AN ASSESSMENT OF BROAD IMPACT OF SEASONALLY FROZEN SOIL ON SEISMIC RESPONSE OF BRIDGES IN THE U.S. AND JAPAN

Sri Sritharan[1], Aaron Shelman[2]

Abstract

This paper summarizes a pilot research project undertaken to examine the effects of seasonally frozen condition on soil-foundation-structure-interaction (SFSI) and seismic response of bridges. Using a combination of experimental and analytical studies, this research focused on the behavior of bridge columns supported on cast-in-drilled-hole (CIDH) shafts in glacial till soils. This research has shown that frozen soil depth as small as 3 in. (7.6 cm) can significantly influence the response of bridges and that bridge columns designed without consideration to seasonally frozen conditions can experience brittle failure in winter earthquakes. Furthermore, an assessment of broad impact of this research was examined for seismic regions in the United States and Japan. In addition to indentifying the potential areas in Japan where both winter weather and seismic activity may be experienced, this study estimated that about 50% of bridges in the US seismic regions may be affected by seasonal freezing and that their seismic response will be dictated by the environmental conditions.

Introduction

Research on soil-foundation-structure-interaction (SFSI) under seismic loading has been gaining momentum over the past decade. Through better understanding of SFSI and addressing its effects in design methodologies, seismic design of bridges is progressively improved, leading towards safer and more reliable bridges in seismic regions. However, an issue that has not been given consideration in routine seismic design is the effects of seasonal temperature variations on SFSI and its impact on seismic response of bridges. Seasonal variation in temperature (e.g., from 73°F [23°C] to -4°F [-20°C]) modifies the engineering properties of construction materials, such as concrete, steel and soil, and in turn alters the seismic performance of bridges. Of the impact of the different material properties, the variation in the properties of the foundation soil in the upper layer plays a significant role in modifying the seismic response of bridges in winter months (Sritharan et al., 2007).

Seasonal temperature variation and SFSI during seismic loading was previously not examined, as it was not considered a cause for earthquake damage in the past. One reason for overlooking the aforementioned issue was that the previously used allowable

[1] Wilson Associate Professor and Assistant Chair, Dept. of Civil, Construction and Environmental Engineering, Iowa State University, Ames, Iowa
[2] Research Assistant, Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, Iowa

design stress method resulted in many structural deficiencies that led to damage during seismic events (Priestley, 1996). In addition, the resources needed to examine in-ground structural conditions are costly and labor intensive and therefore not usually undertaken.

Research Significance

Over the years, both the U.S. and Japan have seen many large magnitude earthquakes that have taken place during the winter months. Examples are the New Madrid earthquake sequence of 1811-1812, the 1964 Great Alaska earthquake (M_L = 9.2), the 1994 Kobe earthquake (M_L = 6.9), several earthquakes in Hokkaido, and the 2001 Nisqually earthquake (M_L = 6.9). A common location for frozen ground to occur is the Central and Eastern United States; however, it should also be noted that the presence of frozen ground occurs in many locations that are not normally considered to experience seasonal freezing. DeGaetano and Wilks (2001), for example, have suggested that frost depths of 4 in. (10 cm) or greater should be expected in the western seismic region of the continental United States, including the State of California (Figure 1). In Japan, Hokkaido Island and the northern part of Honshu Island should be expected to experience both high seismic activity and frozen conditions (Figure 2). Despite the presence of frozen ground in winter months, all seismic regions of the United States, Japan and other countries around the world ignore the effects of seasonally frozen conditions on SFSI and seismic response of bridges. Therefore, a pilot research project was undertaken at Iowa State University (ISU) to quantify the significance of seasonally frozen conditions on seismic response of bridges. Summary of results of an outdoor experimental study (Suleiman et al., 2006) and an analytical investigation (Sritharan et al., 2007) conducted as part of this project and an assessment of broad impact of this research in the U.S. and Japan seismic regions are included in this paper.

