SNOW AND EARTHQUAKE LOAD COMBINATION CONSIDERING SNOW ACCUMULATION

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ABSTRACT:

In certain parts of the USA, both earthquake and snow hazards may be significant. Turkstra's rule is commonly used for load combinations. However, the rule may not be acceptable for structures that are exposed to both snow and earthquake loads that assume a significant level. In this paper, a hazard simulation computer program (HASP) is developed and Monte Carlo Simulation is performed to investigate such cases. Reliability indexes for a one-story structure are evaluated in terms of different snow load factors, including the current code required snow load factor 0.2. The simulation results show that a snow load factor of 0.2 might lead to slightly lower reliability for seismic design in high snow load area.

KEYWORDS: Earthquake, multi-hazard, reliability index, snow loads, stochastic process

1. INTRODUCTION

In some areas of the USA, such as the northeast, northwest, and some mountainous areas, snow loads last over 5 months per year. At the same time, moderate to high seismic loads are possible for these sites. Given such load conditions, the snow load factor to be used in seismic design is an important question.

Turkstra's rule is the basis of the load combination schemes in ASCE 7-05 (ASCE 2006). The snow and earthquake load combination is shown by Eq. (1), in which the earthquake load E takes on a factor of unity, whereas the snow load S takes on a factor of 0.2.

$$1.2D + 1.0E + L + 0.2S \tag{1}$$

Ellingwood and Rosowsky (1996) claimed that this rule is not conservative because chances are that neither the seismic load nor the snow load assumes its maximum value but rather that both assume a significant value. Then they used probabilistic models to investigate 9 cases and conclude that a snow load factor of 0.2 (approximately) is sufficient for a wide variety of site conditions. However, in their simulation the snow accumulation phenomenon was not considered.

Snow and earthquake load combination has been studied (O'Rourke and Speck 1992; Ellingwood and Rosowsky 1996). However, none of those studies considered the snow accumulation phenomena, which is typical for a high snow load area. In order to investigate whether a snow load factor of 0.2 holds true when snow accumulation is considered, in this paper, the Filtered Poisson Process (FPP) is used to simulate the snow accumulation phenomena. Earthquake and snow load simulations are realized by a computer program based Monte Carlo Simulation (MCS). Then the appropriate value of snow load factor, to be used in seismic design for high snow load area, is investigated.

2. SNOW HAZARD MODEL

The Bernoulli and Poisson pulse processes have been used to simulate the snow load (Turkstra and Madsen 1980; Wen 1990; Liu and Bulleit 1995; Mori, Kato et al. 2003). In these two models, the snow load is simulated by a series of independent events with a constant duration, as shown in Fig. (1). However, these models are not capable of simulating the snow accumulation phenomenon which is illustrated in Fig. (2). In order to consider the snow accumulation the FPP is used to simulate ground snow load. A generic FPP can be expressed by Eq. (2), in which, $N(t)$ is the number of events in the time interval $(0, t)$ and has a Poisson distribution with a rate of $\lambda_s(t)$ given by $E[N(dt)] = \lambda_s(t)dt$; $\{Y_k\}$ are a family of independent and identically distributed (IID) variables, which constitute the amplitudes of the Poisson events; and t_k and τ_k are the occurring time and duration of the kth event. $\{\tau_k\}$ are a family of IID variables that are independent of other variables, and $S(\cdot)$ is the step function defined by Eq. (3).

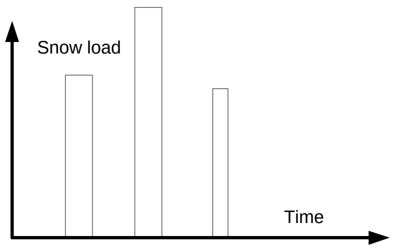

Figure 1 pulse process simulated snow load

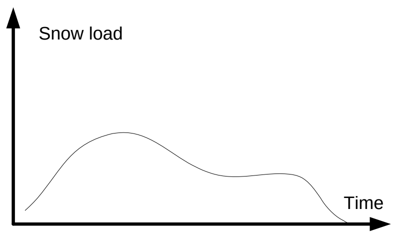

Figure 2 Snow load history with snow accumulation

$$L_{snow}(t) = \sum_{k=1}^{N(t)} Y_k S(t_k, t_k + \tau_k) \qquad (2)$$

$$S(a,b) = \begin{cases} 1, x \in [a,b) \\ 0, otherwise \end{cases}, a, b \in R \qquad (3)$$

