Effect of Seasonally Frozen Soil on Seismic Site Response

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ABSTRACT:

The existence of deep seasonally frozen soils might pose a serious problem in to structures supported by deep foundations. Moreover, in a highly active seismogenic zones, the presence of such layer might alter the ground response during any strong earthquakes. To understand the influence of the seasonally frozen layer on the ground motions, the impact of seasonal frost on the site response at one selected bridge site in the State of Alaska has been study by using 1-D wave propagation method. At this site, 1-D soil profile has been constructed based on the available geotechnical and geological information. The hazard-consistence bedrock motions have been estimated from the recorded ground motion data of several earthquakes occurred at different parts of the world in similar tectonic regime. The generated bedrock motions were then propagated through the soil column and the transfer function between the motions observed at bedrock and surface were computed. The parametric studies have been conducted to investigate the effect of thickness, depth and other physical properties of the frozen layers by comparing the computed transfer functions. The paper discusses the impact of seasonally frozen ground on the amplitude and shape of the site response spectrum.

KEYWORDS: Site Response, earthquake hazard, frozen ground, equivalent linear analysis

1. INTRODUCTION

One of the key factors that might influence the soil properties and hence the observed ground motion is the existence of the seasonal frost. It will be interesting to understand how the presence of this layer in the sub-surface alters the ground motion characteristics during seismic loading. Early studies (e.g. Singh and Donovan, 1977) indicate that the presence of the frozen surface layer affects the ground motion characteristics and reduces the observed acceleration at the surface in compare to the summer months. However, no systematic studies have so far been made to estimate quantitatively the effect of this layer during earthquakes. The existence of deep seasonally frozen soils across the State of Alaska poses a serious problem for the seismic design of infrastructures including the transportation system. Current seismic design codes (e.g. IBC 2000) do not address specifically how to take into account such effects on the structural design.

2. OBJECTIVE

The objective of this study is to understand the effect of the frozen soil on the ground motion characteristics during earthquakes. Several earthquake engineering related parameters, e.g. peak ground acceleration

(PGA), spectral acceleration (SA), response spectra (RS) and site response (SR) have therefore been investigated to study the effect of the frozen soil and permafrost on the ground motion. In the present study, time histories (TH) of selected bedrock motions are applied at the base of the soil column at one of the selected site in Anchorage, Alaska and by assuming different thicknesses of the frozen layer on top of the soil column and the response of the soil is investigated in terms of above-mentioned parameters. The following sections provide in detail the discussion on methodology of the investigation, and the results obtained from the study and a quantitative interpretation of the results.

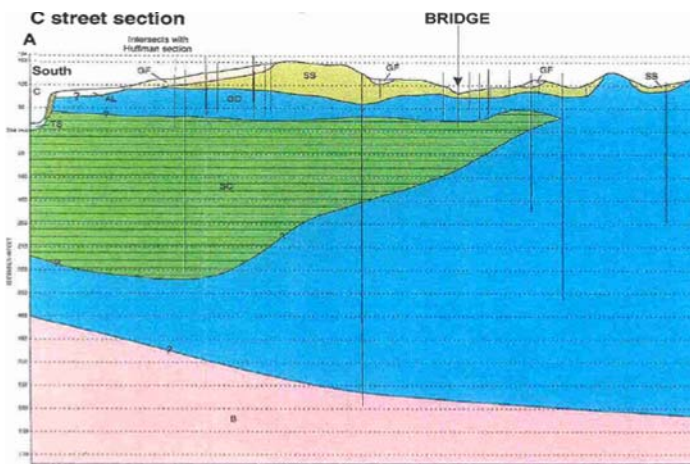

Figure 1: The geological cross-section along North-South direction at C-OM site. The vertical lines represent the shallow borehole locations around the bridge site. The bridge location is marked with an arrow (Adopted from Combellick, 1999).