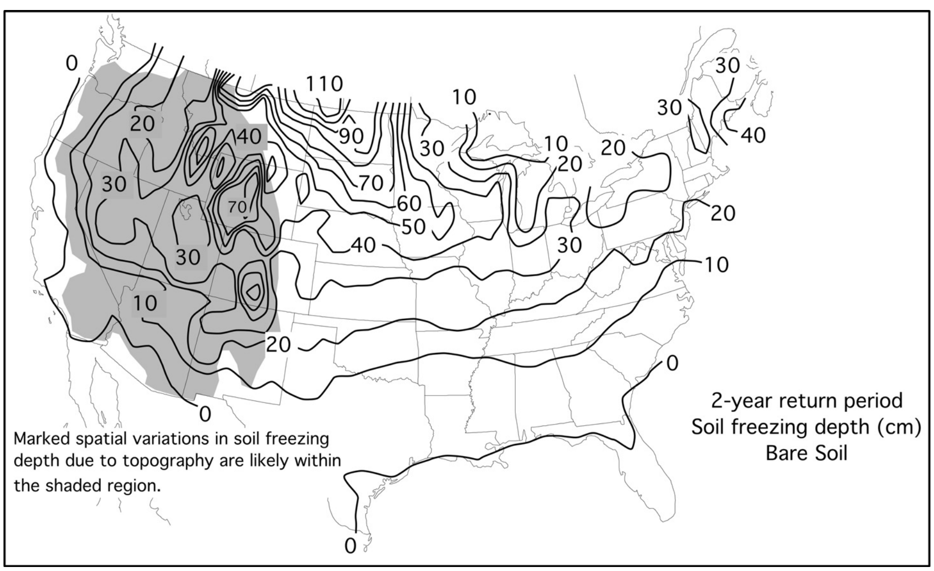


Figure 1: Frozen Soil Depth Contours Produced for a Two-Year Return Period by DeGaetano and Wilks (2001)

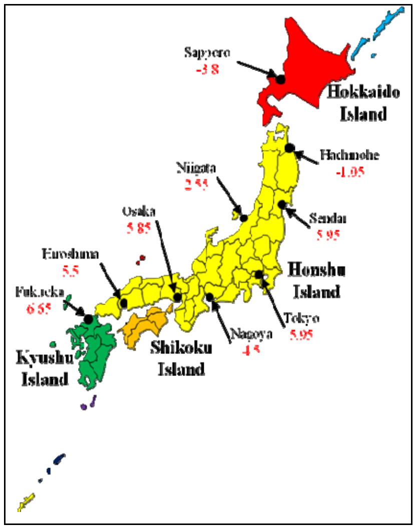


Figure 2: Average Winter Temperatures for Japan's Larger Cities from the Japanese Meteorological Agency (http://www.data.kishou.go.jp/normal-e/normal-e.html)

Experimental Study

Experimental testing consisted of performing three large-scale tests on bridge columns supported by cast-in-drilled-shafts (CIDH) in glacial till soil at an outdoor test facility of ISU (Figure 3). Two of the 24-in. (0.61 m) diameter units were identical in dimension and reinforcement (Figure 4). One of the identical units, SS1, was tested under summer conditions at 73°F (23°C), while the other unit, SS2, was tested under winter conditions at 14°F (-10°C). The third unit, SS3, was also tested in winter conditions and consisted of a 36-in. (0.91 m) diameter shaft for the foundation. Test results of SS3 are not presented within this summary, but more information may be found in Suleiman et al. (2006). All test units were subjected to cyclic lateral loading with respect to a reaction column (RC) located at the test site (Figure 3b), but they were not subjected to any external axial load.

(a) Test units (b) SS2 at lateral displacement of -12 in. (-30.5 cm)

Figure 3: Outdoor Testing of Bridge Columns Supported by CIDH Shafts at Iowa State University

