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EARTHQUAKE HAZARD ASSESSMENT IN GREATER VICTORIA, BRITISH COLUMBIA: DEVELOPMENT OF A SHEAR-WAVE VELOCITY MODEL FOR THE QUATERNARY DEPOSITS

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ABSTRACT

In order to assess the earthquake ground-motion amplification hazard in Greater Victoria, a field testing program was conducted in the spring of 1996 to obtain shear-wave velocity data in the principal Quaternary geologic units. Twelve seismic cone penetration tests (SCPTs) were conducted to depths ranging from 4 to 41 metres and four tests using the spectral analysis of surface waves (SASW) technique were conducted where the soils are too dense for cone penetration. Based on these data, a shear-wave velocity model was developed that will provide the basis both for estimating ground-motion amplification locally and mapping the amplification hazard regionally. Shear-wave velocities in the grey clay facies of the late glacial glaciomarine Victoria Clay are generally between 100 and 160 m/sec. These deposits occur in low lying areas, where they are commonly greater than 10 metres thick. Where these deposits are present, high amplification of ground-motion could occur during an earthquake, particularly where they are overlain by Holocene organic clay and peat. The fundamental site periods for sites underlain by grey clay range from 0.27 to 1 second, so that resonance will occur at ground motion periods less than 1 second at most sites. Generally, shear-wave velocities in the dessicated brown clay facies of the Victoria Clay are between 160 and 270 m/sec. These deposits are generally less than 6 metres thick, so that site effects will be primarily controlled by the underlying materials. In the sands and gravels of the late glacial Colwood delta, shear-wave velocities are generally between 280 and 390 m/sec, and where these deposits are sufficiently thick, moderate ground-motion amplification could occur. In the till of the Late Winsonsinan Fraser Glaciation and older Pleistocene deposits shear-wave velocities are generally between 400 and 600 m/sec and sites underlain by these deposits have low susceptibility to ground-motion amplification.

INTRODUCTION

Greater Victoria, on the southern tip of Vancouver Island, is located in one of the most seismically active regions of Canada. Vancouver Island has experienced two large historic earthquakes, in 1918 (M=7.0) and 1946 (M=7.3). The latter was the most damaging in western Canada and caused minor damage in the Victoria area (Hodgson, 1946; Wuorinen, 1974, 1976; Rogers, 1994). In addition, there is the potential for a very large (M~9) earthquake on the Cascadia subduction zone west of Vancouver Island (Rogers, 1988, 1994).

Because the effects of earthquakes vary considerably due to variations in local ground conditions, the British Columbia Geological Survey is preparing an earthquake hazard map of the area. The principal earthquake hazard here is the amplification of ground-motion that can occur at sites underlain by thick deposits of soft sediments.

Shear-wave velocity (Vs) data for unlithified deposits overlying bedrock are critical to the assessment of the ground-motion amplification hazard. For example, the National Earthquake Hazard Reduction Program (NEHRP) site classes for susceptibility to ground-motion amplification in the United States are defined primarily in terms of Vs (Table 1, Finn, 1996). In order to assess this hazard in the Greater Victoria area, a program was conducted to determine shear wave velocities in the principal Quaternary geologic units in the spring of 1996 (Figure 1). The objective of this paper is to present a Vs model of the Quaternary geologic units of the Victoria area based on this testing program.

An earthquake hazard map of the City of Victoria was prepared by Wuorinen (1974, 1976). His assessment was based on the distribution of the Quaternary deposits using a large volume of geotechnical testholes and also on the accounts of eyewitnesses to the 1946 Vancouver Island earthquake. Damage in Victoria was concentrated in low lying areas that are underlain by thick deposits of soft clay and organic soils, and the effects of the earthquake were the least where bedrock is close to the surface. The objectives of the current earthquake hazard mapping program are to extend the mapping throughout the Greater Victoria urban area and to assess the earthquake hazard in ways that were unavailable to Wuorinen, in particular by the application of shear-wave velocity data.

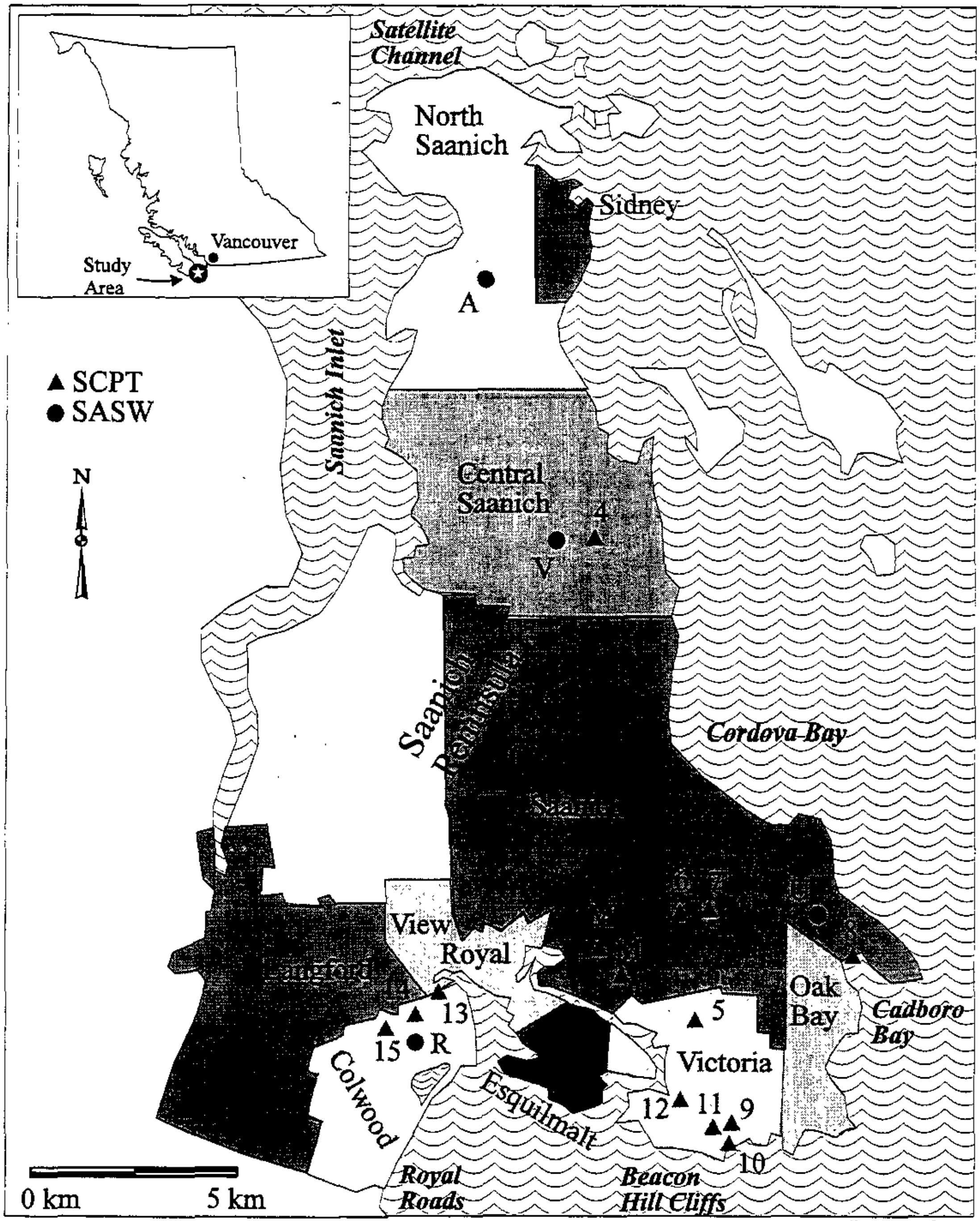

Figure 1. Map of the Greater Victoria area showing the location of the shear-wave test sites. The SCPT sites are numbered, see Table 3 for details. M indicates SCPTs provided by the Ministry of Transportation and Highways. The SASW sites are lettered: Site A is at Victoria Airport; V is on Veyaness Avenue; U is at the University of Victoria; and R is at Royal Roads University.