3. METHODOLOGY

3.1 *Site Selection and Local Geology*

The C-Street/O'Malley Road Bridge (C-OM) has been selected as one of the candidate transportation infrastructure sites for the present study. The selection of the site is based on the availability of geotechnical data from shallow borehole in order to constrain 1-D soil layer model for computing the site response characteristics. The site is overlain on three major geological units belong to unconsolidated Quaternary sediments (Figure 1). The uppermost few meters (~7.5 m) consist of fine sand and silt (SS) followed by approximately 14 m thick gravel deposit. These two units in turn overlies on the Bootlegger Cove formation (BCF), one of the important Quaternary deposits in the Anchorage basin, consists of mainly silt and silty-clay (SC) and located at a depth of 21 m having a thickness around 20 m. Underneath the BCF, a very thick (140 m) highly heterogeneous glacial drift (GD) sediment is present. The GD overlies on Pre-Quaternary sediments (B).

3.2 Identification of Seismic Hazard

Due to lack of available recorded ground motions data at C-OM site, the probabilistic approach has been considered to generate the hazard consistent ground motions at the site. The earthquake ground motions for various probability levels at the C-OM site (Latitude 61.1234 N and Longitude -149.8861 W) have been obtained from the interactive National Seismic Hazard Maps of U.S. Geological Survey (USGS) (http://earthquake.usgs.gov/research/hazmaps/design/). These maps depicts four ground motion parameters (Peak Ground Acceleration, Spectral Accelerations at 0.2 s, 0.3 Sec and 1.0 Sec) at the B/C boundary (with average shear wave velocity 760 m/s) for 7% probability of exceedance in 75 years following the AASHTO's specification (AST). The values of ground motion parameters for different probability levels are provided in Table 1.

Table 1: The Spectral Acceleration (PSA) values and Peak Ground Acceleration (PGA) value at different periods at C-OM from the National Seismic Hazard Maps for three different hazard levels.

Seismic Hazard Level (probability of exccedance)	Hazard level ID	PGA (g)	Spectral Acceleration (g)		
			0.2 sec	0.3 sec	1.0 sec
7 % in 75 years	AST	0.50	1.2	1.13	0.41

3.3 Deaggregation of Seismic Hazard

The deaggregation of the seismic hazard at the C-OM site is done using the USGS deaggregation data (Frankel et al., 1996; Harmsen, 2001) for horizontal peak ground acceleration (PGA) and for spectral acceleration (SA) at several discrete oscillator periods between T = 0.1-2.0 seconds, as contribution in percentage to the total seismic hazard for discrete bins of magnitude and source-site distances. It has been observed that two main principal source zones (1964-Zone M_w 9.2 and shallow random source zone) which contribute higher than 10% to the total seismic hazard level (7% probability of exceedance in 75 years) at the C-OM site for the oscillator periods 0.2-1.0 sec and for PGA, according to the seismic deaggregation model of Alaska (Wesson et al., 1999). It has also been noted the significant seismic hazard (> 35%) at C-OM site is due to earthquakes of shallow random sources in the magnitude range M_w= 5 to M_w= 7.3 located at short distances (10-12 km). The contribution of seismic hazard for these shallow source earthquakes increases from 1.0 s to 0.2 sec. At long period, in addition to the shallow sources, another substantial hazard contribution (>10%) from the 1964-Megathrust zone (M_w= 9.2) is also noticed, the edge of which is located within an average distance of 52 km from C-OM site.

3.4 Selection of the Time Histories

Based on the deaggragation results of C-OM site, the time histories (TH) from shallow random sources (M5.6- M7.3) were used for computing the site response. Due to the lack of recorded earthquake data of comparable magnitude at the C-OM site, the THs were selected from earthquakes occurred in other parts of the world. Due to the availability of abundant number of recorded strong motion data of target magnitude (M5.0-7.3), the KiK-net strong motion database from Japan (http://www.kik.bosai.go.jp/) has been used for selecting the THs. The KiK–net database provides the opportunity of selecting the THs from the surface as well as from the borehole records. From the database, only the THs from events occurred at comparable epicenter distances of the scenario earthquakes at the C-OM site and having PGA in the range of the expected PGA at C-OM site based on probabilistic assessment are selected for the analysis. Since the ground motion parameters from probabilistic seismic hazard maps are defined for the rock site, we have used borehole record of the selected events as the input TH. Table 2 provides five selected events used for the present analysis.