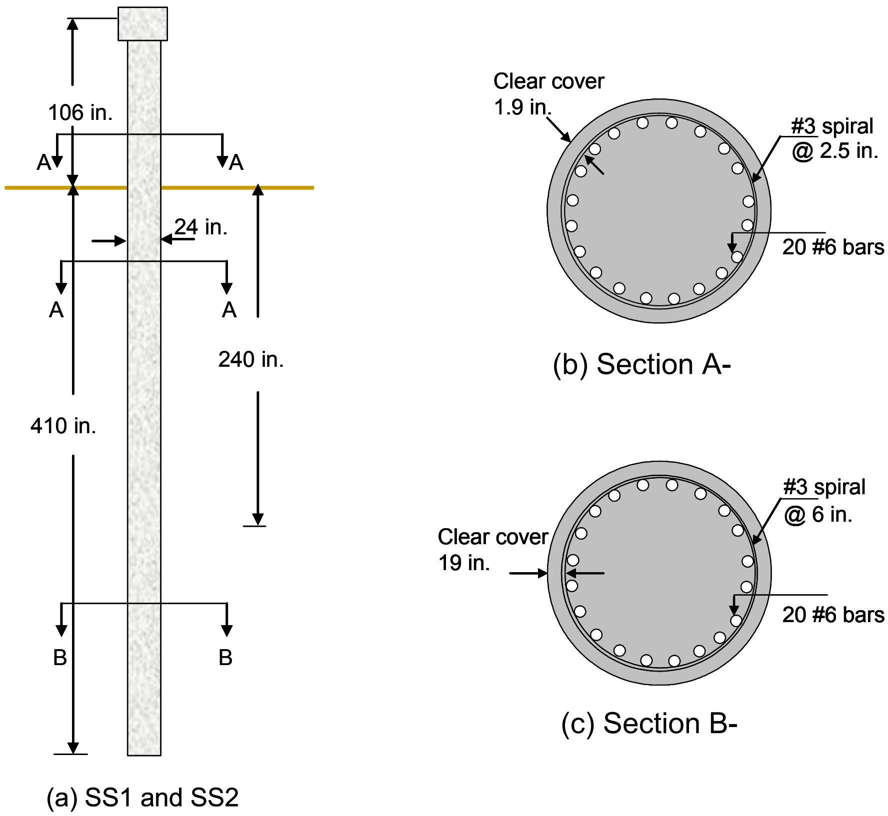
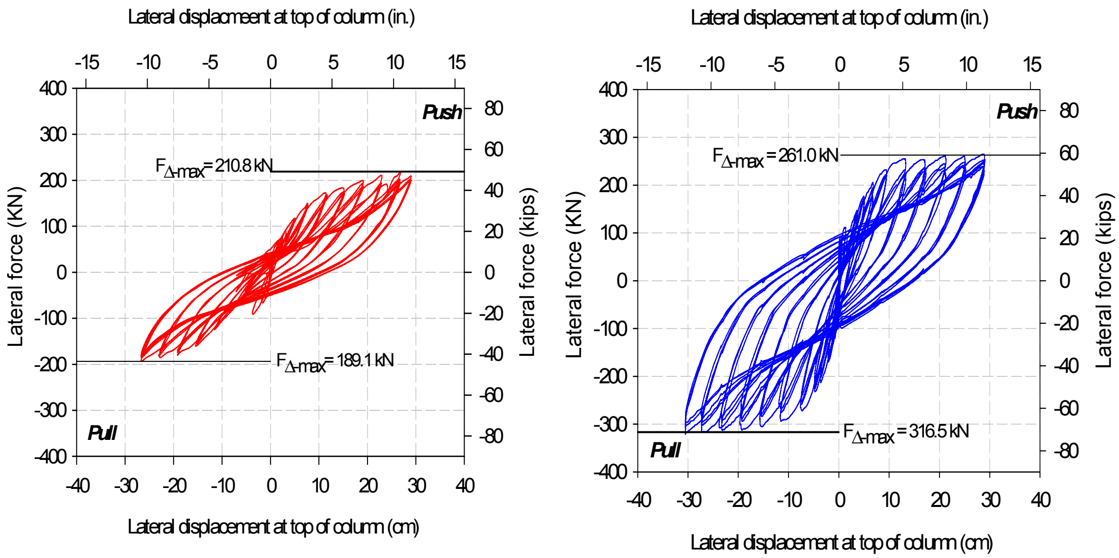


