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BRIDGE COLUMN FOUNDATION-SOIL INTERACTION UNDER EARTHQUAKE LOADS IN FROZEN CONDITIONS

Sri SRITHARAN[1], David J. WHITE[2], and Muhannad T. SULEIMAN[3]

SUMMARY

Seasonal freezing that occurs in several seismic regions around the world including the Midwest and East Coast of the United States and eastern part of Canada may significantly influence the lateral load behavior of structures, especially bridges. With shear strength and stiffness increased by up to two orders of magnitude, frozen soil at the ground surface will alter the seismic behavior of structures in cold conditions. In addition, the stiffness and ductility capacity of structures will be affected as the properties of concrete and steel are modified by the cold temperatures. With emphasis on soil-structure interaction effects, this paper demonstrates the potential effects of freezing temperature on the response of bridge columns supported by Cast-In-Drilled-Hole (CIDH) shafts. From laboratory experimental data found in the literature, p-y curves for the foundation soil are established as a function of subzero temperature. Using these p-y curves, lateral load response of 0.6-m diameter bridge column-foundation system is studied under monotonic loading. The analysis results show that relocation of in-ground plastic hinge, reduction in spread of plasticity in the shaft, reduction to the structure displacement capacity, and increased shear demand in the column and CIDH shaft should be expected in frozen conditions.

INTRODUCTION

In the United States, the design of structures subjected to seismic loads has largely considered the conditions of the West Coast, where there are both frequent seismic activity and observed earthquake damage to structures. However, historical records confirm that the most violent seismic events in the continental United States occurred in the Midwest at New Madrid, which experienced three earthquakes exceeding a magnitude 8 and thousands of aftershocks in the winter of 1811-1812 [1]. In recognition of the potential for experiencing large magnitude earthquakes [2], recently published seismic design provisions suggest the use of capacity design procedures not only in the West Coast but also in the Midwest, Southeast, and East Coast of the United States [3,4].

[1] Assistant Professor, Iowa State University, Ames, Iowa, USA. Email: sri@iastate.edu
[2] Assistant Professor, Iowa State University, Ames, Iowa, USA. Email: djwhite@iastate.edu
[3] Lecturer, Iowa State University, Ames, Iowa, USA. Email: suleiman@iastate.edu

Unlike the West Coast, seismic regions in the Midwest and the East Coast experience large temperature variations including subzero conditions, which significantly modify the engineering properties of the foundation soil and construction materials. In subzero conditions, the stiffness and shear strength of soils within the frozen zone may be increased by up to two orders of magnitude [5]. Subzero temperatures also increase the concrete strength, elastic modulus and Poisson's ratio [6,7] and increase the steel yield strength and ultimate strength but decreases its ductility [7,8]. Therefore, an investigation on the lateral load response of soil-structure systems in frozen conditions becomes of paramount importance. This is emphasized in Figure 1, which shows the locations and magnitudes of the historical seismic events in the continental United States [1,9] and contours of average frost depths [10].

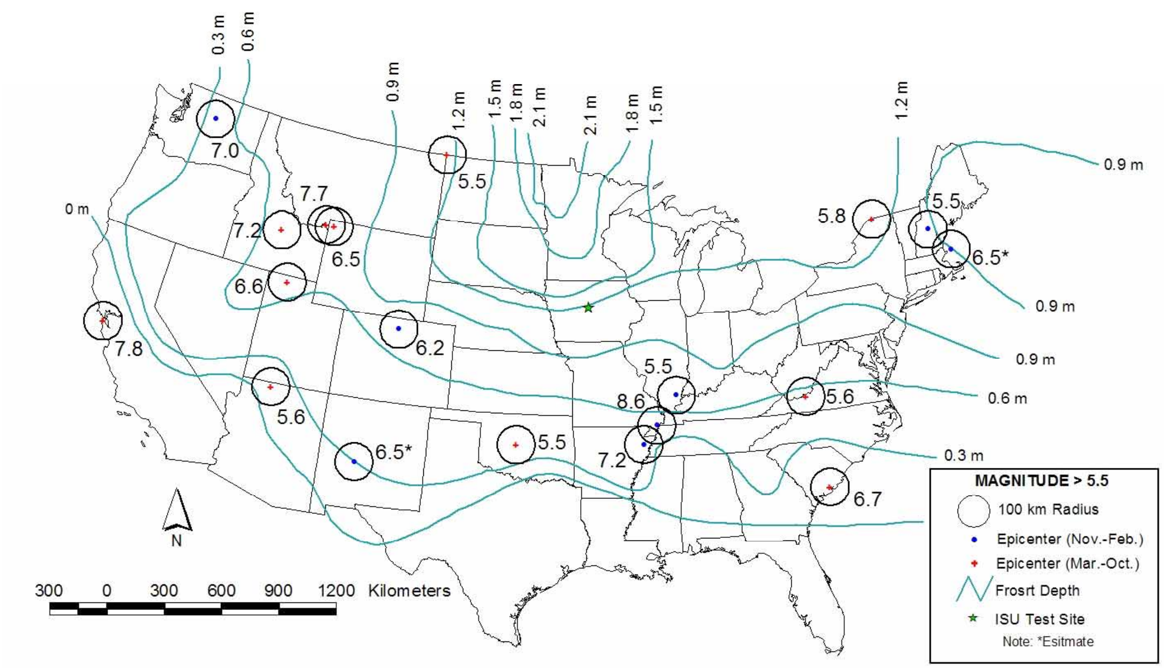

Figure 1 Seasonal frost depth contours in the continental U.S. and epicenter locations and magnitudes of the largest seismic events in various states from historical records.

