Buildings at Risk: Seismic Design Basics for Practicing Architects, AIA, 1994

Chapter 1: The Nature of Ground Motion and its Effect on Buildings

GEOLOGIC BACKGROUND

According to the now generally accepted theory of Plate Tectonics, the earth's crust is divided into several major plates, some 50 miles (80km) thick, that move slowly and continuously over the interior of the earth.

Earthquakes are initiated when, due to slowly accumulating pressure, the ground slips abruptly along a geological fault plane on or near a plate boundary. The resulting waves of vibration within the earth create ground motion at the surface which begins to vibrate in a very complex manner. This, in turn, induces forces within buildings that are determined by the precise nature of the ground motion and the construction characteristics of the building.

The point where the fault first slips is termed the "focus" or "hypocenter." A theoretical point on the earth's surface directly above the focus is termed the "epicenter." (Figure 1.1) The epicenter for the January 17, 1994 Los Angeles earthquake was located in the city of Northridge in the San Fernando Valley.

The initial break in the fault moves rapidly along the line of the fault, and the distance of this movement largely determines the intensity of ground shaking. Thus the 1906 San Francisco earthquake ruptured along some 250 miles (400km) of the San Andreas fault. The Loma Prieta, California earthquake of 1989 was unusual since no surface faulting occured, although a broad area of ground cracking indicated a wide distribution of strain. The fault rupture moved upward to within about 6km of the ground surface area and then spread approximately 20km along the fault to each side of the initial rupture. (Figure 1.2)

GROUND FAILURE

Surface Faulting

Slippage along a fault line deep in the earth's surface may eventually result in *surface faulting*, the crack or split on the earth's surface that provides the layperson's vision of earthquakes. Surface faulting may result in large earth movements: in the 1992 Landers earthquake east of Los Angeles, the earth offset as much as 18 feet at the surface. A building located across a surface fault, no matter how well designed, is almost certain to suffer very severe damage. (Figure 1.3) However, the large disturbance of the ground near a fault is generally quite narrow in width on either side of the fault: in Landers the maximum width of severely disturbed ground was only about 40 meters. Moreover, the probability that buildings will straddle a surface fault is very low

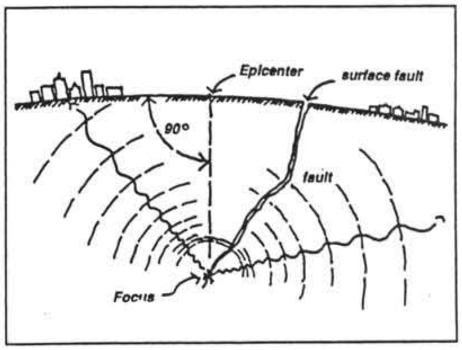

Figure 1.1: Earthquake location

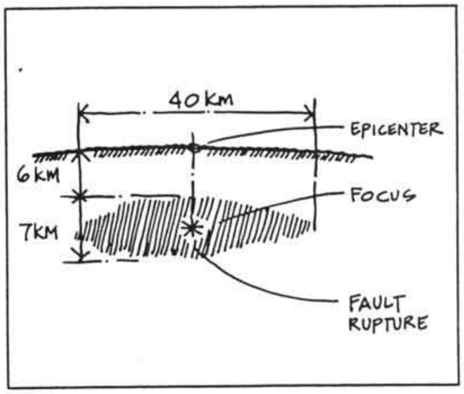

Figure 1.2: The Loma Prieta fault rupture, 1989


James Strata

Figure 1.3: School straddling a landslide-induced rupture, Alaska


National Science Foundation

Figure 1.4: House on Turnagain slide


Unknown

Figure 1.5: Turnagain Heights, Alaska

compared to the likelihood of significant ground motion. So, in seismic design, we design against the vibrations caused by fault slippage and try to ensure that buildings are not built over fault zones.

Landslides, Liquefaction and Subsidence

The energy released by an earthquake can also trigger ground failure in the form of landslides, liquefaction and subsidence which can have devastating effects on a structure. Even well-built structures, designed to withstand earthquake forces, if built on an unstable site or in the path of a landslide, can fall victim.

The Alaskan earthquake of 1964 provides examples of structures with the inherent strength to withstand ground shaking that were devastated as a result of the instability of the sites they were built on. (Figure 1.4) While an architect and contractor could take pride in the performance of their buildings on Turnagain Heights or on 4th Street in Anchorage, the decision to build on geologically unstable sites produced catastrophic results. (Figure 1.5) Avoidance of sites with a potential for liquefaction, landslides or subsidence represents the best design approach.

Ground shaking can also trigger subsidence and liquefaction in soils that are unconsolidated and/or saturated with water. When sandy, water saturated soils are shaken, the bearing capacity of the soil is reduced as the soil liquefies and flows laterally and vertically. Liquefied soils can produce volcano-like sandboils at the ground surface or flow laterally if the soil is not contained. The ground surface and structures built on shallow foundations can subside several feet or be torn apart as spreading occurs. Dramatic examples of liquefaction from recent earthquakes illustrate again, that even well built structures are vulnerable if adequate attention is not paid to site conditions and foundation design. (Figures 1.6 and 1.7)

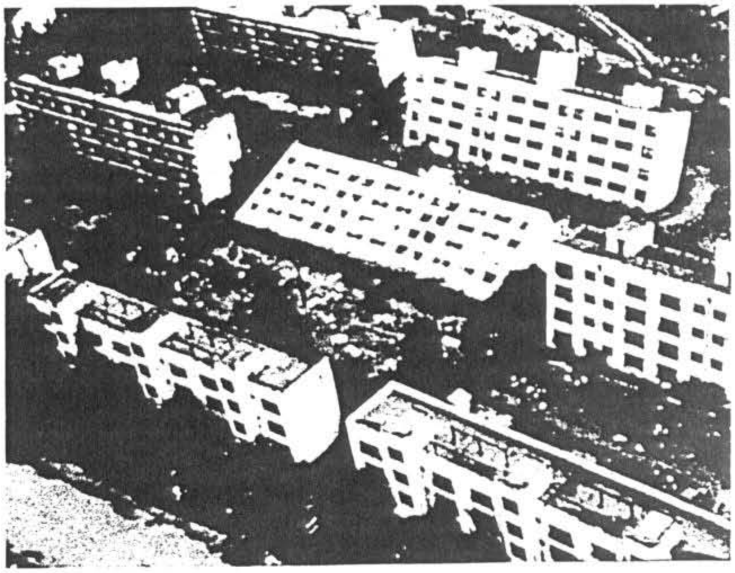
H. B. Seed

Figure 1.6: Liquefaction, Niigata, Japan, 1964

GROUND MOTION

While ground failure can be an important consequence of any earthquake, the primary effect buildings are designed to resist is ground motion. During an earthquake, wave vibrations emanate from the line of fault rupture and so approach the building from a given direction. The waves begin like ripples in a still pond when a pebble is thrown into it, but the seismic waves rapidly become more complex.

There are four main wave types, of which "body" waves, within the earth, are the most important for design purposes. (Figure 1.8) First to arrive at the surface is the *P* or *primary* wave. In this wave the ground is successively pushed and pulled along the wave front. The effect is of a sharp punch - it feels as if a truck has hit the building. The P wave is followed by the *S, secondary* or *shear* wave, which is a lateral motion, back and forth (but sideways to the wave front).

The nature of the waves and their interactions are such that actual movement at the ground will be random: predominantly horizontal, often with considerable directional emphasis, but sometimes with a considerable vertical component. The actual horizontal ground displacement is small, only inches even in a large earthquake, except in the immediate area of the fault rupture where displacements of several feet may occur.

