHRP-91 or soil profile type E in NEHRP-94 and has a period greater than 0.7 s.

A comparison of the directional effects provisions is shown in the "Directional effects" row in Table 2. For NEHRP SPC B and C (except for category C buildings with type 5 plan irregularity—nonparallel system) the directional effects requirement can be satisfied by applying forces nonconcurrently in each of two orthogonal directions. SPC C with type 5 plan irregularity and all SPC D and E buildings require design for the direction that produces the critical effect. As a simpler alternative the requirement can be satisfied by the application of 100% of the design forces in one direction acting concurrently with 30% applied in the orthogonal direction. UBC permits design forces to be applied nonconcurrently to each principal axis. In zones 2–4, where any one of three conditions exist, directional effects must be considered by designing for 100% of the design forces in one direction combined with 30% applied concurrently in the orthogonal direction. The aforementioned three conditions are the existence of type 5 plan irregularity (nonparallel systems), type 1 irregularity (torsional irregularity) about both major axes, or a column that forms a part of two or more lateral force resisting systems.

The vertical force distribution for the ELF procedure is significantly different for the two approaches. The comparison is shown in the "Vertical force distance (ELF)" row of Table 2. NEHRP distributes the base shear linearly in proportion to the story mass and height for T less than or equal to 0.5 s. For T greater than 2.5 s the distribution is parabolic. Between these two values of T the exponent k is determined by linear interpolation from a k of 1 at T of 0.5 s to a k of 2 at T of 2.5 s. UBC applies a concentrated force F_t at the top level up to 25% of the base shear for all T greater than or equal to 0.7 s. The remainder of the base shear less F_t is distributed using a linear distribution in proportion to the story mass and height.

