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Dynamic behaviour of reinforced-concrete bridges in freezing conditions

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ABSTRACT

The strong influence of ambient temperature variation, and especially freezing of near-surface soils, on the transverse modal response of the bridges in cold earthquake-prone regions has been shown in previous research. This paper extends this work and presents an analytical investigation of the modal characteristics of the range of reinforced concrete continuous beam bridges with integral pile-column systems with various geometries over a range of temperatures. The numerical bridge models were geometric modifications of previously validated finite element models of a soil–pile-bridge system representing a prototype three-span bridge located in Anchorage, Alaska. Frozen conditions increased the fundamental modal frequencies across all the bridge schemes. The mode shapes of the short bridges with a few spans undergo significant transformation mainly due to the changes in the stiffness of the pier-foundation-soil system in winter. More flexible, high column and multi-span bridges are less susceptible to these significant mode shape variations. The findings reveal the need for further assessment of the seismic design code requirements for the bridge stock in the cold regions, given that changes in modal parameters may increase the design seismic lateral loads along with potential redistribution of the loads across the structure due to stiffening of the pile-soil system in winter.

1 INTRODUCTION

The dynamic behaviour of the bridges in cold regions have been investigated to a limited extent and need more attention (Peeters et al. 2001; Zhao and DeWolf 2002; Alampalli 1998). Studies focused on the modal response of the bridges in these conditions revealed that the modal periods of some bridges change linearly (Wang et al. 2011; Desjardins et al. 2006) or demonstrate non-linear behaviour when the temperature drops below zero (Zhao and DeWolf 2002; Moser and Moaveni 2011; Fu and DeWolf 2001; Peeters et al. 2001).

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Moreover, the difference between modal parameters in different seasons may be significant. For instance, studies carried out on reinforce concrete highway bridge in Alaska and ballasted railway bridge in Sweden showed 12% and 35% variation of the first transverse modal period, respectively (Xiong et al. 2007; Gonzales et al. 2013), while the study of another highway bridge located in Alaska introduced more than 200% variation (Yang et al. 2012).

Variation of the modal parameters of the bridges in earthquake-prone cold regions such as North-East Russia, North-West United States, Northern China, Japan, may have a significant impact on the bridge seismic behaviour. Considerable reduction in the natural period of the bridges in cold regions when ambient temperatures drop below zero may lead to increased lateral loads calculated by seismic design codes and to redistribution of the loads across of the bridge components (Wotherspoon et al. 2010). The variations in the modal bridge response happen due to changes in material and soil stiffness and changes in boundary conditions (Yang et al. 2007; Sritharan et al. 2004; Suleiman et al. 2006; Wotherspoon et al. 2009; Alaska Bridges & Structures Manual 2017). Significant strengthening of frozen soil well beyond the elastic range has been demonstrated in a range of studies (Shelman et al, 2014; Wotherspoon, 2009) and one example is shown in Figure 1. Since bridges vary in form, geometry and material properties, the effect from these changes in the parameters on bridge modal response will be specific for each case.

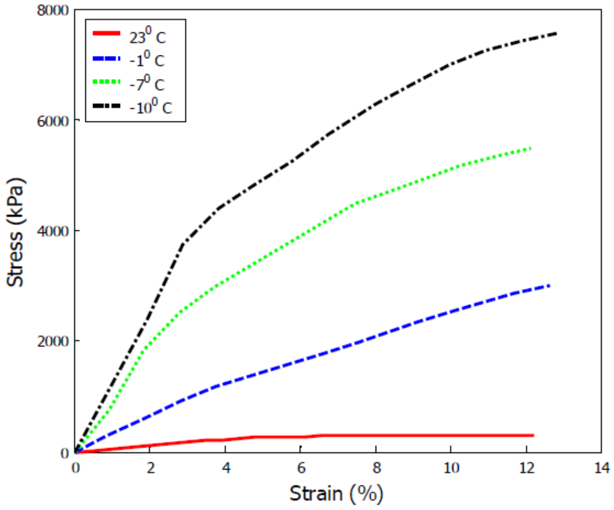

Figure 1: Soil stress-strain curves for glacial till (Wotherspoon, 2009)

In the current study, we focus on the effect of seasonal freezing on modal characteristics of a range of geometric modifications of a reinforced concrete bridge in Alaska, Campbell Creek bridge. The modal periods of several bridge variants were also linked to the design spectrum for Alaska, giving insight into the effect of the bridge geometry and seasonal freezing on the seismic design loads.

