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SEISMIC DESIGN OF SCHOOL BUILDINGS IN COLORADO AND OTHER LOW TO MODERATE HAZARD AREAS: IS THE INTERNATIONAL BUILDING CODE ADEQUATE?"

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ABSTRACT

Colorado has experienced significant historical earthquakes, the 1882 event being the most significant. The geological record indicates faults in Colorado have caused earthquakes as large as 7 to 7 ¼ in the past. Based on probabilistic seismic hazard analysis, the hazard is considered to be "low to moderate." Perhaps it is "negligible" for a small portion of the eastern half of the state. The short time period of historical recorded seismic data for Colorado results in a higher (epistemic) uncertainty than for areas with more data.

The performance of buildings in earthquakes is a function of their vulnerability to the hazard. As a societal risk, the resulting level of risk, or more appropriately, the desired level of safety for school buildings should be subject to close scrutiny given the consequences.

The use of "Seismic Design Category A" is allowed by the International Building Code for the design of buildings in areas of lowest seismic hazard. This provision is not appropriate for school buildings in low to moderate hazard areas. There is no differentiation by Occupancy Category if Seismic Design Category A is allowed. Also, the choice of the spectral response acceleration values below which the use of Seismic Design Category A is permitted throughout the United States is based on data from a single earthquake in California. The emphasis on soils type, the variability of the attenuation functions, and the impact of steeper gradients in the mapped values result in highly variable and changing seismic design requirements for areas such as the Front Range Urban Corridor of Colorado. As a result, the design of new school buildings may include little or no seismic resistance in areas where the earthquake hazard may not be well characterized. This cannot be an "acceptable risk," especially considering that schools are often used as post-earthquake emergency shelters. As a minimum, school buildings in low to moderate hazard areas need to provide a level of safety for students that includes design for the spectral response accelerations that are actually shown on the hazard maps.

Introduction

This paper will focus on the provisions of the 2006 (and 2009) International Building Code

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(IBC) and ASCE/SEI 7-05 (ASCE 7) for the seismic design of buildings, particularly school buildings, in areas of low to moderate seismic hazard. First we will consider the concept of risk and the parameters that define and affect risk. Risk may be characterized as the product of hazard and vulnerability (Nordenson and Bell, 2000). Risk exists in the physical intersection of areas subject to earthquakes with areas having population and buildings. The USGS prepares the ground motion hazard maps. These spectral accelerations are then used to design buildings in populated areas. Risk is a function of a building's vulnerability to the ground shaking. A moderate event in an area where buildings have not been designed to resist earthquakes may result in more damage than a larger event in an area with highly seismic resistant construction.

Although not discussed in detail here, other important and relevant topics are the concepts of "societal risk" (Malhotra, 2009) and "acceptable risk" (May, 2001). The building code seismic requirements are not differentiated based on the density of population affected nor on the risk tolerance of the individual or of society. However, the seismic safety of school buildings can really only be addressed in the context of a societal risk. What is the acceptable risk for school buildings in an earthquake? Are the complicated provisions of building codes providing an adequate measure of risk mitigation for schools? Do the politicians, school administrators and even designers and building officials have an adequate understanding of the implications and ambiguities of the code to determine whether the risks inherent in the use of the provisions are in any way acceptable?

Colorado's rapidly growing Front Range Urban Corridor provides an example of the sensitivity of the building code seismic design parameters to the variation in soil conditions and the significance of the choice of a lower limit for the use of the Equivalent Lateral Force procedures.

Code Background

Areas of low seismicity have been addressed in somewhat different ways in the past. The seismic provisions of the Uniform Building Code (UBC) were based on the Structural Engineers Association of California "Blue Book," the maps of the USGS and the work of the ATC. The maps were "zone maps" and established the geographical limits of the various zones (0 to 3 or 0 to 4).