In this paper, efforts are focused on the areas where the snow-covering time is very long (say more than 5 months per year) such that the snow accumulation keeps snow load on a high level. Table (1) tabulates the parameters used in the snow load simulation. These parameters are determined by trial and error, such that the simulated snow load statistics, including the annual maximum snow load distribution, the average daily ground snow load, and the average length of snow season, capture the characteristics of the areas that have long snow seasons, which are available in some literatures (O'Rourke and Speck 1992; Lee and Rosowsky 2005). A single snow event is defined as a snow load increment due to one snow specification. The amplitude of a single snow event is assumed to be constant until the end of its duration time. Fig. (3) shows a generic snow event.

Table (1) probabilistic model of single snow event

	Amplitude s (mm water)	Duration t (day)
Probabilistic model	lognormal	Lognormal
Mean value $E[\ln(\cdot)]$	38.1	2.2
Standard deviation $\sqrt{var[\ln(\cdot)]}$	10.16	0.3

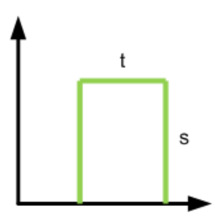

Figure (3) single snow event

3. EARTHQUAKE HAZARD MODEL

Seismic hazard can be described by the Fréchet distribution (i.e. type II extreme value distribution) (Cornell 1968). This model was used to study the snow and seismic load combination (O'Rourke and Speck 1992; Ellingwood and Rosowsky 1996). The Fréchet distribution is given by Eq. (4)

$$P(X < x) = exp\left[-\left(\frac{x}{\mu}\right)^{-\alpha}\right], x > 0 \; and \; \alpha > 0 \qquad (4)$$

where x is the maximum peak ground acceleration in 50 years; α is a site specific parameter, used to describe the slope of the basic seismic hazard curve, ranging from 2.3 to 3.3 for the contiguous United States

(Ellingwood and Rosowsky 1996); and μ can be expressed in terms of a peak acceleration A, once α is determined. A set of values for α and μ determined using Eq. (4) are listed in Table. (2). For a specific site, the acceleration A can be obtained from the United States Geology Survey (USGS). In this study, the value of 2.3 is used in the seismic hazard simulation.

Table (2) Seismic hazard model parameters

Exceedance probability of A	α	2.3	2.7	3.3
10% in 50 years	μ/A	0.376	0.435	0.506
2% in 50 years	μ/A	0.183	0.236	0.307

Wen (1990) derived Eq. (5) for a Poisson pulse process. Combining Eq. (4) and (5), the distribution function of an individual event $F_X(x)$ can be obtained, as shown by Eq. (6).

$$F_{max}(x) = exp\,\{-\lambda_{eq}T\big(1 - F_X(x)\big)\} \tag{5}$$

$$F_X(x) = 1 - \frac{1}{\lambda_{eq}T}\left(\frac{\mu}{x}\right)^{\alpha} \tag{6}$$

The mean occurrence rate of earthquake λ_{eq} is assumed to be 0.05 or 0.1 per year (Ellingwood and Rosowsky 1996).

3. RELIABILITY INDEX

The reliability index β is used to indicate the expected performance of a designed structure. The target value of the ASCE 7 load combinations is approximately 1.75, depending on the load conditions. Given the specific load combination in this paper, a reliability index of 1.65 is consistent with that target (Ellingwood and Rosowsky 1996). The reliability index can be expressed by Eq. (7), where L and L_d are the actual load and design load, respectively (Ellingwood and Rosowsky 1996).

$$\beta = -\Phi^{-1}(P(L > L_d)) \tag{7}$$

Shear force is the critical load in the seismic design. It is assumed to be linearly proportional to the peak ground acceleration. In the case of snow and earthquake load combination, load factors are required by the design code, as shown in Eq. (1). Considering all these factors, the reliability index for seismic design can be expressed by Eq. (8)

$$\beta = -\Phi^{-1}\{P[\gamma A(D+S) > \gamma A_d(D_n + \delta S_n)]\} = -\Phi^{-1}[P\left(\frac{A(D+S)}{A_d(D_n+\delta S_n)}\right) > 1] \tag{8}$$

where, A and A_d are the peak ground acceleration and a peak ground acceleration with a constant (say, 10%) exceedance probability in 50 years (Ellingwood and Rosowsky 1996); D is the dead load; S is snow load; δ is the snow load factor; γ is a constant; and sub n indicates the nominal value.