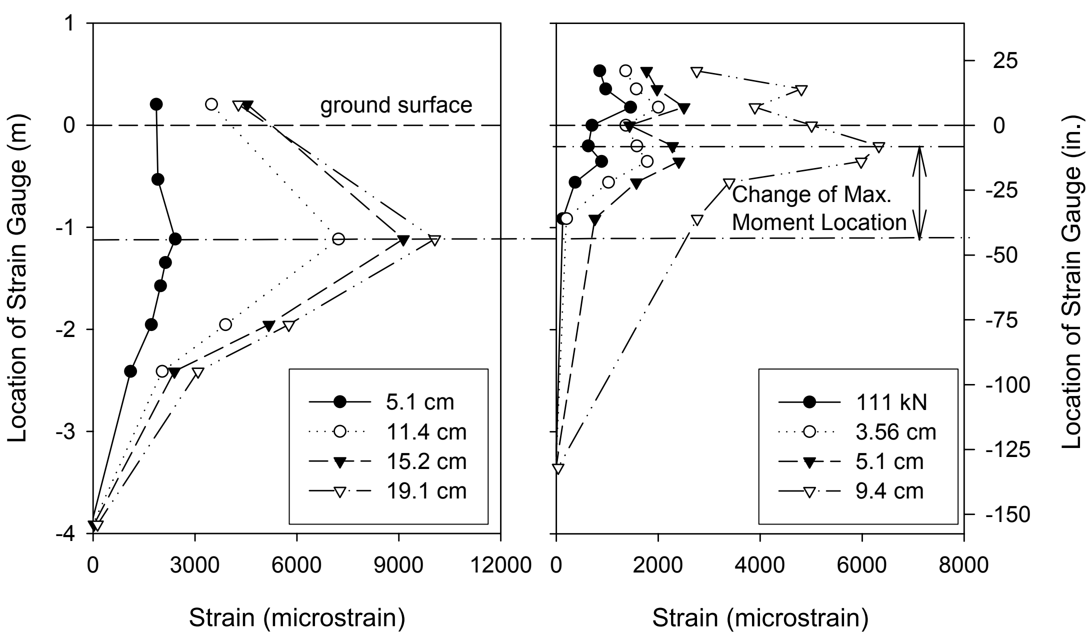
Figure 4: Dimensions and Reinforcement Details of SS1 and SS2 (1 inch = 2.54 cm)

The measured force-displacement responses of SS1 and SS2 under cyclic loading are shown in Figure 5. A comparison of the two responses confirms that the frozen condition caused drastic changes to the lateral load response of the column-foundation system. When the responses were carefully examined, it was found that SS2 experienced a 170% increase in effective lateral stiffness and a 44% increase in the column shear demand. The experiment further revealed that the presence of a 30 inch (0.76 m) layer of frozen soil caused the maximum moment location to be shifted closer to the ground surface by 33 in (0.84 m) and decreased the length of the plastic region by 64%. The change in location of the maximum moment location can be seen in Figure 6 that compares the strain profiles established for two extreme tension bars. In both tests, a gap formed between the foundation and the soil at the ground surface during the cyclic testing; however, spalling of concrete in the foundation shaft did not occur. Figure 7 shows that the gap formed during the experiment was considerably less when the ground was frozen due to the increased lateral stiffness of the soil.



(a) SS1 tested in summer (b) SS2 tested in winter

Figure 5: Cyclic Force-Displacement Response of Two Identical Column-Foundation Systems



(a) SS1 (b) SS2

Figure 6: Comparison of Strain Profiles Established for Extreme Tension Bars

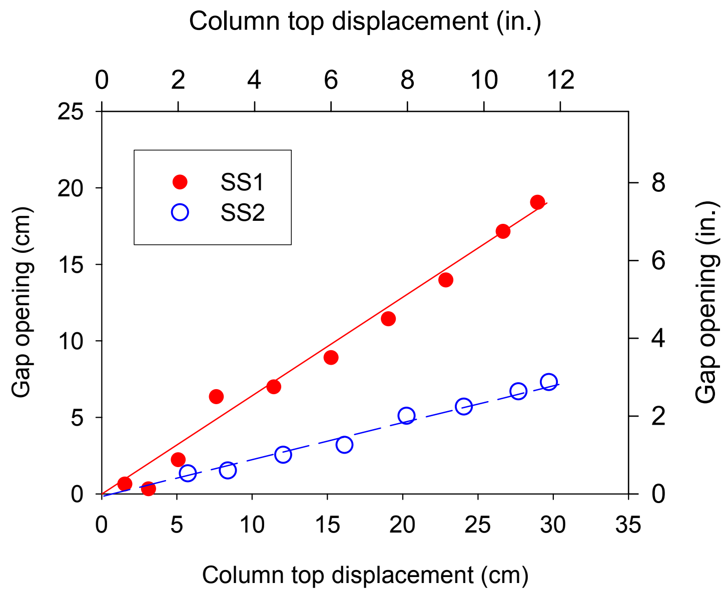


Figure 7: Comparison of the Gap Opening at the Ground Surface between the Tension Side of the Pile and Surrounding Soil

Analytical Study

The analytical study, which examined the influence on seasonally frozen ground and seismic response of bridges by conducting pushover analyses on SS1 using LPILE (Ensoft, 2000), is presented in Sritharan et al. (2007). The analyses were conducted at the following five temperatures by accounting for the variations in material properties: 73°F (23°C), 30°F (-1°C), 19°F (-7°C), 14°F (-10°C) and -4°F (-20°C). The depth of frozen soil chosen for each case was determined by combining the measured temperature profile of soil at the test site, the maximum depth and contour maps provided for frozen soil in Bowles (1996), and Figure 1. The chosen depths of frozen soil for the five cases were 0 in. (0 cm), 3 in. (7.6 cm), 18 in. (46 cm), 30 in. (76 cm), and 47 in. (120 cm), respectively.

