Seasonally Frozen Soil Effects on the Dynamic Behavior of Building Structures

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ABSTRACT :

Some studies have shown that the seasonally frozen soils have a significant effect on the dynamic properties of building structures, which will yield increases in the fundamental frequencies from summer to winter. The changes in frequencies, however, appear a wide range from 4% to 50%. The factors to control the magnitude of this effect are important for earthquake engineering since it determines if the frozen soil effect needs to take account when designing buildings in the cold regions. Three buildings in the similar climate condition are studied in this paper to compare this effect. Through instruments in the field the ambient noise and small earthquake-induced vibrations have been recorded and their dynamic properties are identified. The changes in the first frequency during various seasons are discussed. The further parametric study using FE models is conducted. The relative stiffness between superstructures and soils is founded as a key factor. A ratio coefficient is presented to relate the frequency change when the ground freezing. Another possible factor is the building configuration or foundation design, which determines if the heat inside the building migrates to the soils under and surrounding the building, and if frozen soils occur for individual buildings.

KEYWORDS: Seasonally Frozen Soils, Fundamental Frequencies, Structural Stiffness, Finite Element Modeling, Field Test.

1. INTRODUCTION

Previous studies (Xiong et al. (2007), Yang et al. (2007), and Bai (2007)) have shown that seasonally frozen soils affect the dynamic properties of soil-structure systems. These past projects involving in the field test and numerical analysis yielded increases in the fundamental frequencies ranging from 4% up to 50% from summer to winter season. It is noted that these effects by soil freezing appear to be in a wide range, even if structures are similar in shape and size and expose to similar climate as well as geotechnical characteristics. What factors determine the magnitude of this effect? Understanding this question will greatly help us predict the dynamic properties and seismic performance of civil structures. This study is of great significance for earthquake engineering due to the vast existence of seasonally frozen soils in seismic areas.

Three buildings of various structural types (i.e. steel moment-resistance frame, reinforced-concrete column-wall system and concrete column-slab system) and different configurations (with or without basement, heated or unheated) in Anchorage, Alaska are included in this study. Through instruments in the field the ambient noise and small earthquake-induced vibrations have been recorded to monitor their dynamic properties change. The fundamental frequencies and modes in different seasons have been identified and summarized. The factors that control the effect of seasonally frozen soils are discussed. A parametric study using FE models is conducted to investigate the impact of these factors. It is found that the relative stiffness between superstructures and soils dominates the magnitude of effect of frozen ground. A ratio coefficient is presented to indicate the frequency change when the ground freezing.

2. DESCRIPTION OF TESTED BUILDINGS

2.1. Atwood Building (AB)

AB is a office building located in downtown of Anchorage that was designed and constructed in the early 1980's according to the 1979 Edition of the Uniform Building Code. There are 20 stories above the ground level and a basement used as a parking garage. The typical plan is in a regular rectangular shape with the size of 38.5 m×38.5 m. This building is a moment-resisting steel frame structure with a 14.63 m×14.63 m in-plan center steel shear walled core. The roof is 80.5 m above the ground level. The lateral force resisting system is composed of steel column-beam system with Chevron bracing and built-up steel-plate shear walls. The building foundation consists of 1.52 m thick mat below the core and 1.37 m thick mat at the perimeter of the building plan. Exterior and core mats are interconnected with grid beams.

2.2 Frontier Building (FB)

The Frontier Building is a 14-storey reinforced concrete office building that was constructed and occupied in the early 1980's under the 1979 Uniform Building Code (UBC). It is a very regular building of rectangular shape in plane. The plan dimension is 59.44 m × 32.61 m in the E-W edge and N-S edge respectively. Its structural system includes post-tensioned floors supported by columns. No shear walls are arranged in the plan for structural members. The circle-sectional columns are 0.91 m in the diameter. The typical floor level construction is 0.20 – 0.25 m thick reinforced concrete diaphragm. The roof of the building is set at 50.60 m above the ground level (1ST Floor or Lobby). The building is founded on a series of reinforced concrete strip footing without basement. The footings on the edges are 2.74 m wide and 1.37 m thick while the interior footings are 3.35 m wide and the same thickness as the edge footings. Stemming from the footings are 1.22 m. The first floor of the building is essentially a slab on-grade atop the backfill of the strip footing. The bottom of the foundation is at a depth of 1.68 m below ground.