4. SIMULATION RESULTS

A one-story flat-roof wood frame building is studied in this paper. Information pertaining to the building and the site is listed in Table (3). The structure is intentionally made simple enough to demonstrate the HASP simulation results. The parameters are determined according to the real records, such that they represent characteristics of those areas which have long snow exposure. In total, 10,000 years simulations are run in this paper.

Two realizations of the simulated ground snow load history are shown in Fig. (4), from which we can see the length of the snow season varies. The simulated annual maximum ground snow load is fitted by the lognormal distribution, with a significance level of 97.8% (Chi-Square goodness-of-fit test), as shown by Fig. (5). In the

ASCE 7-05 (ASCE 2006), the design ground snow load is determined by selecting a value with a 2% annual exceedance probability, from a lognormal distribution which is fitted from weather records. Using the same mechanism herein, the design ground snow load is found to be 14.2 kPa (296.64 psf). Fig. (6) shows the histogram of the simulated snow season lengths, which varies from 158 days to 209 days, with a mean value of 187.88 days and a standard deviation of 4.29 days.

Table (3) site and structure information

Building information	Roof area 59.46 m^2	Dead load D 66.7 kN	Thermal factor C_t 1.0	Exposure factor C_e 0.9	Importance factor I 1.1
Site information	Snow season length (day) ≈ 180	Mean occurrence rate of snow λ_{sn} 58.2/year	Mean occurrence rate of earthquake λ_{eq} 0.05/year	Peak ground acceleration with a 10% exceedance probability in 50 years 0.1 g	

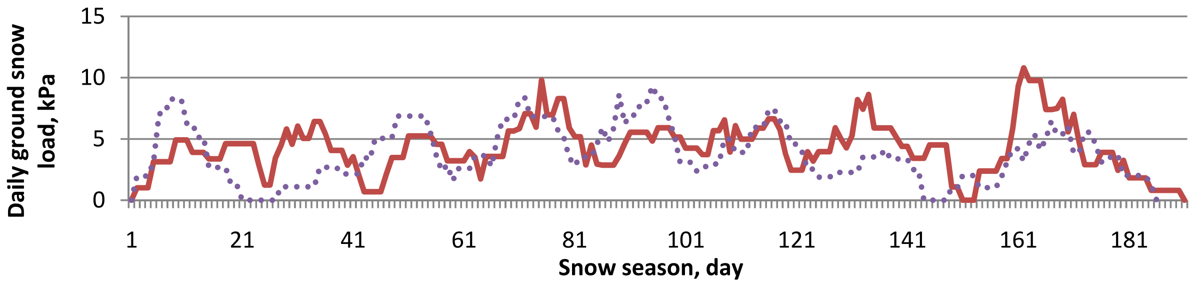

Figure (4) Simulated grounds snow load history

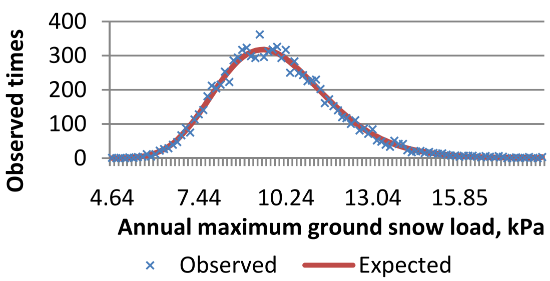

Figure (5) Simulated annual maximum ground snow load histogram vs. expected histogram

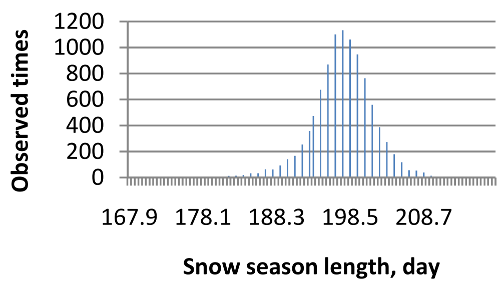

Figure (6) Simulated snow season histogram

Figure (7) shows the simulated occurrences of earthquake. As shown in Eq. (4) through (6), earthquake hazard is simulated every 50 years with a mean rate of 0.05 per year. In order to determine the coincidences of snow and earthquake hazards, occurrence time of the earthquake event is zoomed out to be in units of days, by generating random numbers in the range of (0, 18250) where 18250 is the product of 50 years and 365 days per year.

