Mapping Shear Wave Velocity Structure beneath the Fraser River Delta Sediments - Preliminary Results

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ABSTRACT

Shear wave velocities of thick unconsolidated sediments have been measured at 430 sites in the Fraser River delta using several different geophysical techniques. Large velocity gradients and velocity discontinuities have been mapped within the Quaternary overburden and at the overburden-bedrock interface. Total thickness of Quaternary sediments exceeds 1000 m in some locations with an average value of 500 m. Within the overburden, the Holocene-Pleistocene age boundary represents a significant shear wave velocity discontinuity. This buried boundary has been mapped at depths between 20 and 305 m below surface. Such lateral changes in shear wave velocity-depth structure should perhaps be considered in earthquake ground motion amplification modeling.

INTRODUCTION

The Fraser River delta (Fig. 1) is currently experiencing one of the most rapid urban growth rates in the lower mainland of British Columbia; the developing industrial infrastructure is one of national importance. The delta is also situated within a high earthquake hazard zone (Rogers, 1994) with thick unconsolidated Quaternary-age sediments overlying bedrock. The construction of large earthquake-resistant structures requires additional geotechnical considerations, which includes the effects of seismic amplification and/or damping due to seismic velocity gradients and impedance contrasts at major geological boundaries.

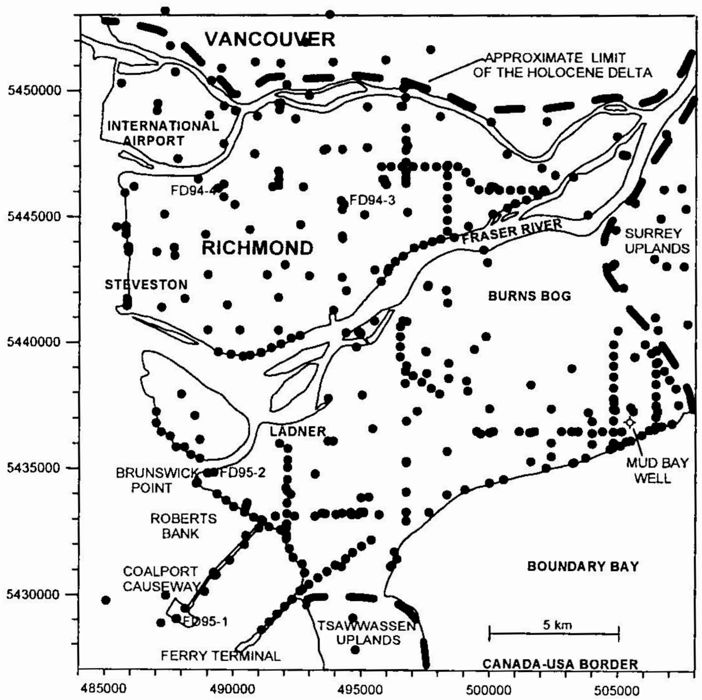

Figure 1. Location of shear wave seismic data sites in the Fraser River delta.

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For the last decade, the Geological Survey of Canada (GSC) has conducted surveys in the Fraser delta area directed towards development and testing of surface and down-hole geological, geophysical and geotechnical techniques. Vertical variations of shear wave velocities within the sediments, as well the presence of significant shear wave seismic impedance boundaries, are perhaps some of the most important geophysical parameters that must be known in order to successfully apply 1-D computer model techniques for surface ground motion response to earthquake shaking (Harris et al., 1995). Such modeling methodologies are being applied in most thick soil earthquake-prone areas in Canada. As our testing program in the delta progressed, it became apparent that sufficient data had been acquired to permit preliminary regional mapping of significant geological structure within the unconsolidated overburden, and to assign ranges of shear wave velocities to geological units for potential use by future modelers of earthquake ground motion response.