Zone 0 was for areas of the lowest seismicity. In the UBC these areas were not required to provide design for seismic forces. However, the limits of Zone 0 did vary somewhat over time, the 1979 UBC having minimal areas of Zone 0 based on Algermissen's 1969 map. The later versions of the UBC have a broader area of Zone 0 starting with the 1988 UBC which was based on the ATC 3-06 document (Algermissen, 1983). The 1988 UBC map is shown in Figure 1. The yellow boundary is the Zone 0 boundary from the map itself. The red boundary is the current expanded boundary allowing for the use of Seismic Design Category A, based on Site Class B spectral acceleration values of $S_S \leq 0.25$ and $S_1 \leq 0.10$ which are discussed later.

Codes other than the UBC, including ASCE 7 and all the IBC versions have been based directly on the NEHRP documents. Zones have not been titled as such in the NEHRP documents. The parameters A_v, the effective peak velocity related acceleration and A_a, the effective peak acceleration were mapped on separate maps. In the 1988 NEHRP Provisions areas with values of $A_v < 0.05$ were considered to be "Seismic Performance Category A" and no seismic design was required although minimum requirements were give for certain connections. In the 1997 NEHRP Provisions, the Index Force Method was added for "Seismic Design Category A" (changed from Seismic Performance Category A). The Index Force Method required 1% of gravity loads, plus 1% of some live loads, to be applied as a lateral load. The 1997 NEHRP provisions were also the first to apply soil factors in the determination of Seismic Design Category. Prior versions and all versions of the UBC did not consider soil conditions until after the Seismic Design Category (or

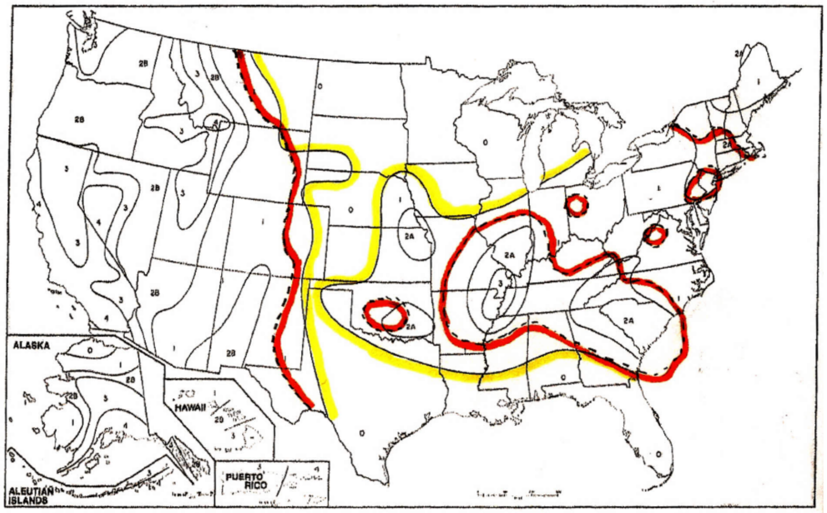


Figure 1. 1988 UBC Zone Map

Zone) had been determined based only on spectral values of ground motion. The procedure of using soil factors F_A and F_V to determine the Seismic Design Category has carried on into the later NEHRP documents and all the editions of the IBC. ASCE 7-05 has also dropped the requirement to include any live or snow loads in the calculation of the 1% lateral force.

Current Code Provisions

The IBC references ASCE 7 for seismic design. The definition of "Seismic Design Category" is as follows (ASCE 7): "A classification assigned to a structure based on the Occupancy Category and the severity of the design earthquake ground motion at the site." The assignment of Seismic Design Category is not based on Occupancy Category for SDC A. Seismic Design Category A does not really meet the definition of a Seismic Design Category.