2 BACKGROUND AND MODELLING APPROACH

The Campbell Creek Bridge is a 109 m long reinforced-concrete skewed in plane structure supported by columns on pile foundation (Figure 2). The bridge has three continuous spans, each consists of 11 prestressed RC girders with asphalt layer at the top, supported by two center capped pile piers. The abutments and piers consist of RC pier caps supported by 11 and 10 concrete-filled steel pipe piles, 0.6 and 0.9 m in diameter, to a depth of 11.7 and 15.8 m, respectively. The soil profile at the site includes the soft peat at the top following by the gravelly silt with sand, gravel with silt and sand, and silty gravel. The bridge has been instrumented to measure the dynamic response and frost penetration continuously since November 2008. The ambient temperature fluctuated between +6°C and +10°C in summer and –1 °C and –17°C in winter during the experimental data collection. The recorded depth of the seasonal freezing was between

1.16 and 1.24 m. The bridge description, monitoring scheme and baseline numerical models are explained in detail by Plotnikova et al. 2019.

The bridge soil-foundation-structure model utilising a Winkler spring approach was developed in CSIbridge (CSiBridge 2016). The modal characteristics of this model were verified by the experimental modal parameters. The linear modelling approach was assumed appropriate since the main focus was to understand the fluctuations in the modal response of the bridges. The elements of the baseline model were modelled by frame elements, beams and piers/piles, with gross section properties located at the centre of their mass; thin shell elements, asphalt layer; elastic link spring elements of a different stiffness representing soil-foundation interaction, bearings, shear keys, and diaphragms. Structural mass of the elements was lumped at each node and based upon the volume and the mass density of the element adjacent to the node. The bearings were fully fixed against rotation about the horizontal axes, constrained against the movement in a longitudinal direction and transverse direction on the abutments due to the effect of concrete shear keys. Rigid spring elements in the transverse direction were introduced to model the diaphragms. The 24 and 26 springs elements were placed on either side along the pile elements at the piers and the abutments, respectively, to model the soil-foundation interaction using Beam on Linear Winkler foundation approach.

