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Regional seismic zonation in the Ottawa and St. Lawrence Valleys, Canada

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ABSTRACT: A standardized method for determining the spatial variation of shear wave velocity (V_S) and fundamental period of vibration (T_O) is presented. It consists of (i) update of the Quaternary geology, (ii) arranging of surficial units with similar physical properties into three different categories: surficial coarse sediments (sand), intermediate fine sediments (clay) and basal glacial deposits (till), (iii) delineating the spatial thickness of each category by way of 3D geologic modeling, and (iv) assigning representative V_S values to model units. Respective T_O was computed with the standard quarter-wavelength relation. Final V_S and T_O spatial distributions were generated at a resolution of 500 m.

1 INTRODUCTION

V_S is undoubtedly a valuable indicator of the soil dynamic behaviour as it is directly related to the shear modulus used for the definition of the stress-strain behaviour of soils. This parameter initiated an intensive mapping effort of the soil conditions and V_S in the last decades. To predict the spatial distribution of this parameter, local scale studies are based in general on intensive geophysical measurements. Several such studies were recently conducted in Eastern Canada, e.g., Montreal Island (Chouinard and Rosset 2011), Ottawa-Gatineau (Hunter et al 2010, and Motazedian et al 2011), and Quebec City (LeBoeuf et al 2013). For regional studies, however, it is impractical to rely on sufficiently dense coverage with field observations of V_S. Hence, a combination of geological and geomorphological information, borehole logs and compilation of shallow geophysical measurements is often applied (Ansal et al 2004, Matsuoka et al 2005). In their state-wide soil classification study for California, Wills and Clahan (2006) grouped together geological units with similar physical properties and age, and assigned a range of respective V_S values. Likewise, Holzer et al (2005) compiled detailed subsurface information and included the variation of V_S with depth for each of the 5 major surficial units in the San Francisco Bay area.

A regional seismic risk assessment study was recently completed in the Ottawa and St. Lawrence Valleys between Ottawa and Quebec City (Nastev, 2014). One of the objectives was to provide standardized estimates of the site conditions as a vital step in predicting the variability of the potential seismic site response over the entire region. In the absence of extensive V_S measurements, it was decided to use surficial geology and simplified three dimensional (3D) geologic model as ancillary data. This paper describes the applied procedure for V_S and T_O mapping. The method consisted of (i) update of the Quaternary geology, (ii) arranging of surficial units with similar physical properties into three different categories: surficial coarse sediments (sand), intermediate fine sediments (clay) and basal glacial deposits (till), (iii) delineating the spatial thickness of each category by way of 3D geologic modeling, and (iv) assigning representative V_S and T_O values.

2 GEOLOGICAL SETTING

The study area extends from Ottawa-Gatineau and Cornwall towards Montreal and then follows the St. Lawrence River to Québec City. It is bounded by the Laurentian Highlands to the North and the US border to the South. It covers approximately 71,560 km^2 and contains a number of large urban centers, including Montréal, Ottawa-Gatineau, Québec City, and Trois-Rivières. Most of them are at least partially located on soft postglacial sediments with low V_S.

Three geological provinces are encompassed in the study area: the Precambrian Grenville Province, the St. Lawrence Platform, and the Appalachian orogen to the south (Figure 1). The Grenville Province represents the basement unit which outcrops to the North in the Laurentian Highlands as

Canadian Shield. It consists mainly of solid highly metamorphosed rocks with significant volume of intrusive rocks. A time difference of about 500 M.y. separates the Grenvillian metamorphosed domain and the preserved succession of the Lower Paleozoic rocks (St. Lawrence Platform and Appalachians). The St. Lawrence Platform is thick (>1000 m) succession of Upper Cambrian-Ordovician sandstones and carbonates (Globensky, 1987). These rocks were deposited in coastal and deeper marine environments during the transgressive phase of the Iapetus Ocean, following the rifting of part of the Grenville mountain range. This sequence was later intruded by alkaline magma during the late Mesozoic, which now forms a series of compact igneous hills referred to as 'Monteregian Hills' that resisted the Cenozoic erosion. The fractured sedimentary rocks of the St. Lawrence Platform overlie the uneven surface of, and are limited to the north and northwest by, the metamorphic and intrusive units of the Grenvillian Orogen. On the southeastern side they are in tectonic contact, through Logan's Line, with the Lower Paleozoic Appalachian Humber Zone. The trusted sheets of the Appalachians consist of the Lower Paleozoic Dunnage zone and the Middle Paleozoic Gaspé belt units as well (Lavoie, 2008). These are mainly deformed metamorphic rocks formed during the Appalachian Orogen.

