Comparison of shear-wave velocity measurements by crosshole, downhole and seismic cone penetration test methods

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ABSTRACT
A field testing program was undertaken at a proposed petrochemical plant site near Edmonton, Alberta to measure shear wave velocities. The proposed site is underlain by lacustrine clay, glacial till and upper Cretaceous clay shale and sandstone bedrock in descending order. The shear wave velocities were measured by Crosshole and Downhole Seismic tests and as well as Seismic Cone Penetration Tests (SCPT). This paper describes the test results and comparisons of three shear wave velocity measurement techniques and discusses the limitations of the various methods.

RÉSUMÉ
Afin de mesurer la vitesse des ondes de cisaillement, des essais en chantier ont été effectué sur un site industriel près d'Edmonton, Alberta. Le site en question est fondé sur un sol argileux lacustre suivi d'un till galciaire et par un schiste argileux ou un grès de la période du Crétacé. La vitesse des ondes de cisaillement a été obtenue par la méthode "crosshole" de mesure de la vélocité d'onde sismique ansi que par des essais de pénétration au cone statique (SCPT). Cet article présente les résultats de ces essais et discute des contraintes reliées à la méthodologie.

1 INTRODUCTION

Site classification for Seismic Hazard Assessment in the National Building Code (2005) is based on shear wave velocity measurements in the upper 30 m. Shear wave velocity measurements are also frequently required to assist in design of machine foundations. The shear wave velocity measurements are becoming an integral part of the geotechnical investigation for major structures and are an important tool in designing structures for site specific conditions such as site-specific earthquake response.

Numerous methods of determining shear wave velocity either directly or indirectly are available. The most commonly used include crosshole seismic tests, downhole seismic tests, and seismic cone penetration tests (Hunter et al (1991) and Sully and Campanella (1995)). Further description of these test methods is presented in the following sections. The choice of method depends on many factors, including soil conditions, local experience, availably and cost.

All three test methods were performed during the geotechnical investigation at an industrial plant site in Alberta. This paper presents the results and provides a comparison of the various test methods.

2 SOIL CONDITIONS

The site is underlain by lacustrine clay, glacial till and Upper Cretaceous clay shale and sandstone bedrock in descending order. The glacial till was noted to contain sand and clay layers at various depths. The clay shale and sandstone bedrock was encountered at depths ranging from 25 m to 30 m below existing ground surface. The test locations are shown on Figure 1. A summary of the soil conditions encountered at the site is shown on Figure 2.

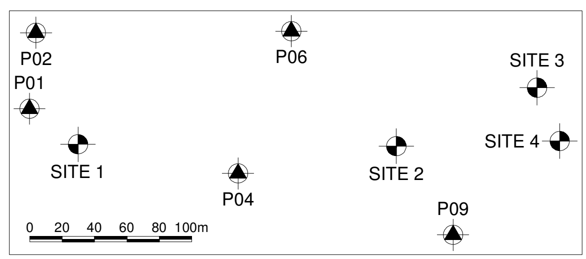

Figure 1. Test Locations

The holes labeled as A1 and A4 were drilled using a solid and hollow stem augers, where the soil samples were collected and logged at discrete intervals. The holes labeled as C1 to C4 were drilled using a sonic drill rig which produced continuous 100 mm diameter cores in PVC liners. The auger drilled holes also show the SPT N values (blows per 300 mm unless otherwise noted) obtained during investigation.

The clay till ranges from stiff to very stiff consistency in the upper 12 m, generally increasing with depth and from very stiff to very hard below 12 m depth. The sand layers are generally very dense below about 12 m depth.

The sand layers are random in both depth and thickness, ranging from less than 1 m to over 5 m in thickness, and the soil conditions were noted to change even between the three cross holes and the SCPT locations, which were about 3 m apart.