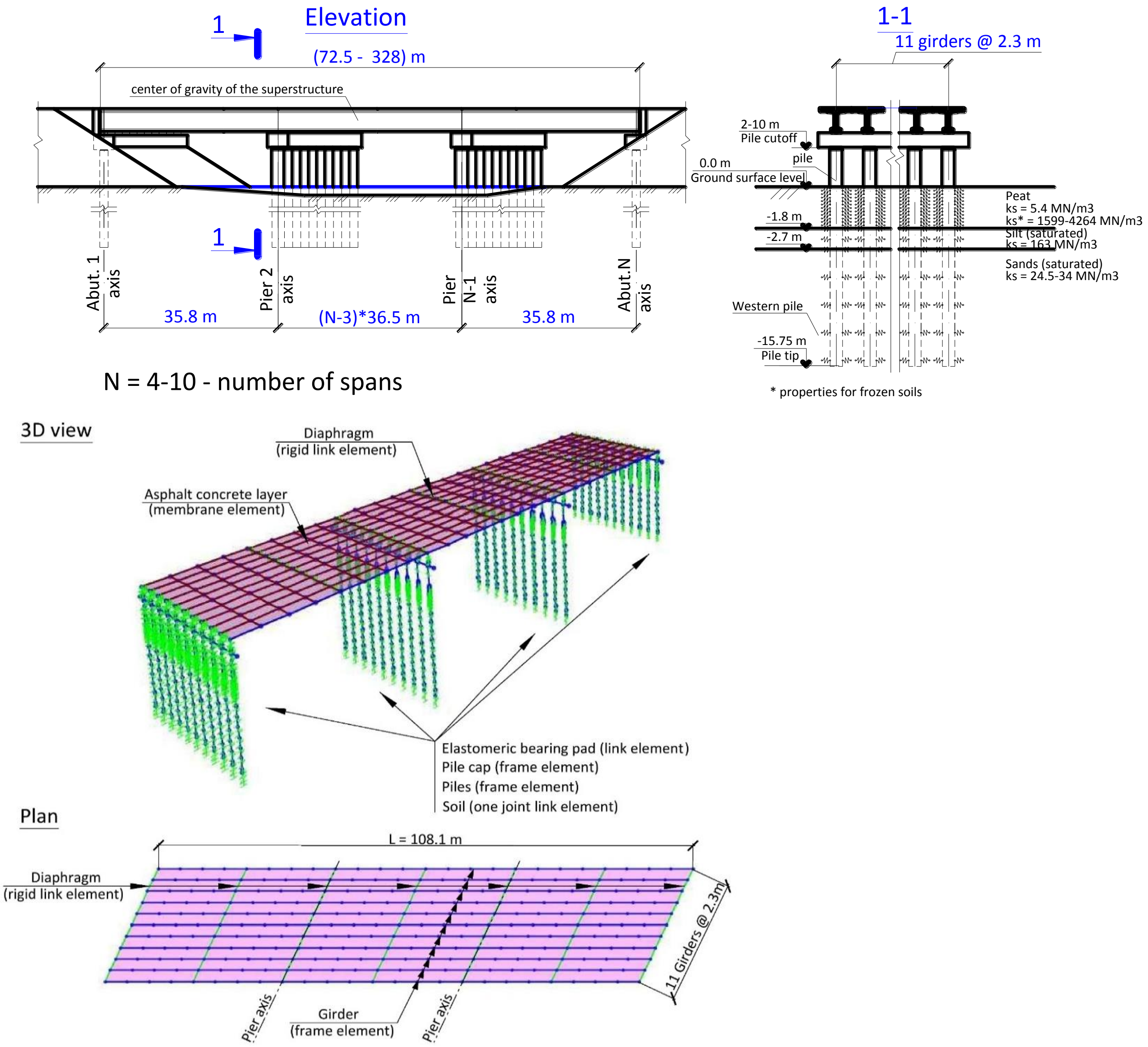

Figure 2: Rendering of the bridge models (top), the baseline model (bottom)

The baseline material properties of bridge elements in warm and cold seasons are summarised in Table 1. Stiffness characteristics of the soil surrounding the foundations were determined based on the modulus of subgrade reaction and shown in Figure 2. The stiffness of the frozen soil increased up to 800 times due to the temperature drop up to minimum recorded temperature mentioned above and varied along the depth due to the linear temperature increase within the soil profile, from ambient temperature at the ground surface to zero at the freezing line (Li 2011). The foundation was divided into multiple segments with a higher density of elements in the top soil level to analyse the effect of the different depth of the freezing. This discretization was to be appropriate for this analysis.

The modified bridge models, developed in the same software, included the variation of the number of spans, of the height of the piers and depth of soil freezing (Figure 2). The variation range is summarised in Table 2. The material properties and cross sections of the bridge elements in different seasons were assumed to be equal to baseline values described above across the whole range of the examined schemes.

Table 1: Material properties of the bridge elements in summer/winter

Bridge element	**Material**	**Density (kg/m3)**	**Young modulus, E (MPa)**	**Stiffness in transverse direction (kN/m)**
Pavement	Asphalt concrete	2600	10,000/30,000	-
Girders	Concrete	2320	32,880/42,500	-
Piles	Concrete	2320	46,028/58,200	-
Bearings	Elastomer	-	-	12,192/260,000

Table 2: Range of the parameters

Parameter	**Variation range**
Number of spans, N	2-10
Height of the piers	2-10 m
Depth of the seasonal freezing	0-1.8 m

3 RESULTS

The summer and winter models of the bridges were compared and discussed below.

