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Shear moduli and damping in frozen and unfrozen clay by resonant column tests

M.O. Al-Hunaidi, P.A. Chen, J.H. Rainer, and M. Tremblay

Abstract: The resonant-column test method was used in this study to determine the dynamic shear moduli and damping ratios of frozen and unfrozen soil samples. Naturally frozen soil specimens were obtained in-situ during the winter. A series of tests were carried out on the frozen soil specimens in a cold room at -9°C. The same specimens, after allowing them to thaw, were then tested at room temperature. Test results show that at low-amplitude shear strains the damping ratio of frozen soil specimens is roughly twice that of unfrozen samples. In addition, the dynamic shear modulus for frozen soil specimens is significantly greater (30 or 50 times) than that of unfrozen specimens. These results provide a basis for explaining an observation that bus-induced vibrations in buildings while the top soil is frozen in winter are about one-half those induced while the soil is not frozen.

Key words: resonant-column test, shear modulus, damping ratio, frozen soil, ground vibration.

Introduction

Recent measurements of building vibration levels induced by transit buses and heavy vehicles at a typical residential site in Montréal indicate that vibration levels measured in winter while the top soil is frozen are about one-half those measured in the fall. This could be attributed to the increase in stiffness, and perhaps damping ratio, of the frozen soil in winter. One may argue, however, that soil while frozen could become a more effective medium for vibration transmission based on the perception that frozen soil has a smaller damping ratio than unfrozen soil. Because no comparison was available in the technical literature between the damping ratio and shear modulus of frozen and unfrozen soil, tests were performed to evaluate the dynamic properties of the topsoil in both the frozen and unfrozen states for a site where traffic vibrations were measured.

Dynamic properties of the frozen and unfrozen soil samples were evaluated by means of the resonant-column test method, which is commonly used to determine the dynamic properties of soils at shearing strains ranging from 0.001 to 0.1% (Richart et al. 1970; Anderson and Stokoe 1978; Drnevich et al. 1978). In this paper, soil sampling procedures and resonant-column tests as well as the test results are presented and discussed.
the top end is attached to a platen connected to a coil magnetic-drive system which is used to vibrate the specimen in torsional motion. The end platens are knurled, by design, to facilitate coupling with the specimen. The drive system consists of a drive plate, drive coils, a sine wave generator, and a power amplifier. Torsional motion is measured using an accelerometer attached to the drive plate. For tests performed in this study, accelerometer output was recorded directly in digital form using a PC-based data acquisition system at rates of 4000 and 40 000 samples/s for unfrozen and frozen specimens, respectively.

Frozen soil and sampling procedure
Frozen soil specimens were sampled in front of a residential house in Montréal where vibration levels induced by transit buses were measured. Three boreholes were augered to a depth of 0.15 m at 3.5 m from the front of the house. A hollow-stem auger with carbide cutters designed by the Cold Regions Research and Engineering Laboratory (CRREL) of the U.S. Army Corps of Engineers, shown in Fig. 2, was then used to sample the frozen clay. The CRREL sampler was rotated into frozen clay using the drill rig shown in Fig. 3. The samples were taken at a depth of 0.6–0.8 m. The frost layer was about 1.1 m deep, as determined from both a drill borehole in front of the house and from a nearby frost indicator. The extruded frozen core samples were first wrapped with two layers of plastic and then with two layers of foil. The packaged samples were carefully placed horizontally in a cooler, and dry ice was used to maintain subzero temperatures within the cooler during transportation from the site in Montréal to the laboratory in Ottawa. The samples were transferred to a cold room, which was maintained at a temperature of approximately −9°C.

Soil specimens
Two frozen core samples obtained from two boreholes were machined in the cold room to specified nominal dimensions (14 cm height and 7 cm diameter). No ice lenses were visible in these samples. Following the completion of tests on frozen specimens, they were sealed in a membrane and kept at room temperature (22°C) for 4 days. The thawed specimens were then tested in the same manner as the frozen ones. The tested soil specimens were identified as slightly oxidized brown-greenish clay with traces of sand.