The nonlinear LPILE analysis results are summarized in Figure 8. Also identified in the figure are three critical reinforcement strains that may be used to define the first yield, ideal and ultimate conditions of SS1. In addition to the analytical responses, the measured force-displacement response envelopes of SS1 and SS2 are included in Figure 8. A close agreement seen between the measured and analytical responses of SS1 and SS2 confirm the validity of the LPILE model. For all five analyses, Figure 9 provides the displacement, shear and moment profiles along the length of the column and CIDH shaft at the ultimate condition. The maximum moment locations shown in Figure 9 at 73°F (23°C) and 14°F (-10°C) agreed well with the experimental observations in Figure 6, further validating the analytical model.

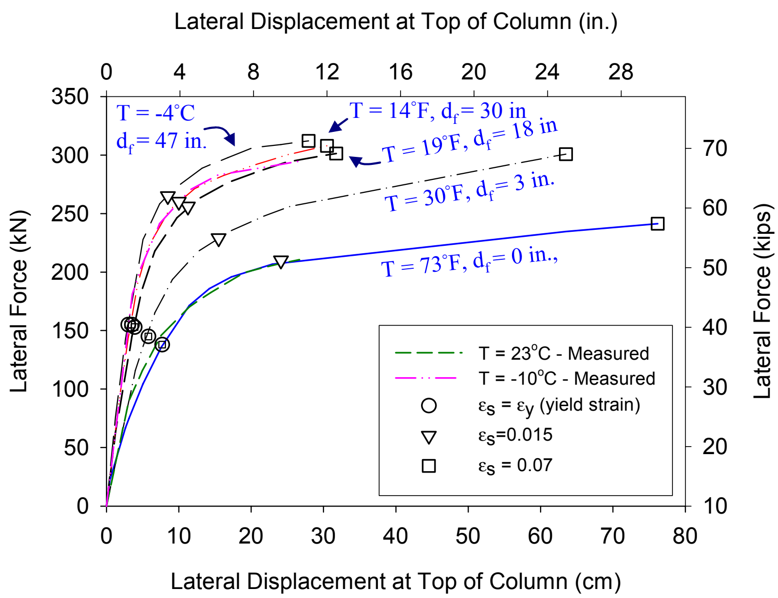


Figure 8: Force-Displacement Responses of Nonlinear LPILE Analyses and Experimental Study

