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FROZEN SOIL EFFECT ON THE OBSERVED GROUND MOTION CHARACTERISTICS

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ABSTRACT

The State of Alaska is located in one of the most seismically active zones in the world. Several large magnitude earthquakes (Prince William Sound Earthquake, 1964 and Denali Earthquake, 2002) have occurred in the state and caused considerable damage to its transportation system, that include several highway bridges and related infrastructures. Some of the damaged could be related to frozen soils effects. However, only limited research has been carried out so far to investigate the effects of frozen soils on seismic site response.

A systematic investigation of the effects of permafrost on 5% damped response spectra have been conducted at the Goldstream Creek bridge site in Fairbanks, AK. The generic soil profiles were constructed based on the available geologic and geotechnical data from the site. A set of input ground motions have been selected from available strong-motion databases and were scaled to generate an ensemble of seismic hazard-consistent engineering bedrock input motions. One-dimensional equivalent linear analyses were applied to compute the spectral acceleration at three seismic hazard levels, i.e. 10%, 5% and 2% probability of exceedance in 50 years. A series of parametric studies were conducted for assessing the sensitivity of the results to the uncertainties associated with the shear wave velocity of frozen soil, thickness of permafrost and bedrock table. The results show that the presence of permafrost can significantly alter the ground motion characteristics.

Introduction

Due to the variation of low mean annual temperature, the uppermost few meters of the soil column in Southcentral Alaska (Anchorage and its adjoining areas) consist of frozen soils, including seasonally frozen ground (active layer which freezes in winter and thaws in summer) and patchy permafrost. However, in the northern parts of Alaska, the soil profile is dominated by approximately 350-600 m thick continuous permafrost that gradually increases in thickness from south to north.

Several studies have been conducted to study frozen soil dynamic properties using both laboratory and field measures (e.g. Vinson et al., 1977; LeBlanc et al., 2004). The large temperature fluctuation causes a drastic change in soil dynamic properties. For instance, the Young's modulus of the frozen soil is in magnitudes of tens to hundreds higher than that of unfrozen soil. The seasonal changes of soil dynamic properties will very likely affect the seismic site response (SR) of the soil column. For structural design, it is important to understand how the

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site response characteristics change from unfrozen to frozen status during earthquake loading. However, only limited research has so far been carried out to investigate the effects of frozen soils on the seismic site responses (Singh and Donovan, 1977; Vinson, 1978; Qi et al., 2006). Studies (Singh and Donovan, 1977; Qi et al., 2006) have shown that the presence of the frozen surface layer affects ground motion characteristics and reduces the observed surface acceleration. A recent study on the Qinghai-Tibet railway embankment (Wang et al., 2004) reported that the existence of a permafrost layer would significantly affect SR at high frequencies. Current design codes, such as American Association of State Highway and Transportation Officials (AASHTO, 2007) and International Building Code (IBC, 2000) don't specifically account for frozen soil effect. With increased demand for natural resources, more infrastructures are being constructed in the broad cold regions including Alaska where both strong seismic activities and arctic or subarctic conditions exist; it becomes imperative to systematically investigate how frozen ground, particularly the permafrost affect the characteristics of seismic site responses.

Objective and Methodology

Main objective of this study is to estimate quantitatively the effect of permafrost on the spectral acceleration (SA) of observed ground motions and hence check the validity of current seismic design code on the frozen ground. For this purpose, a suite of recorded earthquake ground motions were propagated through multi-degree-of-freedom homogenous, isotropic soil layers with permafrost where each layers have been characterized by its shear modulus, density, damping ratio, shear wave velocity, and thickness. The site response analysis was conducted using the spectral acceleration of observed data at the surface. These has been done using following procedures:

- Selection of a soil profile at site from available geotechnical engineering data
- Computation of site specific seismic design spectra of various return period from the probabilistic seismic hazard (PSH) maps
- Selection of the scenario earthquakes at the study site from the deaggregation of the PSH maps
- Generation of hazard-consistent ground motions at the bedrock of the study site by appropriately scaling the recorded earthquake data of comparable magnitude from other parts of the world having similar tectonic settings;
- Propagation of the input bedrock motions through the soil column and computation of the spectral acceleration at the ground surface.