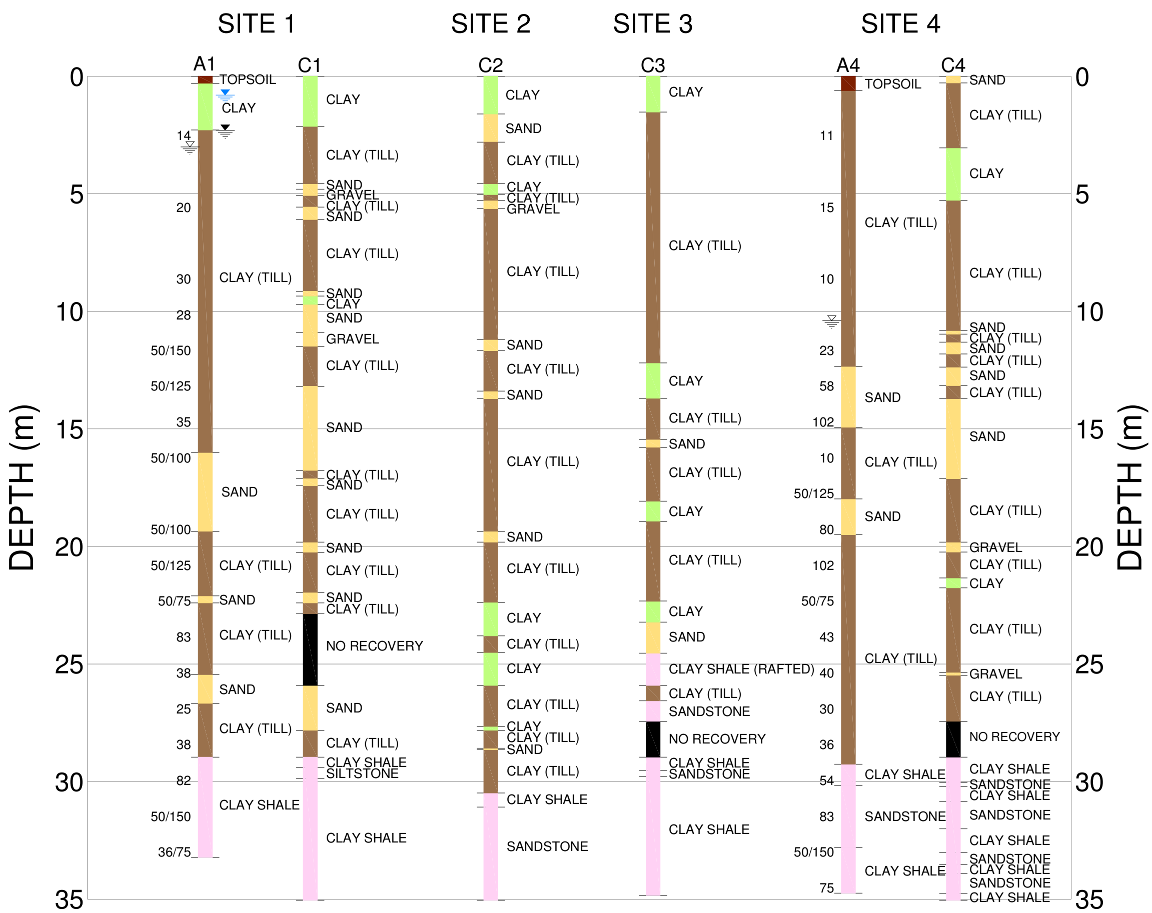

Figure 2. Soil conditions encountered during the field program

3 FIELD TEST PROGRAM

3.1 Crosshole Seismic Test

Four Crosshole tests were carried out at Sites 1, 2, 3 and 4. The Crosshole tests were carried out using the three hole method (ASTM D4428/D 4428M – 00).

In this method, three 85 mm dia. PVC inclinometer casings (with mutually perpendicular aligned grooves) were installed at each test site to a depth of about 35 m below the existing ground surface. One test hole at each site was logged and sampled. The remaining two holes were drilled to the same depth at the specified spacing from the sampled test hole. The inclinometer casings were used to obtain precise vertical alignments of the casings in order to determine exact distance between casings for interpreting shear wave velocities.

A summary of the crosshole test results is presented in Figure 3. The crosshole test results show a common trend of increasing shear wave velocity with depth to about 15 m, below which the velocities are relatively constant. An anomaly is noted in Site 3, where the shear wave velocity reduces between about 15 and 25 m depth. This corresponds to a zone of clay till containing stiff high plastic clay layers.

