Effects of Shear Wave Velocity and Thickness of Soil Layers on 1D Dynamic Response in the Saguenay Region, Quebec

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Abstract. Before reaching the ground surface, the amplitude, duration and frequency content of the vertically propagating seismic waves can be modified by the local stratigraphy and soil physical properties. In this study, we evaluate the impacts of the soil shear wave velocity (V_s) and thickness (H) on the seismic ground response using 1D ground response analysis. Simplified soil profiles typical for the Saguenay Lac-Saint-Jean region (SLSJ) are considered defined with relatively thin glacial sediments overlaid by more than 100m thick marine sequence. Impedance contrasts exist at the bedrock interface and between the fine marine and glacial sediments. Time-domain nonlinear 1D numerical simulations are carried out with Deepsoil®. The seismic input at the bedrock level is defined with synthetic earthquake time histories compatible with eastern Canadian seismo-tectonic settings. It is found that the changes in the Fundamental period of the soil caused by changes in the thickness of the soil deposit and soil V_s have a significant impact on the surficial amplification.

Keywords: 1D nonlinear ground response · response spectrum · fundamental period · soil amplification

1 Introduction

A number of studies have confirmed that seismic shaking during strong earthquakes can be significantly influenced by the local soil conditions through field observations or numerical modeling. Several numerical approaches for ground response analysis exist in the literature [1]. They can be carried out in 1D, 2D or 3D; with linear, equivalent linear, nonlinear or advanced constitutive models; and in frequency or time domain [2, 3].

The soil nonlinear behavior under earthquake loading is defined with soil dynamic stiffness (shear modulus) and damping properties. The maximal acceleration and frequency content of the surface motion are significantly influenced by the level of input

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ground motion intensity and shear stiffness of the soil deposit [4]. The response of ground during an earthquake motion is related to some soil parameters, such as V_{s30}, the fundamental frequency of vibration of the soil column (F_0), and seismic impedance contrast (I_w) where F_0 which is dependent on the V_s and thickness of the soil deposit is the most helpful parameter for the prediction of seismic amplification function [5]. The majority of seismic site response studies have concentrated on the impacts of the shear wave velocity (V_s) on the peak ground acceleration (PGA), spectral accelerations of interest (S_a), and site-specific amplification factors (AF) [6–9].

The objective of the present study is to investigate the potential effects of the local site conditions on the surface ground motion in the SLSJ region, Quebec. Several representative soil profiles for the study area is considered with glacial and fine marine sediments overlying bedrock formations. 1D nonlinear response analyses are carried out with Deepsoil v7.0 software with generic shear modulus reduction and damping curves. The seismic input consists of a series of synthetic time histories compatible with eastern Canadian seism tectonic settings. The simulations are run for varying thickness of the soil units assigned with respective V_s.

2 Study Area

The SLSJ region is located in Eastern Canada, a relatively stable continental region within the North American plate. Nevertheless, strong earthquakes have struck the region in the past, among which the most recent one was the 1988 Mw 5.9 Saguenay earthquake with a shallow crustal depth of 28 km and an epicentral distance of about 35km (https://earthquakescanada.nrcan.gc.ca/). On the regional scale, SLSJ is mainly affected by the Charlevoix–Kamouraska seismic zone, the seismically most active zone in Eastern Canada located about 75 km southward. Glacial sediments (till), consisting of a wide-graded mixture of debris material, compact to semi consolidated are found at the base of the Quaternary stratigraphic column. As a result of the final meltdown and retreat of the ice sheet, marine waters of the successive Laflamme Sea inundated the region. This incursion contributed to the deposition of more than 100 m thick fine marine clay and silt sediments, referred herein as clays, on top of the glacial sediments. A particular problem in the study area is the occasional presence of sensitive clays. They are often related to landslides, liquefaction, lateral spread and other ground failures, where they undergo a quick transition from a solid to a fluid state. In addition, the strong impedance contrast between the unconsolidated deposits and the bedrock formations can have a significant impact on the soil dynamic response.