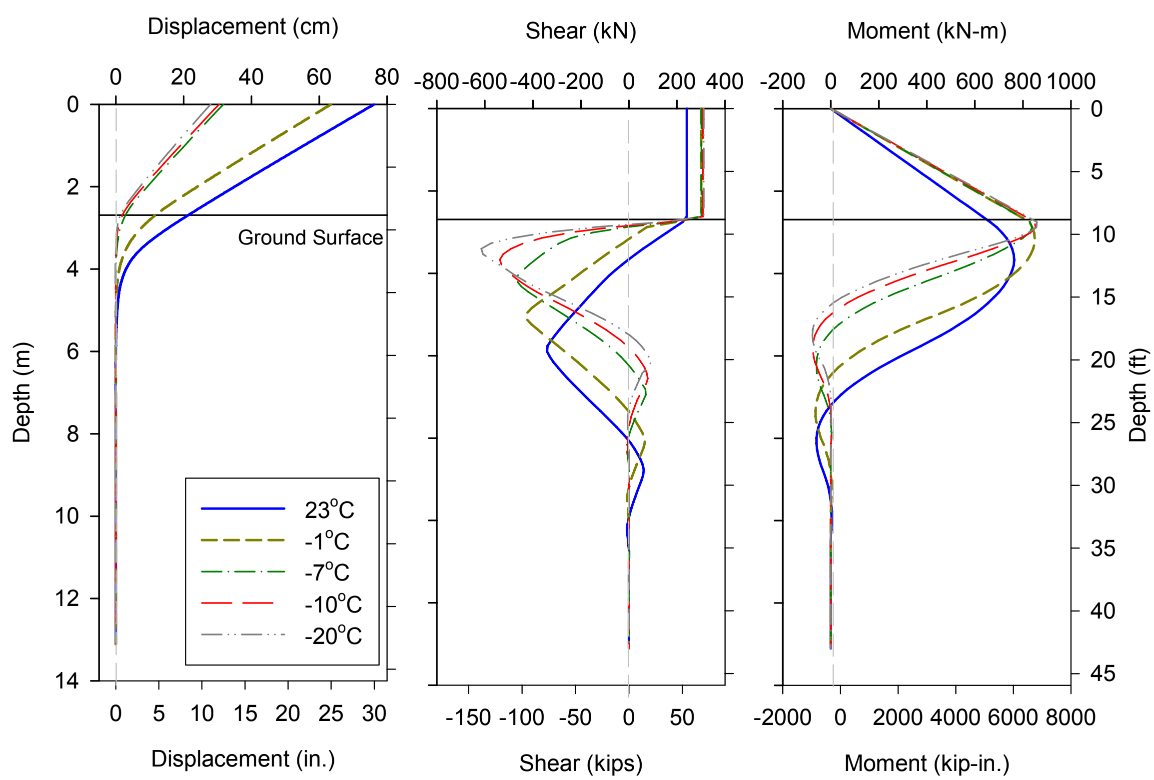


Figure 9: Calculated Displacement, Shear and Moment at the Ultimate Condition

When comparing the responses presented in Figures 8 and 9 with one another, the expected influence of seasonally frozen condition on seismic response of bridges becomes obvious. With respect to the response at 73°F (23°C), the analyses show that the column-shaft system at cold temperatures ranging from 30°F (-1°C) to -4°F (-20°C) will experience:

- 40 to 188% increase in effective lateral stiffness,
- 17 to 63% reduction in the lateral displacement capacity,
- 0.54 m to 0.82 m upward shift in the maximum moment location,
- 25 to 30% increase in column shear demand,
- 25 to 80% increase in CIDH shaft shear demand, and
- 19 to 68% reduction in the length of the plastic region of the CIDH shaft.

The aforementioned differences in the critical design parameters demonstrate that 1) frozen soil will alter the seismic response of bridges; 2) bridges designed using the capacity design philosophy can potentially fail in a brittle manner in a winter earthquake due to the increase in shear demands, reduction in displacement capacity and/or shift in the in-ground plastic hinge; and 3) the effects of frozen soil are significant even at temperatures just below freezing. The last finding was based on an analysis at 30°F (-1°C) with a frost depth of 3 inches (0.076 m), which is frequently experienced in the Western United States and Northern Japan in winter months.

Broad Impact

To better understand the significance of freezing soils and seismic response of bridges, an impact study was performed for the United States as well as for Japan. For the United States, the number of bridges within each state was determined and this distribution was compared to the frost depth contour map in Figure 1 and a seismic hazard map. Due to lack of information, it was assumed that the bridges shown in Figure 10 were uniformly distributed within each state. The chosen seismic map for this study was the 0.2-second spectral acceleration map with a 10 percent probability of exceedance in 50 years as published by the United States geological Survey (2002). With a limiting criterion that the bridges should experience at least 0.2g spectral acceleration at a period of 0.2-second, 66,000 bridges were estimated to be in the seismic region. To examine how many of these bridges would be affected by seasonally frozen condition, the frost contours of Figure 1 were then overlaid on the seismic hazard map (Figure 11), and the number of bridges that may experience both a minimum of 10 cm (~ 4 in) of frost depth and 0.2g spectral acceleration was estimated. This combination showed that seismic response of approximately fifty percent of the 66,000 bridges in active seismic regions would be affected by seasonal freezing, which is a significant finding. When only the minimum of frost depth condition was used (i.e., the bridge site should experience a frost depth greater than or equal to10 cm (~ 4 in)), over 400,000 bridges or 2/3 of entire bridge stock in the U.S. were founded to be affected by seasonally frozen condition, yet this issue is seldom addressed in the routine design methods.

