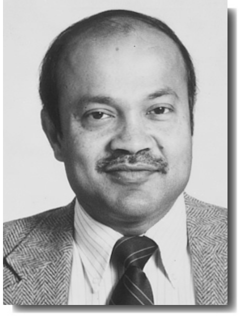
Trends in the Seismic Design Provisions of U.S. Building Codes

Seismic design provisions in building codes of the United States have undergone profound and far-reaching changes in recent years. This paper provides an overview of the major trends that have characterized those changes. Trends in the broad areas of seismic input, site classification and site coefficients, triggers for seismic detailing requirements, and performance basis of seismic design are examined. Implications for precast concrete are briefly discussed and future trends are briefly commented upon.



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The seismic input used in seismic design has changed in a number of significant ways in recent years. Through its 1985 edition, the Uniform Building Code (UBC)[1] used a Z factor that was roughly indicative of the peak acceleration on rock corresponding to a 475-year return period earthquake.

The upper-bound design base shear or the "flat-top" (or acceleration-controlled or constant acceleration) part of the design spectrum was soil-independent; the descending branch or the period-dependent (or velocity-controlled or constant velocity) part of the design spectrum varied with $1/T^{1/2}$ and was modified by a site coefficient S; the lower-bound design base shear was soil-independent.

The Applied Technology Council Tentative Provisions[2] in 1978 introduced two spectral quantities: $A_a = EPA/g$, where EPA was the spectral (pseudo-) acceleration divided by 2.5 (the division bringing EPA close to the peak acceleration on rock), and $A_v = EPV$ (in./second) x 0.4/12 (in./second), where EPV was the spectral (pseudo-) velocity divided by 2.5 (a quantity close to the peak velocity on rock). Both quantities corresponded to a 475-year return period earthquake.

The National Earthquake Hazards Reduction Program Provisions (NEHRP 1985, NEHRP 1988 and NEHRP 1991[3]) used the same spectral quantities as seismic input. The acceleration-governed part of the design spectrum was soil-independent; the velocity-governed part varied with $1/T^{2/3}$ and was modified by a site coefficient S; there was no lower-bound design base shear (no constant displacement part to the design spectrum).

The Z factor of the 1988 UBC became indicative of the larger of the two quantities: A_a and A_v within a seismic zone. The constant-acceleration part of the design spectrum remained soil-independent; the constant velocity part now varied with $1/T^{2/3}$ and was modified by a site coefficient S; the minimum design base shear remained soil-independent. All of this remained unchanged in the 1991 and the 1994 UBC.

The 1994 NEHRP Provisions[3] used soil-modified spectral quantities as the ground motion input. A_a was modified by a short-period site coefficient F_a, yielding C_a; A_v was modified by a long-period site coefficient F_v, yielding C_v. C_a defined the upper-bound design base shear; $C_v/T^{2/3}$ defined the descending branch. Thus, the constant-acceleration part of the design spectrum for the first time became soil-dependent. There was still no lower-bound design base shear.

The 1997 UBC is similar to the 1994 NEHRP Provisions, except that a single Z factor is still used to generate short-period as well as long-period seismic input. C_a of the 1997 UBC is the Z factor modified by a short-period site coefficient, F_a; C_v of the 1997 UBC is the Z factor modified by a long-period site coefficient, F_v. C_a defines the flat-top part of the design spectrum, and C_v/T defines the descending branch.

Note the change from $1/T^{2/3}$ to $1/T$. Two minimum design base shears are prescribed – one applicable in all seismic zones, the other applicable only in Seismic Zone 4. The higher minimum governs when both values are applicable. The minimum value that applies in all seismic zones is soil-dependent; the other minimum is soil-independent.

The 1997 NEHRP Provisions[3] and the International Building Code (IBC)[4] use soil-modified spectral accelerations: $S_{DS} = (2/3)F_aS_s$ and $S_{D1} = (2/3)F_vS_1$. S_s and S_1 are spectral accelerations at periods of 0.2 second and 1.0 second, respectively, corresponding to the maximum considered earthquake on soft rock that is characteristic of the western United States. The maximum considered earthquake has a 2 percent probability of exceedance in 50 years (an approximate return period of 2500 years), except in coastal California where it is the largest earthquake that can be generated by the known seismic sources.