3 Methodology

The applied methodology can be divided into three main steps: selection of soil input parameters, selection of input ground motions, and 1D nonlinear ground response analyses. The simulations are carried out with Deepsoil® assuming that the soil layers are horizontal and infinite and that the seismic excitation consists of vertically propagating horizontal shear waves. The soil behavior is analyzed using numerical integration of the equation of motion in time domain which allows for rigorous nonlinear analyses. The

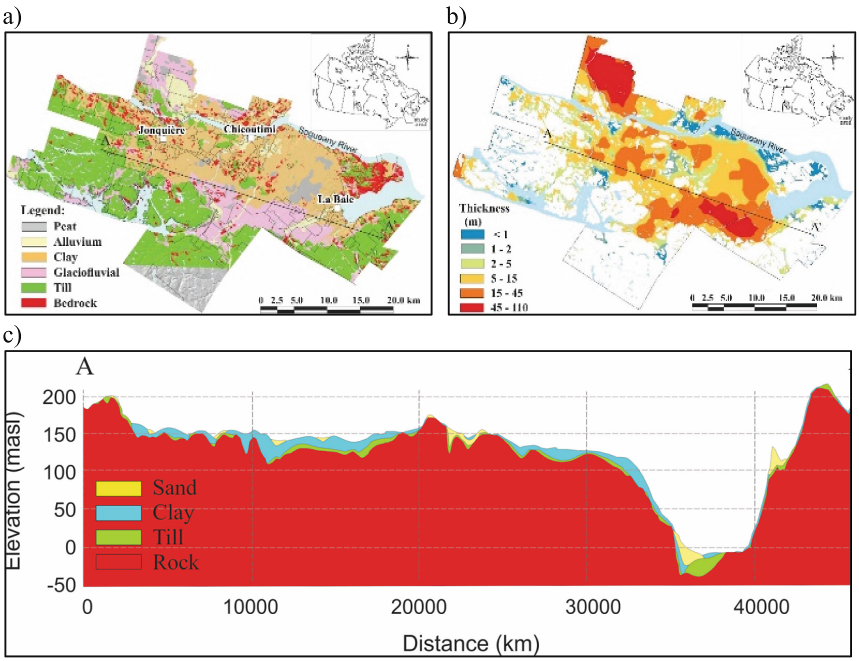

Fig. 1. Saguenay Lac St. Jean study area a) simplified surficial geology, b) thickness of surficial sediments and c) geological cross section [modified from 11 and 12]

strength based general quadratic/hyperbolic (GQ/H) soil model proposed by [10] is used as it has a better shear modulus and damping curve fitting method at the larger strains. The input soil parameters and earthquake ground motion are described in detail in the following section (Fig. 1).

3.1 Input Soil Parameters

Two typical stratigraphic soil columns are considered: (1) a single clay layer, and (2) a combination of clay and till layers on top of the bedrock. The first stratigraphic column is with a strong impedance contrast at the bedrock interface, whereas the impedance contrast is more gradual in the second column: first between the clay and till layers and then at the bedrock interface. Three series of simulations are run by varying the thickness of the surficial units and the respective V_s.

For clayey soil, the nonlinear dynamic behavior between shear strength and strain is defined with the shear modulus reduction and damping curves adopted from [13] considering a plasticity index of 18. The shear strength is determined from the correlation with the V_s developed for eastern Quebec [14]. The V_s, shear modulus reduction and damping curves for glacial Laflamme sea sediments are taken from Hydro Quebec. Based on the 3D geological model developed by [15], the thickness of the LaFlamme clay unit varies between a few meters to about 100 m. In the analyses, discrete clay thickness of 10, 20, 30, 50 and 100 m was considered. The thickness of the glacial sediments at the base of the second soil column was fixed at 10 m. Based on the V_s -depth regression analysis conducted over more than 1000 field measurements by [16], three average shear wave velocities for the clay layer were assumed as $V_s = 150$, 200 to 250 m/s. The bedrock V_s are assumed with fixed value, $V_{s\,\mathrm{rock}} = 1875$ m/s [16]. A total of 30 simulations are conducted, 15 for the clay-rock soil column #1 and additional 15 for the clay-till-rock column #2.

3.2 Input Ground Motions

In the present analysis, a series of six synthetic ground motions for rock site conditions defined with $V_{s,30} \geq 1500$ m/s are selected as representative for eastern Canada [https://www.seismotoolbox.ca/index.html] [17]. Three of the input motions correspond to earthquakes with moment magnitude M6.0 and the other three to M7.0. All the input motions are scaled with respect to peak ground acceleration at PGA = 0.3 g, 0.4 g and 0.5 g. In this way, they are matching approximately the latest NBCC 2020 hazard for SLSJ region with a return period of 475 years, or 10%/50-year probability of exceedance. The time histories and their acceleration response spectra of the selected ground motions are given in Fig. 2 and Fig. 3, respectively.