Unknown

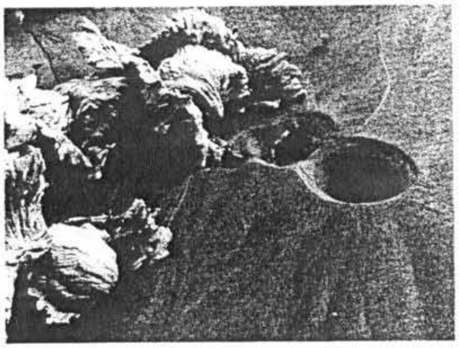

Figure 1.7: Sand boil in a lettuce field, Watsonville, 1989

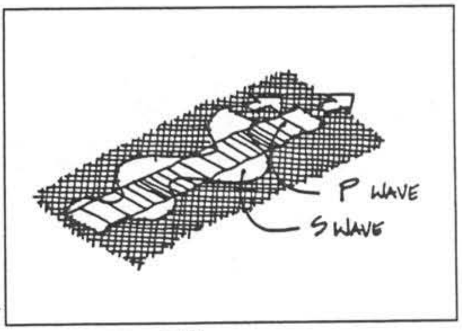

Figure 1.8: "P" and "S" waves

$F=MA$

THE MEASUREMENT OF GROUND MOTION

Measurement of ground motion is important for design purposes because it provides the basis for determining forces, and assessing the relative seismic hazard at different locations.

Earthquake motion is recorded by a seismograph, an instrument that records the movement, over time, of a freely supported pendulum within a frame: the instrument may be placed on the ground or within a structure.

In modern seismographs, pendulum movement is converted into electronic signals on tape. Strong-motion seismographs, called accelerometers, are designed to directly record nearby rather than distant ground movement, and they produce a record called an accelerogram. Instruments are normally placed so as to measure movements along the two horizontal axes as well as one vertical. Three measures are of major interest: acceleration, velocity, and displacement.

Acceleration, Velocity, Displacement

Acceleration is the rate of change of velocity: when multiplied by mass it results in the inertial force that the building must resist. This is a key measure, and forms the basis of the estimation of earthquake forces on buildings: *Newton's Second Law of Motion* states in essence, that an *inertial force, F, equals mass (M) multiplied by the acceleration (A).*

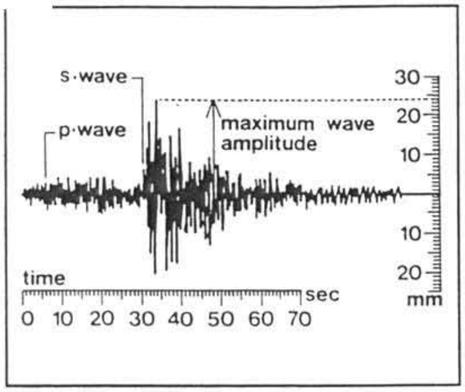

Figure 1.9: This accelerogram illustrates the size of the seismic waves and can be used to derive acceleration, velocity and displacement.

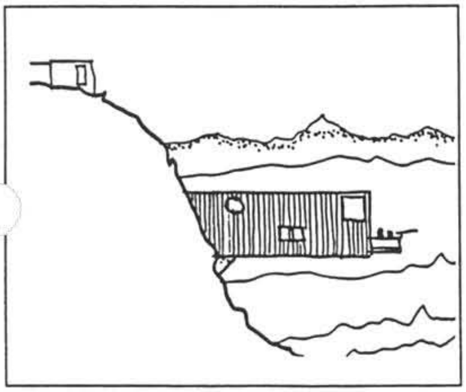

Figure 1.10: A 1.0g design

Acceleration is commonly measured in *"g's"* - the acceleration of a free falling body due to the earth's gravity (approx. 32ft/sec/sec., or 980 cm/sec/sec, or 1.0g.). *Velocity*, measured in inches or centimeters per second, refers to the rate of ground motion at any time. *Displacement*, measured in inches or centimeters, refers to the distance a particle is removed from its "at rest" position. (Figure 1.9)

The level of acceleration generally taken as sufficient to produce some damage to weak construction is 0.10g. The lower limit of acceleration perceptible to people is set by observation and experiment at approximately 0.001g or 1cm/sec^2; at around 0.20g and above most people will have difficulty keeping their footing and sickness symptoms may be induced. An earthquake causing acceleration approaching 0.5g on the ground is very high. On upper floors of buildings, maximum accelerations will often be higher, depending on the degree to which the mass and form of the building act to damp the vibratory effects. A figure of 1.00g, or 100% of gravity, may be reached, for a fraction of a second. To design for 1.00g is diagrammatically equivalent, in a static sense, to designing a building that projects horizontally from a vertical surface. (Figure 1.10) When the behavior of real buildings is observed, several factors modify this diagrammatic equivalence, and structures that could never cantilever from a vertical surface can briefly withstand 1.0g earthquake shaking.

Acceleration is the measure commonly used to indicate the possible destructive power of an earthquake in relation to a building. A more significant measure is that of acceleration combined with *duration*, which takes into account the impact of earthquake forces over time. In general, a number of cycles of moderate acceleration, sustained over time, can be much more difficult for a building to withstand than a single peak of much higher value. Seismic instrumentation also measures the duration of strong ground motion, which generally relates to the length of the fault break.

Typically the extreme vibration will occupy only a few seconds; both the 1989 Loma Prieta and 1994 Northridge earthquakes lasted only a little over ten seconds, yet they caused much destruction. In 1906, in San Francisco, the severe shaking lasted about 45 seconds; in Alaska in 1964 the severe earthquake motion lasted for over 3 minutes.

Two earthquake measurement systems are in common use and neither, for various reasons, is really satisfactory from the building design viewpoint.

Magnitude: The Size of the Wave

Earthquake *magnitude* is the first measure: it is expressed as Richter magnitude based on the scale devised by Professor Charles Richter of the California Institute of Technology in 1935. Richter's scale is based on the *maximum* amplitude of certain seismic waves recorded on a standard seismograph at a distance of 100 kilometers from the earthquake epicenter. The scale, however, tells nothing about duration, which may be of great significance in causing damage, nor does it tell anything about frequency content which, in its relationship to the building period, as discussed later, is also of great significance in determining damage. Because the instrument is unlikely to be exactly 100km from the source, Richter developed a method to allow for the diminishing of wave amplitude (or *"attenuation"*) with increased distance, just as the light of a star appears dimmer with distance. (Figure 1.11)

Because the size of earthquakes varies enormously, the graphic range of wave amplitude measured on seismographs is compressed by using, as a scale, the *logarithm to base ten* of the recorded wave amplitude. Hence, each unit of Richter magnitude indicates a *10* times increase in wave amplitude. But the *energy increase* represented by each unit of scale is estimated by seismologists as approximately *31* times. Since Richter magnitude is a measured quantity, the scale is open-ended, but seismologists believe that a Richter magnitude of about 9 represents the largest possible earthquake. A given earthquake will have only one Richter magnitude, though differences in recording result in some argument as to what this will be.*

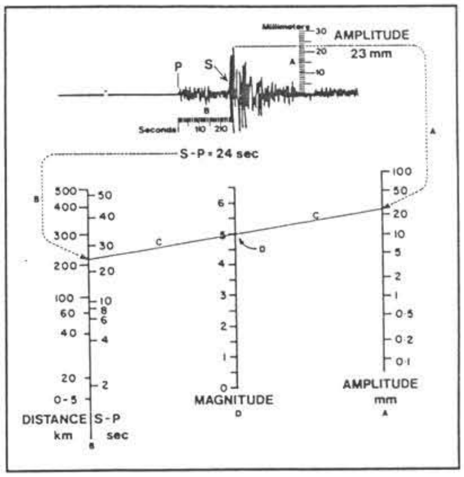

Figure 1.11: Richter magnitude

Intensity: The Amount of Damage

To provide information directly related to local shaking and building damage, *intensity* scales are used. These scales are based on subjective observation of the effects of the earthquake on buildings, ground and people. In the United States the most commonly used scale is the *Modified Mercalli (MM)* originally developed in Europe in 1902, and modified in 1931 to fit construction conditions then prevalent in California and other parts of the United States.