SITE AMPLIFICATION

The NEHRP site classes for amplification are defined primarily on the basis of the average shear-wave velocity in the upper 30 metres (V_{s30}), and are summarized in Table 1 (Finn, 1996; see that paper for complete descriptions). They range from "hard rock" and "rock" (Classes A and B respectively), in which V_{s30} exceeds 760 m/sec and which have no to very low susceptibility to amplification, to "soft soil" (Class E), in which V_{s30} is less than 180 m/sec and which has a high susceptibility to amplification. Site Class E also includes sites underlain by more than 3 metres of soft clay or silt, which is defined as having a plasticity index greater than 20%, a water content greater than 40% and an undrained shear strength less than 25 kPa. In terms of shear-wave velocity, soft clay has been defined as having a shear-wave velocity less than 150 m/sec (Seed *et al.*, 1992). A specific objective of the shear-wave testing program was to determine if the sites in Victoria that had experienced the strongest ground shaking during the 1946 earthquake meet the criteria for Class E.

TABLE 1. SITE CLASSES FOR SOIL SUSCEPTIBILITY TO AMPLIFICATION (SIMPLIFIED FROM FINN, 1993 AND 1996; KLOHN-CRIPPEN 1994; FOR FULL DESCRIPTIONS REFER TO FINN, 1996).

Site Class	General Description	average shear-wave velocity in upper 30 m (Vs30), m/sec	Susceptibility Rating
A	Hard rock	>1500	Nil
B	Rock	760 - 1500	Very Low
C	Very dense soil and soft rock	360 - 760	Low
D	Stiff soils	180 - 360	Moderate
E	Soft soils, or soil profile with >3 m soft silt and clay	< 180	High

The amount of ground-motion amplification varies with the intensity of ground-motion (Table 2). Where accelerations of 0.1 g occur on bedrock, accelerations on Class E sites can be amplified 2.5 times. Such was the case in the San Francisco Bay area during the 1989 Loma Prieta earthquake, which was nearly 100 km north of the epicentre. Accelerations there on bedrock sites were generally less than 0.1 g, whereas on nearby soft soil sites accelerations were amplified to 0.25 g and greater (Clough *et al.*, 1994). However, at higher accelerations, amplification factors diminish, such that at bedrock accelerations of 0.4 g there is generally little or no amplification on soft soil sites, because of the non linear behaviour of soils.

TABLE 2. AMPLIFICATION FACTORS (FINN, 1996)

Site Class	Peak surface horizontal firm ground acceleration				
	0.1 g	0.2 g	0.3 g	0.4 g	0.5 g
A	0.8	0.8	0.8	0.8	0.8
B	1	1	1	[illegible]	1
C	1.2	1.2	1.1	1	1
D	1.6	1.4	1.2	1.1	1
E	2.5	1.7	1.2	0.9	

Furthermore, the amplification of specific periods of ground motion due to resonance in the soil can be much greater than shown in Table 2 and can be particularly damaging to structures whose natural periods match those of the site (Rial, 1992; Reiter, 1990). The fundamental period (T) of a site (Finn 1994) can theoretically be calculated by:

$$T = 4H/V \qquad 1)$$

where:

H = thickness of the soil layer
V = average shear-wave velocity of the soil layer

Equation 1 is applicable to low strain ground motion, because Vs is a low strain property of soil. Site periods are greater for larger amplitudes of ground motion. Nonetheless, equation 1 provides a reasonable order of magnitude estimate for the site period that would occur during an earthquake.

The natural period of a building can be estimated in an approximate way by multiplying the number of stories by 0.1 second.

THE QUATERNARY GEOLOGY OF THE VICTORIA AREA (FIGURE 2)

The Quaternary deposits of the Greater Victoria area overlie a very irregular glacially-scoured bedrock surface. The depth to bedrock can vary from near surface to over 30 metres within the space of a city block (Crawford and Sutherland, 1969; Wuorinen, 1974, 1976; Nasmith and Buck, in press). Bedrock consists of high grade metamorphics throughout much of the area, with metavolcanics and intrusive rocks in the central and northern parts of the Saanich Peninsula, sedimentary rocks at the northern tip of the Saanich Peninsula, and volcanics in the Colwood area (Muller, 1983; Massey *et al.*, 1994).

Pleistocene deposits underlying the Vashon Till of the Late Wisconsinan Fraser Glaciation occur in the central and eastern parts of the Saanich Peninsula, where they have commonly been sculpted into a series of north trending drumlinoid ridges. These deposits are best known from the sea cliffs on the east side of the