Two-thirds of the maximum considered earthquake replaces the design (500-year return period) earthquake of older codes. S_{DS} and S_{D1} define a spectral shape that changes from location to location, whereas in the past, the same spectral shape was scaled down from areas of high to low seismicity. The flat-top part of the design spectrum, defined by S_{DS}, is soil-dependent. The descending branch of the design spectrum, defined by S_{D1}/T, is also soil-dependent. So is the minimum design base shear that is prescribed for all Seismic Design Categories. (Seismic Design Category is discussed later.)

A second minimum base shear is prescribed for buildings assigned to Seismic Design Categories E and F or for any building located where $S_1 \geq 0.6g$. This second minimum is soil-independent. Designing for two-thirds the maximum considered earthquake provides a uniform level of safety against collapse in that earthquake, 2/3 being the reciprocal of 1.5, the lower-bound margin of safety built into seismic design by U.S. codes (as established by surveys).

As long as the 500-year return period earthquake was the design earthquake, the level of safety against collapse in the maximum considered earthquake was non-uniform across the country. This is because in coastal California, the maximum considered earthquake ground motion is only about 1.5 times as strong as the ground motion in a 500-year return period earthquake, whereas in the Midwest and the East, the maximum considered earthquake ground motion may be four or five times as strong as the ground motion in a 500-year return period earthquake.

SITE CLASSIFICATION AND SITE COEFFICIENTS

The 1994 NEHRP Provisions[3] brought about a major change in site classification and site coefficients used in seismic design. The new scheme was adopted (with necessary modifications) into the 1997 UBC and has been adopted (again with necessary modifications) into the 1997 NEHRP Provisions[3] and the 2000 IBC.[4] The significant changes from prior seismic design are as follows:

1. Site Classification – The four Soil Profile Types (S_1 through S_4) of the 1994 edition and recent prior editions of the UBC (and other codes, standards or resource documents directly or indirectly derived from the UBC) have been replaced by six Site Classes: A through F. In the 1994 UBC, S_1 was rock, S_2 was intermediate soil, S_3 was soft soil, and S_4 was very soft soil.

There are now two categories of rock. Site Class A is hard, geologically older rock of the eastern United States. Site Class B is softer, geologically younger rock of the western United States. Site Classes C, D and E represent progressively softer material. Site Class F consists of material so poor that to be able to design any structure founded on it, a designer must have a site-specific spectrum and must perform dynamic analysis using that spectrum.

2. Site Coefficients – There used to be one soil factor S; now there are two site coefficients: a short-period or acceleration-related F_a, and a long-period or velocity-dependent F_v.

3. Dependence of Site Coefficients on Seismicity – Whereas the old S factor was a function of the Soil Profile Type only (1.0 for S_1, 1.2 for S_2, 1.5 for S_3, and 2.0 for S_4), each of the new site coefficients (F_a and F_v), in addition to being a function of the Site Class, is also dependent on the seismicity at the site. F_a, F_v of the 1994 NEHRP Provisions are functions of A_a and A_v, respectively. C_a, C_v of the 1997 UBC are both functions of Z. F_a and F_v of the 1997 NEHRP Provisions and the 2000 IBC are functions of S_s and S_1, respectively.

For the same Site Class, the site coefficients F_a and F_v are typically larger in areas of low seismicity and smaller in areas of high seismicity. This is directly in line with observations that low-magnitude rock motion is magnified to a larger extent by soft soil deposits than is high-magnitude rock motion.

4. Maximum Values of Site Coefficients – While the maximum value of the old soil factor S was 2.0 for Type S_4 soil, the maximum values of F_a and F_v are 2.5 and 3.5, respectively, in the 1997 NEHRP Provisions and the 2000 IBC. This requirement results in significant increases in seismic design forces for buildings (particularly taller buildings) founded on softer soils in areas of low seismicity.

5. Basis of Site Classification – Soil Profile Types S_1 through S_4 were qualitatively defined in the UBC and documents based on the UBC. The structural engineer, after reviewing the soils report, typically determined the Soil Profile Type.

This is to be contrasted with the new situation where the distinction among the Site Classes must be based on one of three measured soil properties at the site: the shear wave velocity, the standard penetration resistance (or blow count) or the undrained shear strength. If one of a number of given conditions is satisfied at a site, it becomes classified as F. If one of a number of other given conditions is satisfied at a site, it becomes classified as E. Once Class F and Class E, based on the given conditions, are ruled out, soil property measurements need to be undertaken.