3.2 Downhole Seismic Test

Downhole test was performed in a single cased test hole (one of the three holes used for the crosshole test) at each site to measure shear wave velocities. The test was performed by lowering the receiver package to the initial start depth in the cased test hole where it was then coupled to the side of the casing using a pneumatic packer. To generate a shear wave, a weighted steel beam is struck horizontally a number of times at both ends of the beam. Doing this generates a horizontally polarized shear wave that travels from the surface to the receiver. The recorded signals from the two horizontally oriented geophones were used to determine the arrival time of the shear wave.

After sufficient data has been recorded at the selected depth, the receiver package was lowered incrementally and the procedure was repeated. By doing this the interval wave velocity between successive depths can be calculated based on the interval travel path and measured interval travel times.

A summary of downhole test results is shown on Figure 4.

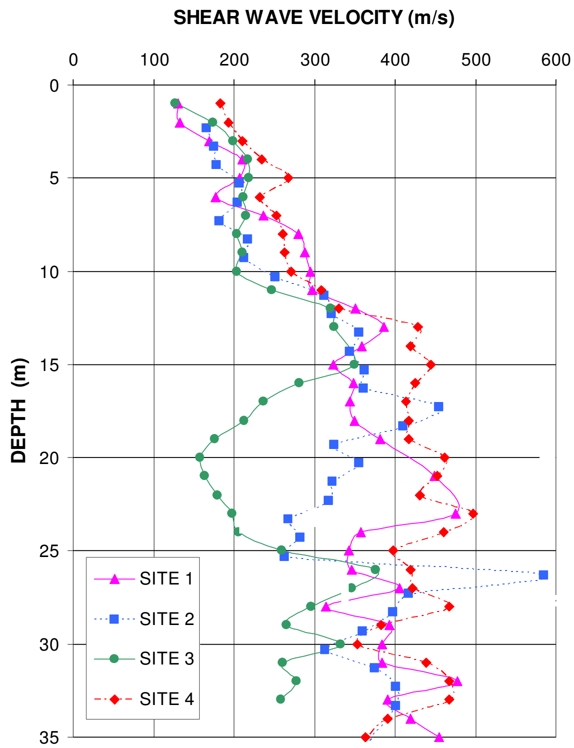

Figure 3. Summary of Crosshole test results

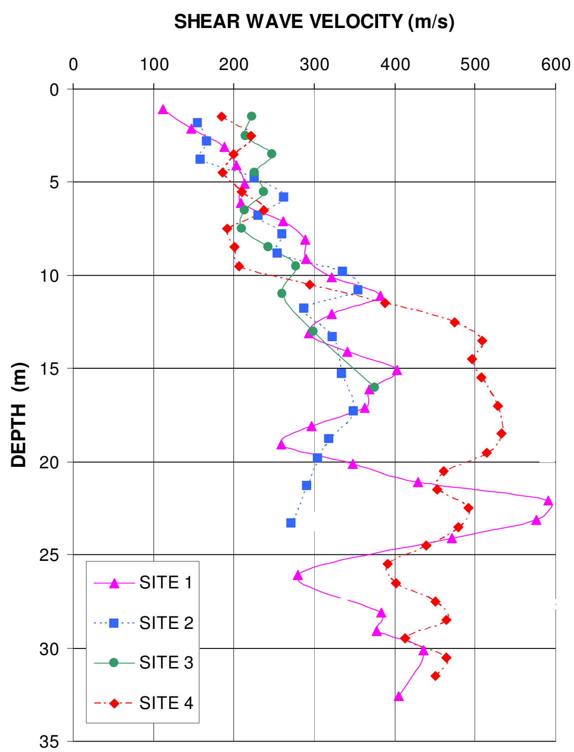

Figure 4. Summary of Downhole test results

3.3 Seismic Cone Penetration (SCPT) Tests

The SCPT tests were conducted during the cone penetration test program using the procedure by Robertson et al. (1986).