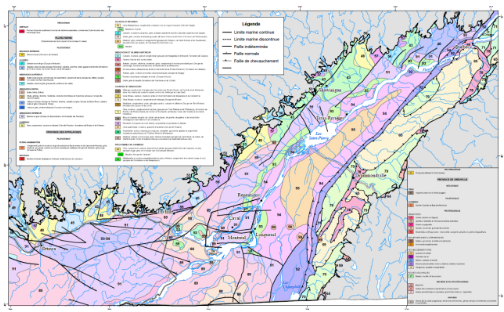

Fig. 1. *Bedrock geology*

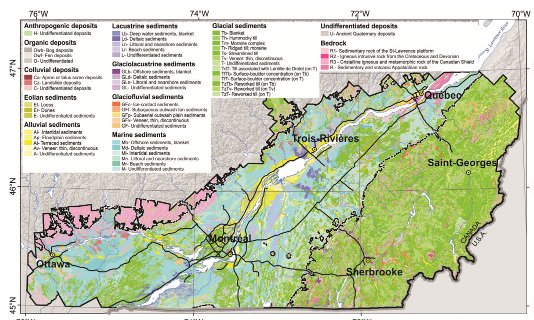

Fig. 2. *Updated surficial geology map (after Parent et al. 2015)*

The overlying Quaternary succession is variable and often discontinuous. The surficial geology map presented in Figure 2 was assembled and standardized from existing or recently prepared 1:50,000 maps (Parent et al. 2015). The typical Quaternary sequence contains (from below) till, glaciofluvial sediments, glaciolacustrine sediments, marine sediments, and fluvial and aeolian sediments. The glacial deposits (till) are the most extensive Quaternary unit in the study area. In the proximity of the St. Lawrence and Ottawa rivers, the regional till is generally covered by a 20 to 30 m thick blanket of marine muds that were deposited in the Champlain Sea, an inland arm of the Atlantic Ocean that lasted for almost 2000 years at the close of the last deglaciation. It inundated the isostatically depressed St. Lawrence and Ottawa valleys up to almost 200 m (ASL). The marine unit locally overlies fine-grained varves that had been deposited during the Glacial Lake Candona episode (Parent and Occhietti, 1988 and 1999).

The shorelines of this large lake lie about 40 to 60 m above Champlain Sea shorelines and have been observed on the Appalachian Piedmont and valleys as well as in the Lake Champlain and Upper St. Lawrence valleys towards the lowlands southwest of Montreal. In the extreme southern and northern parts of the lowlands, the marine clay unit is thinner and much more discontinuous. Here, except in local mud-filled bedrock lows, the surficial units are relatively thin (< 10 m) and consist of a mosaic of wave-reworked till and littoral sands and gravels. Regionally, the marine muds grade upward into freshwater muds that were deposited in Lake Lampsilis, a freshwater body that replaced marine waters as relative sea level fell below about 60 m in the Québec City region. Continued uplift led to further emergence and to the deposition of a discontinuous blanket of alluvial sands by the Proto-St-Lawrence River. This offlap fluvial unit increases in thickness near the modern St. Lawrence River and Lake St-Pierre.

In the Appalachian and Lorentian Piedmonts, the Quaternary sediment cover is thin and rock outcrops are quite common. The top 1 to 2 meters of the surface till were vigorously reworked and winnowed by waves and currents of the Champlain Sea and are therefore coarser and more permeable than the underlying compact till. Littoral sands and gravels along with reworked tills are the most widespread surficial unit of the piedmont. Champlain Sea muds are restricted to the main tributary valleys. In the Appalachian Uplands and Lorentians, the till cover is generally thin and discontinuous on topographic highs and rock outcrops are abundant. In mountainous terrains, coarser melt-out tills commonly cover bedrock or compact basal till. Glaciofluvial sands and gravels occur almost exclusively in valleys where glacial meltwaters were concentrated. Glaciolacustrine sediments, including varved silt and littoral/deltaic sand, are also common in the main valleys.