As shown in Eq. (8), the reliability index can be determined once the peak ground acceleration A, roof snow load S, dead load D, and the corresponding nominal values are available. There are two possible load conditions, earthquake only or earthquake accompanied by snow, which induce shear force. For those earthquake only load conditions, the roof snow load S is equal to zero. For other conditions, the roof snow load S is calculated using Eq. (9) (ASCE 2006)

$$S = 0.7C_tC_eIP_g \tag{9}$$

where the values of C_t, C_e, I are tabulated in Table (3) and the ground snow load P_g is obtained from the simulation results. According to the simulation results, 506 earthquakes are observed in the simulated 10,000 years and 333 of them are accompanied by snow. The value of the fraction in Eq. (8) is calculated 506 times and compared with unity each time. In the calculation, the dead load D is set to be equal to the nominal dead load D_n. At last, the reliability indexes are calculated and plotted in Fig. (8). The reliability index $\beta = 1.561$ corresponding to a snow load factor $\delta = 0.2$. And a snow load factor $\delta = 0.23$ satisfies the target reliability index of 1.65, as mentioned earlier.

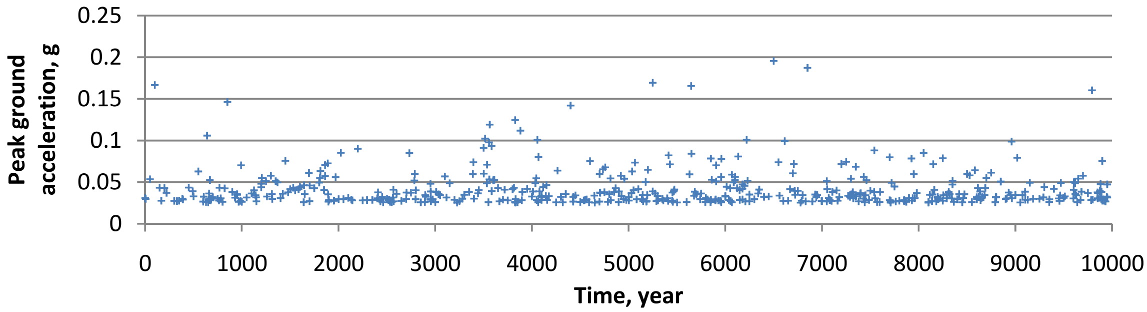

Figure (7) Simulated earthquake history

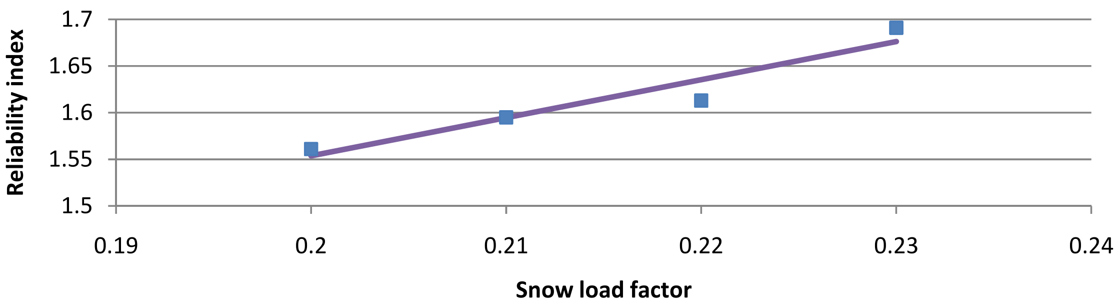

Figure (8) Simulated snow season histogram

6. CONCLUSIONS

A snow load factor of 0.2, based on the Turkstra's rule, is shown to be not conservative for the areas with long snow exposure and moderate to high seismicity. That might lead to a lower reliability than that is expected by the code. The simulation results in this study suggest that a slightly higher snow load factor, 0.23, will provide satisfactory to the reliability requirement. The proposed snow accumulation model simulates the snow load more realistically. Further studies are needed to validate the conclusion, which require site specific information including longtime weather records, seismicity records, and local building specifications.

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