2.3 Parking Garage (PG)

This three-story reinforced concrete parking garage was designed based on the 1997 Uniform Building Code and constructed in 2001. It is an unheated garage, and there are very wide openings on the exterior walls whereas no partitions are arranged inside. It has a square base and floor plan with dimension of 59.7 x 60.3 m. The overall building height is approximately 11 m with an average story height of 3.1 m. Its structural system consists of post-tensioned floors supported by columns and shear walls. Main shear walls are connected into three RC tubes (stairway room) of 254 mm thickness. The dimension of most columns is 450 x 450 mm. No frame beams were used to connect columns except at the perimeter. It is noted that the floor in the center is inclined to allow vehicle access. The foundation system consists of RC spread footings (4.5 x 4.5 m) under each column embedded 1.5 m deep. Subsurface investigation of the parking garage site shows that poor quality fill and peat layers underlie existing ground surface reaching a depth of 2.5 to 5 m. Beneath them lie poorly graded sands and gravels followed by silty sands and gravels to a depth of 10 m. During the construction, the existing fill layer was excavated and backfilled with structural fill to support the spread footings. The frost action can be expected to penetrate as deep as 1.8 m or more during winter season. Considering the cost, the garage has no insulation for the foundation.

3. DYNAMIC TEST RESULTS

Dynamic tests induced by ambient noise and small earthquakes were conducted over three buildings from winter 2004 to summer 2007 to achieve fundamental frequencies and mode shapes through recording, collecting and identifying vibration data. Various frequency properties are utilized to investigate seasonally frozen soil effect on building behaviors.

3.1 Instrumentation and Identification

With the support from the advanced National Seismic System of United States Geological Survey, AB and FB have instrumented to collect structural responses under strong ground motions. In AB There are 32 channels of accelerometers installed on 10 selected levels including in translational, torsional and rocking directions. There are 3 recorders in the data acquisition system connected by 3 telephone lines to enable remote access. In FB the system uses 36 channels with 12 channels per data recorder. Of 36 channels 30 channels monitor lateral movement in 10 of the 14 floors of the building, and remaining 6 channels are set up for monitoring in vertical direction only on the 1st and 14th floors. All sensors, branded Kinemetrics EpiSensors, have a bandwidth of DC to 200 Hz and operation range of -4.0g ~ +4.0g with 1.25 V/g sensitivity. Data collection was performed in two ways, event trigger and keyboard trigger. Event trigger model is used to record actual earthquake responses and threshold acceleration value was set up 1.0 – 80 gal. Keyboard trigger model is for collection of ambient noise data. Signal from each recorder was sampled at 200 samples/s and in 4-7 minutes duration. The dynamic tests for PG were performed by a Portable Data Acquisition System. 16 accelerometers (ranged ±2.0g with 1.25 V/g sensitivity) were deployed from 2nd to 4th level to record horizontal vibration. Ambient excitations were used for each test, and vehicles were driving to intensify ambient noise. Signals were still sampled at 200 samples/s and duration for each test is 6 minutes.

The recorded vibration data were first filtered between 0.01-45 Hz using a fourth order bandpassed Butterworth filter, and then were processed using system identification program ARTeMIS Extractor (Structural Vibration Solution A/S, 2004 and 2007) to identify the structural dynamic properties. The Enhanced Frequency Domain Decomposition (EFDD) method implanted in ARTeMIS Extractor has been used for this purpose

3.2 Results

Dynamic test results for these three buildings are obtained. Targeting to seasonally frozen effect on structural dynamic behavior, all testing covered at least two seasons from winter to summer. In AB the instrumentation began from winter 2004. Hundred sets of records were transmitted among which the most were excited by earthquakes with magnitude (M_L) 3.2 to 5.6. Similar vibration data appeared in FB where instruments have been used since winter 2007. The dynamic testing results excited by earthquakes revealed that earthquake intensity in terms of PGA (peak ground acceleration) would impact on identified fundamental frequencies, lower frequencies associated with higher PGA. It might be caused by the fact that as ground sharking intensity increases, the nonlinearity of the building-foundation-soil system is gradually mobilized and the effective stiffness of the system is decreasing. Therefore results in similar earthquake intensity level of different seasons are selected to compare for the AB and FB. For GP field tests were conducted 5 times during winter 2006 to summer 2007. At least three sets of vibration data were collected in each test and the average values are used in the investigation of this paper. Table 3.1 summarizes the dynamic testing results.