3 3D MODEL

To determine the spatial thickness of the major surficial units, 3D geological modeling was carried out with the gOcad software (www.pdgm.com/products/gocad/). Various data sources provided the necessary input parameters: seamless surficial geology map; digital elevation model with 90 m resolution (http://srtm.csi.cgiar.org/), interpreted public borehole database (gw-info.net), interpretations from various geophysical measurements, and few available 3D geological models built for hydrogeological characterization: Portneuf region (Girard 2000), Mirabel region (Ross et al 2005), South Nation watershed (Logan et al 2009), Chateauguay watershed (Tremblay et al 2010), Québec City (Lamarche 2011), and Chaudière watershed (Caron 2012).

For the purpose of this study the surficial geology units with generally similar age and/or depositional patterns were grouped together into three major categories (from below): basal glacial deposits – *till*; intermediate fine sediments - *clay*; and coarse surficial sediments - *sand*. This subdivision is intimately related to the similarity of physical properties of these geologic materials, in particular grain size distribution and compaction expected to result in distinct V_S ranges.

- *Till*: glacial deposits at the base of the Quaternary sequence include undifferentiated, blanket, veneer, moraine, ridged, streamlined and reworked till sediments, and undifferentiated sub-till sediments in several lowlands areas and in the upper Chaudière Valley. These sediments are almost ubiquitous over the study area and attain average thickness of 7 m. They are heterogeneous and usually contain coarse to bouldery sediments surrounded by fine grained matrix. Their density and compaction systematically increase with depth in such a way that drillers are often uncertain as to whether bedrock is encountered.
- *Clay*: the main unit of concern due to its physical properties are the fine marine, glaciolacustrine and lacustrine deposits, better known as Champlain sea clay, including undifferentiated glaciolacustrine clay in areas above marine limit. Undifferentiated organic, bog and fen sediments were also included in this group. These deposits are presented in approximately 26% of the study area with average thickness of about 10 m, but may reach close to 90 m in certain areas. They represent loosely deposited fine grained and usually saturated soils dating from the last glacial erosion, which may be geotechnicaly highly sensitive, particularly marine clays. They lose much of their strength when disturbed and may behave like a viscous fluid after disturbance. The sensitivity is generally correlated with high natural water content of the deposits, flocculated fabric of the clay particles, low electrical attraction between the clay-size particles, low overburden pressures during deposition, and post-depositional leaching of salts (Locat et al 1984; Torrance 1988). As a consequence, retrogressive earth flows are widespread throughout the study area. Characterised with rapid expansion they encompass large areas of almost horizontal terrain, with slope angles on the order of one degree or less (Quinn 2010, Brooks 2013).
- *Sand*: fine sediments (clay) grade into coarse marine, glaciolacustrine and lacustrine sediments (beach sand), and fluvial, and aeolian sands to form the post-Champlain Sea sediments. This unit includes as well glaciofluvial deposits (sand and gravel) and undifferentiated non marine sand and gravel in areas above marine limit. Sand is generally relatively shallow sediment with mean thickness of 4.5 m.

The construction of the 3D model started with the creation of a 2D grid from the available digital elevation model with a regular 200 m mesh (1,789,037 cells). Continuous boundary surface of the bedrock topography was generated to estimate the total thickness of the surficial deposits. Quaternary sediments extend over 70% of the study area with important variation in the total thickness, which can attain as much as 150 m in buried valleys. Next, the internal stratigraphy was defined by interlocking interfaces that represent the contacts of the lithological units: sand/clay and clay/till. The interpretation was based on data from various sources when existent, or using the surficial geology and general understanding of the stratigraphy and sedimentation processes. Where a given stratigraphic unit was inexistent, the respective top and bottom interfaces shared the same altitude (zero-thickness). To test the impact of the cell size on the final results, interface surfaces were created with resolution of 200 m, 500 m and 1000 m for the Mirabel region, north of Montreal. The up-scaling was simulated based on the dominant unit in the finer 200 m resolution. Minimal differences were observed in low relatively flat relief characterised with gradual variation of the thickness of the stratigraphic units. These are expected to be seismically sensitive low V_S areas containing sand and clay deposits. Slight to moderate differences were observed in hummocky and mountainous terrains where altitudes change rapidly. These, however, are not necessarily of interest due to negligible presence of built environment. Based on these results and to facilitate handling of large amount of data, the retained grid resolution was 500 m (286,246 cells). Details on the applied methodology can be found in Howlett and Ross (2015).