Using above steps, we conducted a series of parametric studies using the generic soil profile at the study site which include the permafrost to assess the variation of spectral acceleration with thicknesses and depth of the permafrost table. Following section discusses all the above steps in detail.

Analysis

Selected Site General Geology and Soil Profile

We have selected the Goldstream Creek (GC) Bridge site in Fairbanks, AK, as the test site for this study. Péwé (1982) has studied the permafrost distribution in Fairbanks area and constructed a geological section (Figure 1) of this area. The GC site is located in the Goldstream Valley just to the north of the hills shown in Figure 1. In general, a discontinuous layer permafrost of approximately 50 m thick (Davis, 2001; Romanovsky, 2007) exists in Fairbanks area; it is underlain by extensive alluvial apron and extends up some distance along the lower slopes of the hills. The bedrock table rises from approximately 150 m (or 500 ft) at the Chena River flood plain to approximately 60 m (or 200 ft) at areas close to the hills.

The soil profile at the GC site is shown in the Figure 2. The uppermost 57 m of the soil column is Sandy silt and gravel which overlain on thick weathered bed rock. The depth of the engineering

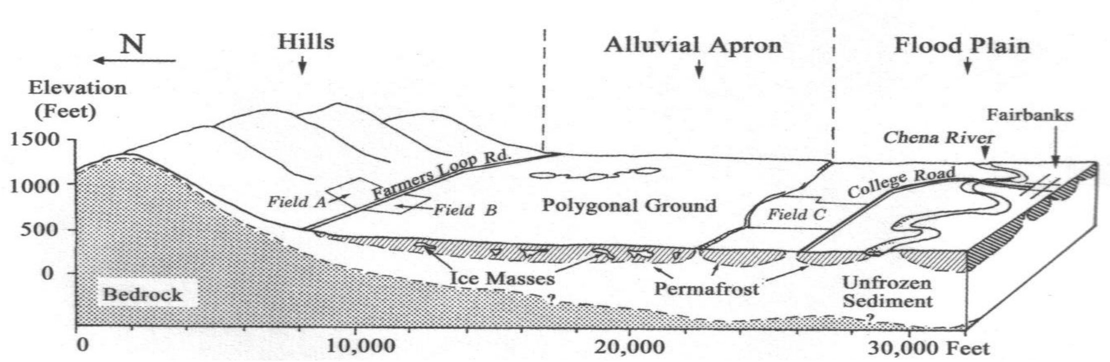


Figure 1: The Cartoon showing the general geological set up of the study site after Pewe, 1982

bed rock at the site is not available directly from the borehole data (Department of Highways, State of Alaska, 1974) but we have assumed it to be located at the depth of 66 m based on the geological information (Péwé, 1982; Romanovsky, 2007) of the area. The borehole data indicates that the permafrost table of the area is located within the sandy silt layer. To study the effect of permafrost on the spectral acceleration we have constructed the soil profile with permafrost table vary from surface at an interval of 5 m and computed the spectral acceleration in each case.

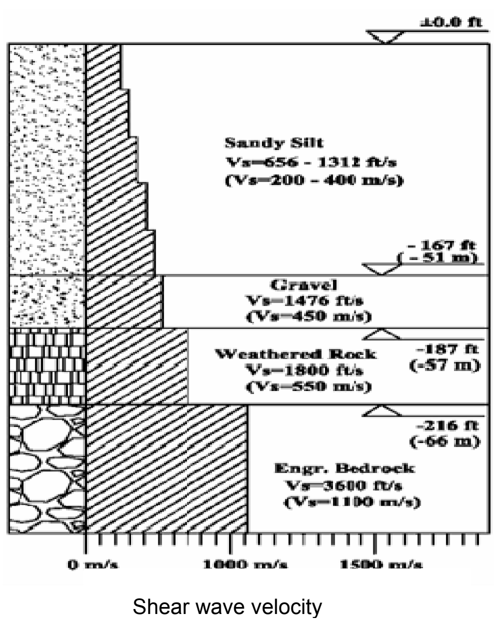


Figure 2: The Soil profile at the GC site along with the assumed Shear wave velocity profile (hatched lines).