The shear waves were generated using a hammer striking a steel beam that was coupled to the ground by placing it under the tracks or jack-pads of the CPT rig. The sledge hammer striking the beam acts as an electrical contact trigger, initiating the recording of the seismic wave traces. The offset of the beam from the cone was taken into account during calculation of the seismic wave velocities. The wave receiver used was a horizontally active geophone located in the body of the Cone Penetrometer.

The SCPT is similar in test methodology to the downhole test, except that the shear waves are recorded by the seismic cone rather than the geophones used in the downhole test. Hence the test results should be similar, where the tests are performed in the same location.

A total of 9 SCPT tests were carried out and the results are shown on Figure 5.

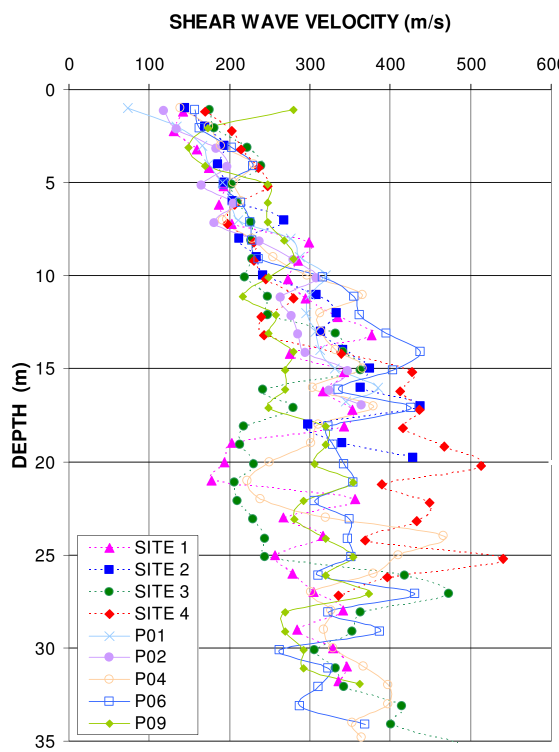

Figure 5. Summary of SCPT test results

4 RESULTS AND DISCUSSION

The comparison of the Crosshole, Downhole and SCPT tests are shown on Figures 6 to 9. A summary log of soil conditions is shown at each site for comparison.