Christopher Arnold

Figure 1.12: Damage to an older masonry building

As a result the MM scale is somewhat dated, with no references to common modern construction systems. This is not much of a disadvantage because earthquake damage is most likely to be concentrated in older buildings, often of the very type that the scale describes. (Figure 1.12) The MM Scale is a twelve point scale, *I - XII*. The descriptions for MM I are, in abbreviated form, "Not felt. Marginal and long-period effects of large earthquakes." For MM XII the descriptor reads, "Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air." Because earthquake effects vary depending on distance from the epicenter, nature of the ground, and magnitude, an earthquake will have many MM values. The MM scale has been correlated with ground acceleration. For example, MM VII corresponds to a peak acceleration between approximately 0.1g and 0.29g.

THE EFFECTS OF GROUND MOTION

Inertial Forces

While the effects of ground failure can be extremely severe, the most common and widespread cause of earthquake damage is ground shaking. Seismically induced shaking affects buildings in three primary ways: inertial forces, period and resonance, and torsion. Shaking causes damage by internally generated inertial forces generated by vibration of the building's mass.

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* *The use of the term Richter Magnitude will eventually be replaced by the use of the terms 'preliminary magnitude' and 'moment magnitude.'*

Chapter 2: Site Issues

SITING OF A STRUCTURE - WHERE DOES THE SITE BEGIN?

From a seismic design standpoint, the "site" is the region within which a structure will be built; and while it is critical that a structure not be built across an active fault trace, it is equally important that siting and design decisions address the potential for increased intensity and duration of ground shaking, accessibility, survival of life lines and potentially hazardous adjacent land uses. Thus, seismic design is not limited to an analysis of the factors within the confines of the site boundary; it extends to a broad environmental analysis of regional and community vulnerability.

SEISMIC RISK AS A SITING CRITERIA

The factors that impact site vulnerability include proximity to active earthquake faults; susceptibility of the site to ground shaking; the potential for ground failure, including subsidence, lateral spreading, liquefaction, and landslides; adjacent structures and land uses that could pose a threat during or after an earthquakes; and, the potential for inundation resulting from tsunami or dam failure.

From a site and urban planning standpoint, however, concern should not be limited to the identification on the site of a fault or potential fault rupture, but to the broader impact of ground shaking and geologic failures that could occur in the region. The failure of the regional transportation network, disruption of power or water supply or the isolation of building as a result of ground failure, can be as devastating to a business as actual structural damage.

Therefore, seismic risks from beyond the building site property line must be considered as design criteria for a structure. These criteria address the relative desirability or risk of an individual site, that is, is one site safer for a particular use than another site; and what factors beyond the site boundary, such as adjacent land uses, geologic stability of adjacent land, or the survivability of lifelines or access, could impact site development?

ACTIVE EARTHQUAKE FAULTS

If a structure is built over an active fault trace, it should be designed to accommodate displacement or fault offset. (Figure 2.1)


Wallace, USGS

Figure 2.1: San Andreas fault in Central California

This is both a challenging and costly effort, with no guarantee of success. The mapping of active faults has been a focus of geologists and urban planners for several decades. It has been a critical element increasing our understanding of regional seismicity: the frequency of seismic activity, the magnitude of previous seismic events, and the potential for future seismic activity. The fault maps indicate where active surface faulting is identified and where future offset potential exists. Where identified, designers should provide a setback from identified faults for new construction.

In many areas, development is limited or prohibited within defined zones adjacent to active faults. Programs to map fault zones and limit new construction within established zones have proven successful in reducing earthquake risks to new construction. Unfortunately, earthquake fault traces were often ignored when land was subdivided and developed, presenting a costly dilemma to owners of existing structures in a fault zone.

Where existing structures are built across fault lines, their structural performance, occupancy and continued use should be reviewed to evaluate the risk they pose. Those sections of structures built across a trace can be removed or occupancy types and loads can be reduced to reduce risk exposure. (Figure 2.2)

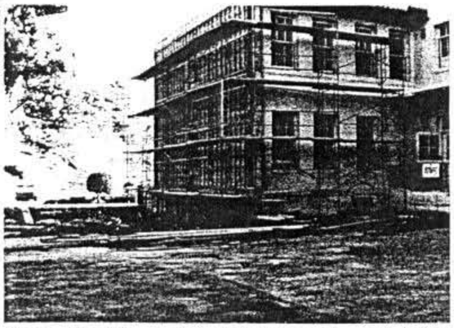

Richard Eisner

Figure 2.2: The section of Fairmont Hospital in San Leandro, California, built across a fault trace, was removed.

IMPACT OF REGIONAL GEOLOGY ON SITE PERFORMANCE

The geology of a region plays a significant role in determining the potential for shaking and ground failure damage. In relatively old geological regions, such as the eastern and midwestern United States where weathering and erosion have leveled the terrain and laid deep deposits of unconsolidated soils, violent ground shaking resulting from fault rupture thousands of feet below the earth's surface can extend for thousands of square miles. Deep soils can amplify ground shaking intensity, extend duration of violent shaking and limit attenuation of shaking; resulting in greater damage over a larger area than would result in younger or bedrock regions.

For example, in the central United States, the violent shaking of the New Madrid, Missouri earthquakes of 1811 and 1812 extended across the midwest and was felt as far away as the eastern seaboard. The earthquakes were felt over 2,000,000 square miles! In contrast, the 1906 San Francisco earthquake, estimated to have released 30 times more energy, was felt over only 375,000 square miles. It impacted a much smaller area because the regional geology in California limited propagation and increased attenuation of shaking. In both examples, one without surface manifestations of faulting, and the other with visible surface faulting, regional geology rather than presence of a surface fault determined the extent of potential damage. (Figure 2.3)

While not building across an earthquake fault is certainly a good rule, building adjacent to a fault may not pose as great a risk as one would expect. A number of recent earthquakes have emphasized that regional and local geology and the lack of attenuation of ground shaking are often more important than proximity to the earthquake's epicenter in determining the impact of an earthquake. The 1985 Mexican earthquake occurred on the coast of Mexico between Acapulco and Ixtapa. Damage close to the epicenter in the coastal resort areas was minor.

However, 250 miles away in Mexico City, the damage to midrise concrete structures was severe, resulting in several thousand deaths. Again in 1989, the Loma Prieta earthquake, centered in the Santa Cruz Mountains resulted in the deaths of more than 40 persons on the Cypress Viaduct, 60 miles north of Santa Cruz in Oakland. In both cases, the most violent ground shaking did not occur at the epicenter of the earthquakes, but a significant distance away as a result of the propagation of the ground waves, the geology of the region and local soil conditions. Understanding the regional and local geology can tell the designer a great deal about the relative risk of an individual site.