3.1 Fundamental transverse frequencies

The correlation between the bridge geometry and fundamental period in the transverse direction in summer and winter is represented in Figure 3. Expectedly, the period rises with an increase in the number of spans or in height of the bridge at any season, due to increased flexibility. The bridges of any height, especially low ones, and any number of spans have substantially lower periods in winter. For example, the periods of the short bridges in summer are 2.5 times and 3.2 times higher than in winter for two-span and ten-span schemes, respectively. The periods of the high bridges rise by up to 1.9 times in winter. The changes of period in different seasons are more prominent for short column bridges, 1.6 times for the 10 m height bridges versus 2.9 times for 2 m height, pointing on the increased flexibility of the supports.

The effect of variation of frozen depth of the top soil level was investigated on the two models, the baseline model of the bridge and its 10 m height variant. The freezing of the soil may result in a significant decrease in transverse period and vice versa (Figure 4). The variation of frozen depth up to 0.4 m and up to 1 m has the largest impact on the modal parameters of the short and high column bridges, respectively. For instance, once the depth of frozen soil reaches 0.4 m, the fundamental transverse period of the short bridges increases by more than twice the summer values. Further increase of the frozen depth leads to small changes in period, less than 10%.

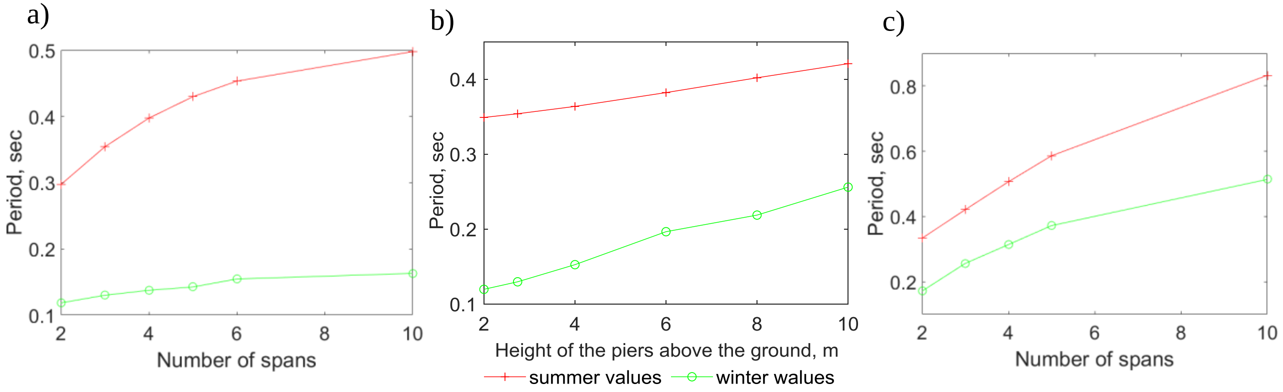

Figure 3: Fundamental transverse period in summer and winter for the various bridge schemes: (a) 2.75 m height bridges; (b) three-span bridges with the height varying from 2 to 10 m, (c) 10 m height bridges