Table 2: The selected event for analysis from Kik-net database

Event ID	Origin Time dd/mm/yyyy	Lat. (^{o}N)	Long. (^{o}E)	Dep (km)	Mag	Borehole PGA (gal)	Borehole depth (m from MSL)
IWTH23	05/26/2003	38.805	141.682	71	7.0	133	-87
MYGH11	08/16/2005	38.147	142.282	42	7.2	98	202
NIGH01	01/18/2005	37.37	138.997	8	4.8	104	-15
SMNH01	10/16/2000	35.275	133.348	11	7.3	185	239
KOCH05	03/24/2001	34.12	132.708	51	6.4	68	160

3.5 Scaling of Time Histories

The spectral parameters obtained from the seismic hazard maps are of probabilistic measures with which the deterministic motions obtained from the recorded data mentioned above are inherently incompatible.

Thus, the spectral levels of the recorded data and that obtained from the probabilistic assessment of the seismic hazard maps at C-OM site do not necessarily match with each other. For that reason, scaling of THs is required. We have scaled the TH of the recorded motion in the following way:

1. The spectral acceleration (SA) from two horizontal components was calculated.
2. A scaling factor was calculated by minimizing the *L2*-norm (least squares) difference between the target spectrum minus the SA at periods up to T = 1.0 seconds.
3. The resulting scaling factor was applied to the individual horizontal spectra and time histories.

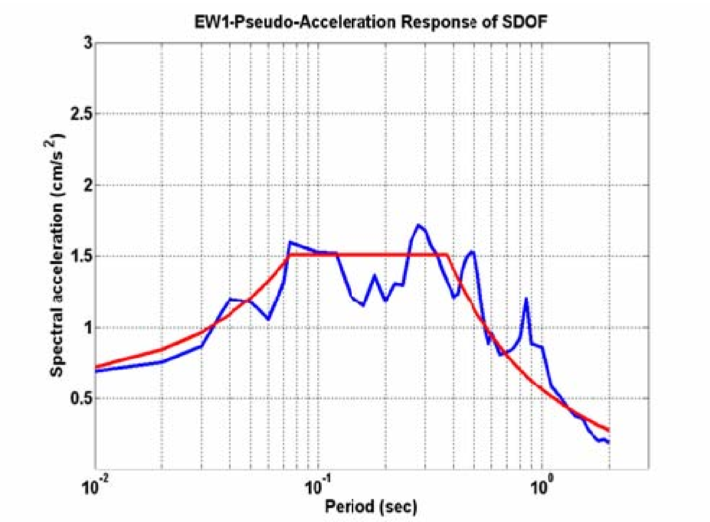

Figure 2: An example of scaling of horizontal motions of three recorded events from Kik-Net data. The blue and red lines are response spectra of scaled acceleration THs and target response spectra corresponding respectively for the C-OM site.

An example of the scaling is shown in Figure 2. We have performed individually the scaling of all selected earthquakes and used the scaled time histories (TH) as the input bed rock motion for the site response analysis.

4.0 RESULTS

4.1 Soil model at C-OM site

The ground motion analysis at C-OM site has been conducted by applying the scaled THs as the input bed rock motion and propagated them through the soil column using equivalent linear approach (EduPro Civil system, 1998). The soil profile at C-OM site has been constructed on the basis of available geological (Figure 1) and geotechnical data. The shear wave velocity values of three main geological units, e.g. silt and Sand (SS), glacial drift (GD) and Bootlegger Cove Formation (BCF) were assigned from the shallow borehole shear wave velocity data of Anchorage basin (Combellick, 1999). The density values of the soil layers were selected from the available borehole log data at C-OM site. To study the effect of the frozen soil on the site response, a frozen sand layer with shear wave velocity