Under sustained lateral loads, the creep behavior of piles in permafrost (i.e., permanently frozen soil) has been studied by several researchers (e.g., References [11-14]). However, the authors of this paper could not find any literature addressing seismic behavior of structure-foundation systems that accounts for the effects of seasonal freezing. Using bridge columns supported by CIDH (Cast-In-Drilled-Hole) shafts, this paper investigates lateral load response of soil-structure systems in unfrozen as well as frozen conditions with different ground surface temperatures. Accounting for the effects of temperature on the soil p-y curves and the moment-curvature responses of the reinforced concrete members, the analyses of soil-structure systems have been performed under monotonically increasing lateral displacements using the computer program LPILE [15], which employs a finite difference method for lateral load analysis of piles.

TEMPERATURE EFFECTS ON MATERIAL BEHAVIOR

In several regions with frost depth of 0.6 m or more (see Figure 1), ambient temperatures near or below -20°C have been routinely recorded during winter [16]. As stress-strain characteristics and engineering properties of soil, concrete and steel are noticeably influenced by temperatures below the freezing point (i.e., at temperatures below 0°C), seismic response of soil-structure systems becomes dependent on the environmental conditions. Presented below is a summary of a literature review that focuses on the effects of cold temperature on the behavior of soil, concrete and steel reinforcement.

Soils

The engineering properties of frozen soil depend not only on the temperature but also on water or ice content, loading rate and duration of load. The strength and modulus of frozen soil decrease as the water content decreases, increase as the strain rate increases, and decrease as the duration of load increases. When compared with unfrozen soil, Tsytovich [5] reported that the shear strength and stiffness of frozen soils may be increased by up to two orders of magnitude. Based on tests conducted at -12°C, Baker [17] reported a five-fold increase in the unconfined compressive strength for fine sand when the moisture content was increased from 5% to 35%. Moreover, triaxial tests performed by Akili [18] on frozen clay examined the effects of loading rates at different temperatures. As the loading rate increased from 0.06 mm/min. to 0.16 mm/min., shear strength of clay increased by 28% and 35% at temperatures of -1°C and -9°C, respectively. When compared to the instantaneous shear strength at -9.5°C, Sayles [19] observed 90% loss in shear strength for Ottawa sand when the duration of load is 1000 hours. A summary of test results reported by researchers for various types of frozen soil are summarized in Table 1. These tests were motivated by understanding the creep behavior of laterally loaded piles in frozen environment and did not address the pile behavior under large lateral displacements similar to that expected under seismic events. For the bridge column-foundation system analysis reported in this paper, the p-y curves for the frozen soil were derived from triaxial test data reported by Akili, which are detailed below under the "Analysis Approach" section.

Table 1. Shear strength for various soil types in subzero temperatures.

Soil Type	Temp. (°C)	Shear Strength (MPa)	Test Performed	Reference
Hanover silt	0 to -10	1.0 – 4.8	Unconfined	[20]
Suffield clay	0 to -10	0.10 – 0.4	Unconfined	
Ottawa sand	-12	1.9 - 5.0	Triaxial (0,0.62,4.82)[1]	[21]
Clay	-1 to -2	0.5 – 1.2	Direct shear (0.1, 1.2)[2]	[5]
Silty sandy moraine	0 to -10	0.03 – 7.3	Unconfined	[22]
Husby sand	0 to -10	0.03 – 3.7	Unconfined	
Silty sandy moraine	0 to -10	0.09 – 2.3	Direct shear (0.06, 0.14)[2]	
Husby sand	0 to -10	0.1 – 1.3	Direct shear (0.06, 0.14)[2]	
Sand	-2 to -15	2.8 – 9.5	Unconfined	[23]

Notes: Strain rates used in the above tests were in the range of 0.003 to 0.2 strain/minute; [1]Confining pressure in MPa; [2]Normal pressure in MPa.

Concrete

Several researchers have studied the behavior of unconfined concrete under cold temperatures (e.g., References [6,7,24-27]). Cold temperatures cause an increase in compressive strength, tensile strength, bond strength, elastic modulus, and Poisson's ratio of concrete. The increase in concrete properties as a function of cold temperature depends on the mix design, curing process, moisture content, load type and rate of loading. Lee et al. [6] reported an increase of concrete compressive strength by 29% and 54% at -10°C and -30°C, respectively, when compared to the strength at 20°C (see Figure 2). The corresponding increases in the Poisson's ratio were 9% and 20%. Filiatrault and Holleran [7] reported a 20% increase of the concrete compressive strength and 7% increase of the concrete modulus at -20°C when compared with the concrete properties at 20°C. Except for the Poisson's ratio and bond strength, the change in concrete properties are included in the analytical study based on the test results reported by Filiatrault and Holleran.