Shear wave velocity measurements of soils have been made using terrestrial and marine shear wave refraction methods, spectral analysis of surface waves (SASW), seismic cone penetrometer, and down-hole seismic methods in cased boreholes. Approximately 250 such sites have been occupied in the delta providing regional near-surface shear wave velocity-depth information. In addition, conventional reflection seismic records obtained from the oil and gas exploration industry have been processed at 180 regional sites to obtain estimates of shear wave velocities for deeper sections of the unconsolidated sediment column as well as within bedrock beneath the delta. A detailed description of the methodologies developed and used are given by Hunter et al. (1998a) and Christian et al. (1994).

For earthquake response modeling purposes we have divided the subsurface geology of the Fraser River delta into 3 major units having distinctly different geophysical characteristics, as given below:

UNIT	GEOLOGICAL AGE	DEPTH TO TOP (m).	RANGE of Vs (m/s)
Deltaic Sediments (sand, silt, clay)	Holocene	On Surface	90-500
Glacial Sediments (sand, gravel, diamicton)	Pleistocene	0-305	400-1200
Bedrock (sandstone, shale, coal)	Tertiary	200-1050	1000-2500

HOLOCENE DELTAIC SEDIMENTS

Silt and sand units which form the Holocene delta exhibit shear wave velocity-depth functions which are relatively uniform throughout the delta, as shown in Figure 2. This figure is a compilation of data from all surface refraction, borehole and seismic cone penetrometer measurements at sites shown in Figure 1. The form of the empirical curve fitted to the data is consistant with established sediment loading models of granular materials. The curve shows relatively little scatter, despite the wide areal extent of measurement sites in the delta. At locations where subsurface geological materials are known (from geological sampling in conjunction with seismic measurements) it has been found that shear wave velocities are relatively insensitive to changes in material types; hence effective stress loading is the dominant effect. Some deviations from the curve do occur at a few sites, such as in the presence of thick peat (Burns Bog area) as well as in young loose sediments (near Steveston), where somewhat lower near-surface shear wave velocities have been measured.

PLEISTOCENE GLACIAL SEDIMENTS

In the GSC data base the Holocene-Pleistocene boundary is the least well-defined to date, yet such measurements are perhaps the most important since the occurrence of this boundary at shallow depth may result in earthquake-induced ground resonance effects in the same natural period range as major structures. Where this boundary has been identified within boreholes in the Fraser delta, it is always associated with a large shear wave velocity contrast within a few meters or so vertically from the geological-age boundary. Sediment age and subglacial compaction are thought to be the main reasons for higher shear wave velocities of the Pleistocene materials.

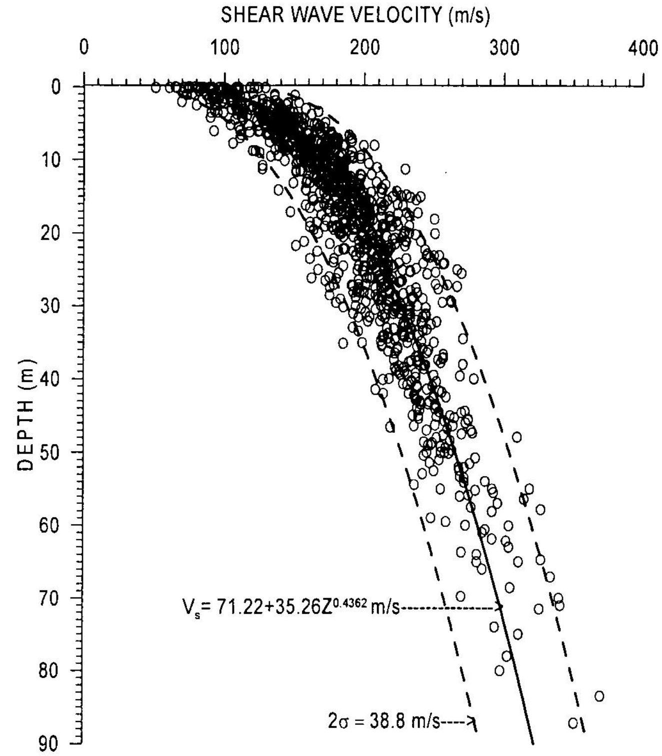

Figure 2. *Compiled shear wave velocities vs depth for Holocene deltaic sediments, Fraser River delta. Every fifth point is plotted for clarity.*