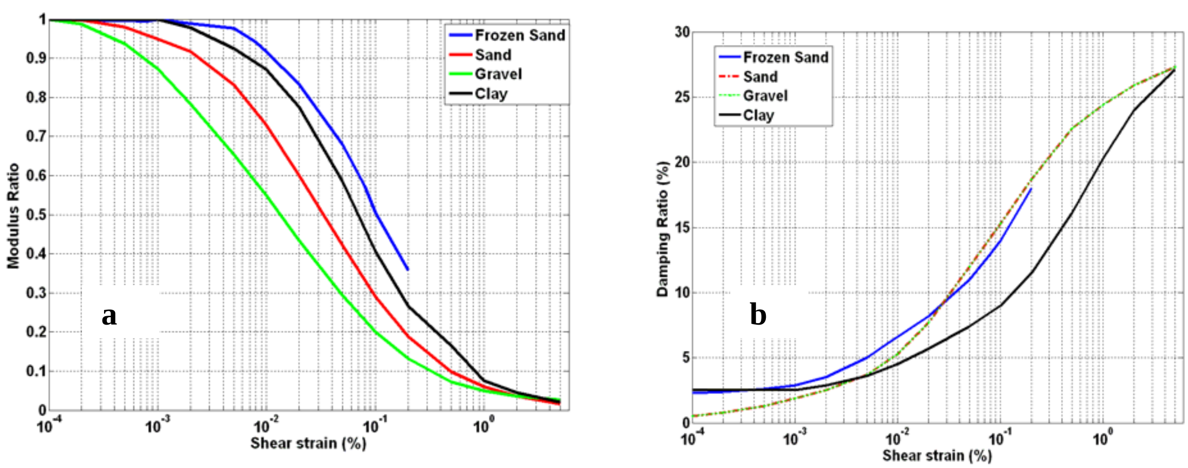

Figure 3: (a) The modulus reduction curves and (b) the damping ratio for three soil units (sand, gravel, clay) and frozen sand layer.

1500 m/s (Vinson et al., 1977) is assumed to be present on the uppermost part of the soil column. The thickness of this frozen layer was assumed to vary from 1.5 to 9.0 m. The dynamic material properties of the soil, e.g. the damping ratios and modulus reduction curves for unfrozen soils (Sand, Gravel and Clay) and frozen soil are shown in Figures 5a and 5b, respectively. Selection of these curves was based on the available results reported by various geotechnical investigations mentioned in Table 3. The time and

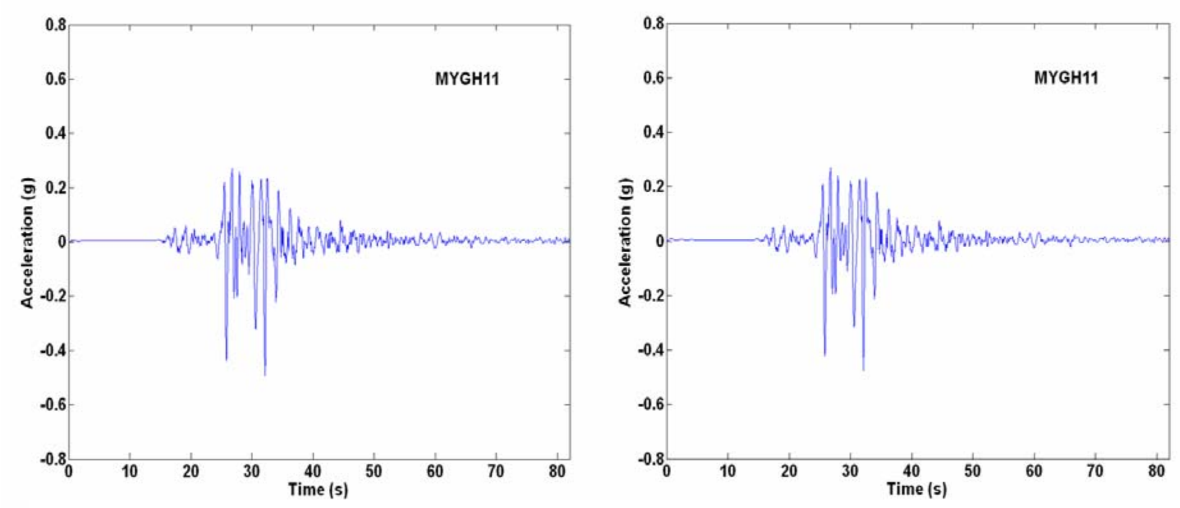

Figure 4. Computed time histories at the surface of C-OM site due to (left) unfrozen soil and (right) frozen soil of 3 m thick for MYGH11 event referred in Table 2.

frequency domain responses of the soil column due to five input bedrock motions were computed for both frozen and unfrozen soil conditions. The site response values of the frozen and unfrozen soil were compared with each other in order to study the effect of the frozen soil on the observed ground motions.

Table 3. Geotechnical parameters of the main geological units at C-OM site. The last two columns specify the references from which the modulus reduction and damping models were adopted.