Steel Reinforcement

It has been widely reported that the ultimate tensile strength, yield strength, and modulus of elasticity of steel increase as temperature deceases, while the ultimate strain decreases as the temperature decreases. As temperatures drop, the yield strength increases more rapidly than the fracture strength, leading to sudden failure of steel at a critical temperature without any plastic deformation [8,28]. Referred to as DBTT (the Ductile-Brittle-Transition Temperature), this critical temperature depends on several factors including steel chemical components and grain size, rate of loading, sample size, and the presence of cracks or notches [29]. The DBTT for conventional reinforcing bars manufactured overseas is reported to be in the range of -20°C [29,30], but similar data for US steel could not be found in the literature. For the analytical study, the yield and ultimate strengths of steel reinforcement as a function of temperature are included based on the results produced by Filiatraunt and Holleran [7]. At a temperature of -20°C, they reported an increase of about 4.5% in the steel yield and ultimate strength; however, no data was provided about the change of ultimate strain with temperature.

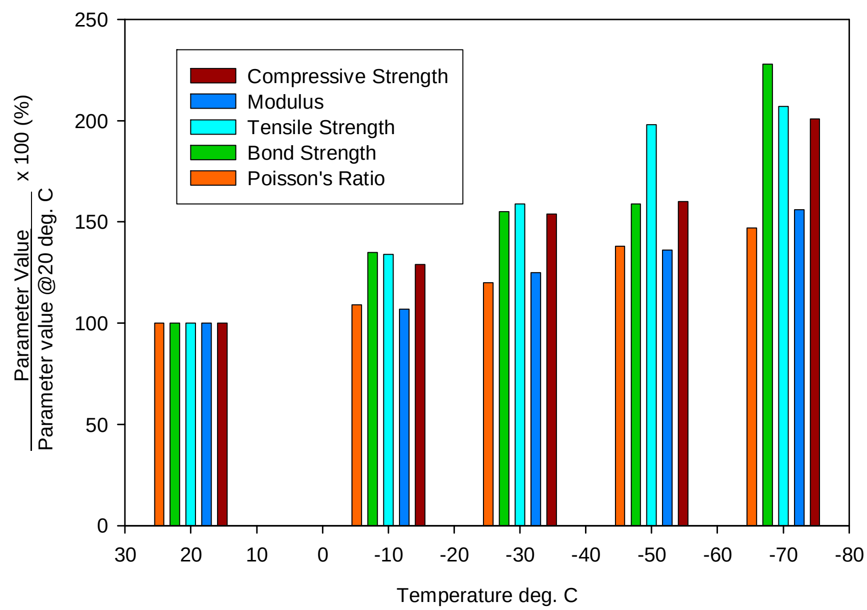

Figure 2 Influence of temperature on concrete properties based on data from Lee et al. [6]

BRIDGE COLUMN-FOUNDATION SYSTEM

The CIDH shaft is a cost effective and widely used foundation for bridge columns. With circular cross-sections, the column and shaft are typically dimensioned to have the same diameter. Hence, the analytical investigation was performed on a 0.61-m diameter column supported by a 0.61-m diameter shaft, which represents a typical bridge column-foundation system in the Midwest and East Coast at one-half to full-scale. A longitudinal steel reinforcement ratio of 2% and a transverse reinforcement ratio of 0.8% were chosen for the column and shaft. These steel ratios represent average longitudinal and confinement reinforcement in bridge column-foundation systems that are designed for high seismic regions [4,31,32]. Figure 3 shows the dimensions and reinforcement details of the column and shaft chosen for the analytical investigation. The foundation soil was assumed to be clay while the selected concrete and steel properties are listed in Table 2.

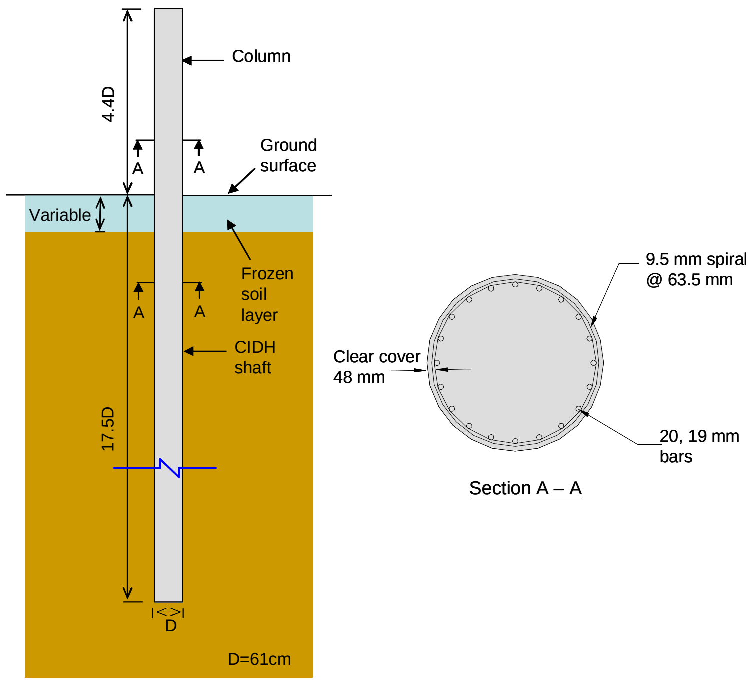

Figure 3 Dimensions and reinforcement details of the bridge column-foundation system.