A map showing the depth below surface of the Pleistocene surface defined from available borehole cone penetration, and surface shear wave refraction data is shown in Figure 3. Topographic trends on this surface are predominantly NW-SE with a secondary NE-SW trend. Topographic highs on this buried surface have been found in central areas of the delta as well as at the edges. On the west side of the city of Richmond, the depth to the Holocene-Pleistocene boundary (and the associated shear wave velocity discontinuity) is >100 m, whereas in the eastern parts of the city the boundary has been found to range from 20 to 100 m.

In southern portions of the delta, the Holocene-Pleistocene boundary is > 100 m in depth in many areas (e.g. the village of Ladner). In contrast however, the Tsawwassen uplands is a Pleistocene sediment outcrop, and the extension of this, in the form of a ridge buried beneath the deltaic sediments, can be traced in a NW direction through the Roberts Bank area at least as far as Brunswick Pt at mid delta. Depth measurements to the top of this buried ridge are in the order of 33 to 52 meters and from a modeling point of view, this linear trend may in part form a seaward edge or boundary to a NW trending trough-shaped Pleistocene surface in the south-western delta. Since the last glaciation this trough has been in-filled by deltaic sediments as the Fraser River delta grew seaward.

A major low in the Pleistocene unconformity has been interpreted to represent a cross-cutting buried channel trending SW across Roberts Bank in the vicinity of the coalport causeway. This supports the view that the Fraser River was diverted northward in the mid Holocene and that this in-filled channel may represent a breaching of the Pleistocene ridge that previously deflected flow southward into Boundary Bay. It is noteworthy that the Fraser River presently occupies almost the same path as the buried paleochannel as far west as eastern Richmond. Raised peat bogs overlie Pleistocene highs in eastern Delta and the eastern end of Lulu Island.

Figure 4 shows shear wave velocity-depth-contrast examples from GSC boreholes with differing depths of burial and seismic impedances. Further examples can be found in Hunter et al. (1998b).

TERTIARY BEDROCK

A rudimentary depth map for the bedrock surface developed by Britton et al. (1995) from seismic and drilling data is shown in Figure 5. A bedrock topographic low in the depth range of 600-1000 m strikes northwesterly projected extension beneath the western side of the city of Richmond. On either side of this low, the bedrock depths are in the range of 200-400 m. The average depth to bedrock in the delta is in the order of 500 m.