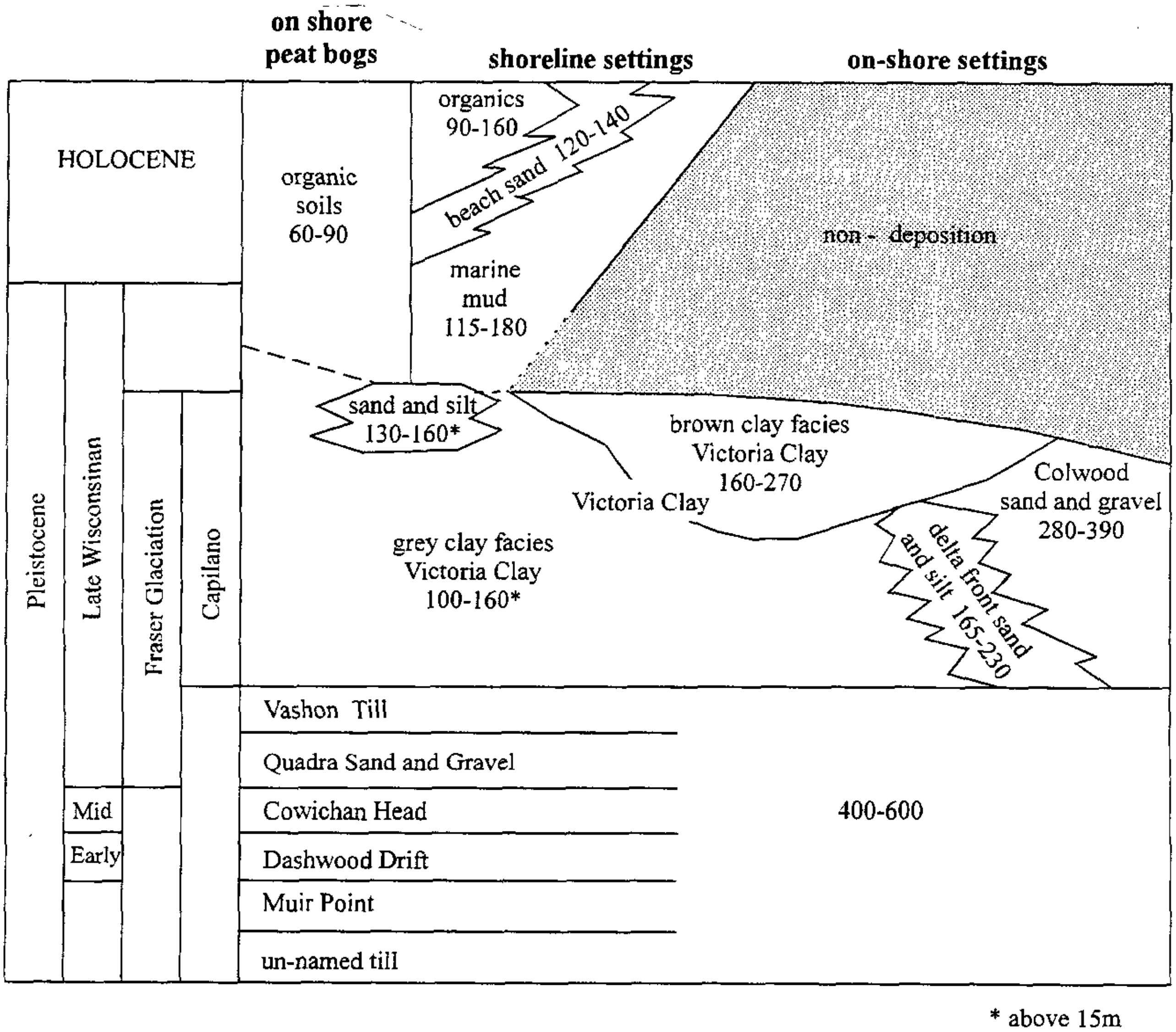

Figure 2. Table of Quaternary Formations in the Greater Victoria area showing general range of shear-wave velocities (approximately ± 1 standard deviation).

peninsula. The following units have been recognized, in ascending order: an undated till; interbedded sand and gravel of the non-glacial Pre-Wisconsinan Muir Point Formation; till and glaciomarine deposits assigned to the early Wisconsinan Dashwood Drift; sand, silt and gravel of the middle Wisconsinan non-glacial Cowichan Head Formation; and sand and gravel of the late Wisconsinan Quadra Formation, which has been interpreted as proglacial outwash from the advancing glaciers of the Fraser Glaciation (Clague, 1976, 1977; Alley, 1979; Howes and Nasmith, 1983; Hicock and Armstrong, 1983; and Nasmith, 1993, 1995; Bean and Buck, 1996; Nasmith and Buck, in press). The total thickness of these deposits locally exceeds 50 metres.

The Vashon Till of the late Wisconsinan Fraser Glaciation overlies the earlier Pleistocene deposits where they are present but overlies bedrock directly in much of the Greater Victoria area. It is a discontinuous unit, generally a few metres thick, but is locally up to 15 metres thick, as along the Beacon Hill sea cliffs (Hicock *et al.*, 1981; Nasmith and Buck, in press). In the following discussions, the Vashon Till and underlying Quaternary deposits are grouped together as "older Pleistocene deposits", because they have been glacially overriden, the shear-wave velocities are expected to be similar, and the internal stratigraphy of the package cannot be readily resolved with the techniques used here to obtain shear-wave velocities.

The Vashon Till is overlain by the Capilano Sediments, which were deposited at the close of the Fraser Glaciation when sea level was higher than present (Armstrong, 1981, 1984). Two principal units of the Capilano Sediments are represented in the Victoria area - the Victoria Clay and the Colwood Sand and Gravel. Shells in these units have provided several radiocarbon dates between 12,100 and 12,750 years B.P. (Dyck *et al.*, 1965, 1966). These deposits are equivalent to those of the Everson Interstade of Northwestern Washington (Easterbrook, 1992, Dethier et al., 1995).

The Victoria Clay is a unit of glaciomarine silt with scattered pebbles that forms a blanket-like deposit over the area below an elevation of 70 metres. It infills much

Figure 3. Drilling rig on site at SCPT 6, Saanich Public Works Yard. The data are recorded digitally in the truck to the right of the drilling rig.

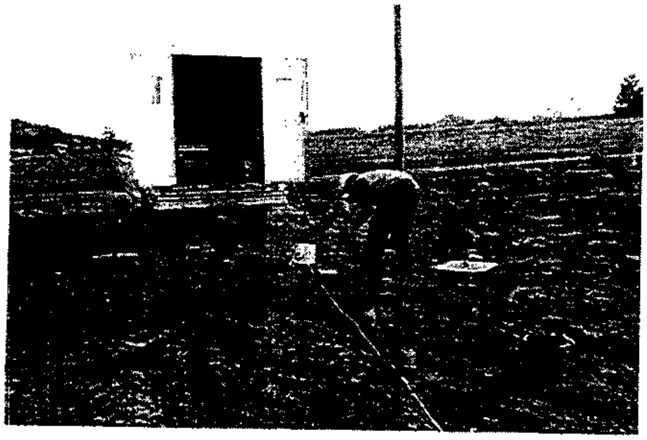

Figure 4. SASW test at site V, Veyaness Rd. Note the two geophones in the foreground beside the measuring tape that leads from the truck and the man striking a rubber plate with a sledge hammer.

of the pre-existing topography, and ranges in thickness from zero over bedrock knolls to over 30 metres in preexisting topographic depressions. The Victoria Clay has two distinct facies. A lower soft to firm grey clay infills low areas on the preexisting topographic surface and is called the grey clay facies in this paper. An upper desiccated and oxidized, stiff brown clay is up to 6 metres thick and is called the brown clay facies in this paper. The contact between the two facies is gradational. The two facies are distinguished on the basis of post depositional changes and they were not deposited in different depositional environments. The Victoria Clay commonly coarsens slightly upward, and is locally capped by sands that may represent shoreline and nearshore deposits formed as sea level fell following deglaciation (Crawford and Sutherland, 1971; Buchanan, 1993, 1995; Nasmith and Buck, in press).

The brown clay facies of Victoria Clay is at the surface in most of the Victoria area. However, in low lying areas, the Victoria Clay is commonly comprised entirely of the grey clay facies and is gradationally overlain by organic silts and peat up to 6 metres thick. The organic soils represent post glacial Pleistocene to Holocene lake and bog deposits and are referred to as Holocene organic soils in this paper (Dyck et al., 1966; Lowdon *et al.*, 1971; Nasmith and Buck, in press).

In shoreline settings, the brown clay facies extends below modern sea level, because sea level fell at least 10 metres below its modern position in the latest Pleistocene and earliest Holocene. In these settings, the brown clay facies is overlain by Holocene muds deposited during the mid to late Holocene rise in sea level (Mathews *et al.*, 1970; Crawford and Sutherland, 1971; Lowdon *et al.*, 1971; Hutchinson, 1992). Holocene muds are locally overlain by prograding shoreline sands derived from erosion of nearby sandy headlands and which are in turn locally overlain by peat. Shoreline peat deposits are locally overlain by intertidal sediments due to continued sea level rise during the Holocene as well as possible earthquake-related elevation changes (Clague, 1989; Clague and Bobrowsky, 1990; Bobrowsky and Clague, 1992; Mathewes and Clague, 1994).