Table 2. Concrete and steel engineering properties used in the analyses.

Parameter	Concrete		Steel	
	20°C	-20°C	20°C	-20°C
Unconfined compressive strength (MPa)	56.5	67.9	–	–
Elastic modulus (MPa)	37600	41210	200,000	200,000
Yield strength (MPa)	–	–	471	495
Ultimate strength (MPa)	–	–	707	743

ANALYSIS APPROACH

The force-displacement behavior of the column-foundation system was studied under monotonically increasing displacements at ground surface temperatures of 20°C, -5 °C, -10°C, and -20°C. Figure 4 shows the 2-D analytical representation of the column-foundation system as modeled in LPILE. The column and shaft were represented by a total of 100 elements with equal lengths. The soil resistance was represented with nonlinear compression only lateral springs located at the mid-height on both sides of the elements modeling the CIDH shaft. Including the influence of overburden pressure, the p-y curves for the lateral springs were assigned by LPILE using linear interpolation of the user defined p-y curves as a function of soil temperature. The moment-curvature responses of the concrete column and foundation sections were modeled accounting for the confinement effects of the transverse steel reinforcement. More details on the specified soil properties and moment-curvature responses are given below, whereas Table 3 lists the different analysis cases presented in this paper.

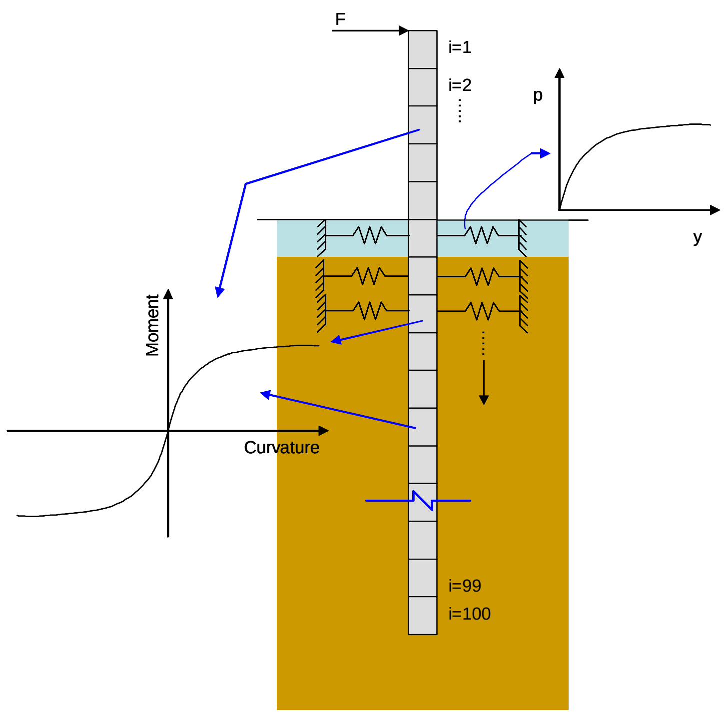

Figure 4 2-D model of the bridge column-foundation system.

Table 3. A summary of different analysis cases.

Case	Ground surface temperature (°C)	Depth of frozen soil (m)	Temperature effects on concrete & steel
1	20	0	Not included
2	-5	0.82	Not included
3	-10	0.98	Not included
4	-20	1.20	Not included
5	-20	1.20	Included
6	-20	0.61	Not included

Soil Properties

In the Midwest and East Coast of the United States, the average freezing depth ranges from 0.3 m to 2.1 m (see Figure 1). For these regions, the mean average temperature in January–the coldest month of the year–is reported to be in the range from 0°C to -20°C based on the data collected over the past 100 years [16]. Although the freezing depth is a function of temperature (or freezing index), thermal conductivity of soil and heat fusion of water in the soil, it was assumed for the analysis purposes that the freezing depth depends only on the ground surface temperature. Furthermore, a maximum freezing depth of 1.2 m was assumed to correlate with a surface temperature of -20°C. Consistent with these assumptions, the depth of frozen soil was taken as 0 m (i.e., unfrozen soil), 0.82 m, 0.98 m and 1.2 m at ground surface temperatures of 20°C, -5°C, -10°C, and -20°C, respectively (see Table 3). However, to investigate the influence of the depth of frozen soil on the lateral-load response of the column-foundation system, the freezing depth corresponding to the ground surface temperature of -20°C was taken as 0.6 m in one analysis.

Andersland and Ladanyi [23] and Nixon [33] reported that the temperature profile within the frozen soil changes linearly with depth. Using this finding, the ground temperature at any depth within the frozen layer can be calculated if the ground surface temperature and the depth of frozen soil (that defines the depth at which the soil temperature is 0°C) are known. To generate the p-y curve for the frozen soil at different temperatures using the normal stress-strain data obtained from unconsolidated undrained triaxial tests, the recommendation of Crowther [34] was followed. Accordingly, the p-y curves for the frozen clay were obtained using the procedure suggested by Reese et al. [35] for unfrozen stiff clay combined with a stress-strain exponent parameter of 0.4 proposed for frozen clays by Sayles and Haines [22] and Weaver and Morgenstern [36].

