Soil Dynamics and Earthquake Engineering 85 (2016) 103–116

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Geospatial modelling of shear-wave velocity and fundamental site period of Quaternary marine and glacial sediments in the Ottawa and St. Lawrence Valleys, Canada

Miroslav Nastev [a,*], Michel Parent [a], Martin Ross [b], Danielle Howlett [b], Nicolas Benoit [a]

[a] Geological Survey of Canada, Natural Resources Canada, 490 rue de la Couronne, Quebec, Quebec, Canada G1K 9A9
[b] Department of Earth Sciences, University of Waterloo, 200 University Avenue West, Waterloo, Ontario, Canada N2L 3G1

ARTICLE INFO

Article history:
Received 11 August 2015
Received in revised form
4 March 2016
Accepted 6 March 2016

Keywords:
Surficial sediments
Shear wave velocity
Fundamental site period
Geologic modelling

ABSTRACT

The shear wave velocity of surficial sediments (V_S) and the fundamental site period (T_O) are important parameters for analysis of the free-field seismic response. Their spatial distribution in the Ottawa and St. Lawrence Valleys, Canada, was determined applying a standardized method consisting of (i) updating the Quaternary geology; (ii) classifying the surficial units with similar physical properties into three broad categories: upper sandy sediments, intermediate clayey sediments and basal glacial and non-glacial deposits; (iii) delineating the spatial thickness of each category by way of 3D geologic modelling; (iv) sorting of available geophysical data with respect to each individual category and assigning representative V_S relationships: a power velocity-depth function for sand and clay units combined, $V_S = 119 + 8.1\ \mathrm{Depth}^{0.5}$ (m/s), and a constant interval V_S equal to the observed geometric mean velocity for glacial and non-glacial deposits, $V_S = 385$ (m/s). The respective T_O values were computed as the ratio between the soil thickness and the average V_S from ground surface to the bedrock. Validation of model results was conducted with V_S and T_O field data and available T_O estimates from detailed urban-scale seismic zonation studies. The analyses of the uncertainty originating from the variation of the V_S measurements showed that the standard deviations were roughly one-third of the modelled V_S and T_O values.

1. Introduction

Local geological conditions can significantly affect the amplitude and frequency content of incoming seismic waves. This may result in considerable short-distance spatial variations of the intensity of ground shaking and associated damage, e.g., [1]. Local site effects were enforced in the National Building Code of Canada [2], which aded the U.S. National Earthquake Hazard Reduction Program guidelines for seismic amplification factors [3] and modifications by Finn and Wightman [4]. Accordingly, the amplitude and frequency dependent site amplification is defined as a function of the travel-time weighted shear wave velocity of the top 30 m from the ground surface. Velocity dependent amplification is also commonly employed in modern ground motion prediction equations, e.g., [5].

The V_S concept, however, is not always well correlated to the observed amplification and is occasionally a poor proxy for the complex phenomenon of the seismic amplification [6–8]. It was developed based on site amplification studies carried out mainly in California where bedrock gradually transforms to regolith and then to soft surficial soils without any distinct interface [9]. Other local seismic parameters may contribute as well to local amplification including diffraction and generation of surface waves in heterogeneous near-surface formations at the edge of sedimentary basins, focusing effects at topographic irregularities, high impedance contrast between soft soils and underlying hard rock, energy trapping in deep sediment-filled valleys, etc. [10–13].

The fundamental site period represents another important site-specific parameter. It is proportional to the ratio between the thickness of the soil column and the average V_S [14]. Resonance amplification at levels greater than the broadband amplification occurs at T_O and often at subsequent harmonics. Thicker soil deposits with longer vibration periods will generally be sensitive to distant strong earthquakes with dominant low frequency content, whereas areas with shorter period will typically amplify energy content at higher frequencies characteristic for closer

* Corresponding author.
E-mail address: miroslav.nastev@rncan-nrcan.gc.ca (M. Nastev).

http://dx.doi.org/10.1016/j.soildyn.2016.03.006
0267-7261/

earthquakes. There is an ongoing research to explicitly consider T_O in the computation of the potential amplification [8,15].

Notwithstanding the reported limitations of the above method, quantifying the potential for site amplification applying the V_S concept is widely used. In 2006, the Geological Survey of Canada in partnership with Carleton University began a five-year pilot project in the Ottawa-Gatineau region [12,16,17]. Additional seismic zonation studies were recently completed in Eastern Canada on the Montreal Island [18] and in Quebec City [19]. These urban-scale studies relied on a dense grid of field V_S and T_O measurements to delineate low velocity zones and create maps of the expected variation in seismic shaking, e.g., [20]. For regional seismic zonation studies, however, it is not feasible to rely on sufficiently dense field measurements. Instead, geological and geomorphological information is used as a proxy for V_S [21–26].