It is possible for a site to get classified as E, based on property measurements as well. The properties need to be measured over the top 100 ft (30 m) of a site. If the top 100 ft (30 m) is not homogeneous, it must be divided into layers that are reasonably homogeneous, and the properties of those layers measured. The 1997 NEHRP Provisions, the 1997 UBC and the 2000 IBC give formulas by which to arrive at average soil properties over the top 100 ft (30 m), based on those measurements.

The 2000 IBC, but not the 1997 UBC or the 1997 NEHRP Provisions, permits the geotechnical engineer preparing the soils report to estimate, rather than measure, the soil properties mentioned earlier, based on known geologic conditions. In the absence of measured or estimated soil properties, the default Site Class is D, unless the building official has determined that E or F may exist at the site.

SEISMIC DETAILING REQUIREMENTS

Seismic Zones – In the Uniform Building Code, through its 1997 edition, and in seismic codes, standards and other documents based on the UBC, seismic detailing requirements and other restrictions such as height limit on certain structural systems depend upon the Seismic Zone in which a structure is located. Zones are regions in which the intensity of seismic ground motion, corresponding to a certain probability of occurrence, is within certain ranges.

The United States is divided into Seismic Zones 0 through 4, with 0 indicating the weakest earthquake ground motion, and 4 indicating the strongest. The level of seismic detailing (ordinary, intermediate or special), the height limits on structural systems, the type of analysis that must, as a minimum, be carried out as the basis of design, are all determined solely or in part by the Seismic Zone.

Seismic Performance Categories – Given that public safety is a primary code objective, and that not all buildings in a Seismic Zone are equally crucial to public safety, a new mechanism called the Seismic Performance Category (SPC) was developed in the ATC 3 document, and was used in all the NEHRP Provisions through 1994, and in all codes and standards based on the 1994 and earlier NEHRP Provisions (BOCA/NBC 1993, 1996, 1999;[5] SBC 1994, 1997, 1999,[6] ASCE 7-93,[7] and ASCE 7-95[7]).

In all these documents, the SPC, rather than the Seismic Zone, is the determinant of seismic detailing requirements (and other restrictions), thereby dictating that, in many cases, the seismic design requirements for a hospital be more restrictive than those for a small business structure constructed on the same site. The detailing requirements for Seismic Performance Categories A & B, C, and D & E are roughly equivalent to those for Seismic Zones 0 & 1, 2, and 3 & 4, respectively.

Seismic Design Categories – The most recent development has been the establishment of Seismic Design Categories as the determinant of seismic detailing requirements in the 1997 NEHRP Provisions,[3] ASCE 7-98,[7] and the 2000 IBC.[4] Recognizing that building performance during a seismic event depends not only on the severity of the sub-surface rock motion, but also on the type of soil upon which a structure is founded, the SDC is a function of location, building occupancy, and soil type. For a structure, the SDC needs to be determined twice – first as a function of the short-period seismic input parameter, S_{DS}, and a second time as a function of the long-period seismic input parameter, S_{D1}. The more severe category governs.

Impact of Changes from Seismic Zones to SPC to SDC – Clearly, the procedure for establishing the seismic classification of a structure has become more complex. Determining the Seismic Zone of a structure simply requires establishing the location of the structure on a Seismic Zone map. Determining the Seismic Performance Category of a structure requires the interpolation of a ground motion parameter on a contour map, based on the location of the structure, determining the use classification of the structure, and consulting a table. The process leading to the establishment of the Seismic Design Category of the IBC for a structure involves several steps, many of which are rather complex.

When ATC 3 in 1978 made the level of detailing (and other restrictions concerning permissible structural systems, height, irregularity and analysis procedure) also a function of occupancy, that was a major departure from prior practice. The departure, as noted, was continued in all the NEHRP Provisions through the 1994 edition. Now, in the 2000 IBC, the 1997 NEHRP Provisions, and ASCE 7-98, also as noted, the level of detailing and the other restrictions have been made a function of the soil characteristics at the site of the structure in addition to occupancy. This is a further major departure from current practice across the United States – a move that is likely to have a significant impact on the economic and other aspects of earthquake-resistant construction.