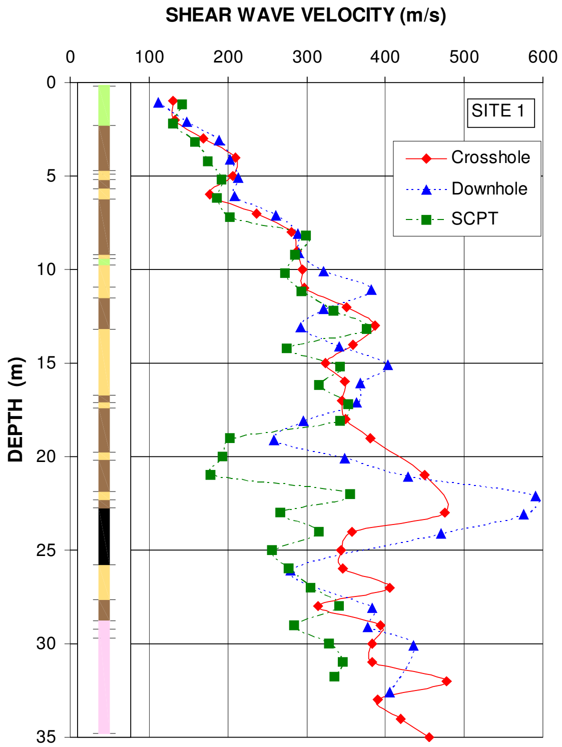

Figure 6. Comparison of tests at Site 1

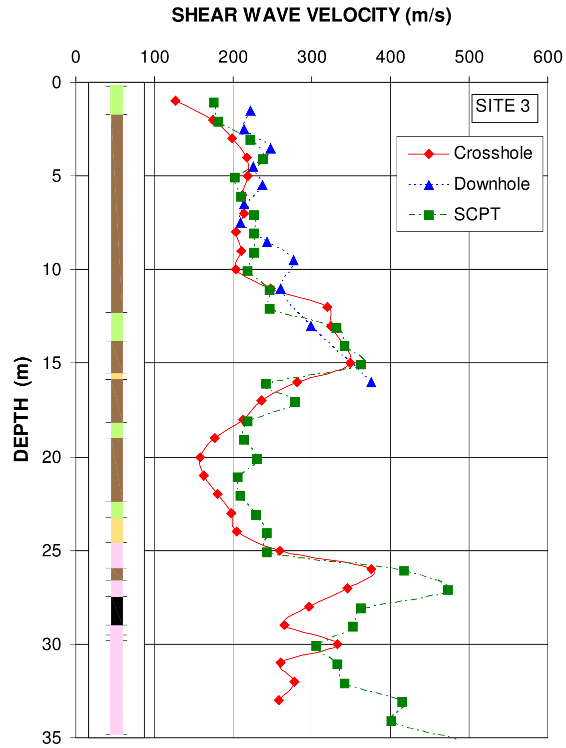

Figure 8. Comparison of tests at Site 3

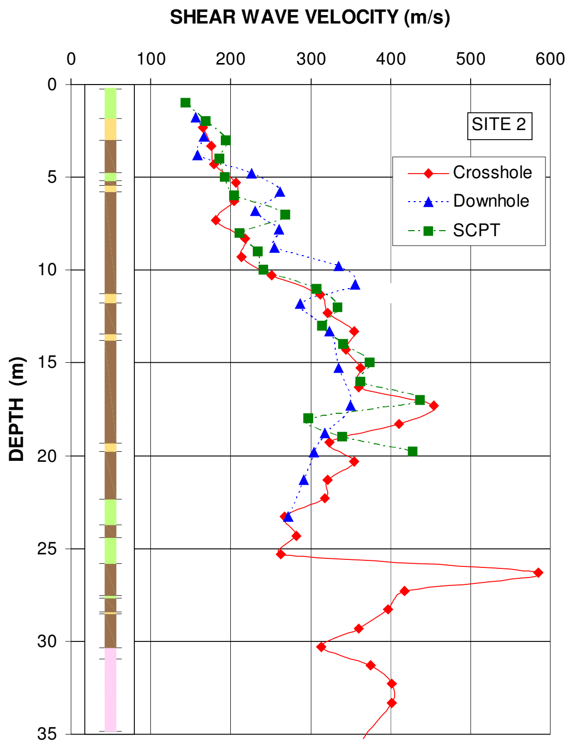

Figure 7. Comparison of tests at Site 2

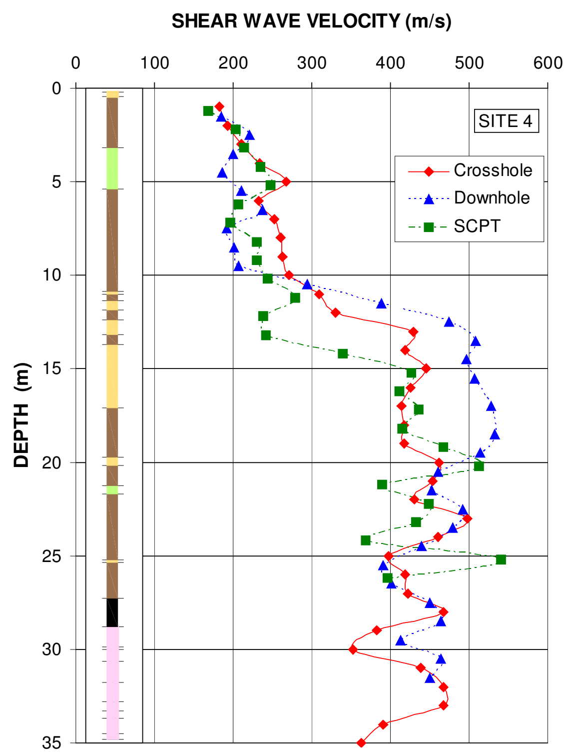

Figure 9. Comparison of tests at Site 4

The main observations are as follows:

1. At Site 1, the three methods provide relatively good agreement in the upper 17 m. Below this depth there is a considerable variation in the test methods, possibly reflecting the potential variation in clay and sand layers between the individual test holes.
2. At Site 2, the three methods were in good agreement to the test depth of 20 m.
3. At Site 3, the three methods are in good agreement to about 15 m. Below 15 m, the SCPT measured shear wave velocities are relatively higher than that of Crosshole tests. Both test methods show the same trend of reduction in shear wave velocity between 15 and 25 m, corresponding to the zone of clay till containing clay layers.
4. At Site 4, the shear wave velocities were in relatively good agreement to a depth of 10 m, below which there is considerable scatter between the three test methods, again likely reflecting the variation in sand layers as shown in Figure 2.
5. At Site 1 and Site 4, the soil conditions encountered in two holes about 3 m apart are shown on Figure 2, where it can be seen that the sand layers are encountered in varying thicknesses and depths between the two holes.

The shear wave velocity measurements at each site with depth, as determined by the crosshole test method are compared with the generalized soil stratigraphy on Figure 10.

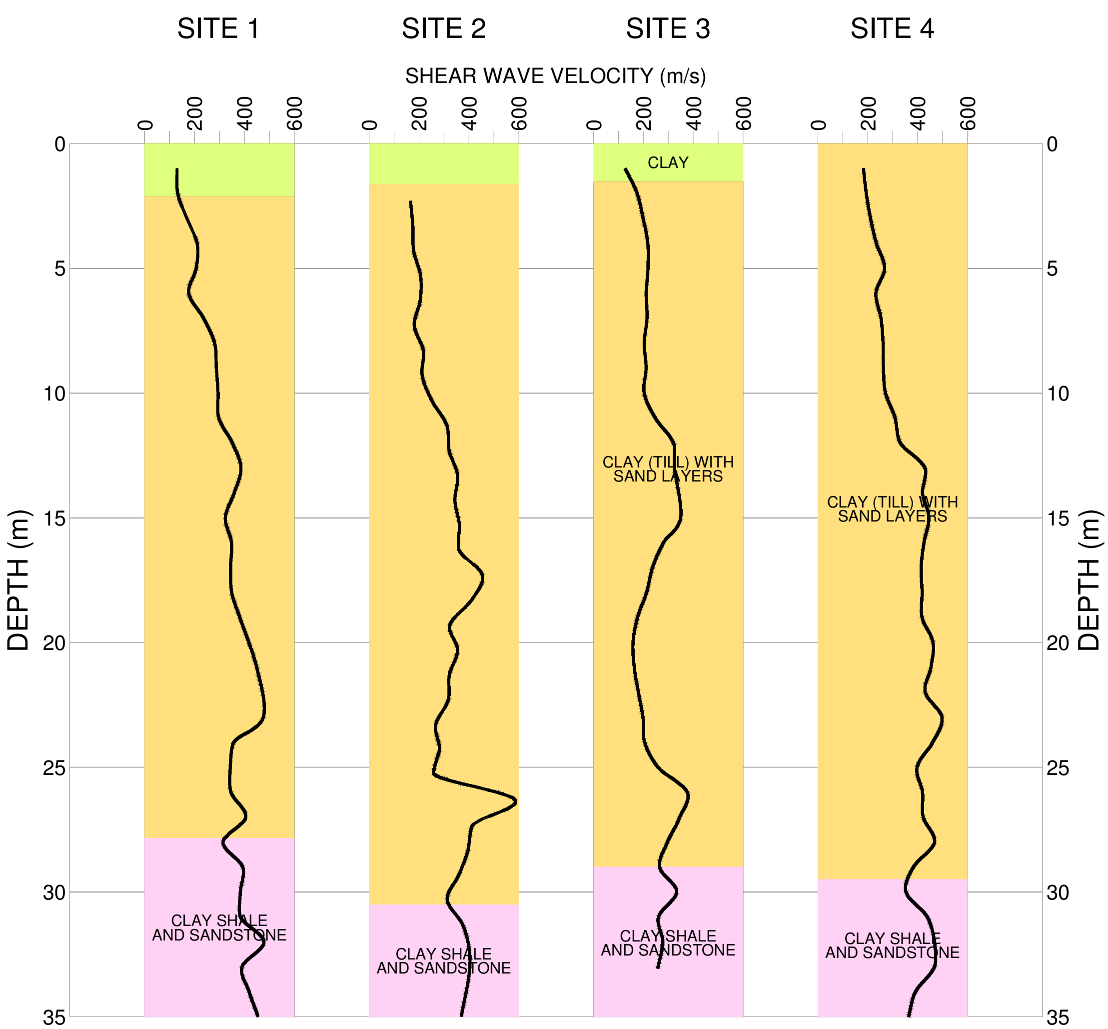

Figure 10. Comparison of Shear Wave Velocity at four sites

The National Building Code defines the site classification for seismic response based on the average shear wave velocity in the upper 30 m of the strata (ref. Table 4.1.8.4.A NBC 2005). Table 1 summarizes the average shear wave velocity measurements in the upper 30 m using the different methods. As noted, the three test methods provide average shear wave velocity measurements differing by about 15% between high and low. At sites 3 and 4, the differences are about 10% and 6% respectively.

Table 1. Summary of average shear wave velocity Measurements in top 30 m.

Site	Test Method	Average Shear Wave Velocity (m/s)
Site 1	Crosshole	312
	Downhole	327
	SCPT	266
Site 2	Crosshole	308
Site 3	Crosshole	238
	SCPT	263
Site 4	Crosshole	357
	Downhole	379

The average shear wave velocity for the site is greater than 180 m/s but less than 360 m/s. Hence the site will be classified as Site Class D: Stiff soil, according to NBC 2005.

However, the NBC 2005 also provides the same site classifications based on SPT N values or undrained shear strengths, where shear wave velocity measurements are not available. The average SPT N values for the upper 30 m are greater than 50 blows per 300 mm penetration and the average undrained shear strength is also greater than 100kPa. If the classification was based on SPT values and/or the undrained shear strength, the Site would be classified as Site Class C: Very dense soil and soft rock. For seismic classification, the shear wave velocity is considered as the fundamental property. Hence, there would appear to be a disconnect between the three classification methods, which reinforces the need to carry out shear wave velocity measurements as part of the soil investigation for seismic hazard assessment.