4 ASSESSING THE V_S

A consistent V_S database was compiled based on more than 6,000 vertical profiles from the recent Montréal, Ottawa, and Québec City seismic zonation studies, and two hydrogeological studies conducted in the Mauricie and Richelieu-Yamaska watersheds, Québec (Mauricie-Richelieu in the further text). Collected geophysical data comprised i) Montreal: 5 downhole interval V_S measurements including 2 downhole surveys in the Mirabel region, and 7.5 km land-streamer high resolution seismic reflection profiling HRSR (Chouinard and Rosset 2011); ii) Ottawa: 750 seismic reflection-refraction survey locations, 25 km of land-streamer HRSR, and 24 downhole interval V_S surveys (Hunter et al 2010); iii) Québec City: 4 km of land-streamer HRSR, 1 downhole and 21 seismic reflection-refraction surveys (LeBoeuf et al 2013); and iv) Mauricie-Richelieu: 93 km of land-streamer HRSR (Miszaniec 2012). A detailed description of the above geophysical methods and V_S interpretation methods is given by Hunter and Crow (2012).

4.1 Postglacial deposits

Average V_S-depth data collected for both postglacial units together with simple regression analyses are compared in Figures 3. As expected, the sand unit displays in general comparatively higher V_S, however, sand V_S values overlap considerably those of clay and the apparent differences are well within the potential uncertainties resulting from field measurement and interpretation methods (Figure 3a). Both soil categories show significant scatter of V_S data, a result of the high variability in the grain-size distribution and compaction of the regrouped geological units. Data seem better constrained when isolated by individual study areas, indicating potential regional dependency (Figures 3b and c). Hence V_S measurements from Montréal show stiffest soil conditions, whereas data from Mauricie-Richelieu are systematically on the softer side. These regional differences can be partially explained by the variability of the erosional processes following the initial deposition, where intense erosion generally results in shallower soils under over-consolidated conditions, which seems to be the case on the Montréal Island. As well, V_S exhibits in general steady increase with depth at approximately similar rates with the exception for the sand unit in Ottawa, which for depths >20 m it displays inverse relationship most probably due to limited data and potential misinterpretation of the encountered lithology. It can also be noted that clay V_S data from Mauricie-Richelieu show positively skewed distribution (Figure 3c). For depths >30m clay deposits in the Québec City region show distinctly higher V_S, but this comes from sparse data originating from a relatively restrained area surveyed by a deep downhole measurement and land-streamer HRSR profiles.

Having in mind the large dispersion of the retained data, it was decided to conduct simple regression analyses for the average V_S-depth relationships (Figure 3b and c). The final regression equations are based on the whole data sets which is of interest for geotechnical practitioners in general. The regression equations with depth cut-off of 30 m of interest for seismic zonation studies, yielded slightly different average V_S estimates, still within ≤10% compared to those presented in Figures 3.

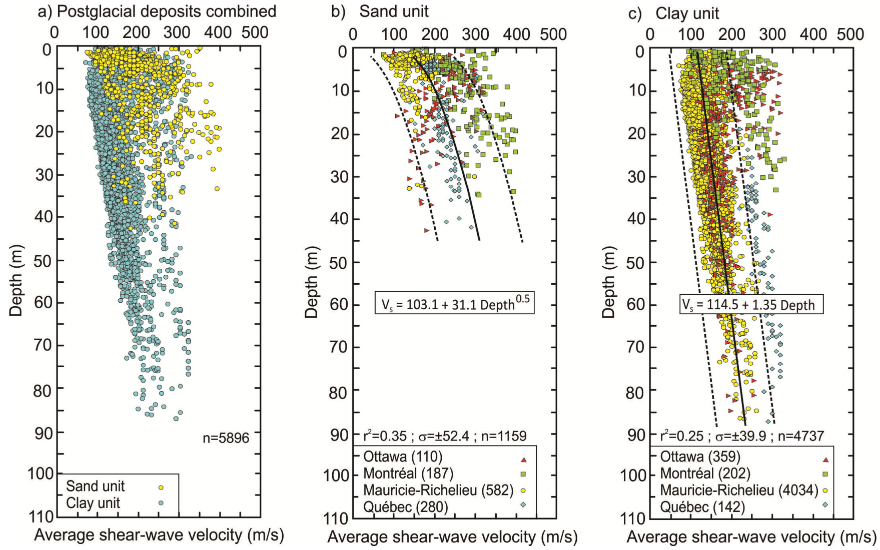

Fig. 3. *Average shear wave velocity (V_{SAV}) data from reflection/refraction, landstreamer and downhole profiles for: a) combined postglacial deposits (sand and clay), b) sand unit, and c) clay unit. Regression functions are indicated with bold lines, 95% confidence prediction intervals are indicated with dashed lines, r^2 denotes the co-efficient of determination, and σ represents the standard deviation (standard error).*

4.2 *Glacial deposits*

Interval V_S observations for glacial deposits were collected from measurements conducted in Ottawa, Montréal and Mauricie-Richelieu (Figure 4). Arithmetic mean interval V_S and standard deviation are shown to describe the statistical tendency, which for the combined dataset is V_S=400±151 (m/s). Again, data from Mauricie-Richelieu show the lowest interval V_S, but at the same time, they are the most numerous and dominate the final distribution.