Strong earthquake events in the St. Lawrence valley, characterized with relatively high stress drops and low anelastic attenuation, typical for the stable continental interior of Eastern North America [5], combined with the significant presence of soft soil sediments, can cause destruction far from the epicentral zone. For example, the 1663 M7 Charlevoix earthquake, Quebec, triggered large landslides along the St. Lawrence River and caused chimney damage in Boston at a distance of ~600 km [27]. Recently, Natural Resources Canada has partnered with federal and provincial/territorial departments, municipalities and academia with the objective to assess the likely consequences of strong earthquakes in the Ottawa and St. Lawrence Valleys [28]. One of the specific objectives of this comprehensive project was to provide a robust method for evaluation of regional scale seismic site conditions, rather than a detailed characterisation of V_S and T_O of surficial soils. In the absence of extensive field measurements, it was decided to use surficial geology and a simplified 3D geological model down to the bedrock as spatially continuous ancillary data.

This paper describes the procedure applied for V_S and T_O mapping consisting of (i) updating of the existing geological maps; (ii) arranging of the various units with similar origins and physical properties into broad categories within a simplified stratigraphic column (from the surface): upper sandy sediments, intermediate clayey sediments, basal glacial and non-glacial sediments; (iii) delineating the spatial thickness of each group by way of 3D geological modelling; and (iv) sorting available geophysical data with respect to each group and assigning representative V_S relationships. The validation of the modelled V_S and T_O with field data and with credible T_O estimates from the detailed microzonation studies is discussed at the end.

2. Geological settings

The study area is located in eastern Canada and extends from the Ottawa-Gatineau and Cornwall regions towards Montreal and then along the St. Lawrence River to Québec City (Fig. 1). This area covers approximately 72,000 km^2 and is bounded by the Laurentian Highlands to the North and the US border to the South and East. A number of large urban centers are founded, at least partially, by soft postglacial sediments with low V_S including Montréal, Ottawa-Gatineau, Québec City, and Trois-Rivières.

2.1. Bedrock geology

Three geological provinces are encompassed in the study area: the Precambrian Grenville Province, the St. Lawrence Platform, and the Appalachian Orogen to the south (Fig. 1). The Grenville Province is the youngest part of the Canadian Shield and represents the basement unit for most of the region though it outcrops mainly to the North in the Laurentian Highlands. It consists mainly of very stiff high-grade metamorphic and intrusive rocks. A time gap 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 a more than 1000 m thick succession of Upper Cambrian-Ordovician sandstones and carbonates [31]. This sequence was later intruded by alkaline magmatic bodies during the late Mesozoic and these now form a series of prominent hills, known as the Monteregian Hills, that resisted Cenozoic erosion. The sedimentary rocks of the St. Lawrence Platform overlie the uneven surface of 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 thrusted sheets of Appalachian rocks constitute the Lower Paleozoic Dunnage Zone and the Middle Paleozoic Gaspé belt units as well [32]. These deformed low-grade metamorphic rocks mainly consist of clastic sedimentary rocks with minor intrusive rocks.

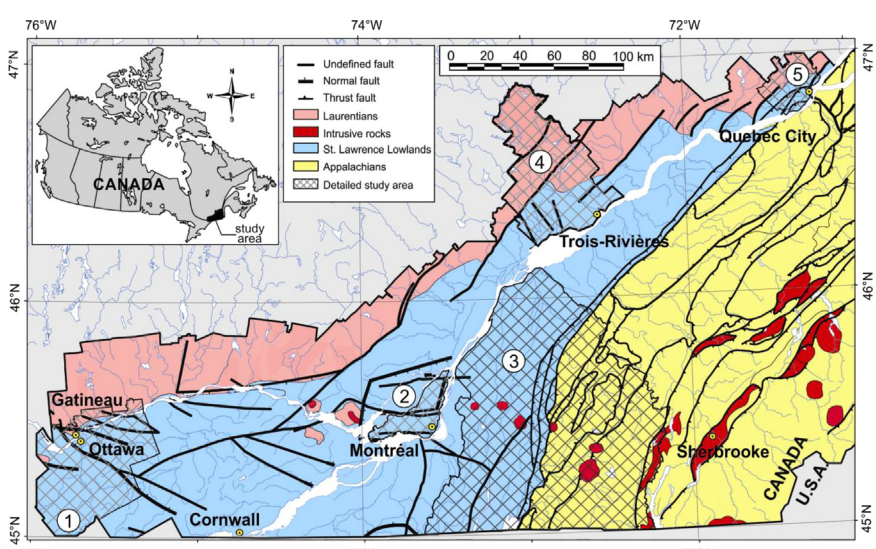

Fig. 1. Study area and simplified bedrock geology (modified from [29,30]). Detailed study areas discussed in the manuscript are (1) Ottawa-Gatineau, (2) Montreal Island, (3) Richelieu, (4) Mauricie, and (5) Quebec City.