PERFORMANCE BASIS

Prior to the 1997 NEHRP Provisions – The seismic design provisions of all U.S. codes and similar documents, except for the 1997 NEHRP Provisions, the 2000 IBC and ASCE

7-98, have the following implicit performance bases:

(1) For standard-occupancy or ordinary structures, ensure life safety under the design earthquake, which has a 90 percent probability of non-exceedance in 50 years or a return period of 475 years.

(2) For assembly buildings or high-occupancy structures, provide enhanced protection of life.

(3) For essential or emergency response facilities, improve capability to function during and following an earthquake.

It is generally uneconomical and unnecessary to design a structure to respond elastically to the design earthquake. The design seismic horizontal forces recommended by codes are generally much less than the elastic response inertia forces expected to be induced by the design earthquake. Code-designed structures are expected to ensure life safety under design earthquake ground shaking because of their ability to dissipate seismic energy by inelastic deformations in certain localized regions of certain members. A decrease in structural stiffness caused by accumulating damage and soil-structure interaction also helps at times.

The use of seismic design forces prescribed by codes requires that the critical regions of members have sufficient inelastic deformability to enable the structure to survive without collapse when subjected to several cycles of loading in the inelastic range. This means avoiding all forms of brittle failure and achieving adequate inelastic deformability by flexural yielding of members. This is achieved through proper detailing of reinforced concrete beams, columns, beam-to-column joints and shear walls, rules for which are presented in the materials chapters of codes and in materials standards.

Enhanced protection of life in high-occupancy structures is provided for in the Uniform Building Code through the requirement of an importance factor of 1.5 for the anchorage of machinery and equipment required for life-safety systems. The anchorage design forces go up by this factor. Structural observation, which is required for this occupancy category, also plays a role.

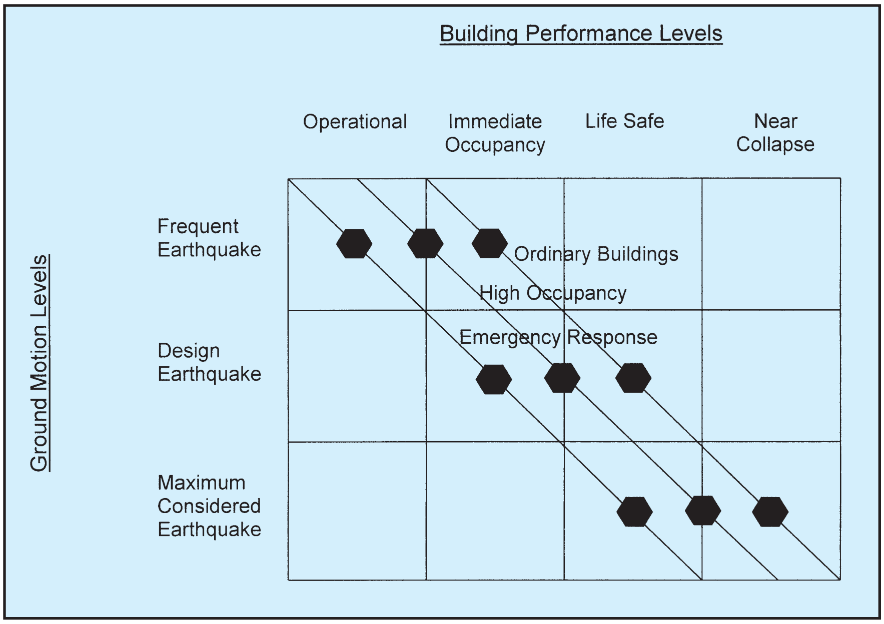

Fig. 1. Performance basis of the 1997 NEHRP Provisions (Reference 8).

An importance factor of 1.25 for the structure itself, an importance factor of 1.5 for elements of structures, nonstructural components and elements supported by structures, and structural observation requirements together are used as a means of improving the capability of essential facilities to function during and following an earthquake.

In ATC 3, in the NEHRP Provisions through the 1994 edition, and in codes based on the NEHRP Provisions predating the 1997 edition, enhanced protection of life in high-occupancy structures (as well as in hazardous and essential facilities) is attempted to be achieved through the device of the Seismic Performance Category, which combines occupancy with seismic risk at the site of a structure. Higher detailing requirements are prescribed for higher seismic performance categories. For essential or emergency response facilities, improved capability to function during and following an earthquake is attempted to be ensured through stricter limits on interstory drift.