TABLE 2. Comparison of Analysis Procedure

Criterion (1)	NEHRP-91 and 94 and ASCE 7-95 (2)	SEAOC-90 and UBC-94 (3)
Analysis type	Related to seismic performance category (SPC) SPC A—none required SPC B and C—ELF procedure SPC D and E—ELF procedure: use for regular buildings $\leq$ 240 ft. and buildings with only type 1, 2, or 3 vertical irregularities, which are $\leq$ five stories and $\leq$ 65 ft SPC D and E—modal analysis with one DOF: Use for regular buildings > 240 ft and buildings with only type 1, 2, or 3 vertical irregularities that are > 5 stories or > 65 ft SPC D and E—3D response spectrum analysis or equivalent: Use for all other buildings with plan or vertical irregularities SPC D and E—site-specific response spectrum analysis: for buildings in seismic hazard exposure group II or III with $A_a = 0.4$ and within 6 mi of fault with capacity for > 7 magnitude earthquake or buildings with $T \geq 0.7$ s in areas of $A_V > 0.2$ and on type S_4 soils (NEHRP-91) or soil profile type E (NEHRP-94).	None for zone 0 Static ELF analysis Regular buildings $\leq$ 240 ft high Irregular buildings in zone 1 Irregular buildings in zone 2 if occupancy Category IV Irregular buildings $\leq$ five stories and $\leq$ 65 ft Buildings with tower supported on platform meeting special criteria. Dynamic analysis required in zones 2, 3, and 4 All buildings > 240 ft Any other building not qualifying for static analysis Any building on S_4 soil with $t > 0.7$ s
Vertical force distance (ELF)	Force distributed linearly in proportion to story mass and height for $T \leq 0.5$ s, parabolically for $T > 2.5$ s, and with a linear interpolation of the exponent k from 1 to 2 for $0.5 < T \leq 2.5$ s	Concentrated force F_t at top level where $F_t = 0.07TV \leq 0.25V$ and $F_t = 0$ when $T \leq 0.7$ With remaining shear $(V - F_t)$ distributed linearly in proportion to story mass and height.
Period	T to be established using substantiated methods. $T \leq C_aT_a$ where $T_a = C_th^{3/4}$ or $T_a = 0.1N$, and in modal analysis to compute V from ELF for scaling purpose using (Section 2.4.8) $T = 1.2C_aT_a$ (NEHRP-91) $T = 1.2C_uT_a$ (NEHRP-94)	$T_a = C_th^{3/4}$ or T_B = Rayleigh method or any other proven analysis p$C(T_B) \geq 0.8C(T_A)$-SEAOC and by UBC-94 $T_B \leq 1.3T_A$—zone 4 $T_B \leq 1.4T_A$—zones 1–3 Upper limits of T do not apply for forces to determine drift For scaling displacements from dynamic analysis upper limit does not apply (SEAOC)
Vertical acceleration	Horizontal prestressed components—check load combination: NEHRP-91—$(0.9-0.5A_v)Q_D + (2R/5)Q_E$ where $2R/5 \geq 1.0$ and $0.5A_v = 0$ if $A_v \leq 0.05$ NEHRP-94—$(0.9-0.5C_a)D + (2R/5)Q_E$ where $2R/5 \geq 1.0$ and $0.5C_a = 0$ if $A_v \leq 0.05$ Horizontal structural cantilevers—minimum net upward force = $0.2Q_D$ in addition to other load combinations	Horizontal prestressed shall be designed using > $0.5DL$ for the gravity load acting alone or in combination with E Horizontal structural cantilevers designed for net upward force of $0.5ZIW_p$ Provisions apply in zones 3 and 4 only.
Dynamic analysis criteria	For each of two mutually perpendicular axes include all modes with $T_m > 0.4$ but at least three lowest modes; For < three stories number of modes = number of stories NEHRP-91 and ASCE 7-93: $C_{sm} \leq 2.5A_a/R$ except category D or E buildings on S_4 soil with $T_m \geq 0.7$ s or buildings on S_3 or S_4 soil with $T_m < 0.3$ s (except for fundamental) then $C_{sm} = A_a(1.0 + 5T_m)/R$ or where $T_m > 4.0$ s then $C_{sm} = 3A_vS/R(T_m)^{4/3}$ NEHRP-94 and ASCE 7-95 Same as above with C_a and C_V substituted for A_a and A_v, and site type E or F substituted for S_3 or S_4 soils	Response spectrum analysis recommended Use sufficient number of modes to include $\geq$ 90% of the participating mass to calculate the response in each principal horizontal direction Time history analysis or other alternative procedures using rational analyses are specifically permitted
Directional effects	Categories B and C except with type 5 plan irregularity: apply forces nonconcurrently in each of two orthogonal directions Category C with type 5 plan irregularity and all categories D & E: design for direction that causes critical effect or as alternative, apply 100% in one direction and combine with 30% applied concurrently in other orthogonal direction	Nonconcurrent for each principal axis except for zones 2–4, design for orthogonal effects if: Type E plan irregularity exists Type A plan irregularity exists about both major axes Column forms a part of two or more lateral force-resisting systems And design for 100% in one direction in combination with 30% in the orthogonal direction applied concurrently.
Overturning moment	Buildings $\leq$ 10 stories—no reduction at story levels Buildings $\geq$ 20 stories—20% reduction at 20th story from top and all levels below; straight line interpolation from zero reduction at 10th story from top to 20% at 20th story from top For all buildings regardless of height except inverted pendulum 25% reduction allowed at foundation-soil interface	No reduction at structural levels. For zones 3 and 4, F_t can be taken as equal to zero for calculation of overturning moment at foundation-soil interface. Distribution to nonlateral force-resisting vertical members specifically permitted
Drift	Difference in elastic story displacements, calculated based on forces determined without the upper bound limit on T, multiplied BY amplification factor, C_d; limit varies from $0.010h_{sx}$ to $0.025h_{sx}$ depending on seismic hazard exposure group (Differences exist here between NEHRP and ASCE)	Elastic displacements determined without lower bound limit of 0.075 for C/R_w and without restriction on T_B: For $T < 0.7$ s Drift $\leq 0.04/R_w \leq 0.005h_s$ For $T \geq 0.7$ s Drift $< 0.03/R_w < 0.004h_s$
P-delta	Analysis not required if stability coefficient $\leq$ 0.10 Stability coefficient cannot exceed $0.5/(\beta C_d)$ or 0.25	Analysis not required if stability coefficient $\leq$ 0.10 Calculation not required for zones 3 and 4 if story drift ratio $\leq 0.02R_w$