Calibration check of resonant-column test apparatus
The performance of the resonant-column test apparatus was first examined by using the apparatus to test an aluminum specimen at room temperature. The resonant-column apparatus was then moved to the cold room and allowed to stabilize at a temperature of −9°C for 2 days. Tests using the aluminum specimen were then repeated. There was virtually no difference between the results of tests at room temperature and those at −9°C. The shear wave velocity obtained for the aluminum specimen in both cases was in close agreement with the nominal value.

Testing procedure of frozen specimens
To improve the coupling between the frozen soil specimen and end platens of the resonant-column apparatus, a thin layer of water was applied to the surface of the platens and then allowed to freeze while the specimen and end platens were in contact. The frozen specimens were tested at a temperature of −9°C. A confining pressure of 14 kPa corresponding to the in situ condition was applied to the specimen, and testing was carried out at shearing strains of 0.0006% or less. It was not possible to perform tests at higher shearing strains, since the drive system of the apparatus used here was not capable of applying the necessary torque.

Testing procedure of unfrozen specimens
Prior to testing, the unfrozen specimens were consolidated for 4.5 h under the same confining pressure used with the frozen specimens (14 kPa). Consolidation was insignificant; no water was extruded. Resonant column tests were then carried out over a shearing strain range of 0.0008 to 0.01% under undrained conditions and at a room temperature of 22°C. As noted earlier, tests were carried out only under a confining pressure of 14 kPa corresponding to the in situ condition. The confining pressure should be expected to affect the elastic modulus and damping: the higher the confining pressure, the higher the dynamic shear modulus and the lower the damping. However, it was beyond the scope of this study to investigate this aspect.

Analysis methods
Shearing strain (γ)
For a solid cylindrical specimen of height h, the shearing strain γ at radius r is calculated from

\[ \gamma = \frac{\alpha r}{h} \]

where \( \alpha \) is the angle of twist in radians. In the resonant column test, the angle of twist is calculated using measurements of the resonant frequency and acceleration levels
Fig. 2. CRREL sampler used for obtaining soil samples and partially extruded sample.

Fig. 3. Drill rig used for soil sampling.
Table 1. Summary of results of resonant-column tests.

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Resonant frequency (Hz)</th>
<th>Peak shear strain (%)</th>
<th>Shear modulus (MPa)</th>
<th>Damping ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BH21-F (frozen)</td>
<td>323.7</td>
<td>0.00015</td>
<td>1298</td>
<td>4.87</td>
</tr>
<tr>
<td></td>
<td>320.6</td>
<td>0.00026</td>
<td>1273</td>
<td>5.60</td>
</tr>
<tr>
<td></td>
<td>297.5</td>
<td>0.00057</td>
<td>1096</td>
<td>5.59</td>
</tr>
<tr>
<td>BH21-U (unfrozen)</td>
<td>42.9</td>
<td>0.00113</td>
<td>22.8</td>
<td>4.17</td>
</tr>
<tr>
<td></td>
<td>41.3</td>
<td>0.00320</td>
<td>21.1</td>
<td>4.90</td>
</tr>
<tr>
<td></td>
<td>42.0</td>
<td>0.00614</td>
<td>21.9</td>
<td>5.65</td>
</tr>
<tr>
<td></td>
<td>39.7</td>
<td>0.01197</td>
<td>19.5</td>
<td>6.57</td>
</tr>
<tr>
<td>BH31-F (frozen)</td>
<td>285.4</td>
<td>0.00002</td>
<td>956</td>
<td>4.01</td>
</tr>
<tr>
<td></td>
<td>284.2</td>
<td>0.00002</td>
<td>949</td>
<td>5.32</td>
</tr>
<tr>
<td></td>
<td>283.5</td>
<td>0.00028</td>
<td>944</td>
<td>5.02</td>
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<tr>
<td></td>
<td>283.5</td>
<td>0.00030</td>
<td>944</td>
<td>5.14</td>
</tr>
<tr>
<td>BH31-U (unfrozen)</td>
<td>53.6</td>
<td>0.00081</td>
<td>33.7</td>
<td>3.39</td>
</tr>
<tr>
<td></td>
<td>52.1</td>
<td>0.00409</td>
<td>31.9</td>
<td>3.69</td>
</tr>
<tr>
<td></td>
<td>48.3</td>
<td>0.01166</td>
<td>27.4</td>
<td>5.06</td>
</tr>
</tbody>
</table>

of the drive plate. For the test equipment used in this study, the shearing strain is given by

\[ \gamma = 2(1.1067 \times 10^{-9}) \left( a p \frac{d}{h} \right) \]

where \( a \) is the accelerometer output in millivolts, \( p \) is the period of vibration in milliseconds, and \( d \) is the diameter of soil specimen.