The stress-strain curves for the frozen soil at temperatures of -5°C, -10°C and -20°C were obtained through linear interpolation of the results of triaxial tests on frozen clay (classified as CH) reported by Akili [18] (see Figure 5). The p-y curves established at the desired temperatures using the stress-strain data in Figure 5 are shown in Figure 6. These data were directly used as input for the LPILE analysis. Because triaxial test data for the unfrozen clay was not available, the p-y curve for the unfrozen clay was established using the empirical relationships for this soil type [15]. Within the unfrozen soil, the p-y curve was not modified as a function of temperature.

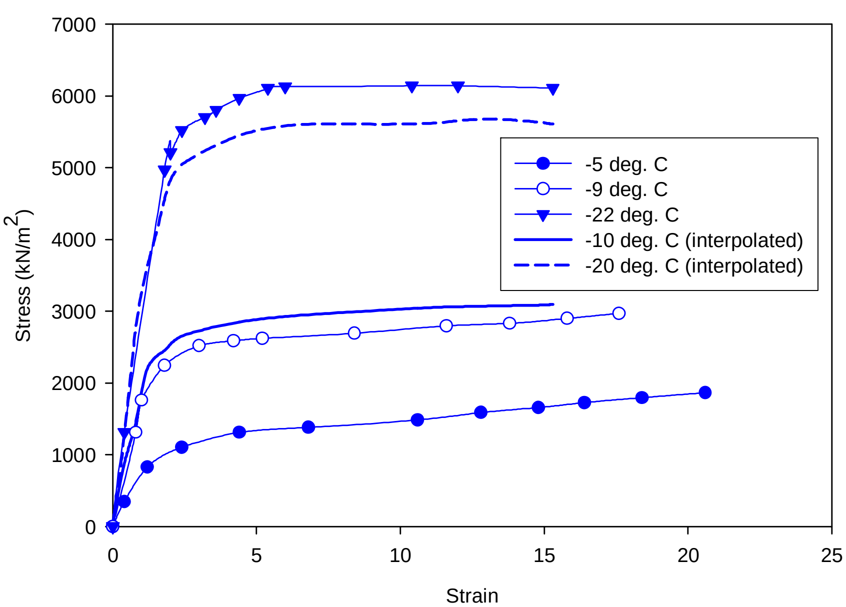

Figure 5 Triaxial test results of Akili [18] and interpolated test data for frozen clay at different subzero temperatures.

The comparison of p-y curves corresponding to different temperatures in Figure 6 clearly emphasize that the cold temperatures would have significant influence on the soil-foundation interaction during seismic loading. As the temperature changes from 20°C to -20°C, it is seen that the ultimate lateral load capacity of the soil increases by a factor of about 80. With cyclic nature of the earthquake loading, some reductions to these factors are possible, which is being currently investigated by the authors.

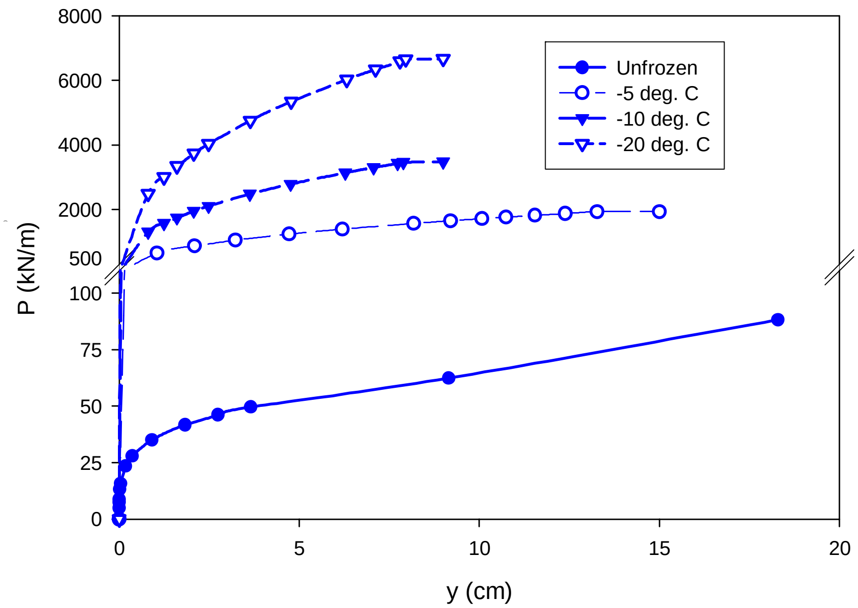

Figure 6 P-y curves generated for clay at different subzero temperatures.

Moment-Curvature Responses

A computer program developed by King [37] was used to perform the moment curvature analysis for the reinforced concrete sections of the bridge column and CIDH shaft. The program assumes that the ultimate strength of the reinforcing steel is equal to 1.5 times its yield strength and the ultimate strain is equal to 0.12. Furthermore, the behavior of concrete was modeled using the concrete confinement model proposed by Mander et al. [38] and elastic modulus of concrete is approximated to $5000\sqrt{f_c'}$, where f_c' is the unconfined concrete compressive strength.