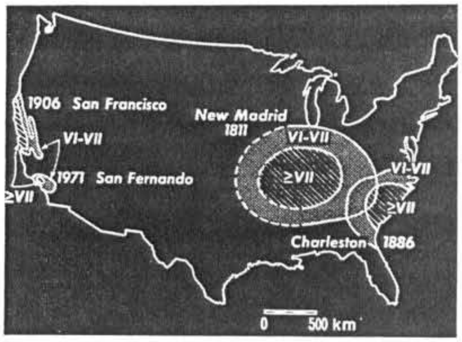


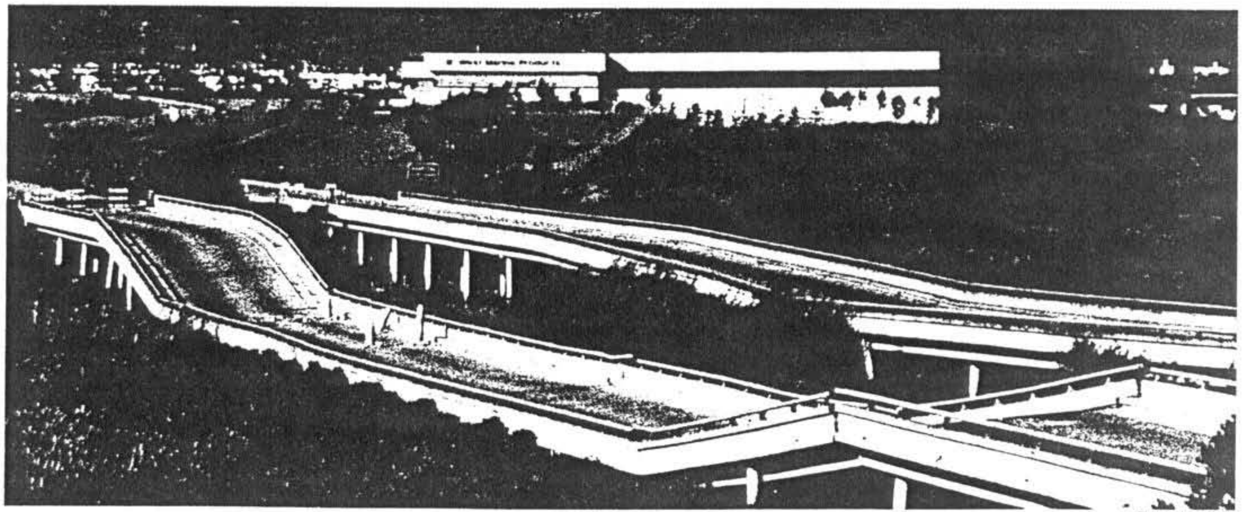
Figure 2.3: Comparison of isoseismals of large U.S. earthquakes

REGIONAL DAMAGE AND ITS IMPACT ON A SITE

Continued function and operation of a building depends on more than merely the performance of the structure. Damage to lifeline systems providing water, sewer, power, transportation and communication services can isolate a structure, cease operations or production, and leave the structure vulnerable to secondary hazards of fire and hazardous material releases. For buildings containing functions where power, water and/or communications is vital for continued operations or safety, analysis should address the vulnerability of regional lifelines serving the site. If access to the site or to regional transportation networks is critical for ongoing operations or for reaching and maintaining market deliveries, the designer should review the vulnerability of the regional transportation system. (Figure 2.4) While these issues cannot be addressed in building design, their identification for the clients will provide a basis for their understanding of the strengths and limits of a specific site, and for determining the need for back-up facilities, water and power sources, and communication systems that may prove critical to safety and post-earthquake response, recovery, and continued business operations.

Regional damage, well beyond the property line, can result in isolation of a facility from resources, market or employees, dislocation, and severe economic disruption, even without damage to the structure.

Figure 2.4: Ground failure occurred at this highway, overstressing column/slab connections.



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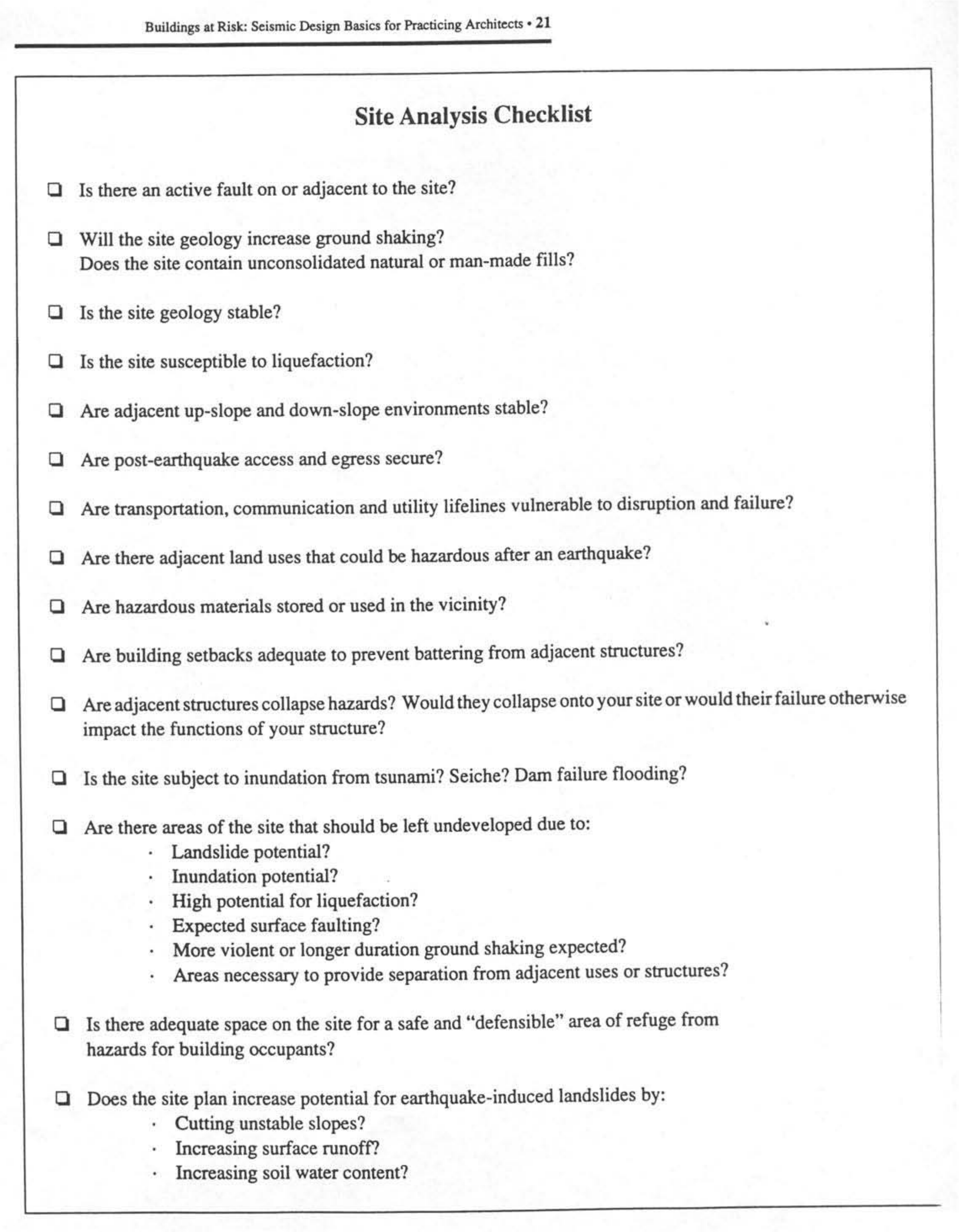
THE ARCHITECT'S ROLE IN SITE SELECTION AND EVALUATION

Only occasionally is the architect responsible for site selection. Most often, the architect is provided with a site by a client unaware of its vulnerability to seismic forces. The more traditional site analysis would include relevant information on zoning and planning restrictions on the site. A "seismic site analysis" should include an evaluation of local site conditions, adjacent hazards and regional geology, to assist the architect in briefing the client on the expected performance of the selected site, the survivability of transportation and access to the site, and the vulnerability of lifelines serving the site. This data can provide valuable insights for the client and design team in establishing design parameters and in defining expected seismic performance of the structure.