The Colwood Sand and Gravel is a unit of outwash and deltaic sand and gravel deposited by a glacial outwash stream flowing south from Saanich Inlet. The surface of the outwash plain is at 75 metres elevation and has been incised by late stage channels that are partially infilled with peat (Blyth and Levson, 1993; Huntley, 1995; Yorath and Nasmith, 1995).

SHEAR-WAVE VELOCITY (VS) INVESTIGATIONS

Vs data for the principal Quaternary geological units were obtained by means of seismic cone penetration tests (SCPTs; Robertson et al, 1992) and spectral analysis of surface waves (SASW; Stokoe et al, 1994). The field work and data processing to generate the Vs profiles were conducted by ConeTec Investigations Ltd. of Vancouver.

A cone penetration test (CPT) is performed by pushing an instrumented cone-tipped rod into the ground at a constant rate using a modified drilling rig (Figure 3). A load cell at the tip records the resistance to penetration (tip resistance) and a friction sleeve above the tip records the frictional resistance of the sediment. A pore pressure element, usually located above the tip records the dynamic pore pressures during penetration. The parameters discussed in the following sections are the tip resistance, corrected for pore pressure effects (q_t), and the friction ratio (R_f), which is the ratio of the sleeve friction to q_t. In a SCPT, a geophone is added near the cone tip to record shear wave arrivals.

The SCPTs in this program were performed using a cone with a standard 10 cm^2 tip projection area, a 150 cm^2 friction sleeve, a pore pressure filter is located immediately behind the tip, and a geophone located 20 cm above the tip. The tip resistance, sleeve friction, and the dynamic pore pressure were recorded digitally every 5 cm. Shear waves were generated by using a sledge hammer to strike either a horizontal steel beam beneath the drill rig or an auger inserted into the ground. Shear wave arrivals were recorded every metre and interval

TABLE 3. SUMMARY OF SCPT DATA AND SITE PERIODS

SCPT	Location	Depth m	Vs average m/sec	Site period sec	Comments
4	Lochside Dr. at Island View Rd., Central Saanich	9.7	141	0.27	may overlie thick older Pleistocene; 5 m grey clay
5	Fifth St. at Vista Heights, Victoria	13.6	123	0.44	12 m grey clay
6	Public Works Yard, Saanich	29.8	141+	0.85+	no Vs recorded below 23.6 m; Vs average and site period minimum values; 24 m grey clay
7	Blenkinsop Rd. at McKenzie Ave., Saanich	4.05	136+	0.12+	refusal in rock fill ; Vs average and site period minimum values
8	Gyro Park, Saanich	41.8	166+	1.0+	Vs30=157 m/sec; did not reach refusal; Vs average and site period minimum values; 26+ m grey clay; Figure 8.
9	Brooke St. Park, Victoria	17.5	113	0.62	12 m grey clay; Figure 9.
10	Bushby St. Park, Victoria	16.35	124	0.54	14 m grey clay
11	Chapman-May Lane, Victoria	25.1	147	0.68	18 m grey clay; Figure 10.
12	Humboldt St., Victoria	13.45	175	0.31	4 m grey clay; Figure 11.
13	Old Island Highway, View Royal	6.45	262	0.1	Brown clay; Figure 12.
14	Wale Road, Colwood	12.55	199	0.25	Colwood delta front; Figure 7.
15	Aldeane Avenue, Colwood	9.15	313+	0.12+	did not encounter base of deposits; Vs average and site period minimum values; Colwood sand and gravel; Figure 6.
	Colquitz River Bridge 2655, Island Highway and Interurban Rd., Saanich	16.77	163	0.41	Data from MOTH; 10 m grey clay
	Colquitz River Bridge 2728, McKenzie Ave. and Interurban Rd., Saanich	15.15	176	0.34	Data from MOTH: 11 m grey clay

velocities calculated by subtraction of the arrival times between successive readings.

SCPTs were conducted at 12 sites (Figure 1, Table 3). They were pushed to refusal, indicating that either bedrock or dense soil such as till had been encountered, at all sites but one. In addition to those SCPTs conducted in this program, data from two SCPTs conducted by the Ministry of Transportation and Highways (MOTH) were used to develop the shear-wave velocity model.

SASW testing is a non-intrusive geophysical technique that uses the variation in the velocity of surface (Rayleigh) waves with depth to model the Vs profile of a site. The depth to which a surface wave penetrates is determined by its wavelength.

SASW tests were conducted at 4 sites, where the soils were considered to be too dense or too gravelly to be penetrated by a SCPT (Figure 1). Rayleigh waves were generated by hammer impacts on a metal or hard rubber plate, and were recorded by a pair of geophones spaced 1 to 10 metres apart and located up to 20 metres from the plate (Figure 4). The data were recorded digitally. In this program, the depth of investigation using the SASW method varied from 9 to 17 m.

At each site the lithology and the stratigraphy were interpreted on the basis of the SCPT data, the Vs profiles and data from nearby testholes. Average shear-wave velocities were then determined for each stratigraphic unit.

In uniform materials, V_S increases with increasing effective overburden stress (Robertson et al, 1991; Olsen, 1994) according the following expression:

$$V_{S1} = V_S\,(P_a/\sigma'_{vo})^v \qquad 2)$$

where:

V_{S1}= normalized shear-wave velocity
P_a = reference stress, normally atmospheric pressure
σ'_{vo}= effective vertical overburden stress, in the same units as P_a
v = shear-wave stress exponent

V_{S1} was calculated at atmospheric pressure, at a depth of approximately 10 metres. The shear-wave stress exponent, v, varies from approximately 0.5 to 0.1, decreasing with increasing grain size and degree of consolidation (Olsen, 1994). V_{S1} and v were calculated in the grey clay facies of the Victoria Clay , the sand and silt facies of the Victoria Clay, and the Holocene marine mud. Overburden stresses were estimated using an average unit weight of 17.5 to 18 kN/m^3, based on interpretations of the SCPT by ConeTec and using the CPT interpretation program CPTINT (Campanella, 1993).

At each SCPT site, the average shear-wave velocity was calculated and the fundamental site period was derived using this value in equation 1.

RESULTS

The location, average shear-wave velocity, fundamental site period and thickness of the grey clay facies at each SCPT site are summarized in Table 3. At 3 sites, the calculated average shear-wave velocity and site period are minimum values because the thickness of the soil column is unknown: at SCPT 8, where the cone was pushed to a depth of 41.8 metres without meeting refusal; at SCPT 7, where the cone met refusal at 4 metres within probable rock fill (C.N. Ryzuk, personal communication); and at SCPT 15, where the cone was pushed to refusal at a depth of 9.15 metres within a sequence of dense sands and gravels. The calculated average shear-wave velocity and site period are also probably minimum values at SCPT 6, where Vs was not recorded in the lower part of the section. The Vs characteristics (average, average ± 1 standard deviation, minimum, and maximum) for the various Quaternary geological units investigated are summarized in Table 4, shown on Fig 2, and described in more detail below.