The process for determining the Seismic Design Category per the IBC is as follows:

1. Find the short period, S_S, and one second, S_1, spectral response accelerations from the maps.
2. Determine whether the structure is exempt from some or all of the IBC Seismic requirements. For areas where $S_S \leq 0.15$ and $S_1 \leq 0.04$ (ASCE 7-05, Section 11.4.1) or where $S_{DS} < 0.167$ and $S_{D1} < 0.067$ (ASCE 7-05, Tables 11.6-1 and 2), a structure need only comply with the requirements for SDC A.
3. Determine the Site Class. The Site Class can vary from Site Class A (hard rock) to Site Class F (very poor soils). Site Class C is quite common along the Front Range of Colorado. The Site Class may have more influence on the seismic design parameters than the variation in the ground motion values. Geotechnical testing can become critical in this determination.
4. Determine the design spectral response accelerations for short periods, S_{DS}, and for 1-second periods, S_{D1}. These are a function of S_S and S_1, and of the Site Class.
5. Determine the Occupancy Category. Occupancy Category IV is for essential facilities. Schools with over 250 students are currently considered Occupancy Category III.
6. Next, Tables 1 and 2 are used to determine the Seismic Design Category. These are based on S_{DS} and S_{D1} and are also supposed to be a function of the Occupancy Category. The more stringent of the two tables determines the SDC.

Table 1. Seismic Design Category
(ASCE 7-05, Table 11.6-1)

Value of S_{DS}	Occupancy Category		
	I or II	III	IV
$S_{DS} < 0.167$	A	A	A
$0.167 \le S_{DS} < 0.33$	B	B	C
$0.33 \le S_{DS} < 0.50$	C	C	D
$0.50 \le S_{DS}$	D	D	D

Table 2. Seismic Design Category
(ASCE 7-05, Table 11.6-2)

Value of S_{D1}	Occupancy Category		
	I or II	III	IV
$S_{D1} < 0.067$	A	A	A
$0.067 \le S_{D1} < 0.133$	B	B	C
$0.133 \le S_{D1} < 0.20$	C	C	D
$0.20 \le S_{D1}$	D	D	D

7. The engineer is then required to design the structure for an equivalent lateral force that is derived from the ground motion contours of the map, the natural period of the structure, and considerations of ductility and occupancy, unless SDC A is allowed. If SDC A is allowed, the engineer need only design for 1% of gravity as a lateral load with no consideration of these other parameters. The 1 % value is not derived from the hazard maps.

Limitations of Seismic Design Category A

The IBC does not differentiate among Occupancy Categories for SDC A. Where SDC A is allowed, ordinary structures are treated the same as essential facilities such as hospitals, fire stations, emergency shelters, etc. For SDC A there is no requirement for a linear or exponential increase in the vertical distribution of the seismic forces with increasing height. The 1% is applied at each level. There is also no limitation on the height of a building if the site qualifies for SDC A. There is no differentiation of regular and irregular structures when using SDC A. When computing service loads, or in any comparison with wind loading, the earthquake loads, including the Index Force method, are to be multiplied by 0.7. Therefore, the 1% value is further reduced to 0.7% when designing for foundation overturning and soil pressure criteria.

The 1% value has been represented as a "stability parameter," but actual structural stability is not achieved simply by designing for a 1% of the vertical load as a lateral force. The following are excerpts from the 2003 NEHRP Provisions Commentary:

> "The 1 percent value has been used in other countries as a minimum value for structural integrity. For many structures, design for the wind loadings specified in the local building codes normally will control…However, many low-rise, heavy structures or structures with significant dead loads resulting from heavy equipment may be controlled by the nominal 1 percent acceleration."

> "The selection of 1 percent of the building weight as the design force for Seismic Design Category A structures is somewhat arbitrary. This level of design lateral force was chosen as being consistent with prudent requirements for lateral bracing of structures to prevent inadvertent buckling under gravity loads and also was believed to be sufficiently small as to not present an undue burden on the design of structures in zones of very low seismic activity."