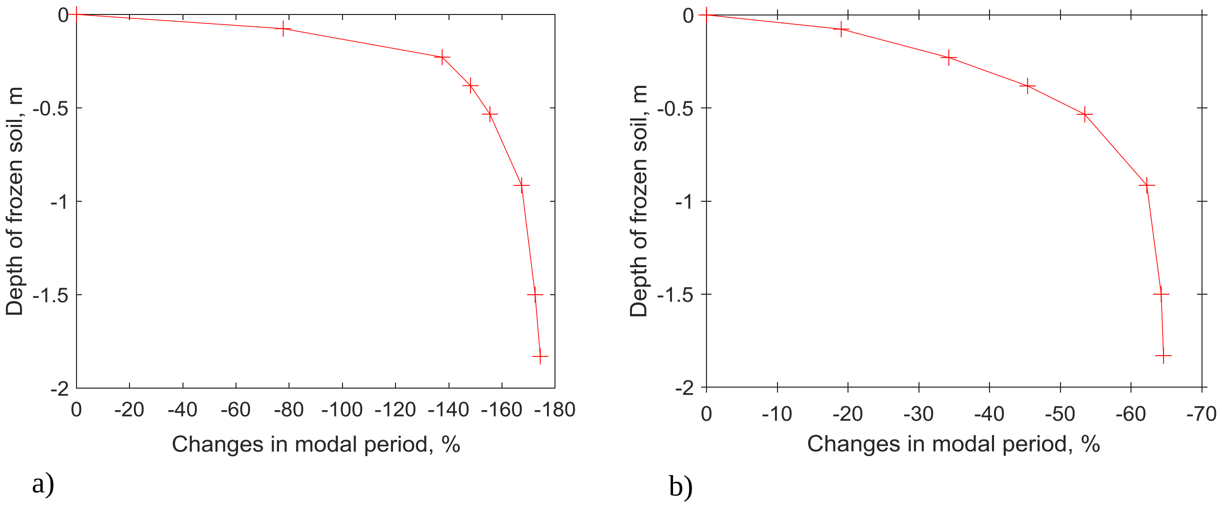

Figure 4: Fundamental transverse period variations for 2.75 m height of the bridge (a) and 10 m height bridge (b)

3.2 Fundamental transverse mode shapes

The summer and winter mode shapes of short column bridges are poorly correlated (Figure 5). The difference in amplitudes increases as the number of spans increases, with the values in summer almost twice that of winter values for the ten-span scheme. The shape of the modal amplitudes in winter is a result of the significant difference between the stiffness of the superstructure and substructure due to increase in soil and bearings stiffness (Table 1), shown by sensitivity analyses carried in the previous studies (Plotnikova et al. 2019).

On the other hand, the summer and winter mode shapes of the high bridges become well correlated when the number of spans increases. The highest difference between the amplitudes occurs at the abutments, indicating that the amplitudes of the vibration of these bridges are less sensitive to seasonal freezing of the soil and to the high stiffness of the bearings due to increased flexibility of the piers.

The summer modal amplitudes are highly correlated and smooth for the bridges of any height (Figure 6a). However, the winter mode shapes are sensitive to the changes in the bridge height (Figure 6b). In particular, they may be smooth or not, may have winter amplitudes equal or up to two times lower than summer ones. Modal amplitudes, in turn, at the abutments in winter remain stable being by about two times lower than summer pointing on the dominant effect of the stiffness of the embankment fill around the piles.