4 Results

A total of 30 nonlinear 1D ground response simulations are performed with Deepsoil® each using the 18 input ground motions (6 synthetic ground motions scaled at PGA = 0.2, 0.3 and 0.4 g). From the obtained 540 resulting response time histories, the average spectral acceleration values for each model are taken as measures of the model predictive capability. The respective amplification functions are computed as the ratio between the response spectra at the ground surface and at the bedrock level, where the input motions are assigned to the model. The corresponding nonlinear analysis was compared to the equivalent linear analysis results recommended by the Deepsoil manual, and they were found to be a good match.

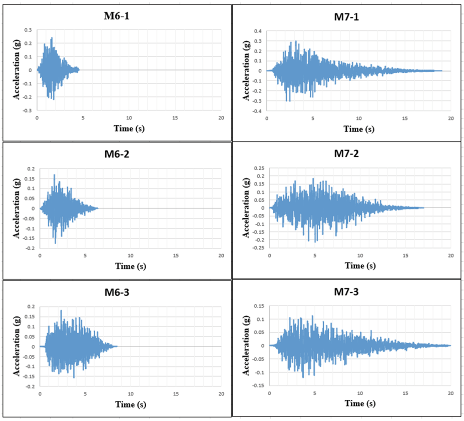

Fig. 2. Time histories of the input ground motions

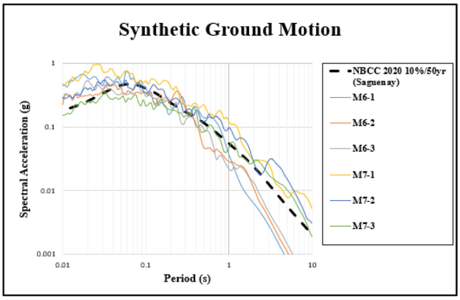

Fig. 3. Spectral acceleration of the selected motions with respect to the NBCC 2020 10%/50year response spectra

4.1 Response Spectra at Ground Surface

Impact of clay thickness: In this set of simulations, the response spectra at the ground surface are compared for 5 different thicknesses of the clay unit, separately for each of the 3 assumed average clay V_S. Figure 4 illustrates the response spectra at the ground surface for soil column #1. The average response spectrum of the input motion is also represented and indicates that the seismic energy content is concentrated in the medium period range ($\leq$1.0 s). It can be observed that the increase of the clay layer thickness results in decrease the spectral acceleration values and this result can be explained by the gradual increase in the overall stiffness of the soil layer with thickness increase. The same observations are valid for soil column #2.

Impacts of clay V_s: Fig. 5 illustrates the response spectra at ground surface for soil column #1 for variation of the clay layer thickness from 10 to 100 m and of V_s from 150 to 250 m/s. Provided that the thickness remains the same, the increase of V_s is reflected in the increase of the overall stiffness of the soil columns. This contributes to a shift of the predominant response period towards shorter values. At the same time, the spectral acceleration values increase in the medium period range (around 0.1 s), where as they appear to be practically the same with those of the input motions at longer periods. The same observations are valid for soil column #2.

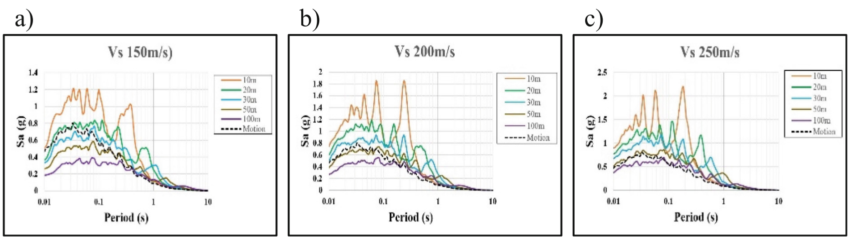

Fig. 4. Response spectra at ground surface for soil column #1 (clay on top of bedrock) with variable thickness and average V_S of: a) 150 m/s b) 200 m/s and c) 250 m/s. The average spectral accelerations of the input motions are indicated with dashed line