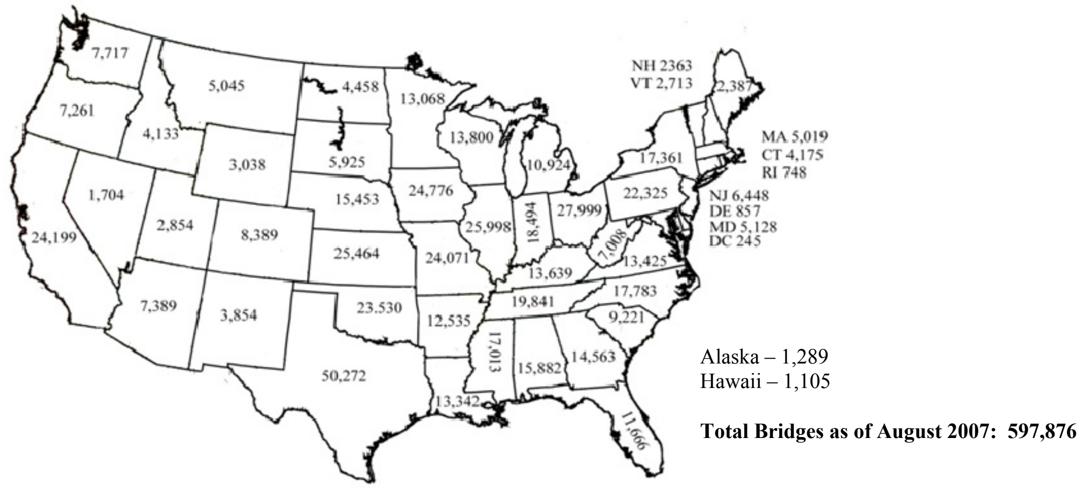
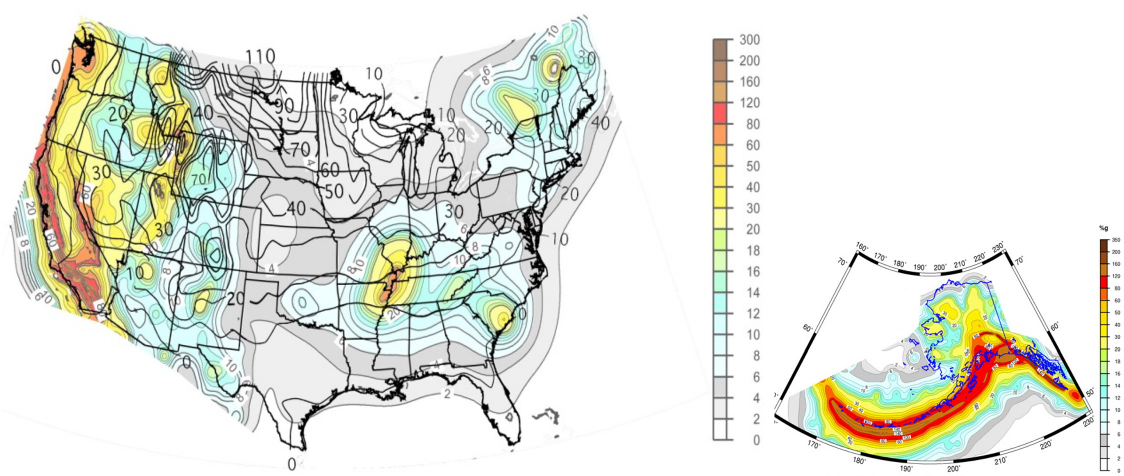


Figure 10: Statewide Distribution of Bridges in the United States (Bureau of Transportation Statistics, 2007)

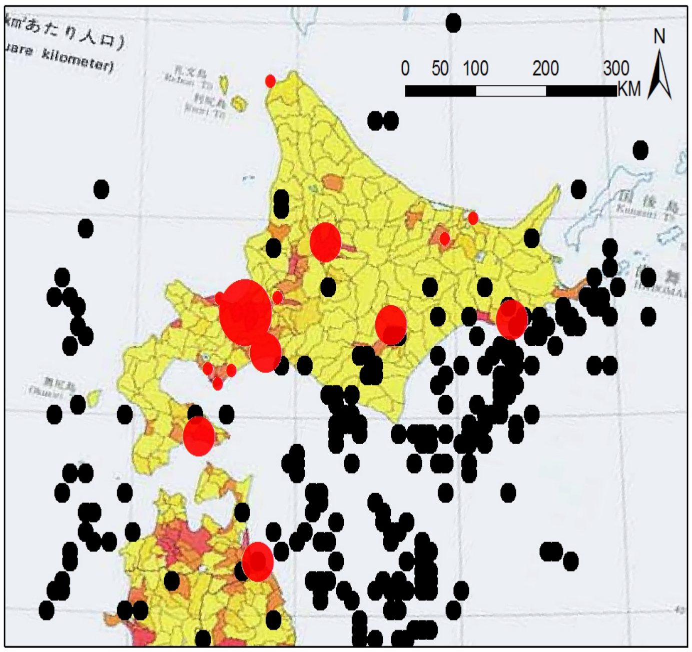
The broad impact study of Japan consisted of examining the average winter temperatures and comparing the locations of possible frozen soils to seismic hazards and concentration of population. Figure 2 demonstrated that the locations for possible frozen soils are Hokkaido and the northern part of Honshu Island. Within this region, the seismic hazards were found using the National Earthquake Information Center's historical and present data and compared to the frozen soils area. With this information, the population distribution was examined to provide a risk estimate, as distribution of