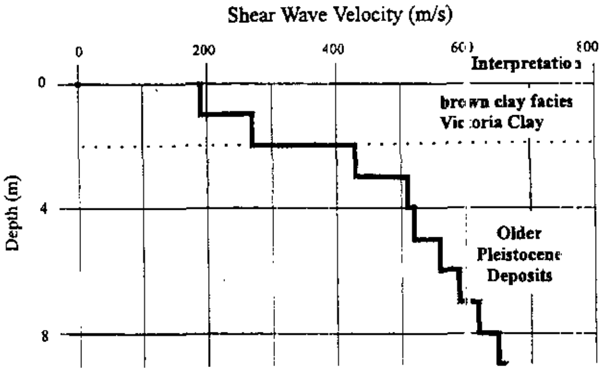

Figure 5. Shear-wave velocity profile at SASW site V, Veyaness Avenue, with stratigraphic interpretation. At this site older Pleistocene deposits are interpreted to underlie the brown clay facies of the Victoria Clay.

OLDER PLEISTOCENE DEPOSITS

Older Pleistocene deposits are inferred to be present at three SASW sites (Sites A, V and U, Figure 1) , where high velocity sediments occur beneath an abrupt Vs increase and are overlain by a thin low velocity surficial layer 2 to 4 metres thick (Figure 5). The latter is interpreted to be the brown clay facies of the Victoria Clay on the basis of Vs data. Vs in deposits interpreted to be the older Pleistocene deposits averages 500 m/sec and is generally between 420 to 580 m/sec. These values cover a considerable range, probably due to the variety of older Pleistocene units in the area, including glaciofluvial sands and gravels, till, and glaciomarine silts and clays.

CAPILANO DEPOSITS

DEPOSITS OF THE COLWOOD DELTA

Deposits of the Colwood Delta occur at three sites - at two sites on the level surface of the delta plain and at a

TABLE 4. V_S SUMMARY BY GEOLOGICAL UNIT

Stratigraphic unit	number of sites	number of values	Vs average m/sec	Vs av ± 1 SD m/sec	Vs min m/sec	Vs max m/sec
Artificial Fill	3	4	130	111-149	102	143
Holocene organic soils	3	9	85	52-113	40	164
Holocene beach Sand	1	4	131	122-140	120	140
Holocene marine mud	2	4	147	121-173	117	178
Victoria sand and silt	2	7	165	131-199	126	217
Victoria brown clay	8	28	213	164-262	121	298
Victoria grey clay	10	126	147	114-180	89	279
Victoria grey clay <15 m depth	9	69	132	104-160	89	214
Colwood delta top	2	15	335	282-388	225	475
Colwood delta front	1	10	199	165-233	133	237
Older Pleistocene	3	17	499	420-577	350	650

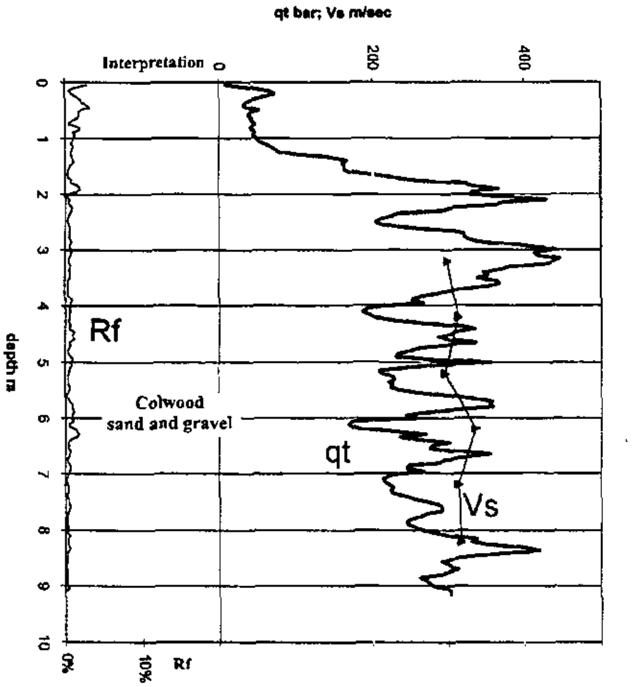

Figure 6. SCPT 15 Aldeane Avenue, Colwood, with stratigraphic interpretation. SCPT parameters: Vs= shear-wave velocity; qt=tip resistance; and Rf = friction ratio.

third on the north slope of the delta. Those on the delta plain include SCPT 15, where the deposits consist of 9 metres of dense sand and gravel (Figure 6), and SASW site R (Figure 1). There, Vs averages 335 m/sec and is generally 282 and 388 m/sec. At SCPT 14, on the north delta slope on Wale Road in Colwood, a section consisting of 4 metres of sandy silt overlain by 5 metres of sand is interpreted to be a delta front deposit (Figure 7). The sand is sharply overlain by 3 metres of silt and organics that includes the brown clay facies of the Victoria Clay as well as Holocene deposits. In the delta front deposits at this site, Vs averages 199 m/sec and is generally 165 and 233 m/sec).

GREY CLAY FACIES OF THE VICTORIA CLAY

Deposits of the grey clay facies occur at 10 sites, where they range from 4 metres to greater than 26 metres in thickness. These deposits are characterized by very low tip resistance, generally 5 bars or less at a depth of 5 metres and increasing linearly with depth in response to increasing effective overburden stress (Figures 8, 9, 10 and 11; see Robertson, 1990; Olsen, 1994). The deepest tip resistance measurements in this facies are greater than 18 bars at a depth of greater than 41 metres. The base of the grey clay facies is marked by refusal on the SCPTs, indicating the presence of older overconsolidated Pleistocene sediments or bedrock. The grey clay facies is gradationally overlain by either the brown clay facies of the Victoria Clay, which is characterized by higher tip resistance (Figure 11), or in low lying areas by Holocene organic silts and peats, which are characterized by higher friction ratio values (Figure 9). Locally, an interval of

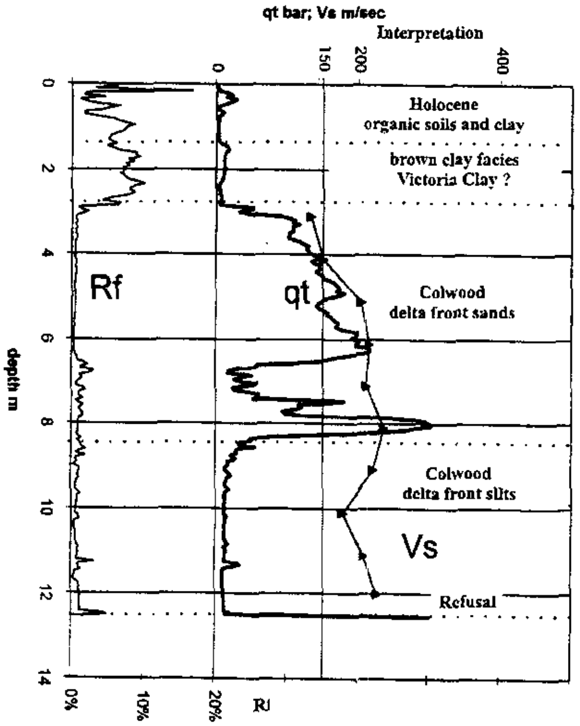

Figure 7. SCPT 14, Wale Road, Colwood, with stratigraphic interpretation. SCPT parameters: Vs= shear-wave velocity; qt=tip resistance; and Rf = friction ratio.