Figure 7 compares the moment-curvature responses established for the reinforced concrete section shown in Figure 3 at temperatures of 20°C and -20°C, and indicates an increase of 6% in the ultimate moment strength for the cold condition than that obtained for the warm condition. Between the two analyses, the unconfined concrete strength and yield strength of the reinforcement were varied based on the test data reported by Filiatrault and Holleran [7]. Consequently, the concrete strength and yield strength for the analyses at -20°C were taken as 20% and 4.5% higher than those specified for the analyses at 20°C. According to the approximations made in the moment-curvature program, the elastic modulus of the concrete and ultimate strength of the reinforcing steel were increased by 9% and 4.5%, respectively, at -20°C. These increases are comparable to the respective increases of 7% and 4.7% reported by Filiatrault and Holleran [7]. The critical parameters used in the moment curvature analysis at the two temperatures are listed in Table 2.

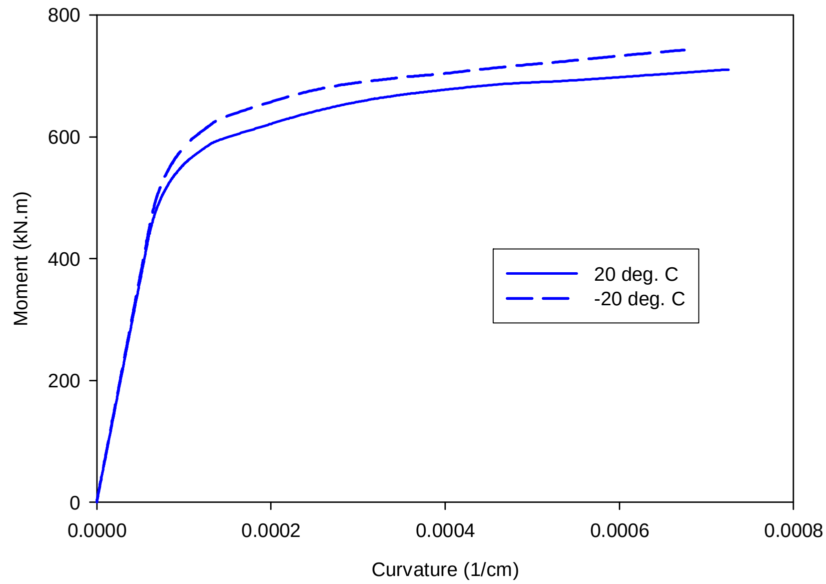

Figure 7 Moment-curvature responses of the concrete section assumed for the column and CIDH shaft.

ANALYSIS RESULTS

Two series of analyses are presented below. In the first series, which includes Cases 1 through 4 (see Table 1), the temperature effects on the soil response are examined as a function of ground surface temperature. However, the temperature effects on concrete or steel are not included in this series of analyses. In the second series, the results from Cases 4 through 6 are presented, in which the temperature effects of concrete and steel and the influence of the depth of frozen layer are examined while the ground surface temperature is kept at -20°C.

For the analysis Cases from 1 through 4, Figure 8 shows the lateral load vs. lateral displacement at the top of the column and Figure 9 compares the deflection, shear, and moment diagrams obtained at the ultimate condition. The ultimate condition was defined by the ultimate compressive strain suggested for confined concrete by Mander et al. [38] or a tension strain of 0.06 in the reinforcing steel, whichever occurred first. The concrete compressive strain controlled the ultimate condition for the concrete section used for the column and shaft. Although it was not accounted in the analyses, it is noted that the actual lateral displacement capacities of the column-shaft system would be higher than those shown in Figures 8 and 9. This is because spalling of cover concrete and buckling of the longitudinal reinforcement are unlikely to occur in the in-ground plastic hinge region of the shaft and the behavior of concrete in this region would benefit from the soil confinement pressure at large lateral displacements. However, defining the ultimate condition as detailed above enables displacement capacities and shear demands in the column-foundation systems to be compared when similar strain conditions are developed at the critical section.

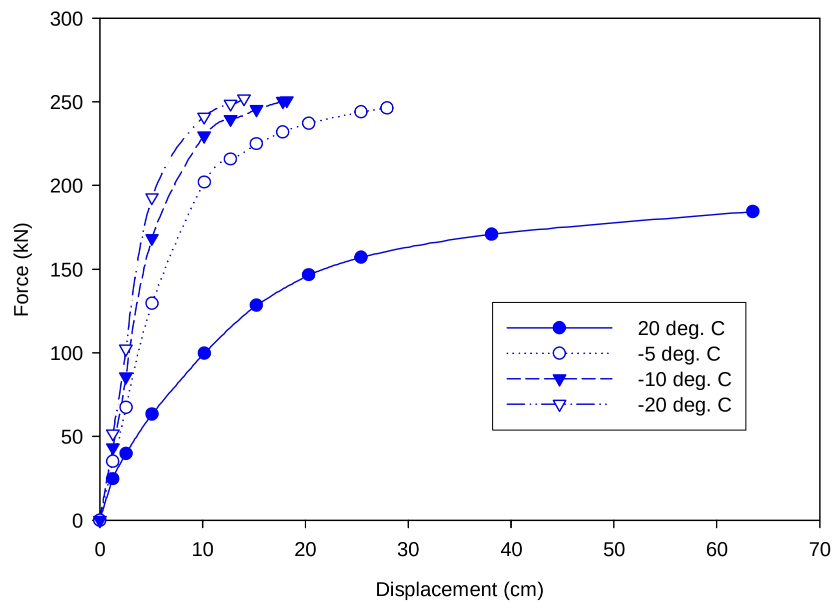

Figure 8 Force-displacement responses for the column-foundation system.