1997 NEHRP Provisions, ASCE 7-98, 2000 IBC – The performance bases of the 1997 NEHRP Provisions, on which the seismic design provisions of the ASCE 7-98 standard and the 2000 IBC are directly based, are different from the above. Hamburger[8] has suggested that the performance bases of the 1997 NEHRP Provisions are as illustrated in Fig. 1, reproduced from Reference 8.

The ordinary buildings, the high-occupancy buildings and the emergency response facilities of Fig. 1 belong to Seismic Use Groups I, II and III, respectively, Seismic Use Group being the new name for the Seismic Hazard Exposure Group of the 1994 and prior NEHRP Provisions.

For ordinary structures, life safety under the design earthquake and collapse prevention under the maximum considered earthquake are ensured by designing the structure for the effects of code-prescribed seismic forces and by conforming to the detailing requirements in the materials chapters.

Enhanced life safety and collapse prevention under the same earthquakes are accomplished through the device of the Seismic Design Category (SDC), which has now replaced the Seismic Performance Category of the 1994 and prior NEHRP Provisions. The SDC combines occupancy with the soil-modified seismic risk at the site of a structure.

The 1997 NEHRP Provisions also assign occupancy importance factors, I, of 1.25 and 1.5 to Seismic Use Groups II and III, respectively, to partly achieve the higher levels of seismic performance desired for these structures. The I-values higher than 1.0 have the effect of reducing the effective *R*-values, permitting less inelastic behavior and, consequently, reduced levels of damage.

It may be noted that essential facilities in so-called near-fault areas are now assigned to a new SDC F, while other near-fault structures are assigned to SDC E.

From SDC A, B to C to D, detailing requirements increase, and the applicability of certain limited-deformability structural systems becomes restricted. In SDC D, height limits begin to apply on certain structural systems, and dynamic analysis as the basis of design begins to be required for certain irregular structures.

From SDC D to E to F, detailing requirements do not change. However, height limits often become more restrictive and more and more restrictions apply to irregular structures. Also, structural redundancy must be considered in the design of structures belonging to SDC D, E, and F. For structures with lateral force-resisting systems consisting solely of moment resisting frames, structural redundancy requirements are tougher in SDC E, F than in SDC D.

According to Hamburger,[8] as shown in Fig. 1, the 1997 NEHRP Provisions are supposed to ensure that ordinary buildings will be immediately occupiable following "frequent earthquakes," that essential facilities will remain operational during and following such earthquakes, and that assembly buildings will exhibit performance between the above two. These performance objectives are sought to be met through imposition of limits on the design story drift, Δ, defined as "the difference of the deflections of the center of mass on the top and bottom of the story under consideration." The deflection at Level x, δ_x, is determined as follows:

$$\delta_x = C_d\, \delta_{xe} / I$$

where δ_{xe} is the deflection determined by an elastic analysis under prescribed seismic forces.

Drift limits for high-occupancy buildings are typically more stringent than they are for ordinary buildings; for essential facilities, they are typically more restrictive than those for high-occupancy buildings.

IMPLICATIONS FOR PRECAST CONCRETE

The fact that seismic detailing requirements are now determined by the Seismic Design Category, which is a function of (1) the occupancy of a structure, (2) the seismicity at the site of the structure, and (3) the soil characteristics at the site of the structure, have important economic implications that have been discussed elsewhere.[9-11]

Earthquake design is no longer just a regional concern. In unlikely places such as Nashville, Tennessee, the equivalent of California detailing may be required, particularly on softer soils. Precast concrete structures are particularly affected by this change.

Precast concrete solutions that have been more or less traditional in many parts of the country will no longer be permitted in the same areas under the newer codes. New solutions will have to be devised. The groundwork for this change has been laid by the PRESSS tests and other efforts. Much still remains to be done.

THE FUTURE

Direct performance-based design, where the design professional together with the owner or his representative choose one or more performance objectives (a performance objective is a desired performance level at a particular ground motion severity or seismic demand), and those objectives then directly drive the design, is still in the future of the U.S. codes for new buildings. Such a performance-based approach is already available in a prestandard for existing buildings (Reference 12).

There is little doubt that such direct performance-based design is the way of the future. Provisions for such design will replace today's code provisions where the performance basis is implicit, rather than explicit.

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