New school buildings are often low-rise buildings, with large footprints relative to height. If the 1% force were to govern over wind, then why not use the actual mapped values since seismic is then the governing design condition? The selection of 1 % being somewhat arbitrary it is also apparent that any determination of an "undue burden on the design" is also arbitrary.

In what appears to be an error, ASCE 7-05 includes a requirement for a vertical seismic load effect when designing for a lateral force of only 1%. Section 12.4.2.2, Exception 1, allows the vertical effect to be taken as zero "where $S_{DS} \leq 0.125$." Since SDC A is allowed for values of $S_{DS} < 0.167$ the code is saying that a vertical effect should be included for $0.125 < S_{DS} < 0.167$. This is an indication that attention to detail can fall off somewhat for code requirements in the lower seismic regions.

Colorado Seismicity and the NEHRP regions

Colorado's largest historical earthquake was the November 7, 1882 event which occurred when the population was very sparse. No instruments were then in use to develop magnitudes. Based on felt reports and correlation to Modified Mercalli intensities, the magnitude has been estimated at 6.6 ± 0.6 (Spence, et al). The location of this event, which has been the subject of much debate, appears to be in the northern Front Range west of Fort Collins (Kirkham and Rogers, 1986 and Spence, et al). Although included in the USGS maps as a contributing earthquake, the methodology used to include the 1882 earthquake has resulted in no significant effect on the hazard maps for Colorado as a result of its inclusion.

Colorado is one of only fourteen States that have documented historical earthquakes of magnitude 6.0 or greater. (Stover and Coffman, 1993). Four hundred and seventy-seven earthquakes have been felt or have had magnitudes of 2.0 or greater between 1870 and 1996. (Kirkham and Rogers, 2000). There are over 90 potentially active faults in Colorado (Widmann, et al) but only three have been individually included in the USGS maps. The inclusion of specific faults in the modeling has a significant effect on the hazard analysis. The Cheraw fault is a major contributor. (Crone, et al, 1997).

The 1960's Rocky Mountain Arsenal earthquakes, just northeast of Denver, were not included in the earthquakes contributing to the USGS hazard maps. They were probably induced by the deep injection of waste fluids at the Arsenal. These events included the Front Range's largest instrumented earthquake, a 5.3M in August 1967. A 4.1M earthquake occurred in the Arsenal area in April 1981. Only those earthquakes that occurred near the Arsenal between 1962 and 1970 are considered to have been induced by fluid injection (Charlie, et al, 2002). The 1981 earthquake was included in the earthquakes contributing to the USGS hazard maps.

The 2003 NEHRP Provisions Commentary states that "Structures in areas with extremely low seismic risk need only comply with …Seismic Design Category A." NEHRP defines three seismic regions based on fault sources and seismicity. They are:

1. Regions of negligible seismicity with very low probability of collapse of the structure.
2. Regions of low and moderate to high seismicity, and
3. Regions of high seismicity near known fault sources with short return periods.

For brevity, we will refer to the NEHRP seismic regions as Regions 1, 2 and 3. Is the Colorado Front Range an area with "extremely low seismic risk?" and of "negligible seismicity"? Around 80% of Colorado had been considered to be UBC "Zone 1" prior to the IBC 2000. How has the characterization of the hazard changed so as to warrant a decrease in seismic design requirements? Zone 1 UBC base shear coefficients have always been well in excess of 1% g for Colorado. The calculated base shear coefficients of the IBC are much higher than 1% g unless SDC A is used. UBC coefficients ranged from about 3.5% to 7.5% for an R_w of about 5.5 and varying values of I, the importance factor. Similarly for the IBC, if SDC A is not used, short period coefficients vary from 3% to 8% for an equivalent R of 4 and varying values of Site Class and of the importance factor. Calculations of these values are not provided here.