Some of the criteria for dynamic analysis was covered in the preceding discussion. The additional requirements are described in the row "Dynamic analysis criteria" in Table 2. In the simplified modal analysis procedure of the NEHRP provisions specific guidance is given to the designer for implementing the modal analysis. For each of two mutually perpendicular axes, the designer must include all modes with T_m greater than 0.4 s but at least the three lowest modes. For buildings that have three stories or less the required number of modes to be included equals the number of stories. The same spectral shape for the modal seismic design coefficient, C_{sm}, exists as for the ELF procedure. For SPC D or E buildings on S_4 soil (NEHRP-91) or soil profile type E or F (NEHRP-94) with T_m greater than or equal to 0.7 s a site-specific spectrum must be used. For buildings on S_3 or S_4 soil (NEHRP-91) or soil profile type D, E, or F (NEHRP-94) all modes that have a period less than 0.3 s (except the fundamental mode) have an alternative equation for calculating C_{sm}, which will result in lower values. Also, for buildings where any modal period exceeds 4.0 s, C_{sm} can be calculated using a different alternative equation, which will result in lower values. Guidance for the more rigorous dynamic analysis is required when the modal analysis procedure is not allowed. The commentary does provide a section on how to incorporate the applicable provisions; in general terms it is a six-step procedure to perform the recommended 3D response spectra analysis. Inclusion of sufficient modes to capture a minimum of 90% of the seismic reactive mass of the structure in each of two principal directions of response is specifically stated.

To meet the dynamic analysis requirements of UBC, a response spectrum analysis is recommended as being sufficient except where the site-specific response spectrum analysis is required. General guidance as well as some specific requirements are presented in the code. The designer is given several options for determining the ground motion representation. A normalized response spectrum is provided in the code as one of these options. A 3D analysis is required for structures with highly irregular plan configurations. Otherwise, no requirement for 3D design is stated. For response spectrum analysis, the inclusion of sufficient modes such that at least 90% of the participating mass of the structure is included in the calculated response for each principal horizontal direction is required. Time history analysis is permitted and must only conform to the general requirement that the rational analysis be based on established principles of mechanics. No other guidance for time history analysis is provided.

Both general approaches require scaling of the dynamic analysis results using the value obtained from the ELF provisions. If the base shear in any direction from the dynamic analysis is greater than the value calculated from the ELF procedure the values from the dynamic analysis may be reduced to those values and the other results scaled accordingly. If the base shear calculated from the dynamic analysis is less than the corresponding base shear from the ELF procedure, then the dynamic results must be scaled by the ratio of the ELF value to the corresponding dynamic base shear value. NEHRP permits the base shear for this purpose to be calculated using a higher upper limit on T resulting in a possible lower value of base shear for scaling purposes from the ELF method. UBC completely removes the upper limit on T_B for this purpose. The comparison of T is shown in the row "Period" of Table 2 and was also presented during the discussion on lateral force criteria.

The results from each mode must be mathematically combined to obtain the total response. NEHRP requires that the complete quadratic combination (CQC) method be used. UBC requires that results be combined by recognized methods.

A comparison of the vertical acceleration provisions is shown in the row "Vertical acceleration" of the Table 2. In the past vertical acceleration has not been generally considered much of an issue since conventional structures tend to be very strong in the vertical direction due to gravity load design. However, the Northridge earthquake demonstrated that significant damage can result from the vertical acceleration induced by thrust faults. Both documents address only special cases where vertical acceleration could be a significant problem. NEHRP requires that horizontal prestressed components be checked for a special load combination. Horizontal cantilevered structural elements must be also designed for a minimum net upward force in addition to the other applicable load combinations. UBC requires horizontal prestressed components to be checked for combinations using not more than 50% of the dead load for a gravity load acting alone or in combination with a seismic load. Horizontal cantilevered structural elements located in zones 3 or 4 must be designed for a specified minimum net upward force.