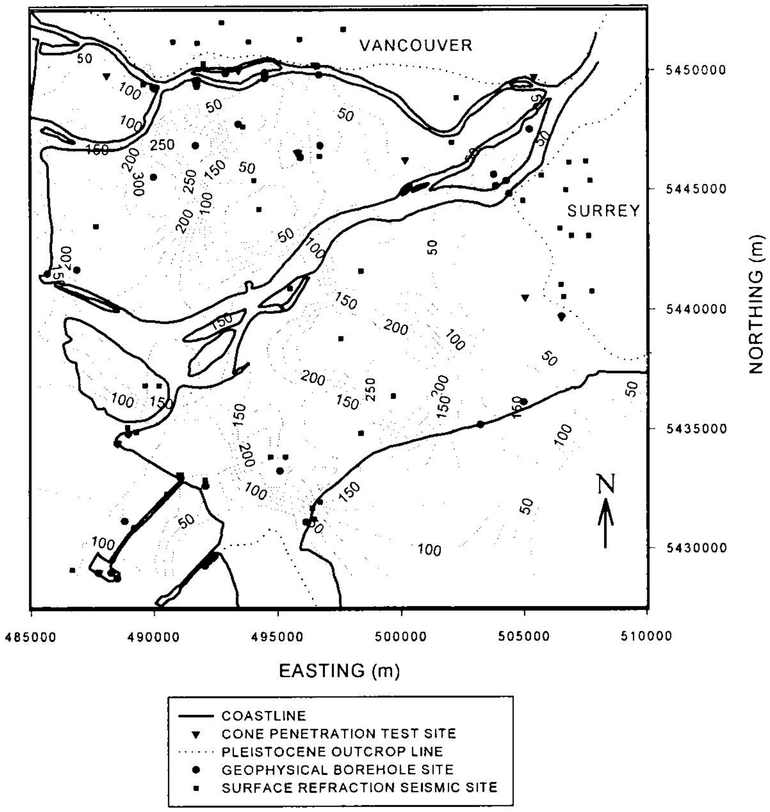

Figure 3. *Computer-generated map of estimated depth below surface to the Holocene-Pleistocene shear wave velocity boundary based on available data.*

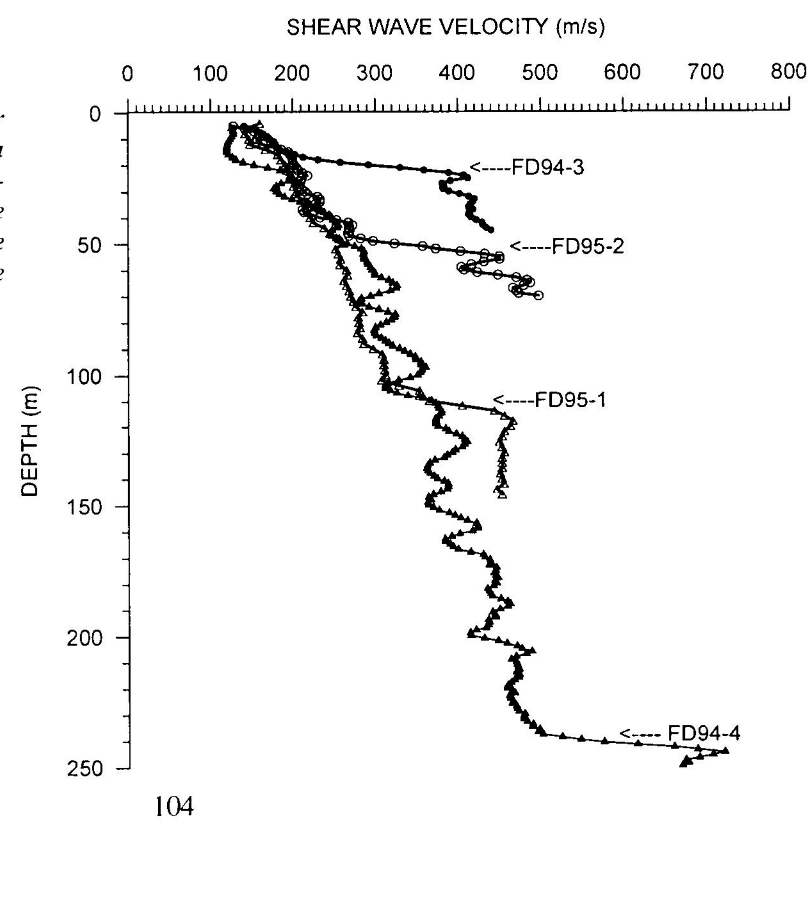

Figure 4. *Some examples of downhole shear wave velocity measurements in Fraser delta boreholes encountering the Holocene-Pleistocene boundary. Arrows indicate the abrupt velocity contrasts associated with the boundary. See Figure 1 for borehole locations.*

Shear wave velocity contrasts at the Pleistocene-Tertiary boundary can only be estimated since no direct measurements have yet been made in a borehole. From seismic reflection velocity analyses, shear wave velocity contrasts appear to be relatively large. Perhaps some credence to these estimates is given by Hunter et al. (1998b) where shear wave velocities have been derived from the P wave sonic log measurements in the Mud Bay well (see Fig.1 for location). The shear wave velocity-depth log from this well given in Figure 6 indicates strong velocity contrasts at both the Holocene-Pleistocene and Pleistocene-Tertiary bedrock boundaries.