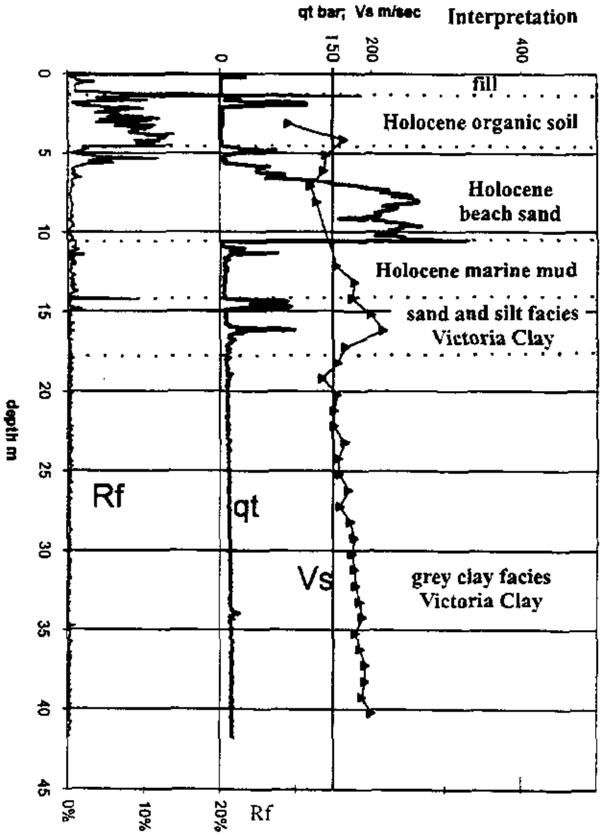

Figure 8. SCPT 8, Gyro Park, Saanich, with stratigraphic interpretation. SCPT parameters: Vs= shear-wave velocity; qt=tip resistance; and Rf = friction ratio.

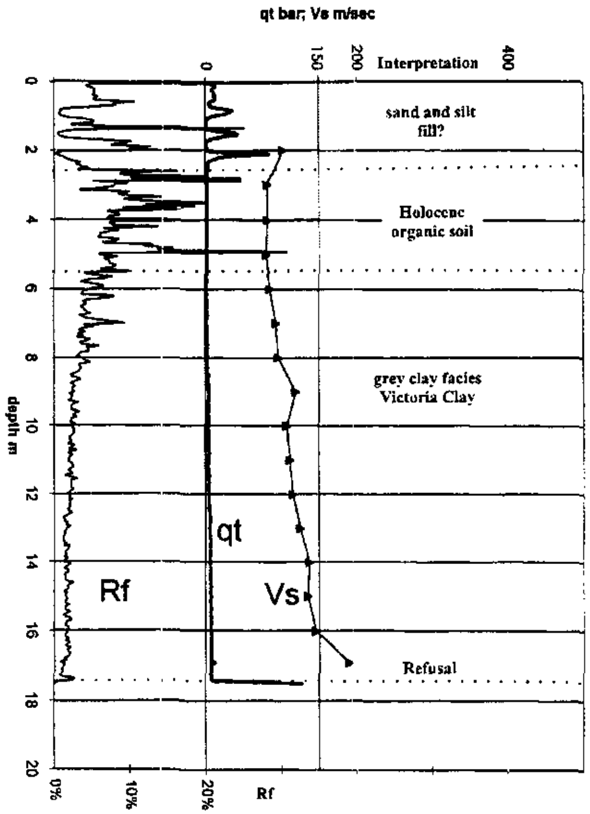

Figure 9. SCPT 9, Brooke Street Park, Victoria, with stratigraphic interpretation. SCPT parameters: Vs= shear-wave velocity; qt=tip resistance; and Rf = friction ratio. Note the low tip resistance and high friction ratios in the Holocene organic soils; the increase in Vs with depth in the grey clay facies; and the presence of sandy clay at the base of the grey clay indicated by slightly higher tip resistance and higher Vs.

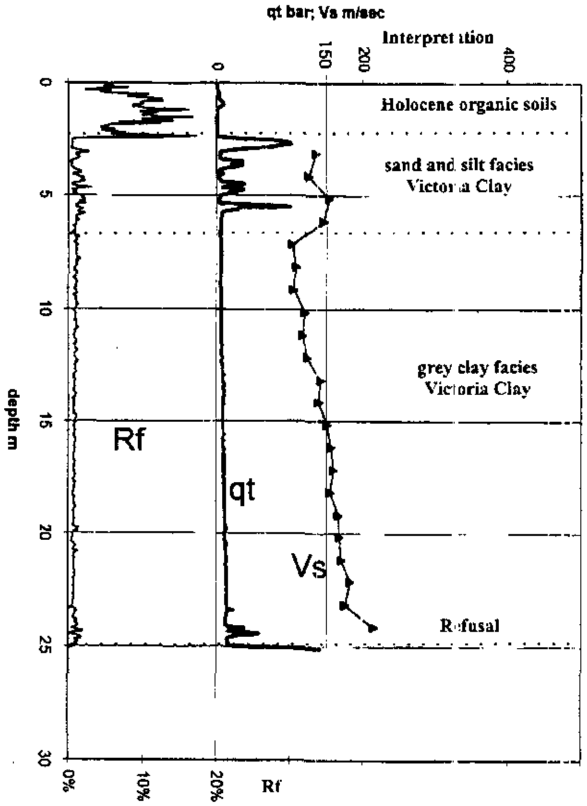

Figure 10. SCPT 10, Chapman-May Lane, Victoria, with stratigraphic interpretation. SCPT parameters: Vs= shear-wave velocity; qt=tip resistance; and Rf = friction ratio. Note the low tip resistance and high friction ratios in the Holocene organic soils; the increase in Vs with depth in the grey clay facies; and the presence of sandy clay at the base of the grey clay indicated by higher tip resistance and higher Vs.

interbedded sand and silt occurs at the top of the grey clay facies (Figures 8 and 10); this sand and silt unit is discussed separately below.

In the grey clay facies, Vs averages 147 m/sec and is generally between 114 and 180 m/sec. Above average Vs values occur near the contact with the overlying brown clay facies and in sandy intervals, which commonly occur near the base (Figures 9 and 10) and less commonly throughout the grey clay unit. Where the grey clay facies is thicker than 12 metres or where it is not overlain by the brown clay facies, Vs also increases with depth in response to increased overburden stress, so that at depths of over 40 metres Vs exceeds 200 m/sec (Fig 8,9 and 10). However, within 15 metres of the ground surface, where most deposits of the grey clay occur, Vs averages 132 m/sec and is generally between 104 and 160 m/sec. Interestingly, the increase of Vs with depth is not generally evident in sections of grey clay that are thinner than 12 metres and are overlain by the brown clay facies.

In order for future workers to predict Vs for grey clay in very thick sections beyond the depths investigated in this study, the normalized shear-wave velocity (V_{S1}; Vs at 1 atmosphere or ~10 metres) and the shear-wave stress exponent, v, were calculated from equation 2 at 4 sites where Vs increases with depth. At those sites, V_{S1} averages 127 m/sec (119 to 139 m/sec range), and v averages 0.52 (0.40 to 0.58 range).