Past seismic codes have allowed some reduction in the overturning moment. The justification of this practice was based on the assumption that story level shears would not all reach maximum value simultaneously and other factors. Both review documents continue this practice to a limited degree. NEHRP permits a 25% reduction at the soil-foundation interface for all buildings, except inverted, pendulum-type structures, regardless of height. The overturning moment at the building levels can be reduced if they have more than 10 stories. For buildings taller than 20 stories a 20% reduction in calculated overturning moments at the 20th story from the top and all levels below can be used. No reduction is permitted in the top 10 levels. A linear interpolation from 0% reduction at the 10th story to the full 20% reduction at the 20th level is used for stories 11–19. No reduction in story level overturning moments is permitted for shears determined by the modal analysis method. However, a 10% reduction is permitted at the soil-foundation interface. The provisions do not appear to address this for other forms of dynamic analysis. UBC does not permit any reduction in overturning moment at the structural levels. However, in zones 3 and 4 the force, if any, applied at the top level of a regular building can be taken as zero for calculation of the overturning moment at the soil-foundation interface. SEAOC permits redistribution of overturning effects to other vertical members if framing members of sufficient strength and stiffness are provided to transfer the loads. UBC contains two additional load combinations, applicable only in zones 3 and 4, to be used for checking columns supporting a discontinuous, lateral, load-resisting element. SEAOC contains an identical provision except that it is applicable for zone 2 in addition to zones 3 and 4.

The drift criteria for each document is given in the row "Drift" in Table 2. Drift provisions will control the member selection in many situations. The more flexible structural systems such as moment frames of steel and concrete will tend to have the most difficulty in conforming to stringent drift control requirements. NEHRP computes the drift as the difference in elastic story displacements calculated using forces determined without the upper limit on T, multiplied by the deflection amplification factor C_d. The amplification factor is determined by the type of structural system and varies from 1.25 to 6.5. Limits on drift in NEHRP vary from 0.025 h_{sx} to 0.010 h_{sx} depending on the seismic hazard exposure group. For some single story buildings, there is no limit on drift. NEHRP-94 added more detailed information for masonry shear wall and masonry wall frame buildings and relaxed allowable story drift requirements for SPC group I. As previously stated ASCE increased the maximum allowable drift for some categories by as much as 50% from the values shown in NEHRP. UBC uses elastic displacements determined without the lower bound limit of 0.075 for C/R_w and without the restriction on T_B. Drift limits in UBC are a function of the period, T, and R_w as shown.

P-delta analysis requirements are shown in the row "P-delta" of Table 2. Many of the most popular computer analysis programs used by engineers today have P-delta capability. This capability eliminates the computational effort required and makes simplified formulas unnecessary. Both code approaches use the stability coefficient as an indicator of the need to include P-delta effects in the analysis. If the stability coefficient exceeds 0.10 then the effects of P-delta must be included. NEHRP establishes an upper limit for the stability coefficient of $0.5/(\beta C_d)$ but less than or equal to 0.25, where C_d is the deflection amplification and beta is the ratio of shear demand to shear capacity for the story. Beta can be conservatively taken to be equal to 1.0. UBC does not require that P-delta effects be included if the stability coefficient for all stories is less than or equal to 0.10. In addition P-delta does not have to be considered in zones 3 and 4 if the story drift ratio does not exceed $0.02/R_w$. SEAOC does not have the lower limit for the stability coefficient included in the provisions but it is located in the commentary.

SUMMARY

The purpose of this paper was to make comparisons between four of the major seismic design codes used in the United States. This comparison shows that the four codes can be easily categorized by the design approach adopted. NEHRP-91 and NEHRP-94 and ASCE 7-95 are based on the strength design approach. UBC and SEAOC use a working stress design approach. There are other fundamental differences such as the required methods of analysis, amplified displacements versus elastic displacement, and the method of assigning an importance factor. There appears to be a developing consensus that the material design and detail requirements cannot be easily separated from the load provisions if the assumed limit state occurs beyond elastic yield. As confirmation of this one should note that significant detailing requirements are incorporated into each of these documents.

It is also guaranteed that these codes and others that model them will continue to undergo significant changes. Each new major earthquake provides more data to be analyzed and new problems to be solved. It is important that the engineers, building officials, and others involved with using and administering the earthquake codes keep up with the changing tide and be prepared for the inevitable changes ahead.

APPENDIX. REFERENCES

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