Identification of the Seismic Hazard

The 1998 Probabilistic Seismic Hazard Maps for Alaska prepared by U.S. Geological Survey (USGS) (http://earthquake.usgs.gov/research/hazmaps/design/) has been adopted here to assess the seismic hazard at the GC site (Latitude 64.8938 N and Longitude -147.8757 W). Peak Ground Acceleration (PGA) and 0.2 and 1.0 sec SA with 10%, 5% and 2% Probability of Exceedance (PE) in 50 years have been retrieved from these maps. Three spectra levels namely design level spectrum (DS), AASHTO (American Association of State Highway and Transportation Officials) design spectrum (AASHTO) and maximum considered earthquake spectrum (MCE) have been constructed from 10%, 5% and 2% of PE in 50 years, respectively. The parameters corresponding to 5% PE in 50 years have been used to approximate 7% PE in 75 years in accordance with AASHTO design specification for transportation infrastructure. The values of ground motion parameters (PGA and SAs) corresponding to three different hazard level are listed in Table 1.

Table 1. Ground motion parameter at the GC Site

Seismic Hazard Level	PGA (g)	Spectral Acceleration (g)	
		0.2 sec	1.0 sec
MCE level	0.425	1.103	0.304
AASHTO level	0.289	0.646	0.201
DS level	0.294	0.735	0.203

Deaggregation of Seismic Hazard

The seismic hazard at the GC site has been deaggregated for PGA, SA at period of 0.2 and 1 sec, respectively corresponding to all the hazard levels mentioned above. The hypocentral distance and magnitude of earthquake (known as scenario earthquake) of principal source zones of seismic hazard at the site are listed in Table 2. It can be observed from Table 2 that over 90% of the total seismic hazard is contributed by the shallow random sources at a distance of 11-20 km from the site having magnitude M5-7.3.

Table 2 Summary of principal sources for the GC site at PGA and 0.2s, 1.0s period SA

	PGA			
Source	% contr.	R(km)	M	ε_0
Shallow random sources M5-M7.3	98.17	11.1	6.07	0.45
	Spectral Acceleration at 0.20 sec.			
Source	% contr.	R(km)	M	ε_0
Shallow random sources M5-M7.3	98.65	12.5	6.14	0.64
	Spectral Acceleration at 1.00 sec.			
Source	% contr.	R(km)	M	ε_0
Shallow random sources M5-M7.3	94.31	17.9	6.48	0.57

Time Histories Selection and Scaling

Time Histories Selection

Due to lack of earthquake ground motion records at GC, the time histories of ten earthquakes recorded elsewhere have been selected from Pacific Earthquake Engineering Research Center (PEER) and Consortium of Organizations for Strong Motion Observation Systems (COSMOS) database. These selections have been made based on following criteria:

- Magnitude: The time series data of selected earthquakes should be of magnitudes M ± 0.5, where M is the average magnitude of the scenario earthquake at the GC site

- Amplitude: The peak horizontal acceleration (PHA) of selected time histories should not be less than 5 times of the PHA of the selected site. This will avoid using high scaling factor which sometime create large error between the scaled and target spectrum over the time period of interest.
- Site Condition: To exclude effects the site on the selected time histories, the recorded data have been selected either from sites located on geologic rock or stiff soils or from the borehole.

The source parameters of the selected events and the site conditions of the selected time histories are listed in Table 3.

Table 3. Selected events for analysis from COSMOS database

Event ID (component)	Origin Time	Dep. (km)	M	PGA (gal)	Station Code	Site Condition	Epi.Dist (Km)
Denali (N-S)	11/03/2002	4.9	7.9	98.0	Carlo	stiff soil	64.2
Hector Mine (N-S)	10/16/1999	5.0	7.1	143.0	CSMIP 22170	Shallow alluvium over granite bedrock	51.5
Hector Mine (N-S)	10/16/1999	5.0	7.1	76.6	CSMIP 12647	weathered rock	75.4
ImperialValley(E-W)	10/15/1979	9.9	6.5	153.6	Cerro Prieto	Rock	20.0
Landers (N-S)	06/28/1992	7.0	7.3	39.4	CSMIP 12206	weathered granite	52.4
Loma Prieta (E-W)	10/18/1998	17.5	7.0	426.6	CSMIP 47379	weathered rock	Closest dist to fault: 2.8
North Palm Springs (N-S)	07/08/1986	11.0	6.2	107.5	CSMIP 12206	weathered granite	19.5
Park Field (E-W)	09/28/2004	7.9	6.0	178.2	CSMIP 36431	soil sand stone	Closest dist to fault: 0.5
Petrolia (N-S)	08/17/1991	10.0	6.0	128.8	CSMIP 89005	Cretaceous Rock	15.4
SMNH01 (N-S)	10/16/2000	11.0	7.3	185.0	SMNH01	Borehole	8