BROWN CLAY FACIES OF THE VICTORIA CLAY

Deposits of the brown clay facies, 2 to 6 metres thick, occur at 5 SCPTs and 3 SASW sites. These deposits are distinguished from the underlying grey clay facies by higher tip resistance values, generally between 20 and 40 bars, and higher friction ratio values. Higher friction ratios in clays are indicative of overconsolidation (Robertson, 1990), which in this case is an apparent overconsolidation due to desiccation. In these deposits, Vs averages 213 m/sec and is generally between 160 and 270 m/sec. A typical expression is shown in Figure 12, where the deposits are 6 metres thick and overlie bedrock or till. This unit extends below sea level in shoreline settings. At SCPT 12 (Figure 11), for example, the brown clay facies gradationally overlies the grey clay facies and is in turn gradationally overlain by Holocene marine mud and fill for the Empress Hotel (Crawford and Sutherland, 1971). At this site, the elevated Vs resulting from early Holocene desiccation has survived resubmergence during the mid to late Holocene marine transgression. At the SASW sites, the brown clay facies was interpreted to be present in those intervals with Vs

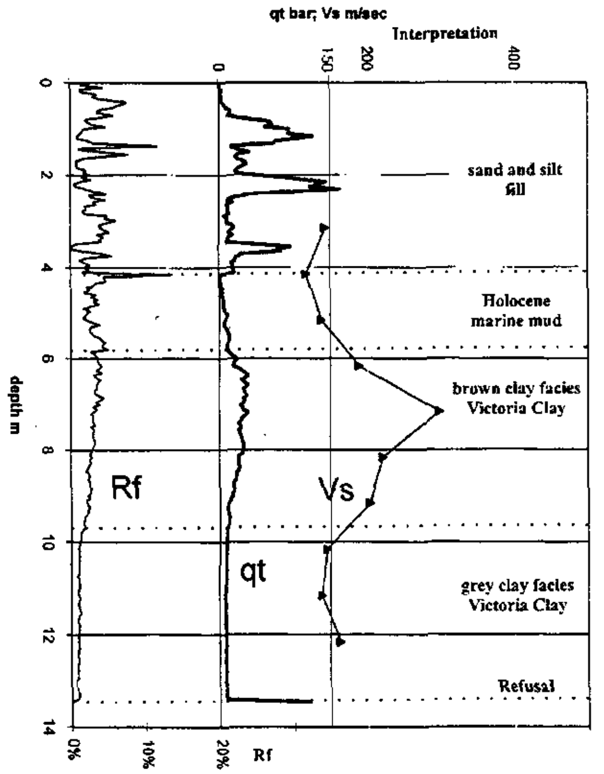

Figure 11. SCPT 12, Humboldt Street, Victoria, with stratigraphic interpretation. SCPT parameters: Vs= shear-wave velocity; qt=tip resistance; and Rf = friction ratio. Note the higher Vs, tip resistance, and friction ratio values in the brown clay facies than in the grey clay facies.

values similar to those in the brown clay facies in the SCPTs. Nearby boreholes support these interpretations.

SAND AND SILT FACIES OF THE VICTORIA CLAY

Interbedded sands and silts are present at two sites above deposits of the grey clay facies. These sediments are interpreted to have been deposited in a nearshore setting as sea level dropped following deglaciation. At SCPT 11 the sands are silts are overlain by Holocene organic soils (Figure 10) and at SCPT 8, they are overlain by muds interpreted to be Holocene marine deposits (Figure 8). At the latter site, the sand and silt facies has been observed in core, where it contains a shelly marine fauna (Bobrowsky and Clague, 1992), and may include sediments deposited during the early Holocene transgression.

In sand and silt facies, Vs averages 165 m/sec and is generally between 131 and 199 m/sec. However, these deposits are 10 metres deeper at one site than at the other, and Vs values average 140 m/sec at the site where the unit occurs at a depth of 5 metres (SCPT 11). Vs normalized for effective overburden stress (V_{S1}) using a shear-wave stress exponent of 0.25 in equation 2, typical for normally consolidated sands (Olsen, 1994), has a much narrower range, demonstrating that the sediments are similar at both sites: V_{S1} averages 179 m/sec and is generally between 165 and 193 m/sec. The Vs characteristics of this facies presented here are based on data from only two sites. At other sites, where thicker sands occur, Vs could be higher.

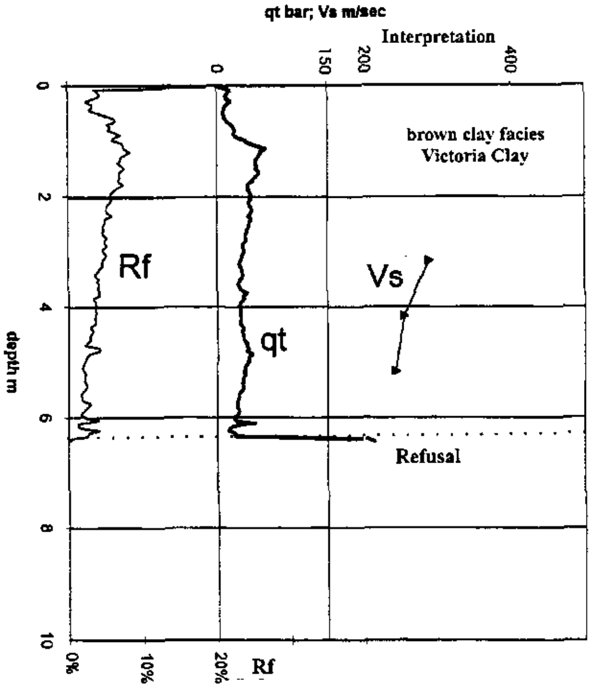

Figure 12. SCPT 13, Old Island Highway, View Royal, with stratigraphic interpretation. SCPT parameters: Vs= shear-wave velocity; qt=tip resistance; and Rf = friction ratio. Note the high Vs, tip resistance, and friction ratio values in the brown clay facies compared to the grey clay facies in Figures 8 to 11.

HOLOCENE DEPOSITS

HOLOCENE ORGANIC SOILS

Deposits of organic silt and peat that represent Holocene bog deposits occur at four sites, where they are distinguished by low tip resistance values and high friction ratios. These sites are in low lying areas that were swamps and bogs in historic times. At two sites, SCPT 6 and SCPT 9 (Figure 9), the organic deposits gradationally overlie the grey clay facies, and at SCPT 11 (Figure 10) they overlie the sand and silt facies of the Victoria Clay that in turn overlies the grey clay facies. At the fourth site, SCPT 8 (Figure 8) the organic deposits overlie Holocene beach sand (Bobrowsky and Clague, 1992). All the Vs measurements in this unit were taken at depths between 3 and 6 metres; in these deposits, Vs averages 85 m/sec and is generally between 52 and 113 m/sec. The range is skewed by one high value of 164 m/sec at SCPT 8 . Excluding this value, Vs averages 75 m/sec and is generally between 59 and 91 m/sec.