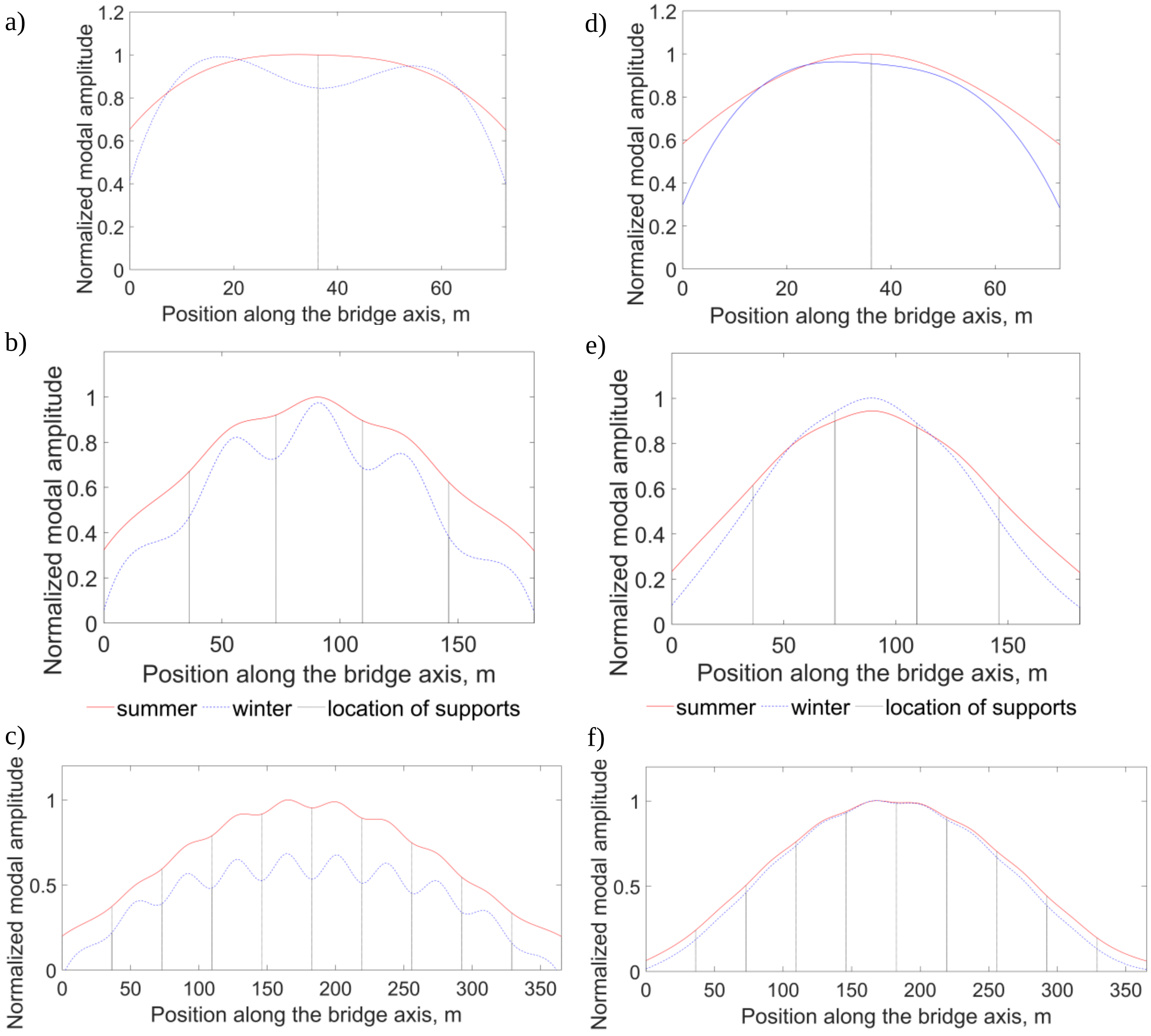

Figure 5: Normalised modal amplitudes for 2.75 m height bridges: (a) 2 spans, (b) 5 spans, (c)10 spans; for 10 m height bridges: (d) 2 spans, (e) 5 spans, (f)10 spans

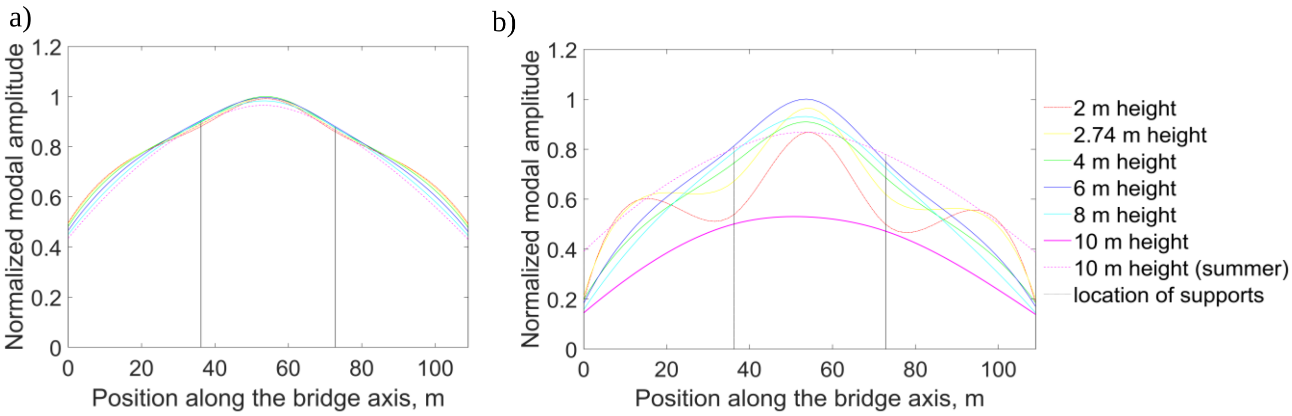

Figure 6: Comparison of (a) summer and (b) winter normalized modal amplitudes for various bridge heights