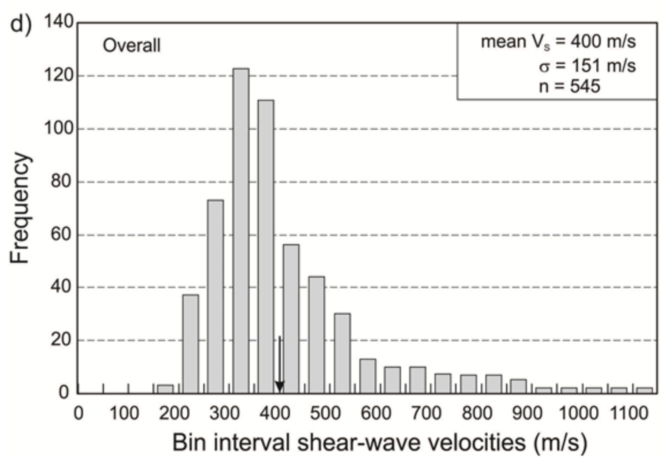

Fig. 4. *Frequency distribution of interval shear-wave velocity observations for glacial deposits.*

5 V_S AND T_O MAPPING

Shear wave velocity distribution for the entire study area was developed based on the V_S measurements discussed above. As data points varied largely, it was decided to retain the average statistical values where possible, i.e., for the sand, clay, and till units. Average shear wave velocity vs. depth functions were assigned to the sand unit, V_S=103.1+31.1depth$^{0.5}$ m/s, and the clay unit: V_S=114.5+1.35depth m/s, whereas unique interval V_S value was assigned to the till unit, V_S=385 m/s. The well-known quarter-wavelength relation was applied to compute the approximate fundamental site period. The results are given in figures 5 and 6.

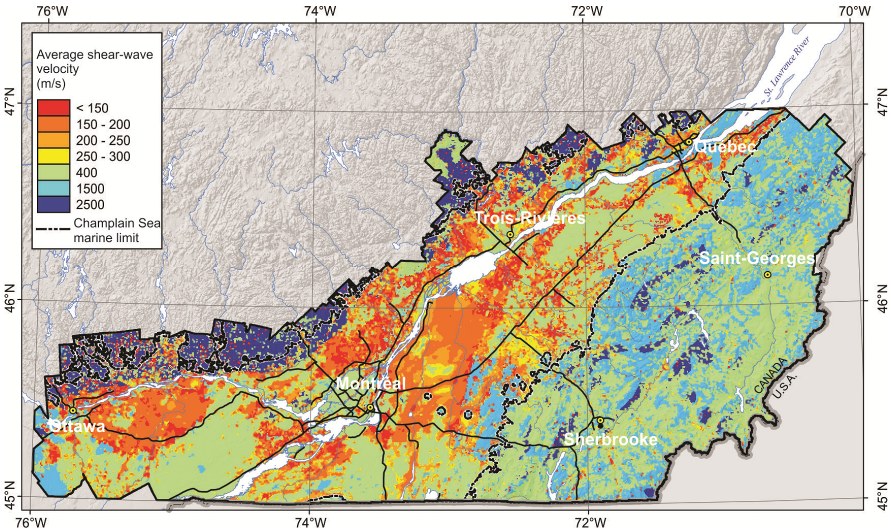

Fig. 5. Average shear wave velocity calculated over the total depth of the soil profiles down to the bedrock. V_S-depth relationships were retained for the clay and the sand unit, whereas unique V_S values were considered for till and for rock outcrops.