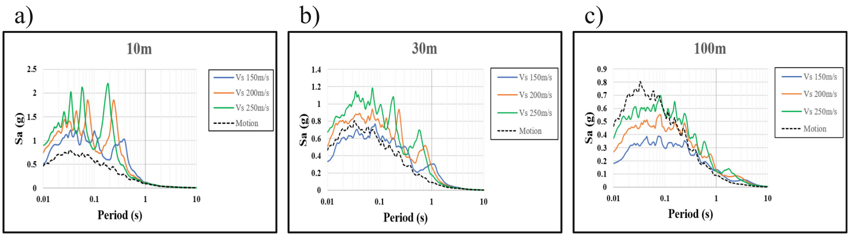

Fig. 5. Response spectra at ground surface for soil column #1 whereas the clay thickness varied as a) 10 m, b) 30 m and c) 100 m. The average spectral accelerations of the input motions are indicated with dashed line

4.2 Amplification at Surface

Impacts of clay thickness: Fig. 6 shows the amplification functions for soil column #1 and #2 with varying thickness and V_s of 200 m/s. It can be observed that the predominant period of amplification shifts to ward longer value with the increase of the thickness as the fundamental period is increasing both for two soil columns. Also, amplification of soil column #2 has lower value compared to the soil column #1 as the presence of till layer lower the impedance contrast ratio.

Impacts of clay V_s: The amplification functions results for soil having 30 m thickness are presented for both soil columns in Fig. 7. As expected, a gradual shift of the dominant vibration period toward shorter values occurs with the increase of V_s, due to the increase of the stiffness of the both soil columns and the decrease of the fundamental period of soil columns and the shift is less in soil column #2 compared to soil column #1 for the presence of 10 m glacial sediment. Also, the presence of glacial sediments results lower amplification in soil column #2 as compared to soil column #1.

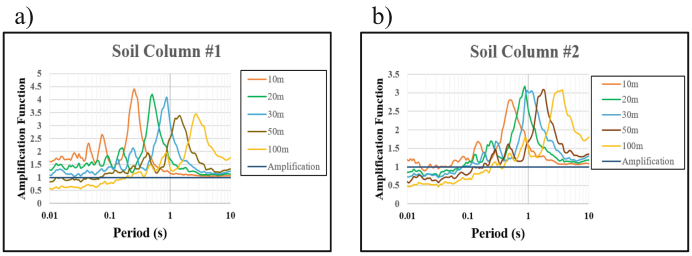

Fig. 6. a) Amplification functions for soil column with varying thickness and V_s of 200 m/s: a) soil column #1 and b) soil column #2

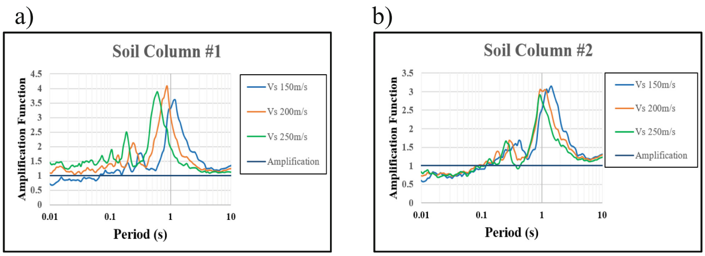

Fig. 7. Amplification function for the variation for V_s for 30 m soil deposit a) soil column #1 and b) soil column #2

5 Conclusion

A site-specific numerical simulation of the effects the V_s and thickness of surficial soil sediments exert on the seismic ground response is evaluated for the SLSJ region of Quebec, Canada. It was observed that, due to the gradual increase in the overall stiffness of the soil column with the increase of the clay layer thickness, the spectral acceleration values decrease. The stiffer soil columns with assigned higher clay V_s in case of the same clay layer thickness generated higher dynamic responses with dominant response periods shifted toward the shorter period range. At the same time, de-amplification was observed at shorter period ranges depending on the soil thickness. The amplification of the input ground motions is higher in soil column #1 than the soil column #2 and there is a gradual shift in the predominant period of amplification due to the change of Fundamental period by the soil thickness or V_s. This result demonstrates that the presence of till layer between the clay and rock in the eastern Canada, reduced the impedance contrast that reduce the amplification and hazard potentials. These preliminary results will help to plan the next series of numerical simulations of the dynamic soil response considering more complex soil models with gradually increasing V_s with depth and 2D analyses of the dynamic slope stability.

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