Region 2 takes in a lot of ground, literally and figuratively. The NEHRP Commentary acknowledges that there have been different opinions as to how the low seismicity areas of Region 2 are to be handled. One recommendation is to increase the Region 1 area to get the low seismicity area out of Region 2. Another is to require a higher minimum level of ground motion for the low seismicity areas in Region 2. The relevancy of this discussion to Colorado is that Colorado has historically been primarily in Region 2 although in the low seismicity area, at least for most of the state. The discussion also emphasizes the potentially variability of the boundary for Region 1. Some think that the design for the ground motion levels of the low seismicity areas in Region 2 may not be meaningful. If so, then how can the 1% design be meaningful?

Region 1 has been defined by NEHRP for Site Class B as being any area where $S_S \leq 0.25$ and $S_1 \leq 0.10$. The boundaries of Region 1 for Site Classes C and D are then determined by applying the site coefficients, as shown below, and keeping the same upper limit of $S_S \leq 0.25$ and $S_1 \leq 0.10$. As a result there is effectively a different boundary for each Site Class. Maps of these boundaries are not published but the boundaries can be calculated.

NEHRP has made the choice of $S_S \leq 0.25$ and $S_1 \leq 0.10$ as the boundary between Regions 1 and 2 based on instrumental recordings during the Northridge earthquake and their correlation to observed damage and Modified Mercalli Intensities. Also, Region 1 areas are stated to be areas where the seismic hazard is controlled by earthquakes with $M_b \leq 5.5$. The Front Range of Colorado appears to be a borderline situation, especially considering the 1882 earthquake. Although the research from Northridge is valuable, the application of these boundaries to the entire United States may be too "broad a brush." Certainly the seismic resistance of the majority of existing buildings in the United States is lower than those of southern California.

Let's see how the Colorado Front Range structural design requirements develop from the mapping. Using the values of F_A and F_v from the IBC tables and the IBC equations for S_{DS} and S_{D1}, the values of S_S and S_1 corresponding to the SDC breakpoints can be back calculated. The results calculated from equations (5) through (8), are shown in Table 3:

$$S_{DS} = 0.167 = 2/3\ F_A\ S_S \quad (5)$$
$$S_S = 0.25 / F_A \quad (6)$$
$$S_{D1} = 0.067 = 2/3\ F_V\ S_1 \quad (7)$$
$$S_1 = 0.10 / F_V \quad (8)$$

Equations 6 and 8 determine the breakpoints discussed in the NEHRP Commentary.

Table 3. SDC A to SDC B breakpoint as a function of soil and spectral values

Site Class	F_A	S_s (for SDC B or higher)	F_V	S_1 (for SDC B or higher)
B	1.0	0.25	1.0	0.10
C	1.2	0.209	1.7	0.0591
D	1.6	0.157	2.4	0.042

For Front Range cities, the IBC will allow the use of SDC A for any Site Class B (rock). The shaded values for Site Class C are of particular interest. S_S and S_1 values of for twelve Front Range cities are shown. There are a significant amount of Site Class C conditions along the Front Range. See Figure 7. For Class C sites, the Seismic Design Category requirements have the potential to toggle back and forth along the Front Range as shown in Table 4. The more stringent of the two entries for S_S and S_1 determines the SDC for a given city.