Shear modulus (\( G \))
The dynamic shear modulus of the soil is determined from the resonant frequency, specimen dimensions, and system constants. The shear wave velocity, \( V_s \), from resonant-column tests is calculated on the basis of the theory of elasticity as (Richart et al. 1970)

\[ V_s = \frac{2\pi h}{\beta p} \]

where \( \beta \) is a function of mass polar moment of inertia of both soil specimen and resonant-column drive system and is found from

\[ I = \beta \tan (\beta) \]

where \( I \) is the mass polar moment of inertia of soil specimen, and \( I_o \) is the mass polar moment of inertia of the resonant-column drive system. Once the value of shear wave velocity is determined from eq. 3, the shear modulus, \( G \), is calculated from

\[ G = \rho V_s^2 \]

where \( \rho \) is the mass density of the soil specimen.

Damping ratio (\( D \))
The damping ratio is determined from the free-vibration decay curve, which is generated by shutting off the input signal at resonance. A typical free-vibration decay curve from a resonant-column test is shown in Fig. 4. The damping ratio \( D \) is calculated from the logarithmic decrement \( \delta \) of the decay curve as follows:

\[ D = \frac{\delta^2}{4\pi^2 + \delta^2} \times 100 \]

where

\[ \delta = \frac{1}{n} \ln \left( \frac{z_1}{z_{1+n}} \right) \]

and \( z_1 \) and \( z_{1+n} \) are the amplitudes of cycles 1 and \((1+n)\), respectively.

Test results and discussion

Typical results of the resonant column tests are listed in Table 1 for the two test specimens used in this study. For the unfrozen specimens reliable results at shearing strains significantly less than 0.001% were not possible to obtain because of difficulties with system noise and (or) ambient
noise. Results from tests on frozen specimens are for shearing strains less than about 0.0006%. As mentioned earlier, it was not possible to achieve higher strains because of the torque limitation of the apparatus. From the results shown in Table 1, one can observe the usual trend of decreasing shear modulus and increasing damping ratio with increasing strain level. This can be seen clearly for the unfrozen specimens. For frozen specimens, this trend is not as pronounced for the range of strains tested.

Since ground vibrations generated by buses are considered to induce strains in the low-amplitude range (i.e., less than 0.001%), only results in this range will be compared. The dynamic shear modulus as well as the damping ratio at a shearing strain of 0.001% or less are generally considered to be independent of the strain amplitude (Stokoe et al. 1980). This is affirmed from Table 1 by noting the slight variation in the modulus values for strain levels less than 0.001%. The low-amplitude dynamic shear modulus taken as the average value of the results obtained from shearing strains less than 0.001% are summarized in Table 2. From Table 2 it can be seen that the moduli of soil specimens in the frozen state are about 30 or 50 times greater than those of specimens in the unfrozen state.

Damping ratio versus shearing strain amplitude is shown graphically in Fig. 5 for both actual results and curves fitted and extrapolated "by eye." For shearing strains less than 0.001%, the damping ratio of frozen soil specimens is seen to be roughly two times that of the unfrozen ones.

Conclusions

The resonant-column method was used to compare the low-amplitude shear modulus and damping ratio of naturally frozen and unfrozen clay soil specimens. Test results obtained with two soil specimens show that at low-amplitude shearing strain: (i) the shear modulus of frozen specimens is 30 or 50 times greater than that of unfrozen specimens, and (ii) the damping ratio of frozen specimens is roughly two times that of unfrozen ones. Although the tests and results presented here are of limited scope, they provide a basis for explaining the reduction in bus-induced building vibrations measured when the top soil is frozen in the winter in comparison with those measured in other seasons.

Acknowledgments

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References