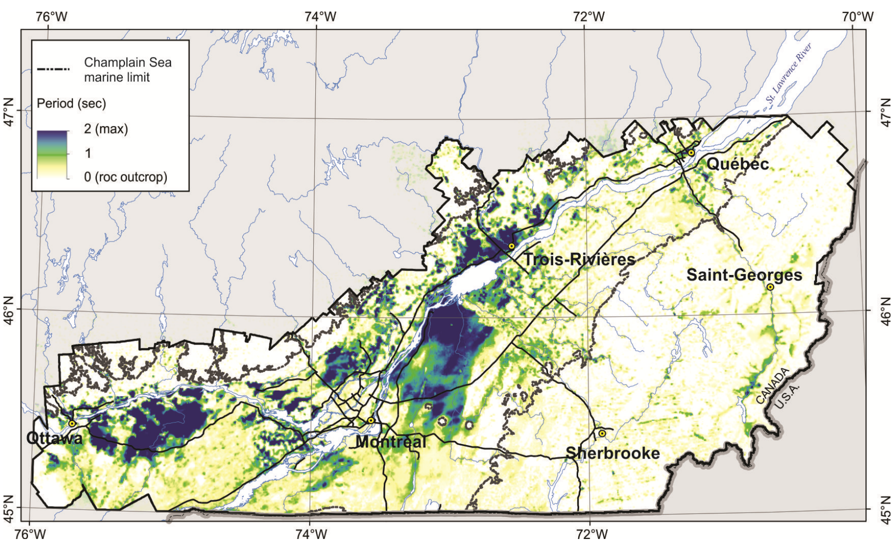

Fig. 6. Fundamental period of vibration T_O (sec) of the soil profiles down to the bedrock.

Several features can be observed on the final V_S map (Figure 5): (i) V_S spatial distribution follows the similar variation pattern of the surficial units (Figure 2) and their thickness. Lower V_S estimates, <200 m/s, coincide almost exclusively with the extent of the Champlain Sea sediments, where the probably most seismically sensitive zones are delineated with the extent of the deep sedimentary basins just east of Ottawa and southwest of Trois-Rivières. Most of the major urban centers in the study area overlap at least partially these low V_S zones.; (ii) the narrow valleys in the Grenville Province filled with soft sediments also exhibit low V_S velocity values; (iii) glacial deposits exposed mainly south of the St. Lawrence River close to the American border are characterized with intermediate V_S values; and (iv) outcropping bedrock units to the north and southeast are clearly indicated with contrasting high V_S.

The spatial distribution of T_O, which corresponds to the elastic period of vibration of the soil deposit at low strains, and is usually measured in field as the ratio of the horizontal to the vertical vibration, is given in Figure 6. Most significant amplification of the earthquake motion can be expected in frequencies close to T_O, which when coincident with the predominant frequencies of the earthquake motion can exhibit resonance. Deep sedimentary basins, which exhibit longest periods of vibration close to 2 sec, will be sensitive to distant strong earthquakes which tend to have their high frequency content filtered out (e.g., Charlevoix-Kamouraska seismic zone), whereas areas with shorter period, T_O<0.3 sec, will amplify predominantly closer earthquakes with higher frequency content. During intensive ground shaking non-linear stress-strains dominate the soil response and contribute to an increase of the period of vibration. This gradual shift can be beneficial for mid-rise and tall structures characterized with longer vibration periods coincident usually with the decaying part of the response spectrum. For stiffer low-rise well anchored structures with shorter period of vibration (≤0.1 sec), on the other hand, the non-linear period shift may actually signify increase of the seismic forces. It is therefore desirable to consider T_O when developing a design strategy for new structures and for retrofit of existing structures.

6 CONCLUSION

Shear wave velocities V_S and fundamental periods of vibration T_O are important parameters for prediction of the intensity and predominant frequencies of the ground shaking. A standardized method for V_S mapping was applied in Ottawa and St. Lawrence Valleys using available geophysical measurements compounded with correlations with surficial geology and a simplified 3D geologic model. Surficial units with similar physical properties were grouped together as surficial sand, intermediate clay, and basal glacial deposits. Statistical distributions of the available measurements showed relatively distinct V_S ranges for the sand and clay units and permitted the development of separate V_S-depth functions: $V_S=103.1+31.1depth^{0.5}$ m/s for sand, and $V_S=114.5+1.35depth$ m/s for clay. Respective T_O was obtained with the quarter-wavelength relation. Regional V_S dependencies were observed in these postglacial sediments which need further attention. Glacial deposits were assigned unique statistical mean V_S=385 m/s. The spatial distribution of the V_S was generated with a resolution of 500 m. Regardless of the shear size of the study area and the uneven coverage with field measurements, the developed preliminary V_S and T_O maps represent a credible first approximation for consideration of site conditions in seismic hazard and consecutive seismic risk assessments at regional scale.

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