Time History Scaling

We have computed 5% damped response spectra of the selected time histories. These spectral values are inherently incompatible with the target hazard spectrum of the study site. For this reason, scaling of time histories is required. The intent of scaling is to provide an ensemble of time histories with its average spectral amplitudes closely match with the probabilistic estimate of the hazard spectrum at the GC site, while retaining the inherent variability of the time histories. The selected time histories were scaled according to the following procedure:

- Set the hazard response spectrum of a study site as target response spectrum, denoting it as $RS_{tg}(T_i)$ at period T_i;
- Individual time history (say k^th time series) of the selected records is then scaled by a

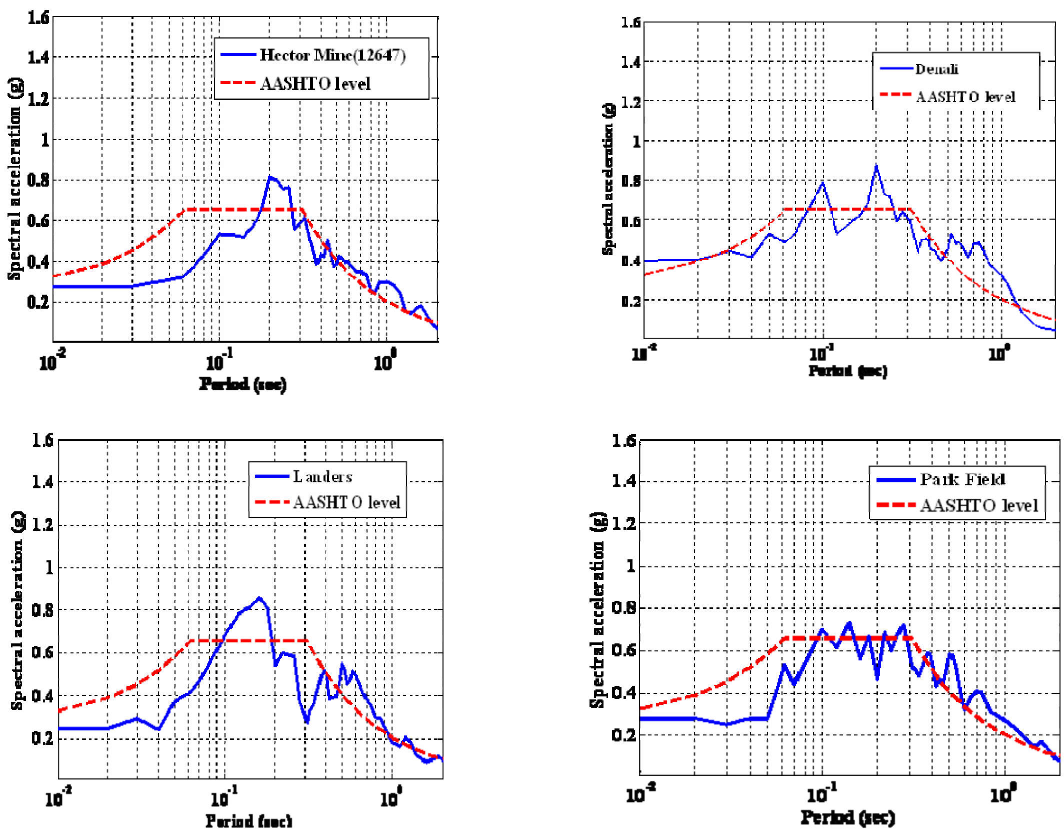


Figure 3: Comparison of the response spectra of scaled ground motions with target engineering bedrock site response spectrum for the GC site corresponding to AASHTO level hazard

factor, F_k and the spectral acceleration (SA) for two horizontal components ($SA^K(T_i)$) at period T_i was calculated. The value of F_K is allowed to vary from 0.01 to 5.0

- For each, F_k, the $L2$-norm difference, denoted as e_k [Eqn. (1)], between the target spectrum and the $SA^k(T_i)$ of for period T_i over the range 0-1.0 second is calculated;

$$e_k = \sqrt{\sum_{i=1}^{n}\{F_k * SA^k(T_i) - RS_{tg}(T_i)\}^2} \quad (0 \le T_i \le 1) \qquad (1)$$

- The process was repeated for all values of F_k and the scaled time history with minimum e_k has finally been selected as the hazard consistent input bedrock motion.