The frozen ground thicknesses listed in Table 3.1 are calculated from Modified Berggren Equation by environmental temperature data. Since no temperature data were collected during testing in the AB, frozen ground thickness column leaves blank in Table 1. However general frozen season in Anchorage is referred from Nov. 15 to May 15. Since recordings in the PG are ambient vibration, the signals are very weak. Only the first frequency was identified. Also the frequency serials are not complete for the AB and FB.

3.3 Changes of fundamental frequencies from summer to winter

From Table 3.1 it is noted that the effect of freezing ground on structural frequencies is different for three buildings. Table 3.2 describes the change rates of the first frequency of three buildings from winter with deepest frost to summer, where the frequency in summer is the average value of measurements during summer.

Table 3.1 Dynamic Testing Results

Atwood Building							
Event Date	Frozen ground thickness	Frequencies (Hz)					
		1st Mode			2nd Mode		
		EW	NS	Tor	EW	NS	Tor
02/17/05		0.479	0.545	-	1.560	1.785	-
03/25/04		0.484	0.543	0.611	1.543	1.808	-
04/23/04		0.488	0.537	0.610	1.545	1.794	-
05/30/04		0.464	0.525	-	1.501	1.770	-
07/27/05		0.464	0.537	-	1.550	1.758	-
08/23/05		0.452	0.537	-	1.538	1.721	-
Frontier Building							
Event Date	Frozen ground thickness	Frequencies (Hz)					
		1st Mode			1st Mode		
		EW	NS	Tor	EW	NS	Tor
03/01/07	1.84	0.595	0.677	0.918	1.861	2.059	2.736
04/05/07	1.89	0.594	0.667	0.901	1.845	2.025	2.698
04/25/07	1.34	0.599	-	-	1.836	-	-
05/22/07	0.73	0.589	0.672	-	1.833	-	-
06/01/2007	0.50	0.602	0.677	0.907	1.870	2.019	2.709
08/17/07	0.00	0.606	0.673	0.908	1.889	2.048	2.709
Parking Garage							
Event Date	Frozen ground thickness	Frequencies (Hz)					
		1st Mode			1st Mode		
		EW	NS	Tor	EW	NS	Tor
10/22/06	0	1.16					
12/02/06	0.52	1.39					
01/13/07	0.57	1.42					
03/01/07	1.04	1.69					
04/02/07	1.40	1.74					

Table 3.2 Change rates of first frequency

1st frequency	summer	Winter (deepest frost)	Change rate (%)
Atwood Building	0.464	0.484	4.31
Frontier Building	0.606	0.594	-1.98
Parking Garage	1.16	1.74	50.0

A very various change range is observed from the comparison in Table 2. The PG has the largest increase, i.e. 50%, in first frequency from summer to winter; however the AB only increases 4.31%. A negative change rate for the FB means that the frequency drops from summer to winter. In fact 1.98% change rate often may be caused by measuring errors. So for the FB it only can be concluded that there is little change in frequencies due to the season switch. Three buildings locate in the same city, and climate conditions encountered is also similar. But the effect of frozen soil on fundamental frequencies is so different. What is the key factor lead to frequencies change when soil freezing? In other words, what buildings should consider the effect of frozen soil in structural design? It will be a valuable question for engineering communication.

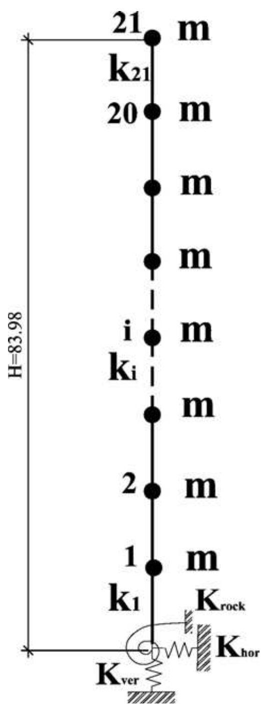
Three buildings have different structural types or different structural stiffness. The AB is the steel frame; the FB and PG are concrete column-slab system. The structural stiffness is supposed to be a factor. On the other hand, the AB has a basement garage; the FB has no basement and foundation is placed on shallow soil layer directly; the GP is an unheated building. Those configurations absolutely effect the temperature of surface soil, and then frozen depth. So it could be another factor.