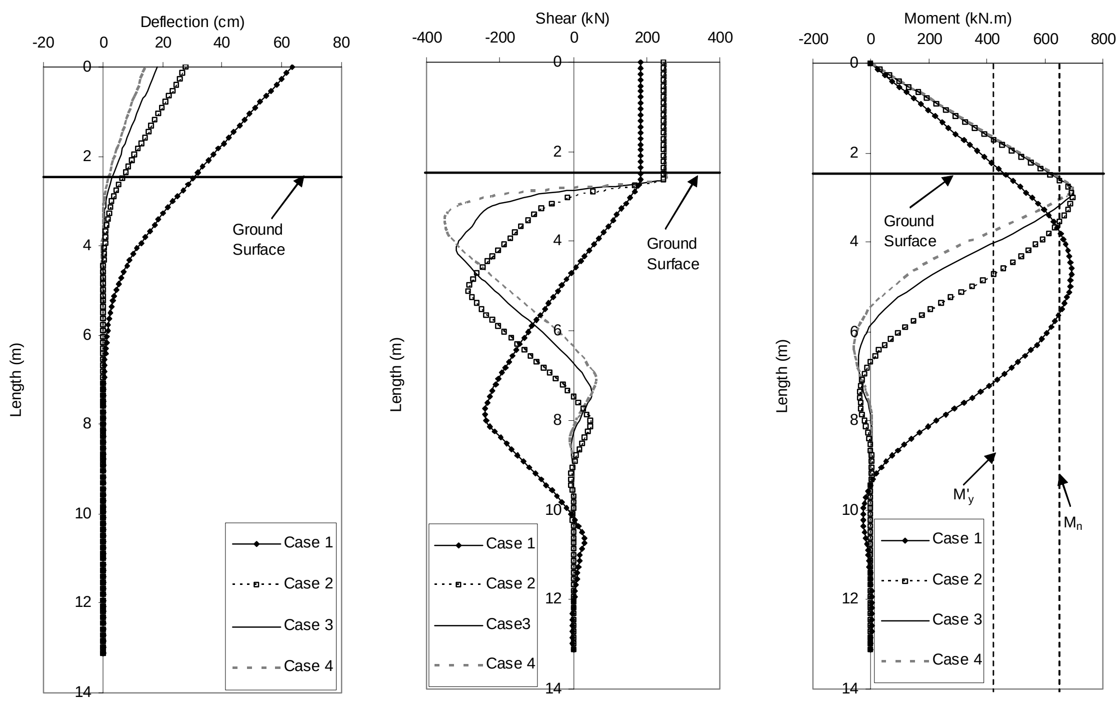

Figure 9 Displacement, shear and bending moment diagrams at the ultimate condition for the column-foundation system at different ground surface temperatures.

Comparing results from Case 1 with those for Cases 2, 3, and 4 in Figures 8 and 9, it is observed that the lateral displacement capacity at the top of the column decreases with decreasing temperatures. When compared to the temperature at 20°C, the displacement capacity reduced by 55%, 70% and 78% at -5°C, -10°C, and -20°C, respectively. Furthermore, the corresponding shear demand increase in the column was found to be 35%, 37%, and 39%, respectively. In the CIDH shaft, the respective shear demand increases were 18%, 32% and 45%. The significant discrepancies in the lateral displacement capacity and shear demand were due to the relocation of the in-ground plastic hinge and the reduction in the spread of plasticity of this hinge in the CIDH shaft. For the column-foundation system at 20°C, the maximum moment developed in the CIDH shaft at 2.06 m from the ground surface. This distance was reduced to 0.41 m, 0.19 m, and 0.06 m as the ground surface temperature was reduced to -5°C, -10°C, and -20°C, respectively.

Analysis results from Cases 4 through 6 are presented in Figure 10. With respect to the changes observed in Figure 9, the lateral displacement capacity and shear demand did not vary significantly between these analyses. The conditions used for Cases 4 and 5 were identical, except that the temperature effects on concrete and steel reinforcement were included in Case 5. With no change to the location of the maximum moment, the shear demand in the column and shaft was increased by 7% in Case 5 when compared to the results of Case 4. This increase was due to the difference in moment capacities of the concrete section seen in Figure 7. When compared to Case 4, the lateral displacement capacity was increased by 6% in Case 5.

Small changes to the displacement capacities and shear demands are seen between the analysis results of Cases 4 and 6 (see Fig. 10), for which the ground surface temperatures were assumed to be at -20°C while the depth of frozen layer was reduced from 1.2 m to 0.61 m.