This procedure ensure that the average response spectrum of the scaled time histories closely match with the target spectrum, while the inherent variability of the time histories are still preserved.

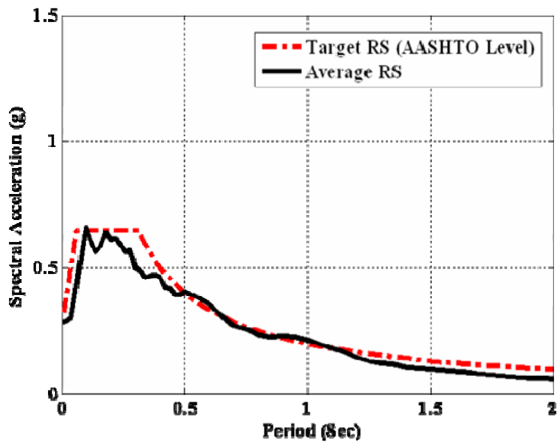


Figure 4: Comparison between the average response spectrum of the ten selected ground motions with engineering bedrock response spectrum of the GC site corresponding to hazard with 5% PE in 50 years (AASHTO level)

Using the above procedure, a suite of scaled time histories for three hazard levels at the GC site was generated. Figure 3, for instance show 5% damped response spectra of some selected earthquake ground motions scaled to AASHTO level hazard along with corresponding hazard spectra for the engineering bedrock at the GC site.

To verify the adopted scaling procedure and the representativeness of the selected earthquake ground motions, 5%-damped response spectrum computed from the scaled time histories were averaged geometrically and compared with the target hazard spectra of the site. Figure 4 shows an example of such comparison between the averaged response spectra for all selected earthquake motions and target design spectra of the AASTHO level at the study site. It can be concluded from this comparison that the average response spectra of the scaled time histories are comparable with the target response spectra for hazard levels.

Propagation of Input bedrock motion

The hazard consistent scaled time histories from all selected earthquake have been used as the input bedrock motion for computing the site response of the GC site. These input motions were propagated through the soil profiles shown in Figure 2 using 1-D wave propagation technique. We have used ProSHAKE (EduPro, 1998.) for the analysis of the SR analysis assuming equivalent linear wave motions through the soil. To study the effect of the permafrost on the SR characteristics, we have assumed that the bottom of the permafrost layer is fixed at a depth of 50 m while the top of the layer varies from 0 m (corresponding to a very shallow permafrost table, Figure 5a) to 50 m (corresponding to no permafrost, Figure 5b). Shear wave velocity, V_S for permafrost was set to 1500 m/s according to LeBlanc et al. (2004). The hatched areas in Figure 5 show the variation of shear wave velocity. To model the transition from unfrozen gravel layer to permafrost, we assigned a transition layers with Vs about 600 m/s at the top of the permafrost layer. For each