4. EFFECT FACTORS OF SEASONALLY FROZEN SOILS ON STRUCTURAL DYNAMIC PROPERTIES

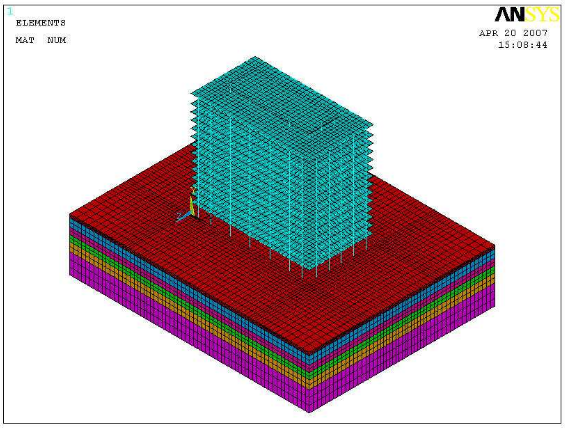
To investigate the effect factors a series of analysis is conducted over three building models. These calculation models are first calibrated by measurements, and then finite element method is employed to simulate the environmental conditions and get frequency results.

4.1 Modeling

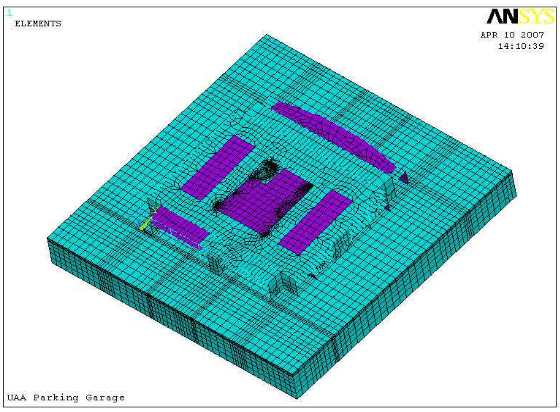
The interaction models including the superstructure and soil over three buildings are founded to calculate fundamental frequencies. A lumped parameter model (LPM) is developed for the AB (Fig. 4.1 (a)), and the elastic spring coefficients of soil were derived from a FE modeling based on the 3D foundation－soil model.



(a) Atwood Building



(b) Frontier Building



(c) Parking Garage

Figure 4.1 Finite Element Models

Full FE models including the soil and superstructure are used to simulate dynamic behaviors for the FB and GB on the computational software ANSYS, where Element Beam189 and Shell63 are employed for beams, columns and shear walls on the superstructure and Element Solid65 is for the soil. All numerical models are calibrated by the summer test results by adjusting some parameters of structure to match the computational frequencies to test ones, i.e. floor mass chosen for the AB model, stiffness of structural member for the FB and soil elastic modulus for the GB. (Xiong et al. 2006, Bai 2006 and Yang et al. 2006). In this approach, numerical models represent real structures better. For comparison purpose three buildings are placed in the same frozen condition that is 1.5m frozen-depth and 100 times increase in elastic modulus of frozen soil layers, when conducted FE modal analysis.

4.2 Numerical analysis results

Table 4.1 shows the results from FE analysis over three buildings. The AB has a good agreement with test results. The change of the first frequency is 4.09%. For the FB, however, the computational first frequency in the winter reaches 0.672 Hz, higher than the test value 0.594. It would occur another reason beyond structures stiffness to cause decrease of frozen effect in the real building. By investigating the building configuration it could be concluded that soil under the building has not experienced frost as expectation, which will be discussed in upcoming section 4.4. The PG has a first frequency of 1.86Hz from numerical analysis in, which is also higher than the test value of 1.74Hz. It is because the increase in elastic modulus of frozen soil. In numerical computation 100 times increase of elastic modulus based on unfrozen soil is assumed, however its real increase coming from the geotechnical survey of the GB is abound 40 times. If taking the 40 times value as the numerical condition, a first frequency of 1.71Hz is obtained, which fits the test result very well.