Notes:
1. Hawaii omitted as no frost concerns.
2. Entire State of Alaska Greater than 10cm frost depth

Figure 11: USGS Seismic Hazard Map Overlaying the Frost Depth Contours in Figure 1

bridge locations were unavailable. It was noted that some major cities were located within this region, such as Sapporo. A final map correlating with Figure 2 was produced that shows the population distribution and seismic events in the area (Figure 12). It appears that bridges in four major cities and south eastern part of the Hokkaido Island may be mostly affected by both earthquakes and seasonally frozen condition.



Key:
1. Small Black Circles are Earthquakes (http://neic.usgs.gov/neis/epic/epic.html)
2. Large Red Circles are High Population Density (http://www.biodic.go.jp/reports/2-2/aa000.html)

Figure 12: Seismic Activity of Japan near the Hokkaido Island

Conclusions

This paper has summarized a pilot research project completed on the effects of frozen conditions on SFSI and its influence on seismic response of bridges in winter months and an assessment of the broad impact of seasonally frozen condition on bridge infrastructure in the United States and Japan. The experimental study included lateral load testing of two identical bridge columns that extended into the ground as CIDH foundation shafts at two different ambient temperatures (i.e., 73°F [23°C] and 14°F [-10°C]). A frozen layer of 30 in (0.76 m) was present during the cold temperature test. The analytical study examined the effects of the same column-shaft system at five different temperatures: 73°F (23°C), 30°F (-1°C), 19°F (-7°C), 14°F (-10°C) and -4°F (-20°C). The experimental response of the test units and their analytical lateral responses were in agreement, confirming the analytical model's accuracy. The impact study examined the effects of frozen conditions on the bridge infrastructure in the United States and Japan.

The pilot research has conclusively shown that seasonally frozen conditions will significantly alter the seismic response of bridge columns supported on CIDH shafts. The change in material properties resulting from cold temperatures, specifically those of soil near the ground surface, influences the SFSI dramatically. Consequently, the elastic stiffness of the column-foundation system increases with reducing temperatures, while its lateral displacement capacity reduces. The cold temperatures also migrates the maximum moment location towards the ground surface, increases the column and foundation shear demands, and reduces the length of the plastic region in the column-shaft system. Should the current state of practice remain the same, bridges in seismic regions that experience seasonal freezing may fail in a brittle manner in winter earthquakes. Furthermore, the seismic response of bridges may not be accurately predicted unless cold temperature effects on SFSI are included adequately.

Impact of seasonally frozen soil is not routinely addressed in bridge design practice. However, it was found that over 400,000 bridges in the U.S. may experience seasonally frozen conditions. Of these bridges, 33,000 bridges may experience both seasonally freezing and winter earthquakes. This number is also very significant as it represents 50% of bridges estimated to be in active seismic regions. Bridge distribution information was not available for Japan. However, the available winter temperatures and past earthquakes indicate that the combined effects of frozen soil and seismic loading are of significant importance for bridges in four cities and south eastern part of the Hokkaido island.

The research has shown that a frozen soil depth of only 3 inches (0.076 m) can influence the seismic behavior of bridges. Although experimental validation must be performed, this finding is of great importance as 3-in. (0.076 m) thick frozen soil is experienced in seismic regions around the world, including the Western United States, the Central and Eastern United States, and Northern Japan. To improve the seismic-resistant design of bridges and other structures, researchers should perform a comprehensive study on this topic area with emphasis on other soil types and conditions just below the freezing.

Acknowledgements

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