IMPLICATIONS OF THE FRASER RIVER DELTA SHEAR WAVE VELOCITY MODEL

Small strain 1-D ground motion models indicate significant amplification due to the velocity gradient between near surface sediments and bedrock at depth, for vertically incident earthquake waves beneath the delta. In addition, both the Holocene-Pleistocene and the Pleistocene-Tertiary subsurface boundaries are associated with marked shear wave velocity discontinuities on the order of 2:1 suggesting the possibility of additional resonance effects. Of the two, the Holocene-Pleistocene boundary is perhaps the most significant for potential resonance effects within the natural periods of large structures wherever it occurs within 100 meters of ground surface; more definition of this buried boundary is required so that there is reasonable assurance that all anomalous shapes are adequately defined. This may require development and application of new lower cost geophysical technologies.

The Fraser River delta Quaternary sediment structural model is not a simple bowl-shaped one. Topographic highs on the Pleistocene surface with associated high shear wave velocity contrasts have been delineated in the middle portion of the delta; shallow depths to this surface are not necessarily confined to the delta edges. There are NW-SE trending bounded topographic lows in both the Pleistocene and Tertiary buried surfaces with associated substantial lateral changes in shear wave velocity-depth structure. Should these be considered in geotechnical site assessment for earthquake-resistant construction in the Fraser River delta or is the scale of these lateral changes such that 1-D models are adequate? Perhaps it is time to initiate investigations of ground motion response models for the Fraser River delta which address the 3-dimensional variability of the shear wave velocity structure.

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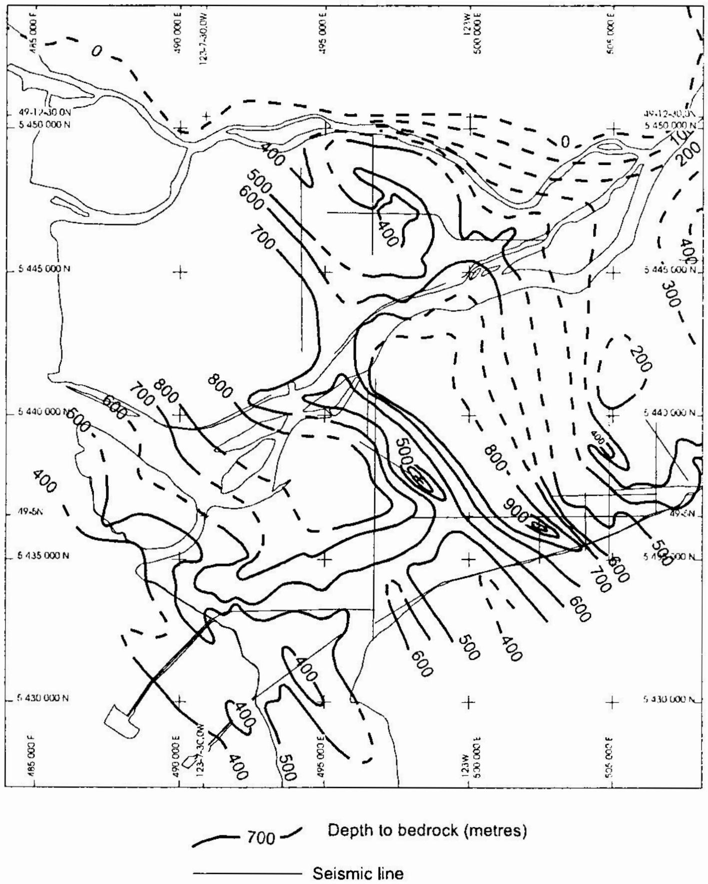

Figure 5. Depth below surface to Tertiary bedrock after Britton et al. (1995), based on seismic reflection measurements.

Figure 6. Derived shear wave velocity log for the Conoco-Dynamic Mud Bay well. See Figure 1 for location.