Table 4.1 First frequency from numerical analysis

First frequency (Hz)	Unfrozen	Frozen	Change rate
Atwood Building	0.464	0.483	4.09%
Frontier Building	0.606	0.672	10.9%
Parking Garage	1.16	1.86	60.3%

4.3 Stiffness ratio between superstructure and soil

Table 4.1 indicates the effect of frozen soil on the fundamental frequencies for various structures. The PG enduring the largest frozen effect is a multi-storey concrete structure, and has the highest structural stiffness among three structures. The AB with steel frame structure is the lowest in structural stiffness. It implies that the structural stiffness could play an important role in the frozen effect. Table 4.2 lists the horizontal stiffness of the superstructure and soil for three buildings, where the superstructure stiffness K represents whole horizontal stiffness with fixed foundation, and K_s is the horizontal stiffness of soil model without the superstructure. They are obtained from the horizontal displacement when applying a unit force in associated FE models. Which does stiffness between K and K_s dominate the frozen effect? In fact the relative stiffness between the superstructure and soil will control the changes of frequencies when soil becomes frozen. Therefore a ratio β is introduced to indicate the relative stiffness. It is defined as the soil stiffness Ks divided by the sum stiffness (K+Ks). It is observed from Table 4.2 that the less this ratio is, the greater the frozen effect on fundamental frequencies

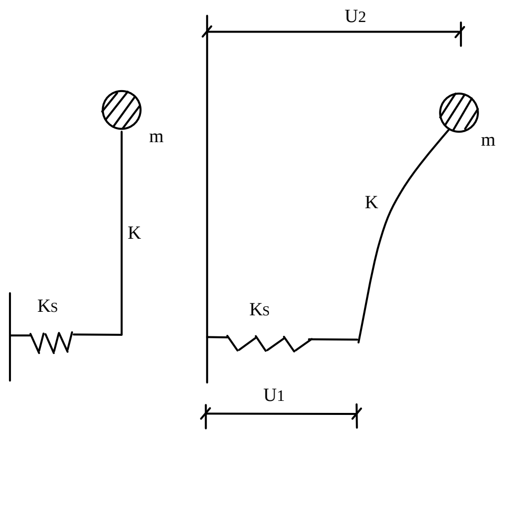


Figure 4.2 Single Freedom Degree Model

will be, i.e. the AB, whose β approaches to 1 and the change rate of the first frequency when soil freezing increasing only 4%. The GB, having the least β of 0.039, experiences the greatest change in the frequencies of 60% when soils become frozen. The indication of β can be proven by a simple single-freedom-degree model (fig. 4.2) supported on the soil springs.

Table 4.2 Structural horizontal stiffness

	Superstructure Stiffness (K) (kN/m)	Soil Stiffness (K_s) (kN/m)	$\beta = \frac{K_s}{K + K_s}$
Atwood Building	6.75×10^4	3.41×10^6	0.981
Frontier Building	1.07×10^5	3.91×10^4	0.271
Parking Garage	3.38×10^6	1.37×10^5	0.039

The dynamic motion equation for the model in figure 4.2 can be given:

$$K(u_2 - u_1) + m\ddot{u}_2 = 0 \tag{4.1}$$

$$K_s u_1 = K(u_2 - u_1) \tag{4.2}$$

Solving equation 4.1 and 4.2, the circular frequency of this system is formulated:

$$\omega = \sqrt{\frac{K}{m}}\sqrt{\frac{K_s}{K_s + K}} = \sqrt{\frac{K}{m}}\sqrt{\beta} \tag{4.3}$$

It is seen that β can represent the change of frequency caused by the stiffness, where the first term SQRT(K/m) is the frequency of fixed superstructure model. When soil freezing, K_s will increase. If β is very small or K is very large relative to K_s, i.e. the PG, the soil stiffness increasing will lead to the enhancement of β. If β is very large, i.e. approach to 1 where K can be approximatively neglected comparing with K_s, β will change little or remain unchanged. It explains the variety occurred in three buildings. Therefore β can be defined an index to help deciding if the effect of frozen soil is necessary to consider in design. Of course to achieve this purpose further quantifying work will be needed.