If, however, the architect participates in site selection, desired structural building performance and post earthquake function can be measured against expected site performance, life line survival and site access in determining the most appropriate location.

In either situation, a site analysis should include an assessment of the environment beyond the property line and include adjacent structures and site conditions that could "spill over" onto your site. (Figure 2.5) A complete analysis should address the issues identified in the Site Analysis Checklist.

Figure 2.5: Building adjacencies can have major impacts on performance during earthquakes. A large number of structures suffered pounding damage during the 1985 Mexico City event, leading in many cases to partial or full ollapse.



Site Analysis Checklist

☐ Is there an active fault on or adjacent to the site?

☐ Will the site geology increase ground shaking?
Does the site contain unconsolidated natural or man-made fills?

☐ Is the site geology stable?

☐ Is the site susceptible to liquefaction?

☐ Are adjacent up-slope and down-slope environments stable?

☐ Are post-earthquake access and egress secure?

☐ Are transportation, communication and utility lifelines vulnerable to disruption and failure?

☐ Are there adjacent land uses that could be hazardous after an earthquake?

☐ Are hazardous materials stored or used in the vicinity?

☐ Are building setbacks adequate to prevent battering from adjacent structures?

☐ Are adjacent structures collapse hazards? Would they collapse onto your site or would their failure otherwise impact the functions of your structure?

☐ Is the site subject to inundation from tsunami? Seiche? Dam failure flooding?

☐ Are there areas of the site that should be left undeveloped due to:
- Landslide potential?
- Inundation potential?
- High potential for liquefaction?
- Expected surface faulting?
- More violent or longer duration ground shaking expected?
- Areas necessary to provide separation from adjacent uses or structures?

☐ Is there adequate space on the site for a safe and "defensible" area of refuge from hazards for building occupants?

☐ Does the site plan increase potential for earthquake-induced landslides by:
- Cutting unstable slopes?
- Increasing surface runoff?
- Increasing soil water content?

Chapter 5: The Basics Of Seismic Codes

BUILDING CODES AND SEISMIC PROVISIONS

The first seismic building code to be developed in the United States was the seismic portion of the Uniform Building Code (UBC) published by the International Conference of Building Officials (ICBO) in California. The seismic provisions of the UBC were developed on a volunteer basis by the Structural Engineers Association of California (SEAOC). Currently, in addition to the UBC, the following are important seismic codes in use:

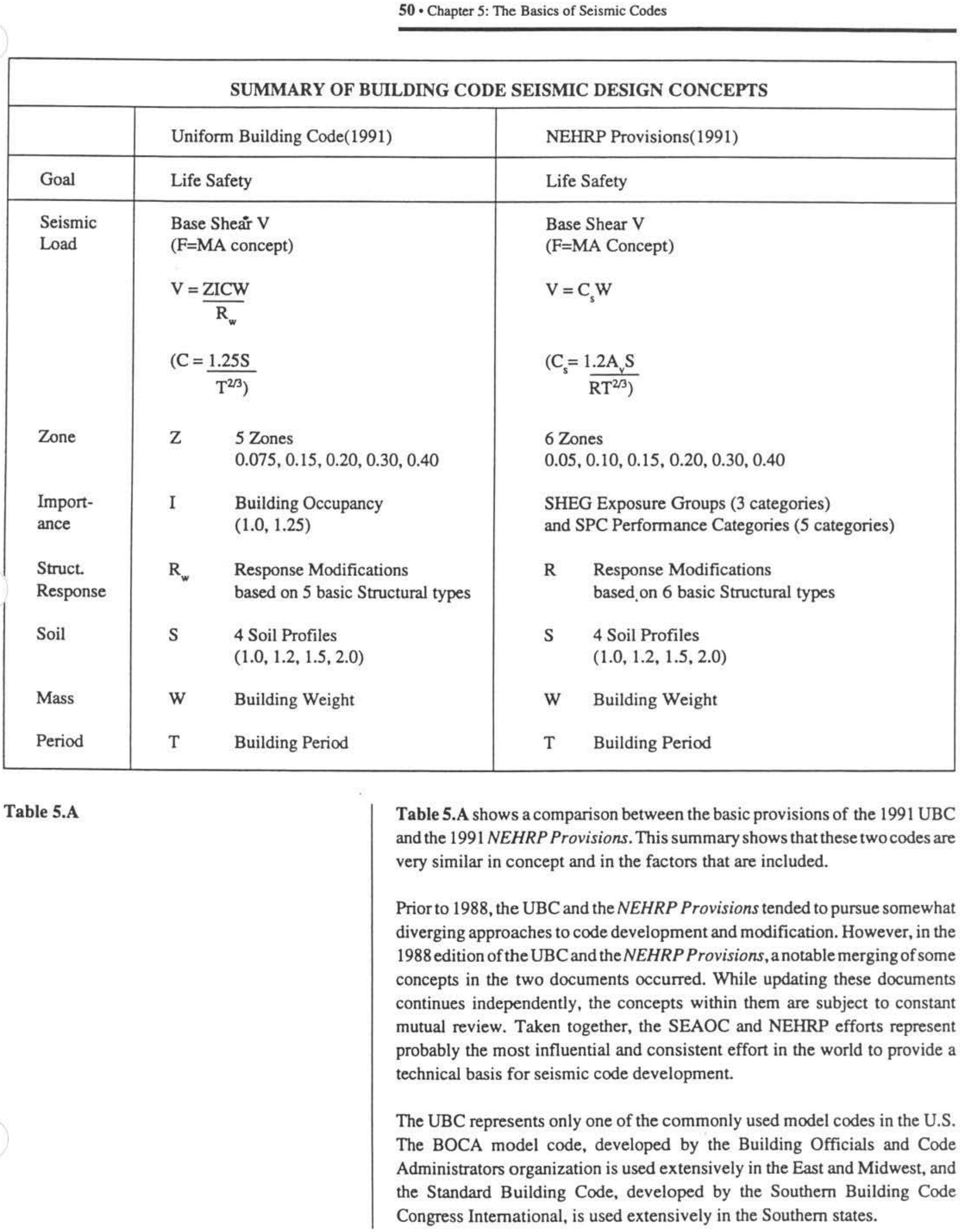
- BOCA National Building Code
- SBCCI Standard Building Code
- GSA (Federal Buildings)
- Tri-services (Department of Defense-Military)
- Title 24, California (Hospitals and Schools)
- Veterans Administration (Veterans Hospitals)
- State Historic Building Code (SHBC) [California]
- City of Los Angeles, Section 88 (Existing URM Buildings)
- Uniform Code for Building Conservation (UCBC)

Most of the codes listed above have the stated goal of maintaining life safety; only Title 24 (California) has a higher performance goal of damage control to maintain post-earthquake function in hospitals. The last three listings, which relate to existing buildings, permit lower design force levels than those required for new buildings. (Figure 5.1)

Starting in the mid-1970s the Federal Government initiated a research program to develop a state-of-the-art approach to a seismic code that would have nationwide applicability. This effort resulted in the 1978 publication of the ATC-3 document (named after the Applied Technology Council, the non-profit engineering research group that developed it). Subsequently, the document has undergone several revisions and is now known as the *National Earthquake Hazards Reduction Program: Recommended Provisions for the Development of Seismic Regulations for New Buildings* or the *NEHRP Provisions*. Published by the Building Seismic Safety Council in Washington, and updated on a 3-year basis, the *NEHRP Provisions* document is not a code, but a technical resource document to assist in code development. In format, language and content, however, the document is very similar to a seismic code.