Geological Unit Description	Modulus reduction	Damping ratio
Frozen Sand	Singh and Donovan (1977) and Vinson et al. (1977)	Vinson et al. (1977)
Sand	Seed and Idriss	
Gravel	Seed et al. (1986)	Seed et al. (1986)
Clay	Sun et al. (1988)	Sun et al. (1988)

4.2 Site Response: Transfer Function and Response Spectra

Figure 4 shows an example of scaled bedrock motion (AST level) at the surface due the input base motion for MYGH11 event. Figures 4(a) and (b) show the THs computed at the surface with unfrozen and seasonally frozen (3 m thick) soil condition, respectively. The ground motion parameters (PGA, Spectral Acceleration at 0.2 sec and 1.0 sec) obtained from the surface motions with increase in thickness of the frozen soil are compared and the results are shown for PGA (Figure 5a), spectral acceleration (SA) at 0.2 sec (Figure 5b) and at 1.0 sec (Figure 5c) period.

From Figure 5, it is observed that with the increase in thickness of frozen soil, the PGA and SA at surface decreases. This is due to the increase in stiffness of the uppermost frozen soil layer. However, the rate of decrease of SA with increase in thickness of frozen layer is much steeper at 0.2 sec (5 Hz) that at 1.0 sec (1 Hz) period. Hence, the presence of thin (~10 m) frozen layer on the top of the soil column (40 m thick in

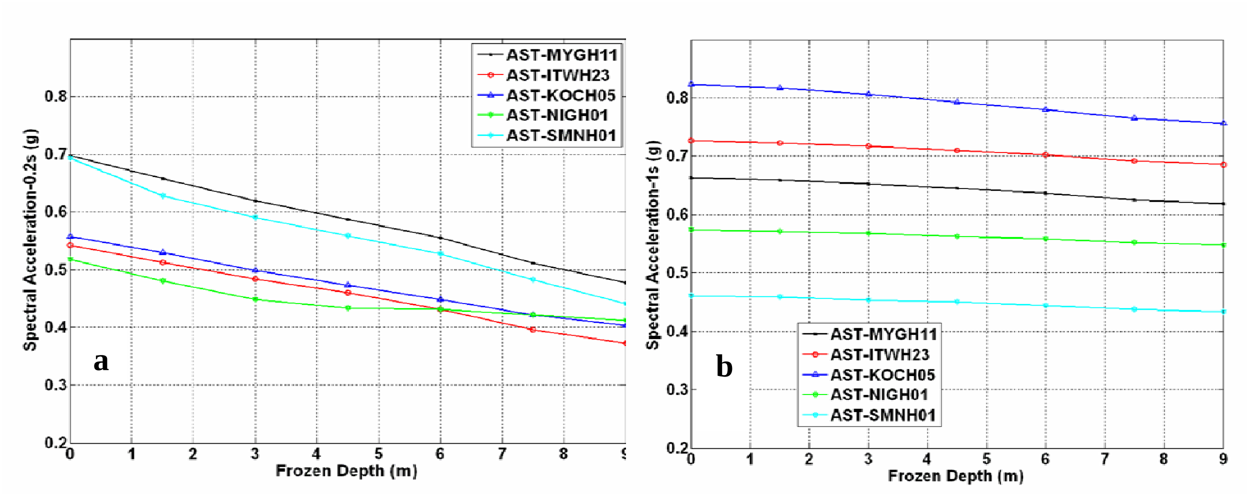

Figure 5: Effect of frozen depth on SA at (a) 0.2 sec and (b) at 1 sec for selected earthquakes scaled according to the AST –level hazard (7% probability in 75 years) at C-OM site.

present case) alters the ground motion at short period. To study the response characteristics of seasonally frozen soil in the frequency range 0.05-10.0 sec, 5% damped response spectra of the surface motion (Figure 6) and the transfer function between the surface and the bedrock motion (Figure 7) are analyzed for all the