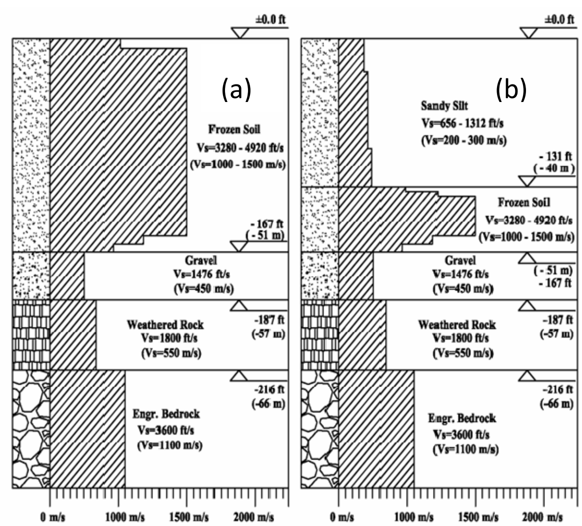


Figure 5: Soil profiles with varying permafrost table

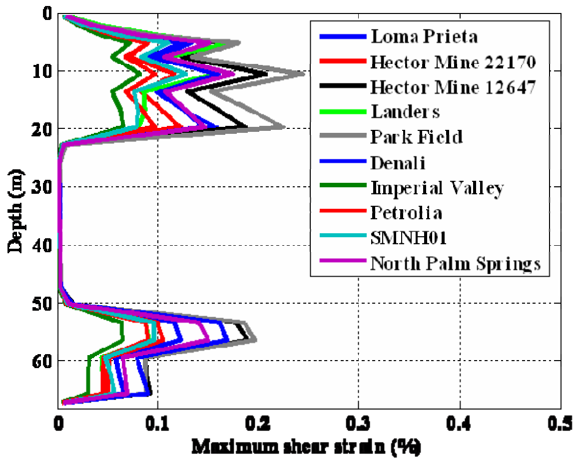


Figure 6: Peak shear strain vs. depth for ten selected events scaled to AASHTO level hazard for a soil profile with permafrost table at 20 m

input bedrock motion, we obtained a set of time histories at the ground with the permafrost table varies from 0 to 50 m. We computed and checked the peak shear strain developed in the soil profile during each propagated motion. Figure 6 shows the plot of maximum shear strain Vs depth for all earthquake input motions when the top of the permafrost table was located at a depth of 20 m. It is noticed from this plot that the maximum shear strain is less than 0.3% for all these events which suggest that the induced strains are within the strain levels for equivalent linear analysis to produce acceptable results.

The damped (5%) response spectra of the computed ground motions for varying permafrost table are logarithmically averaged using the following equation:

$$aveRS(T) = \sqrt[n]{\prod_{i=1}^{n} RS_i(T)} \qquad (2)$$

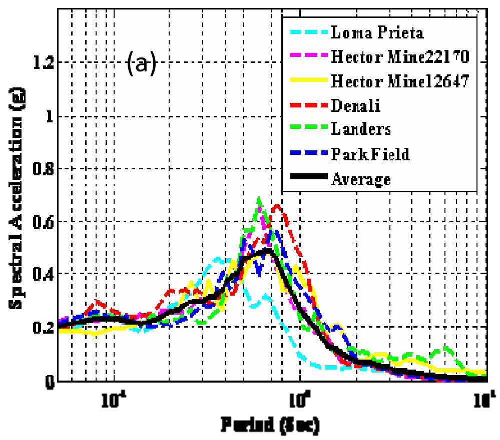
Where n represent the number of available ground motions. This averaged response spectra (avers) has been considered for comparing the ground motion characteristics for different depth of permafrost table.

Results and Conclusions

Effects of Permafrost Table/Thickness on Seismic Site Response

Figure 7 shows the variation of response spectra of ground motions with the depth of the permafrost table. The plot clearly indicates that the thickness and the depth of the permafrost influence the average response spectra. It is observed that the amplitude of response spectra of ground motion attains a minimum when the permafrost table is near the surface (0 m). The average amplitude of response spectra gradually increase with the decreases of the permafrost table and the highest spectral amplitude are observed when the permafrost table drops to 20 m below the surface. As the permafrost table continues to drop further from 20 to 50 m, the response spectra amplitude of the ground motion decrease gradually.

Both the non-permafrost soil profile (permafrost table depth 50m below surface) and that with permafrost table at 20 m can be classified as AASHTO site D (the average shear wave velocity of upper 30m soil profile is within 183 to 366 m/s). It is interesting to compare the maximum site response spectrum with the AASHTO design response spectrum. In Figure 8, the ground motion response spectra obtained at the GC site with permafrost table at 0, -20 and -50 m are shown. AASHTO design response spectrum for site class D and that for site class B/C boundary at the GC site are also shown for reference. It is seen that the response spectrum of ground motions for the soil profile with permafrost table at 0 m is well below that of site class D. This observation can be explained by the attenuation of high frequency component of ground motions due to the presence of thick (50 m) permafrost layer near the ground surface. The soil profile with no permafrost (permafrost table at a depth of 50 m) matches closely with the hazard spectra of site class D. However, the response spectrum of ground motions substantially amplifies (25%) for period ranging from 0.35 to 0.9 sec for the soil profile with permafrost table at 20 m depth than that of AASHTO site class D. Therefore, it is not always conservative to classify a permafrost