Richard Eisner

Figure 5.1: Advances in building code seismic provisions are intended to ensure life-safety and prevent the types of failure and collapse that occur in pre-code buildings.



SUMMARY OF BUILDING CODE SEISMIC DESIGN CONCEPTS

	Uniform Building Code(1991)		NEHRP Provisions(1991)	
Goal	Life Safety		Life Safety	
Seismic Load	Base Shear V (F=MA concept) $V = \frac{ZICW}{R_w}$ $(C = \frac{1.25S}{T^{2/3}})$		Base Shear V (F=MA Concept) $V = C_s W$ $(C_s = \frac{1.2A_v S}{RT^{2/3}})$	
Zone	Z	5 Zones 0.075, 0.15, 0.20, 0.30, 0.40	6 Zones 0.05, 0.10, 0.15, 0.20, 0.30, 0.40	
Import-ance	I	Building Occupancy (1.0, 1.25)	SHEG Exposure Groups (3 categories) and SPC Performance Categories (5 categories)	
Struct. Response	R_w	Response Modifications based on 5 basic Structural types	R	Response Modifications based on 6 basic Structural types
Soil	S	4 Soil Profiles (1.0, 1.2, 1.5, 2.0)	S	4 Soil Profiles (1.0, 1.2, 1.5, 2.0)
Mass	W	Building Weight	W	Building Weight
Period	T	Building Period	T	Building Period

Table 5.A

Table 5.A shows a comparison between the basic provisions of the 1991 UBC and the 1991 *NEHRP Provisions*. This summary shows that these two codes are very similar in concept and in the factors that are included.

Prior to 1988, the UBC and the *NEHRP Provisions* tended to pursue somewhat diverging approaches to code development and modification. However, in the 1988 edition of the UBC and the *NEHRP Provisions*, a notable merging of some concepts in the two documents occurred. While updating these documents continues independently, the concepts within them are subject to constant mutual review. Taken together, the SEAOC and NEHRP efforts represent probably the most influential and consistent effort in the world to provide a technical basis for seismic code development.

The UBC represents only one of the commonly used model codes in the U.S. The BOCA model code, developed by the Building Officials and Code Administrators organization is used extensively in the East and Midwest, and the Standard Building Code, developed by the Southern Building Code Congress International, is used extensively in the Southern states.

Until recently, the two latter model building codes groups have lagged behind in the development of seismic codes, primarily because these model codes were used in areas of little perceived seismic hazard. Concern for the seismic hazard present in other states in the U.S. besides California has resulted in a new interest in the development and adoption of appropriate codes, an interest which the development of the *NEHRP Provisions* was intended to support. Consequently, both the BOCA model code and the Standard Building Code now incorporate slightly modified versions of the *NEHRP Provisions* in their model building codes. (Figure 5.2)

Thus, on a national basis, the seismic code issue is basically accommodated by variations of the two main technical documents; the *NEHRP Provisions* and the UBC (or, more precisely, the SEAOC provisions upon which it is based.)

Christopher Arnold

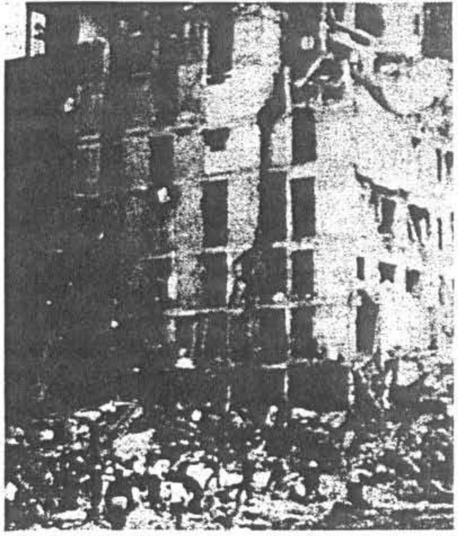


Figure 5.2: Seismic code provisions have undergone continuous development since the 1950's in response to both damaging earthquakes and to advances in engineering science.

APPLYING CODES

The primary purpose of seismic building codes is to provide a simple uniform method to determine the seismic forces for any location with enough accuracy to ensure a safe and economical design. The code needs to provide for approximate uniformity of results so that no building owner, building type, or materials supplier is unfairly discriminated against.

In Chapter 1 it was shown that the earthquake forces on a building can be referred back to the basic formula for inertial forces - *F equals MA*. *M* is easy to obtain by calculating the weight of the building. How about *A*, the acceleration?

The *NEHRP Provisions* provide a number of sets of maps of the United States: these provide contour lines, or color codes of the counties in each state, so that the entire country is divided into seven areas. (Figure 5.3 shows a small scale reproduction of one of the maps provided with the *Provisions*.) Each area in turn is equivalent to a number from *0.05 to 0.40* in steps of *0.05, 0.10, 0.15, 0.20, 0.30,* and *0.40*. These represent *accelerations* in percentages of G - so that 0.40 represents 40% of G. This is the *A* for the *F = MA* formula. It's not quite as simple as that, but nevertheless the relationship of the maps to the fundamental formula is quite direct and clear.

These maps reflect a number of assumptions. The general criterion is that the risk at any location has only a *10 percent probability of being exceeded in 50 years*, which translates into a *mean recurrence interval of 475 years*. This is a statistical number and not a prediction: the important thing is that the map is expressing a uniform risk, so that by looking at the different numbers you get an approximation of the relative risk among different regions of the country.

The *Provisions* state that, for most instances the horizontal force on the building can be represented as a horizontal shear force trying to push the base of the building across the ground where the building is attached to its foundation. This force is called the *base shear*, and a formula is provided for its estimation. Application of this formula is a key part of the code methodology and is called