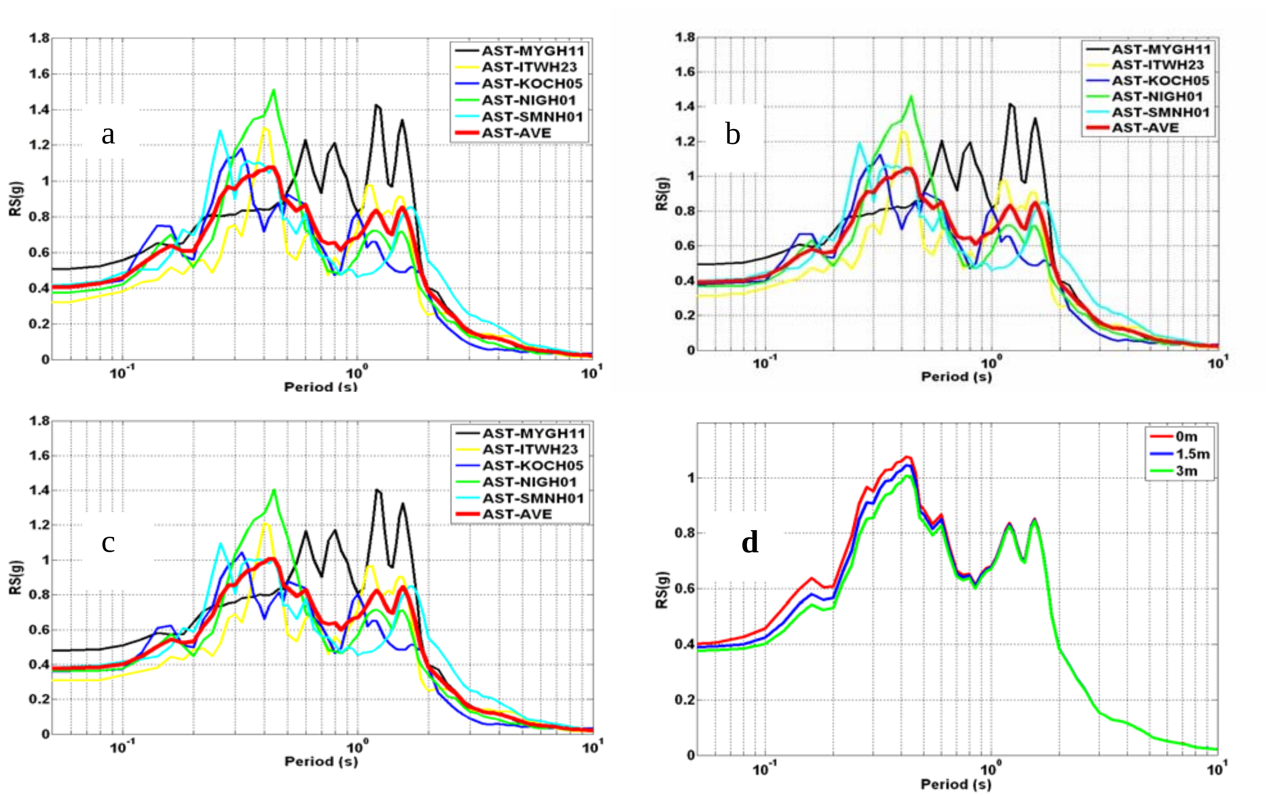

Figure 6: The plot of 5 % damped response spectra at the surface motions for five selected input motions for three soil conditions: (a) unfrozen soil and seasonally frozen soil of thickness (b) 1.5 m and (c) 3.0 m. Figure (d) compares the average value of response spectra for above three soil conditions.

events. The comparison between the average value of 5% damped response spectra from the surface motion for frozen and unfrozen soil condition (Figure 6d) indicates that with increase in thickness of the frozen layer the response spectral amplitude decreases in the period range from 0.1 to 08 sec. The computed transfer function of the unfrozen soil column at C-OM site for different scaled input motions are shown in Figure 7a along with an average transfer function from all the events. Figures 7b and 7c, respectively shows the plot of transfer function in case the presence of 1.5 m and 3 m thick frozen soil is assumed at the C-OM site. To compare the effect of frozen soil, the average values of transfer functions are plotted in Figure 7d. The plot indicates that with the increase in thickness of the frozen soil, the amplitude of the transfer function for frequencies higher than 1.0 Hz decreases. However, no change in spectral amplitude and