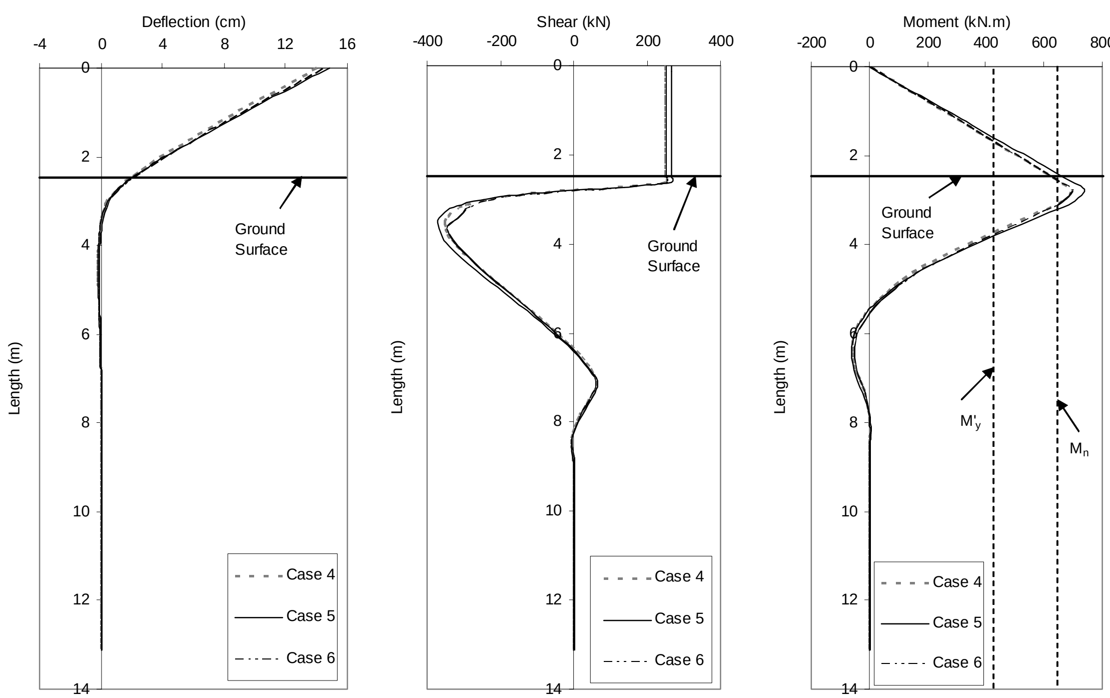

Figure 10 Displacement, shear and bending moment diagrams at the ultimate condition for the column-foundation system at a ground surface temperature of -20°C. (M'_y = First yield strength and M_I = Ideal strength [31].)

CONCLUSIONS

An analytical investigation on the effects of cold temperatures on lateral load behavior of a concrete bridge column supported by a CIDH shaft has been presented in this paper. At 0.6-m diameter, the column and shaft represented a typical bridge column-foundation system in the Midwest and East Coast of the United States, where large magnitude seismic events and subzero ground temperatures in the range of 0°C to -20°C are anticipated Accounting for the temperature effects on the soil, concrete and steel reinforcement based on test data reported in the literature, the behavior of the column-foundation system was studied under monotonic loading at ground surface temperatures of 20°C, -5°C, -10°C, and -20°C. From the literature review, modeling of column-foundation system, and comparison of analysis results of the cold temperatures with those obtained for the analysis at 20°C, the following conclusions have been drawn:

1. Seasonal freezing that is experienced in several regions of the US, Canada and other countries will have significant influence on the seismic response of bridge column-foundation systems.
2. As the ground surface temperatures drop below zero, the shear strength and stiffness of clay may increase by two orders of magnitude.
3. Cold temperatures modify the properties of concrete and steel reinforcement. At -20°C, the compressive strength of concrete and tensile strength of steel reinforcement are increased by 20% and 4.5%, respectively.
4. Without accounting for the effects on concrete and steel reinforcement, the analysis revealed that the frozen soil reduces the lateral displacement capacity of the column foundation system by 78% and increases the shear demand in the column and shaft by about 40% at -20°C. These drastic changes in the displacement capacity and shear demand were attributed to the relocation and reduction to the spread of the in-ground plastic hinge caused by the presence of the frozen soil near the ground surface.
5. At a ground surface temperature of -20°C, the temperature effects of concrete and steel were found to have relatively small influence on the lateral load behavior of the column-foundation system when compared to the effects due to the frozen soil.
6. The depth of frozen soil was also found to have minimal effect on the lateral response of the column-foundation system at -20°C. When the depth of frozen soil was reduced from 1.2 m to 0.61 m, neither the lateral displacement capacity of the column nor the shear demand in the column and CIDH shaft was significantly altered at the ultimate condition.

While the focus of this paper is on the response of bridge column-foundation system under monotonic loading, the effects of reversed cyclic loads, column axial loads and strain rate are important aspects and must be included in future investigations to more accurately quantify the response of structure-foundation systems under seismic loading. Through an outdoor experimentation program, some of these aspects are currently being studied at Iowa State University.

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