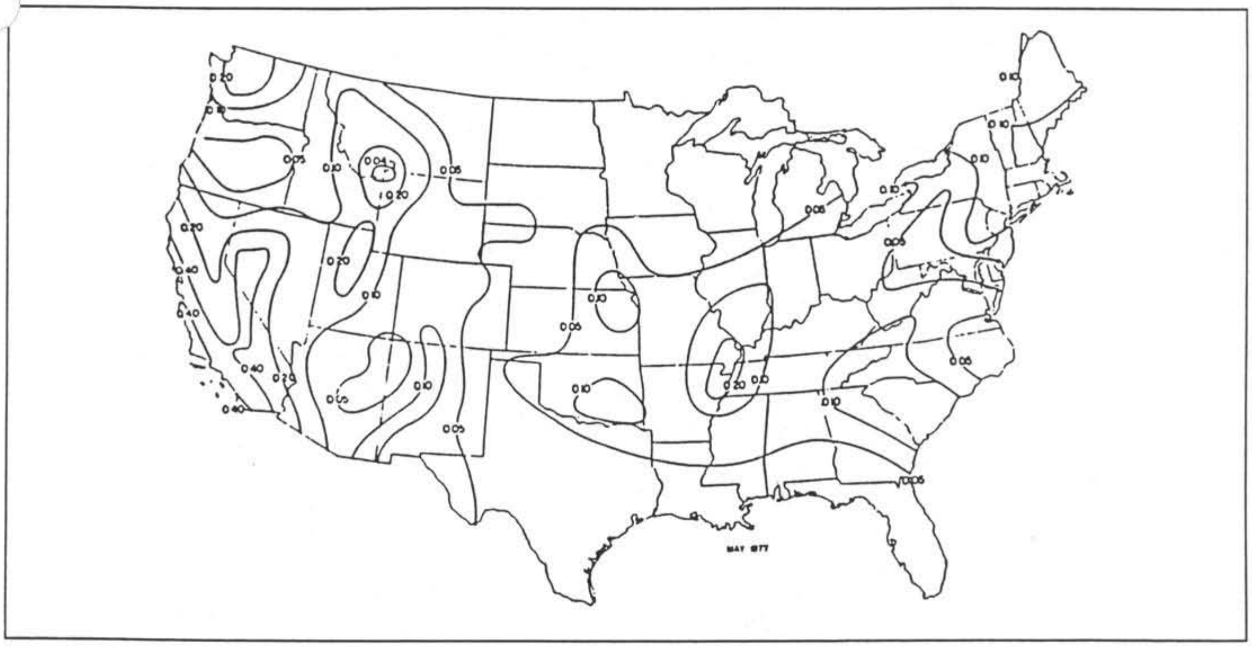


Figure 5.3: Contour map for coefficient A_a for the ontinental United States.*

the *equivalent lateral force procedure*. This general methodology is characteristic of all seismic codes throughout the world.

In the *Provisions* this formula is $\mathbf{V=C_sW}$ where:

$\mathbf{C_s}$ = the seismic design coefficient, which is related to an "expansion" of A, the acceleration number. The expansion adds other coefficients, or multipliers, which represent some of the other factors discussed in Chapter 1.

W = the building weight, which can easily be calculated.

$\mathbf{C_s = 1.2A_v\ S/RT^{2/3}}$

where A_v is obtained from the contour map.*

S is the Coefficient for *soil profile type* (i.e. relating to soil amplification). This is obtained from a table in the *Provisions*. The coefficient varies from 1 to 2.0. For poor ground, where the coefficient is 2.0, the acceleration number is multiplied by two, thus increasing the *design force* - the forces for which the building must be designed.

R is a *response modification* coefficient, relating to the type and ductility of the chosen structural system. R factors are also obtained from a table in the *Provisions*. This is a number from 1.25 to 8: it is a divisor, so it has the

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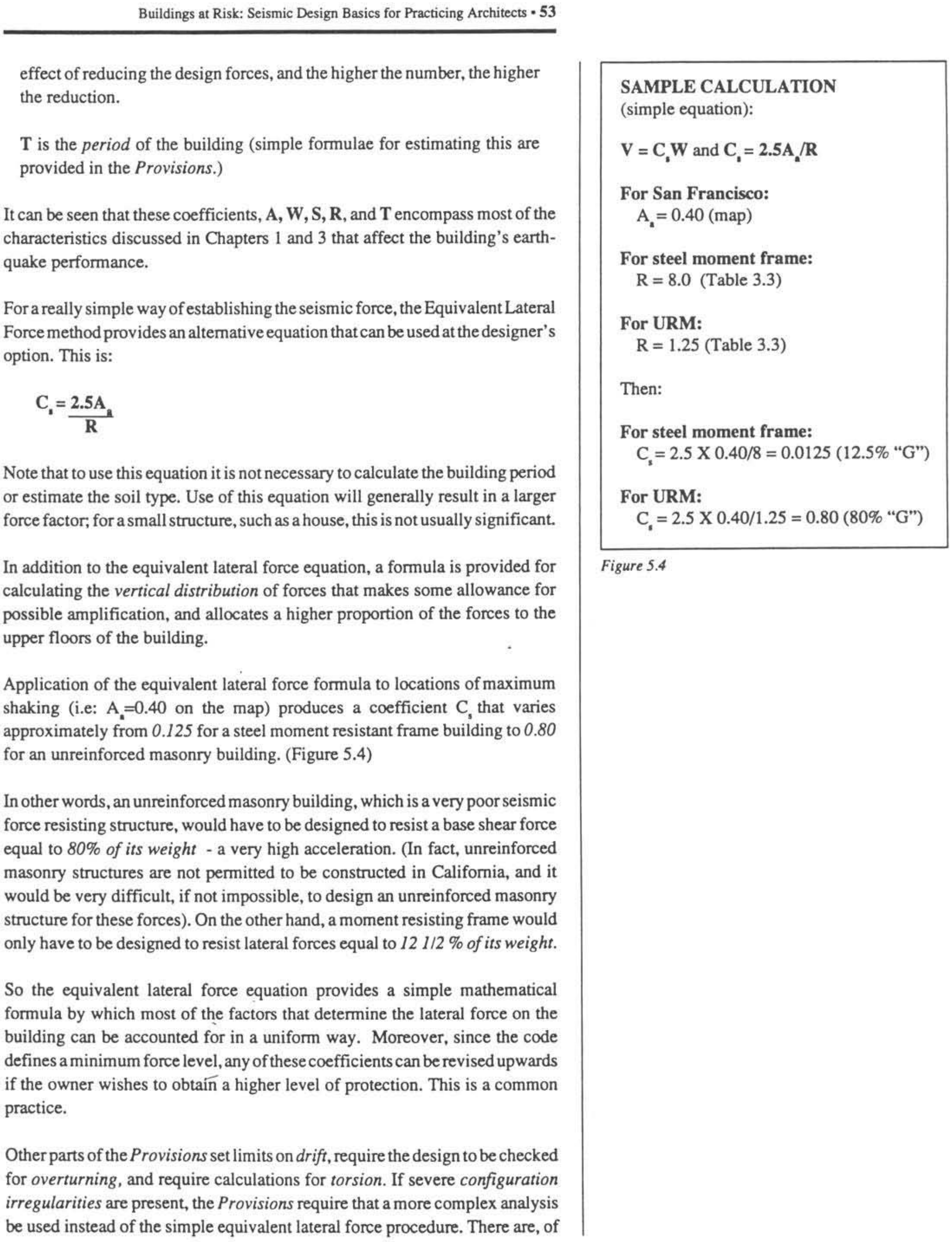
*A_v and A_a are two slightly different expressions of the acceleration factor used for design, and separate maps are provided for each in the *Provisions*.



effect of reducing the design forces, and the higher the number, the higher the reduction.

T is the *period* of the building (simple formulae for estimating this are provided in the *Provisions*.)

It can be seen that these coefficients, **A, W, S, R**, and **T** encompass most of the characteristics discussed in Chapters 1 and 3 that affect the building's earthquake performance.

For a really simple way of establishing the seismic force, the Equivalent Lateral Force method provides an alternative equation that can be used at the designer's option. This is:

$$C_s = \frac{2.5A_a}{R}$$

Note that to use this equation it is not necessary to calculate the building period or estimate the soil type. Use of this equation will generally result in a larger force factor; for a small structure, such as a house, this is not usually significant.

In addition to the equivalent lateral force equation, a formula is provided for calculating the *vertical distribution* of forces that makes some allowance for possible amplification, and allocates a higher proportion of the forces to the upper floors of the building.