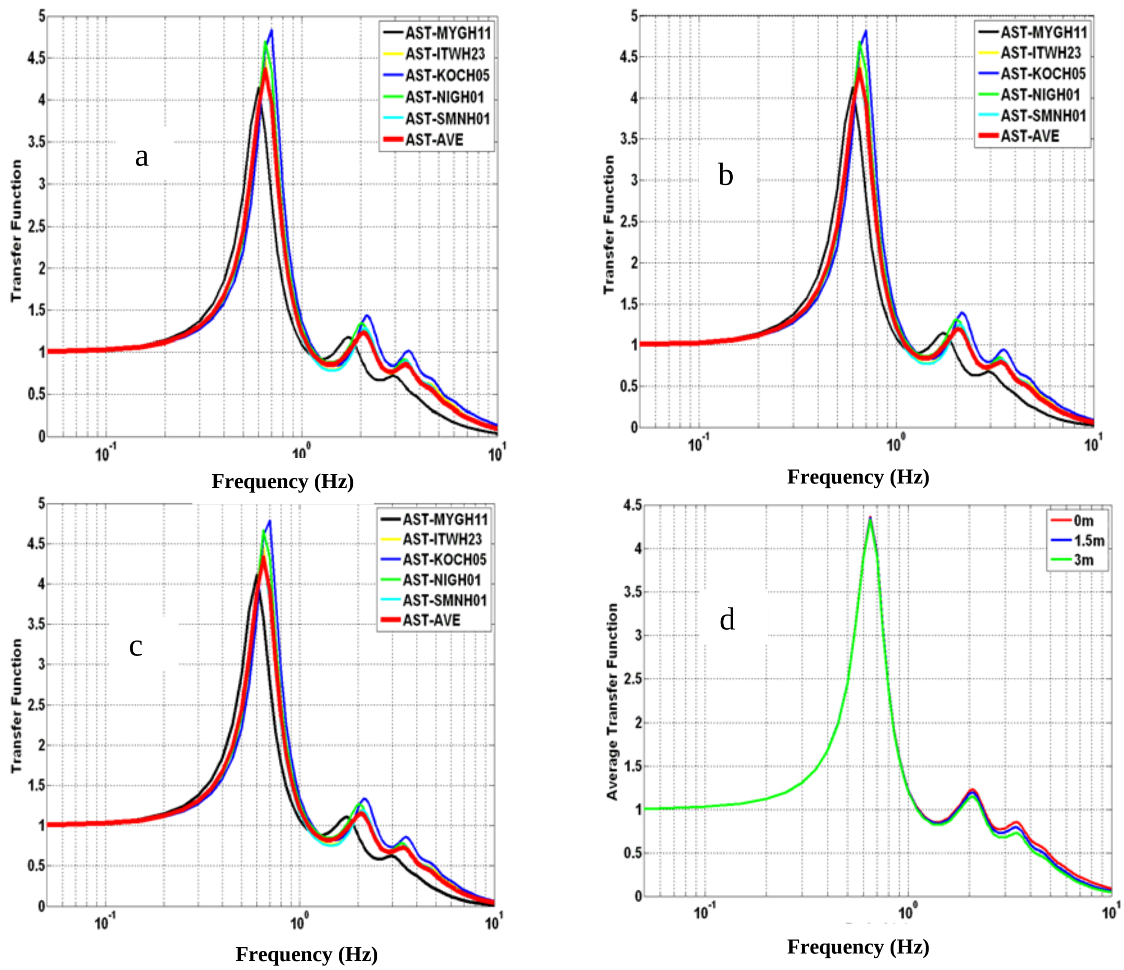

Figure 7: The plot of transfer function between the surface and bed rock motion for selected events as labeled in individual plots for three types of soil conditions: (a) unfrozen soil and seasonally frozen soil of thickness (b) 1.5 m and (c) 3.0 m. The solid red line in each plot indicates the average value of the transfer function. (d) Comparison between the average value of transfer functions for above three soil conditions.

transfer function is noticed for spectral frequency less than 1.0 Hz or greater than 1s.

5. CONCLUSIONS

A study of the effect of the seasonal frost on the seismic site response has been conducted by propagating the hazard consistent earthquake motion through the soil column at one of the transportation infrastructural site in Anchorage, Alaska. The results show that the presence of frozen soil in general reduces the transfer function and spectral response of the ground motion in compare to the unfrozen soil. This reduction is observed for the frequency higher than 1 Hz. The spectral response with the presence of frozen soil does not affect the seismic motion lower than 1 Hz.

6. ACKNOWLEDGEMENT

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