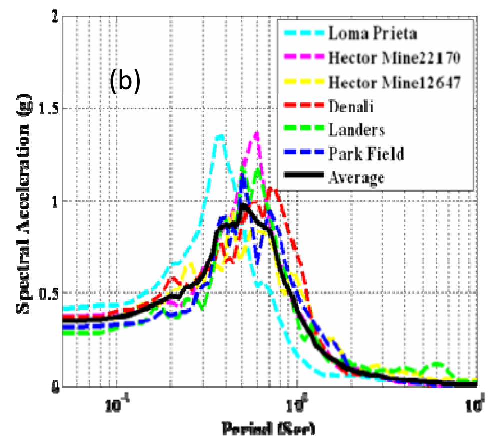


Figure 7: Response spectra of six ground surface motions and their average response spectrum for the soil profile for AASHTO level with permafrost table at (a) 0 m, (b) 20 m.

site the same as one would do for a non-permafrost site. It is also interesting to note that the amplitude of the response spectrum of ground motion for period ranging from 0 to 0.3 sec with permafrost table at 20 m is much smaller than that of AASHTO site class D. This pronounced reduction is due to the selective attenuation of certain high frequency components.

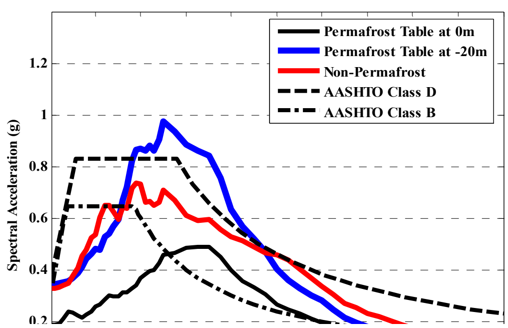


Figure 8: Comparison of average ground surface motion response spectra for the GC site with permafrost table at 0, -20 and -50 m with AASHTO design response spectra of site class D and B/C boundary.

To explain the effects of permafrost table/thickness on the site response, the transfer functions of the unfrozen top layer and the underlying permafrost layer in the soil profile shown in Figure 9. Figure 9(a) shows that with the decrease of the permafrost table drops from 0 to -35 m, the peak amplification factor of the top unfrozen layer varies from 4 to 5, whereas the predominant period shifts from 0.3 to 0.8 sec. However, Figure 9(b) shows that the peak amplification for the permafrost layer is no more than 1.5. Thus, the permafrost layer with table at a depth of 0, -10, -15 and -20 m attenuates the input motions components for period less than 0.3 sec. This indicates that the top unfrozen layer plays a dominant role in amplifying ground motion components with relatively longer period while permafrost layer attenuate ground motion components with relatively shorter period.

For the soil profile with permafrost table at -20 m, it amplifies the components around 0.4-0.75 sec by more than 200%, therefore forming a peak around 0.55 sec in the average ground surface response spectra, which is significantly larger than the spectral values in the AASHTO design.

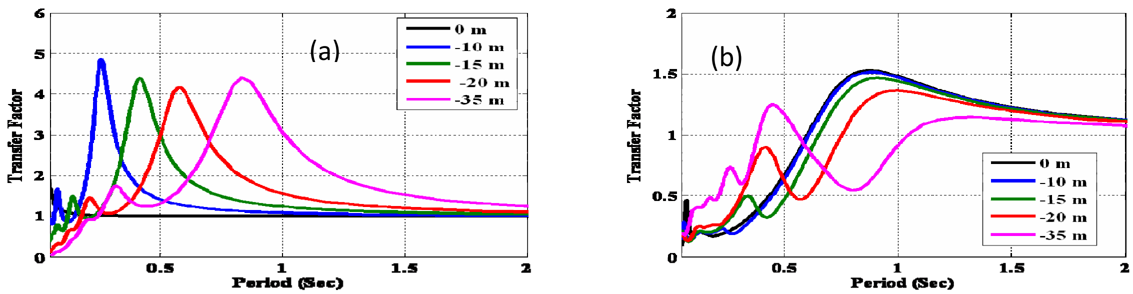


Figure 9 Transfer functions of (a) the top unfrozen layer and (b) underlying permafrost layer for soil profiles with the permafrost table varying from 0 to -35 m

Acknowledgement

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