3.3 Effect on seismic design loads

To demonstrate the effect of seasonal temperature changes on seismic design loads, the spectral accelerations corresponding to the fundamental transverse period of the 10 m high bridges was shown on the acceleration response spectra for a 1000-year return period in Anchorage, Alaska (Figure 7). The seismic design loads, proportional to the spectral acceleration, was shown to increase by 1.5 times for the ten-span from summer to winter. This is a significant increase in the design input, requiring a substantial change in the capacity of the structural and foundation components. For the two-span bridge, both summer and winter fundamental periods are located on the plateau of the spectrum, leading to equal design loads. However, the redistribution of the loads along the piers and foundations that will take place due to the change in soil and bearing will result in higher demands in areas that are not critical during summer conditions. Therefore, the seismic performance of the all types of bridges should be assessed in both cold and warm seasons at the design stage.

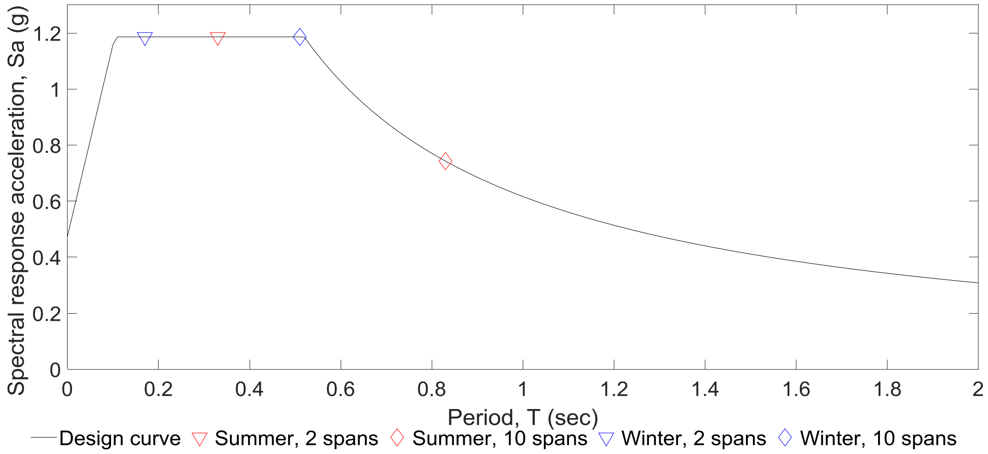

Figure 7: Design acceleration response spectrum for very dense soil, Alaska, 1,000-yr Return Period (7% PE in 75 Years) and subsequent spectral acceleration for bridges with a varying number of spans (AASHTO 2009).

4 CONCLUSIONS

The influence of the bridge geometry, the depth of seasonal freezing on the modal response of finite element models of the soil–pile-bridge system in winter and summer was investigated. The results demonstrate that the fundamental transverse period of bridges of any configuration drops significantly in winter. The fundamental period was found to be very sensitive to the freezing of the soil, even at a small depth. Once the frozen soil reaches a particular depth, there will be the little additional effect on the bridge modal response. The fundamental transverse mode shapes have significantly different amplitudes and forms in summer and winter pointing at the significant rearrangement of the stiffness at a support level. Although, this difference minimises for the high multispan bridges due to the increased flexibility of piers.

The obtained modal characteristics were linked back to the US design standard spectra, highlighting the need in the separate assessment of the dynamic response of reinforced-concrete bridges in summer and winter if they are located in the regions experiencing seasonal soil freezing. It was found that the spectral values and, as a result, seismic design loads in winter can be significantly larger than summer values due to shortening of fundamental period. Both this and the redistribution of the internal forces due to change in soil and bearing stiffness may lead to higher demand in regions that may not be critical in summer conditions.

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