Table 4. Selected Front Range spectral acceleration values

	2000 / 2003 IBC		2006 / 2009 IBC					
	1996 NSHMP		**2002 NSHMP**		**2008 NSHMP**		**2012 IBC**	
City	S_S	S_1	S_S	S_1	S_S	S_1	S_S	S_1
Aurora (80011)	0.186	0.057	0.207	0.055	0.169	0.048	0.168	0.056
Boulder (80302)	0.233	0.061	0.239	0.059	0.207	0.053	0.207	0.062
Castle Rock (80104)	0.192	0.059	0.216	0.057	0.184	0.051	0.182	0.059
Colo Springs (80903)	0.18	0.06	0.210	0.059	0.185	0.052	0.182	0.061
Denver (80202)	0.199	0.058	0.220	0.057	0.183	0.050	0.182	0.059
Ft. Collins (80521)	0.212	0.058	0.226	0.057	0.189	0.051	0.190	0.059
Golden (80401)	0.222	0.061	0.234	0.059	0.198	0.052	0.198	0.061
Greeley (80620)	0.18	0.054	0.194	0.052	0.155	0.046	0.156	0.054
Lakewood (80226)	0.211	0.060	0.226	0.058	0.190	0.052	0.190	0.060
Littleton (80120)	0.2	0.059	0.222	0.058	0.187	0.051	0.186	0.059
Pueblo (81001)	0.167	0.059	0.190	0.059	0.165	0.052	0.164	0.060
Trinidad (81082)	0.208	0.059	0.243	0.068	0.345	0.073	0.334	0.086
Average	0.199	0.059	0.219	0.058	0.196	0.053	0.195	0.061
Variation of the Average from Table 3 Site Class C breakpoint values	-4.6%	-0.6%	4.8%	-1.7%	-5.9%	-11.2%	-6.6%	3.8%

The average values of Table 4 are very close and in some cases virtually the same as the Site Class C shaded breakpoint values in Table 3. Thus very small variations in S_S or S_1 will determine whether SDC A or SDC B is used. For each entry in Table 4, the SDC for Site Class C is either A or B. The 2012 IBC (2009 NEHRP, 2010 ASCE) values for the one-second response are significantly higher than those given in the 2008 NSHMP. This code development decision results in SDC B for five of the cities that would otherwise use SDC A.

The Trinidad values given in the 1996 maps are almost exactly on the breakpoints. A swarm of earthquakes occurred during 2001 near Trinidad. Seismic activity has continued in the Trinidad area, including the M = 3.8 earthquake on January 18, 2010. The 2008 NSHMP short period spectral values have increased by 66% from the 1996 numbers and the one-second values by 25%. When any significant seismic activity can alter the mapping this quickly shouldn't there be a buffer against the transition boundary? Otherwise, SDC A is used and the USGS hazard maps are ignored based on variations at the 3rd decimal place of the spectral values. Remember we are looking at mapped accelerations that are intending to reflect a 2500 year MRI. These mapping changes occurred over a decade.

Figures 2 through 5 indicate the relatively steep gradient for the three Site Class ground motion acceleration boundaries in Colorado. The variation from map to map and code to code can result in inconsistent seismic design requirements for the Front Range and even for the mountains of Colorado. The differences between the Site Class B map for Region 1 and the Zone

0 map of the older codes is shown in Figure 1. The red boundary is representative of the 2006 IBC combined boundary when using the most restrictive of the $S_S = 0.25$ and $S_1 = 0.10$ contours for Site Class B soils. The area in the United States that is allowed for SDC A, based on Site Class B, is much larger than was allowed for Zone 0 and is much larger than it would be if using $S_S \leq 0.15$ and $S_1 \leq 0.04$ alone. The Zone map was not a function of soil type. The $S_S = 0.15$ and $S_1 = 0.04$ contours are essentially the breakpoint values for Site Class D. In the IBC, without regard to Site Class, the $S_S = 0.15$ and $S_1 = 0.04$ contours may be used (ASCE 7, Section 11.4.1).