4.4 Building configuration

From previous analysis, the FB is an exception if predicting the effect of frozen soil on the fundamental frequencies by the structural stiffness. In fact another fact lying on building configuration controls the frost problem. Mentioned previously, the FB superstructure is founded directly on the strip foot foundation without basement. Such design of the FB allows heat from the inside of the building lobby to migrate to the foundation soil and prevents any ground freezing in the vicinity of the building. The AB, however, has an unheated basement garage beneath the 1st floor of the building, which has the similar temperature as outside environment and impossibly transfers heat into surrounding soil. Further the GB is a totally unheated building, and all the structure, foundation and surface soil are exposed in the same temperature. The different configurations decide if these building foundations endure the ground freezing. To proving the analysis, a thermal finite element model is generated for the Frontier Building as well as the Atwood Building to examine and compare the two buildings' thaw bulb (Miranda et al. 2007). The results show that (1) sufficient heat migration was allowed from the building into the foundation, thus preventing frozen ground to develop in the Frontier Building; (2) the unheated parking garage/basement in the Atwood Building acts as a thick insulating layer preventing heat from infiltrating the surrounding soil, thus allowing frozen ground to develop. Therefore the fundamental frequencies from the site text have not been observed an obvious change during season switch in the FB.

5. CONCLUSION

After the comparing the change rate of fundamental frequencies from summer to winter for three buildings, the effect of seasonally frozen soils on dynamic properties is related to the ratio of stiffness between the superstructure and soil. Fallowing conclusions can be obtained.

1) Seasonally frozen soils affect the structural dynamic properties to different extent. The magnitude of effect depends on the relative stiffness between the superstructure and soil.

2) A relative stiffness ratio β is presented as an index to indicate the effect of frozen soils. The less the β is, the greater the effect will be perform by frozen soils on dynamic frequencies.

3) Building configuration, especially foundation design, with respect to heated or unheated, plays a crucial role in whether or not the structure's foundation will be influenced by frozen ground leading to potential impact on dynamic properties.

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REFERENCES

Bai, F. (2007). Effects of Seasonally Frozen Ground on Dynamic Properties of UAA Parking Garage Structure-Soil System. University of Alaska Anchorage, School of Engineering, Civil Engineering Graduate Project.

Xiong, F. and Yang, Z. (2007). Effects of Seasonally Frozen Soil on the Seismic Behavior of bridge-Bent-Foundation-Soil System. *Proceedings of ASCE Structural Congress*, Long Beach, California.

Finn, W. D. L. and Yong, R. N. (1978). Seismic Response of Frozen Ground. *American Society of Civil Engineers, Journal of the Geotechnical Engineering Division*, **104:10**, 1225-1241.

Ventura, C. E., Laverick, B., Brincker, R., Andersen, P. (2003). Comparison of Dynamic Characteristics of Two Instrumented Tall Buildings. *Proceedings of the 21st International Modal Analysis Conference (IMAC)*, Kissimmee, Florida.

Vinson, T. S. (1978). Parameter Effects on Dynamic Properties of Frozen Soils. *American Society of Civil Engineers, Journal of the Geotechnical Engineering Division*, **104:10**, 1289-1306.

Yang, Z., Dutta, U., Xiong, F., Biswas, N. and Benz, H. (2008). Seasonal Frost Effects on the Seismic Behavior of a Twenty-Story Office Building. *Cold Regions Science and Technology*. **51:1**, 76-84.

Yang, Z., A. Elgamal, and E. Parra. (2003). A Computational Model for Cyclic Mobility and Associated Shear Deformation. *J. of Geotechnical and Geoenvironmental Engineering*. **129:12**, 1119-1127.

Yang, Z., U. Dutta, D. Zhu, E. Marx and N. Biswas (2007). Seasonal frost effects on the soil-foundation-structure interaction system. *J. of Cold Regions Engineering*. **21:4**, 108-120.

Miranda, R., Yang, Z., Dutta, U. (2007). Seasonally Frozen Ground Effects on the Dynamic Response of High-Rise Buildings. *Proceedings of the Ninth International Conference on Permafrost,* Fairbanks, Alaska.