HOLOCENE MARINE MUD

Deposits interpreted to be Holocene marine muds are present in two sites in nearshore settings. These deposits are characterized by an interval with low tip resistance, generally 2 to 10 bars, occurring between the sand and silt facies of the Victoria Clay and Holocene beach sand at SCPT 8 (Figure 8), and between the brown clay facies and artificial fill at SCPT 12 (Figure 11; Crawford and Sutherland, 1971). The latter site is adjacent to the Empress Hotel, where radiocarbon dating has confirmed the Holocene age of this unit (Lowdon *et al.*, 1971). Vs averages 147 m/sec and is generally between 121 and 173 m/sec. However, these deposits are 10 metres deeper at one site than at the other, and Vs values average 127 m/sec at the site where the unit occurs at a depth of 4 to 5 metres. Vs normalized for effective overburden stress (V_{S1}) using a shear-wave stress exponent of 0.5 in equation 2, typical for normally consolidated sits and clays (Olsen, 1994), has a much narrower range: V_{S1} averages 150 m/sec and is generally between 139 and 161 m/sec.

HOLOCENE BEACH SAND

Holocene beach sand occurs at SCPT 8, where it overlies Holocene marine muds and is overlain by Holocene peat (Figure 8). Tip resistance is generally high in this unit, exceeding 200 bars, although lower values occur at the top. Vs averages 131 m/sec and ranges between 120 and 140 m/sec. These values are low for Holocene sands, and may not be representative of beach deposits elsewhere.

ARTIFICIAL FILL

Artificial fill occurs at three sites. In two cases the unit is characterized by interbedded sand and silt; at SCPT 12, the sand and silt fill occurs above Holocene marine mud and is well known to be fill (Fig 11; Crawford and Sutherland, 1971), and at SCPT 9, the sand and silt is inferred to be fill based on its position above Holocene organic soils (Figure 9). At SCPT 7, the fill consists of 4 metres of silty sand at a site where fill was known to have been placed (C.N. Ryzuk, personal communication). Vs in fill averages 130 m/sec and ranges between 102 and 143 m/sec.

DISCUSSION

Shear-wave velocities in Quaternary deposits of the Victoria area cover a wide range of values. Where sufficiently thick, the older Pleistocene deposits meet the criteria for NEHRP Site Class C and have low susceptibility to amplification, and the deposits of the Colwood delta meet the criteria for Class D, susceptible to moderate amplification (Table 1).

Where present, sites underlain by the grey clay facies of the Victoria Clay potentially meet the criteria for Site Class E, *susceptible to high amplification*. At SCPT 8 (Figure 8;, Table 3), the V_{s30} is 157 m/sec, within the range defined for this site class. Site Class E also includes sites with more than 3 metres of soft silt and clay, which is defined as having a plasticity index greater than 20%, a water content greater than 40%, an undrained shear strength less than 25 kPa, and a shear-wave velocity less than 150 m/sec (Seed *et al., 1992;* Finn *1996*). Vs in the grey clay facies is generally below 150 m/sec (Figures 8, 9, 10, 11), so that sites with greater than 3 metres of this facies are potentially in this site class, both where the overlying brown clay facies is present and where it is absent. The principal exceptions to this generalization are sandy intervals in the grey clay, that can be identified by higher than average tip resistance, and reduce the total thickness of soft silt and clay to less than 3 metres.

A preliminary review of other geotechnical data obtained for the earthquake hazard mapping program indicates that the grey clay facies commonly, but not always, meets the plasticity, water content, and undrained shear strength criteria for soft silt and clay. Vs does not increase with depth in the grey clay facies where it is less than 12 metres thick and overlain by the brown clay facies, likely due to a greater degree of consolidation (probably caused by partial desiccation) in the upper part of the grey clay facies compared to where it is overlain by Holocene organic soils. Nasmith and Buck (in press) report that the grey clay is slightly overconsolidated where overlain by the brown clay facies but normally consolidated where overlain by Holocene organic soils. These observations suggest that a greater thickness of grey clay is required to meet the criteria for Site Class E where the grey clay is overlain by brown clay than where it is overlain by Holocene organic soils.

Holocene marine muds and organic rich silts and peat overlying the grey clay facies can potentially add to the thickness of soft silt and clay to meet the criteria for Site Class E, although the contribution of peat to site amplification requires additional study (Klohn-Crippen, 1994; Finn, 1996). More importantly for regional mapping, where the grey clay is overlain by Holocene organic soils, not only is the grey clay facies likely to be thick, but more of the grey clay facies is likely to meet all the criteria for Site Class E. In the Victoria area, the 1946 Vancouver Island earthquake was felt most strongly in those areas underlain by thick accumulations of grey clay, capped by either Holocene organic soils or shoreline fill (Figs 9, 11; Hodgson, 1946; Wuorinen 1974, 1976). Although the site shown in Fig 11 marginally meets the criteria for Site Class E, the grey clay facies thickens to over 20 metres less than 100 metres to the west, where the criteria for site class E are potentially met.

The average shear-wave velocity and site period calculated for the grey clay sites that reached refusal (Table 3) are minimum values and may be increased by an undefined thickness of till or other older Pleistocene deposits below the base of the test. However, this effect is likely to be small: the older deposits are generally thin and the largest Vs contrast in most cases occurs at the contact between the grey clay and underlying materials. Due to the extreme irregularity of the bedrock surface, site periods must vary considerably in the Victoria area, even within a city block. However, the calculated site periods at the grey clay sites are between 0.27 and 1 second, indicating that amplification due to resonance is likely to occur at ground motion periods generally less than 1 second in the low-lying areas underlain by grey clay in the Victoria area, within the natural period of many buildings.

Holocene and late glacial sandy deposits have low Vs values and would contribute to a low V_{s30} for a site, but not to the total thickness of soft silt. At sites where only the brown clay is present, it is likely to be less than 6 metres thick and the site effect will be dominated primarily by the underlying deposits.

CONCLUSIONS

A shear-wave velocity testing program in the Greater Victoria area based on SCPT and SASW tests has provided the basic data for a shear-wave velocity model, required to assess the amplification of ground-motion hazard due to earthquakes. This model provides the basis for mapping the amplification of ground-motion hazard on a regional scale and for estimating the fundamental period at sites where the stratigraphy is known.

Till of the Fraser Glaciation and earlier Pleistocene deposits have shear-wave velocities generally in the range of 400 to 600 m/sec and have low susceptibility to amplification. Late glacial sands and gravels of the Colwood delta have shear-wave velocities generally in the range of 300-400 m/sec and sites underlain by a sufficient thickness of these deposits are susceptible to moderate amplification.

Within 15 metres of the surface, the grey clay facies of the late glacial glaciomarine Victoria Clay has shear-wave velocities generally between 100 and 160 m/sec, and sites underlain by more than 3 metres of these deposits are potentially susceptible to high ground-motion amplification. This is particularly true where they are overlain by Holocene organic sediments or marine muds, in which shear-wave velocities average 85 and 147 m/sec respectively. These Holocene deposits may contribute to the total thickness of soft silts, and the presence of organic sediments indicates that the underlying grey clay facies has been subjected to less consolidation than where it is overlain by the brown clay facies. These conclusions are consistent with those of Wuorinen (1974, 1976), who showed that the highest ground shaking during the 1946 earthquake occurred in former swamps, in which organic deposits overlie thick accumulations of the grey clay.

The fundamental site periods for sites underlain by grey clay at the sites investigated in this program range between 0.27 and 1 second, so that amplification due to resonance is likely to occur at ground motion periods generally less than 1 second in the low lying areas underlain by the grey clay facies in the Victoria area.

The brown clay facies of the Victoria Clay has shear-wave velocities generally in the range of 160 to 270 m/sec; however, these deposits are thin and the site effects will be primarily controlled by the underlying deposits.

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