Figure 2. 2002 NSHMP S_S Map

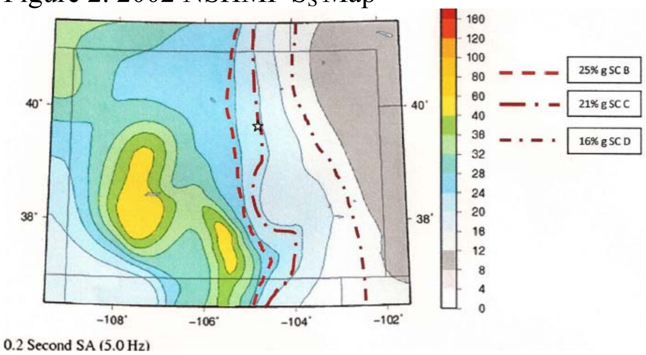


Figure 3. 2008 NSHMP S_S Map

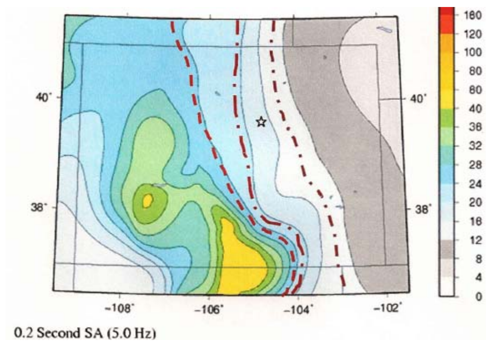


Figure 4. 2002 NSHMP S_1 Map

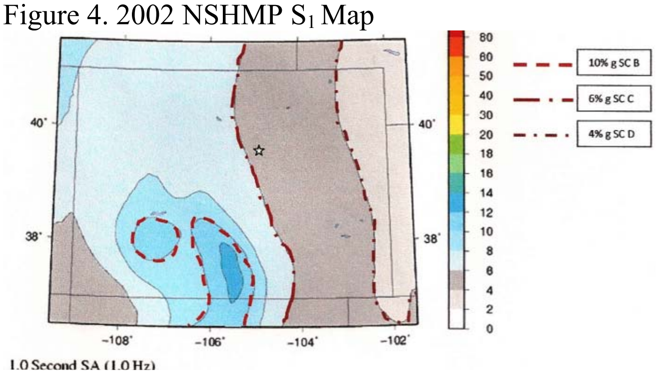
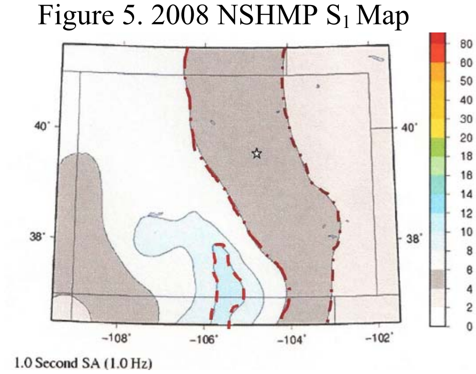


Figure 5. 2008 NSHMP S_1 Map



Although the codes do not consider population, it is important for real risk assessment. See Figure 6. The population centers of Colorado are primarily along the Front Range Urban Corridor. There are a lot of people affected by decisions on the use of soil type and the breakpoint values of ground acceleration in seismic design. Figure 7 shows a generalized representation of the predominant Soil Classes in Colorado based on estimates of the shear wave velocity, V_{S30}, averaged over 30 meters of depth. Refer again to Figures 2 through 5 and Table 3. The Class C breakpoint contours, $S_S = 21\%$ and $S_1 = 6\%$ are located in high population areas with predominantly Class C soils. Without code changes or local amendments, if these contours keep moving west, more new buildings will have increased potential for seismic vulnerability.

If $S_S = 0.15$ and $S_1 = 0.04$ are used alone as the breakpoint contours between SDC A and B, the boundary is maintained well into eastern Colorado at about the location of the former Zone 0 to Zone 1 boundary. This is clearly a more conservative approach than is currently being taken. Even so, it is not overly conservative. The Cheraw fault is in immediate proximity to both the $S_S = 0.15$ and $S_1 = 0.04$ contours.

The City and County of Denver has chosen to not allow the use of SDC A at all for any buildings and structures. The amendment has been in place from the first adoption of the IBC.