Application of the equivalent lateral force formula to locations of maximum shaking (i.e: A_a=0.40 on the map) produces a coefficient C_s that varies approximately from *0.125* for a steel moment resistant frame building to *0.80* for an unreinforced masonry building. (Figure 5.4)

SAMPLE CALCULATION
(simple equation):

$V = C_sW$ and $C_s = 2.5A_a/R$

For San Francisco:
$A_a = 0.40$ (map)

For steel moment frame:
R = 8.0 (Table 3.3)

For URM:
R = 1.25 (Table 3.3)

Then:

For steel moment frame:
$C_s = 2.5 \text{ X } 0.40/8 = 0.0125$ (12.5% "G")

For URM:
$C_s = 2.5 \text{ X } 0.40/1.25 = 0.80$ (80% "G")

Figure 5.4

In other words, an unreinforced masonry building, which is a very poor seismic force resisting structure, would have to be designed to resist a base shear force equal to *80% of its weight* - a very high acceleration. (In fact, unreinforced masonry structures are not permitted to be constructed in California, and it would be very difficult, if not impossible, to design an unreinforced masonry structure for these forces). On the other hand, a moment resisting frame would only have to be designed to resist lateral forces equal to *12 1/2 % of its weight.*

So the equivalent lateral force equation provides a simple mathematical formula by which most of the factors that determine the lateral force on the building can be accounted for in a uniform way. Moreover, since the code defines a minimum force level, any of these coefficients can be revised upwards if the owner wishes to obtain a higher level of protection. This is a common practice.

Other parts of the *Provisions* set limits on *drift*, require the design to be checked for *overturning*, and require calculations for *torsion*. If severe *configuration irregularities* are present, the *Provisions* require that a more complex analysis be used instead of the simple equivalent lateral force procedure. There are, of course many other issues presented in the *Provisions* that are not reflected in this simplified presentation. Nevertheless, the essence of any seismic code philosophy resides in the equivalent lateral force formula, and its relationship to the basic principles that have been discussed can readily be seen.

PERFORMANCE OBJECTIVES

One issue currently the focus of considerable effort is that of attempting to define performance objectives for seismic design, and ultimately to embody these in guidelines and codes. Performance objectives are statements of the limits of damage which a structure will be expected to sustain when subjected to specified earthquake demands, expressed in terms of defined ground motion. Performance objectives are expressed in terms of the performance of both the structural and nonstructural components.

The Guidelines for the Seismic Rehabilitation of Buildings, now under development by the Building Seismic Safety Council, defines three performance levels. Collapse Prevention requires that all significant components of the gravity load-resisting system must continue to carry their demands, although significant risk of injury due to falling hazards may exist. Life Safety requires that, while considerable structural damage may have occurred, major structural and nonstructural components have not become dislodged, creating a threat to life: the risk of life-threatening injury is very low. Immediate Occupancy is a damage state in which only very limited damage may have occurred. Nonstructural damage is minimized such that basic access and life safety systems including doors, elevators, emergency lighting, fire alarms, and suppression systems remain operable if power is available. Minor clean-up could be required.

While the specific terms for these damage states, and others, may change as work on this document proceeds, the philosophy of recognizing the inevitability of damage is characteristic of all the current focus on performance.

Eric Elsesser

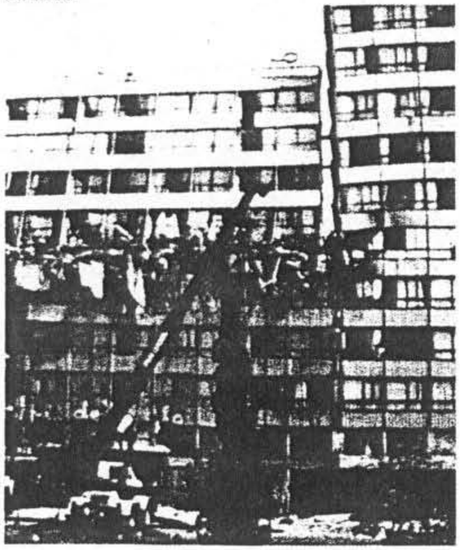


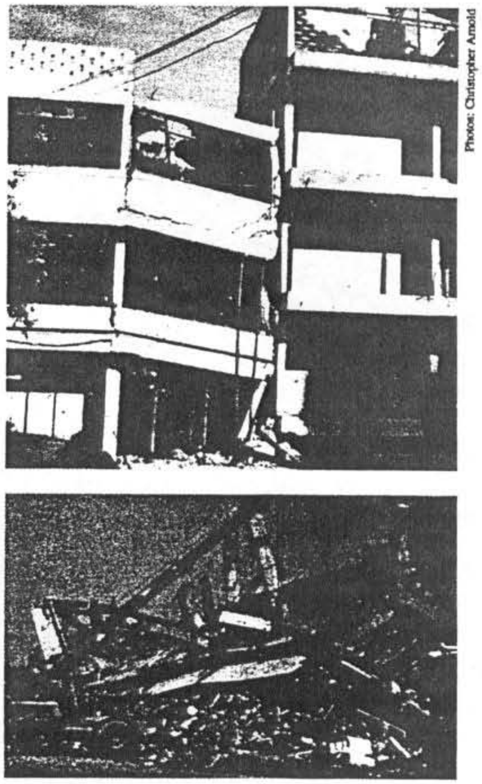
Figure 5.5: Executive Order 12699 requires adoption of seismic standards in the design of all new buildings used, purchased or constructed with Federal assistance. The purpose is to avoid failures, such as that pictured above and opposite, and to reduce risks to occupants.

PRESIDENTIAL EXECUTIVE ORDER

An important development in the nationwide regulation of seismic building standards was the enactment into law in January 1990 of Executive Order 12699. This order requires that methods be taken to *reduce risks to the lives of occupants of buildings leased for federal uses or purchased or constructed with federal assistance, to reduce risks to the lives of persons who would be affected by engineering failures of federally assisted or regulated buildings, and to protect public investments, all in a cost-effective manner.*

The order directed federal agencies to issue regulations or procedures by February 1993 that incorporate seismic safety measures for all federal buildings that are owned, leased, assisted, or regulated by the federal government.

The link between seismic safety requirements and the availability of federal funds for new building construction was expected to encourage local governments and private sector building designers and contractors to update their codes and practices. (Figures 5.5, 5.6 and 5.7)



Figures 5.6 and 5.7

Photos: Christopher Arnold

The order applies to any building located worldwide which is federally owned, lease constructed, leased (15 % or more of total space), regulated or financially assisted. This includes new construction financed with federal grants or loans, or federally insured or guaranteed loans or mortgages.

Individual federal agencies must ensure that building construction under their programs complies with the Executive Order. The Interagency Committee on Seismic Safety in Construction (ICSSC), which is a committee of federal agencies, recommends the use of seismic design and construction standards and practices equivalent to or exceeding those in the most recent (or immediately preceding) edition of the *NEHRP Provisions*.

The ICSSC determined that the following model building codes, including local codes that adopt and enforce these model codes in their entirety, are substantially equivalent to the *NEHRP Provisions*, and thus are appropriate for implementing the Executive Order.

- 1991 *Uniform Building Code* of the International Congress of Building Officials (ICBO)
- 1992 Supplement to the Building Officials and Code Administrators (BOCA) *National Building Code*, and
- 1992 Amendments to the Southern Building Code Congress (SBCCI) *Standard Building Code*.

Revisions of these model codes are considered appropriate for order implementation, as long as they are substantially equivalent to the latest version of the triennially published *NEHRP Provisions*. The order allows federal agencies to use local building codes if they, or the ICSSC, determine that the local codes provide adequately for seismic safety. Each federal agency must determine the steps that participants in its program must take to comply with the provisions of the Executive Order. FEMA has the responsibility of reporting every two years to the President and Congress on the execution of the order.

The implications of this Executive Order are far-reaching. In effect, the federal government is taking a leadership role in earthquake hazard mitigation by insisting that its own buildings, whether owned, leased or assisted, meet appropriate seismic standards. The results of the Executive Order will be watched with interest. Under normal rates of construction and retirement of buildings, a large proportion of federal buildings will be seismically resistant in 25 years.