Figure 6. Colorado population density

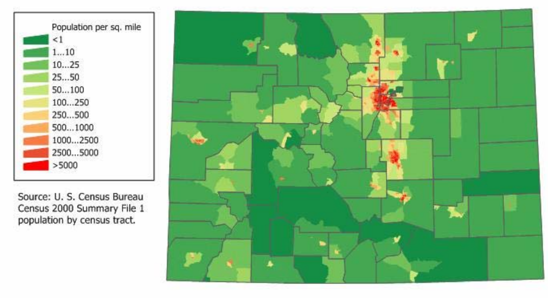
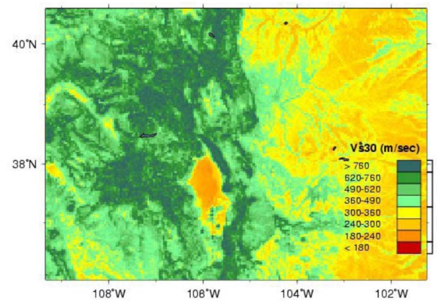


Figure 7. V_{S30} and Site Class



Occupancy Category of Schools

The risk associated with the use of Seismic Design Category A is of particular concern in the case of schools. Per Tables 1 and 2, no differentiation is made among Occupancy Categories for the design acceleration values for which Seismic Design Category A has been determined to be allowed. The Colorado Earthquake Hazard Mitigation Council (CEHMC) has recommended to the State of Colorado that Seismic Design Category A not be used for public school buildings in Colorado. The CEHMC's recommendation reads in part as follows:

> "The International Building Code Seismic Design Category A shall not be used for design of schools in Colorado. Schools in Colorado shall be designed for a minimum of Seismic Design Category B. In addition, where the code would otherwise allow the use of Seismic Design Category B, the design requirements for the school shall be increased to Seismic Design Category C, as a minimum. The exemptions for non-structural attachments as allowed by ASCE 7-05: 13.1.4, or by ASCE 7-02: 9.6.1, shall not apply to schools."

Similar concerns have prompted the Western States Seismic Policy Council to consider a policy recommendation for the seismic design of new schools. In review at the time of this paper, the policy would require schools to be increased from Occupancy Category III to IV and require a minimum of Seismic Design Category C. Schools are often used as post-earthquake emergency shelters. These concerns extend beyond the low to moderate seismic regions.

Conclusions

The use of Seismic Design Category A and its 1% requirement where ASCE 7-05 Section 12.8 would require many times higher equivalent lateral force does not transfer the USGS research results into engineering practice per ATC-35 (Applied Technology Council, 1994). The engineering community is not encouraging better maps and more thorough ground motion monitoring when we do not use the mapped values for an increasingly large part of the country.

If Seismic Design Category A is to be used it should be used only in areas that have truly negligible seismicity. The exemptions for non-structural attachments, as allowed by ASCE 7-05 Section 13.1.4 should not be allowed for schools in Seismic Design Category B or higher.

The ASCE 7 (and corresponding IBC 2006/2009) Tables should be revised as follows. These revisions eliminate the use of Seismic Design Category A based on Site Class:

Table 5. (Revision of ASCE 7-05, Table 11.6-1)

Value of S_{DS}	Occupancy Category		
	I or II	III	IV
$S_{DS} < 0.33$ *	B	B	C
$0.33 \le S_{DS} < 0.50$	C	C	D
$0.50 \le S_{DS}$	D	D	D

Table 6. (Revision of ASCE 7-05, Table 11.6-2)

Value of S_{D1}	Occupancy Category		
	I or II	III	IV
$S_{D1} < 0.133$ *	B	B	C
$0.133 \le S_{D1} < 0.20$	C	C	D
$0.20 \le S_{D1}$	D	D	D

*Footnote to Tables 5 and 6:
Structures may be assigned to Seismic Design Category A per the criteria of ASCE 7-05 Section 11.4.1 ($S_S \le 0.15$ and $S_1 \le 0.04$) based only on the mapped spectral response accelerations, S_S and S_1.

Acknowledgments

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