The SCPT tests can be incorporated into the field investigation program without significant increase to costs, particularly where cone penetration testing forms part of the geotechnical investigation. The major problem of doing SCPT’s is that the cone tip may encounter refusal in very hard or very dense soils such as very dense gravels or very hard clay shale and sandstone bedrocks. There is not much information in the literature on shear wave velocity measurements in the upper cretaceous bedrock of the Edmonton Area. The shear wave velocity measurements using the different tests during the field program are tabulated in Table 2.

Table 2. Summary of shear wave velocity measurements in clay shale/sandstone bedrock.

Site	Test Method	Shear Wave Velocity (m/s)
Site 1	Crosshole	315-480
	Downhole	380-440
	SCPT	300-350
Site 2	Crosshole	315-400
Site 3	Crosshole	265-485
	SCPT	310-485
Site 4	Crosshole	350-465
	Downhole	450-465

The typical shear wave velocity for the Edmonton area bedrock appears to vary between 265 m/s and 485 m/s.

The advantages and disadvantages of the different tests are discussed below:

Crosshole test method is the only method that is an ASTM standard. However, the Crosshole method requires two or three cased test holes and the holes also must be surveyed to accurately determine the horizontal distances between the holes at each depth. It also requires a downhole hammer to carry out the test. The crosshole test also measures the vertical shear wave velocity. The crosshole shear waves can refract down (or up) and travel through higher velocity layers taking the quickest path between the holes. This may limit the ability to resolve thin layers.

For the Downhole test method only one hole is needed. During the Downhole method the shear waves travel vertically and measure the horizontal shear wave velocity.

The SCPT test method is becoming popular because it can be carried out during the CPT program at significantly less cost than the other tests. The major limiting factor for SCPT is that the tests cannot be performed in very hard or very dense soils due to cone refusal.

5 CONCLUSIONS

The field program demonstrates that reasonable agreement in shear wave velocity measurements can be made using Crosshole, Downhole and Seismic tests in the same soil conditions.

The National Building Code provides correlations for site classification for seismic response based on shear wave velocity measurements, Standard Penetration Tests and undrained shear strength averaged over the upper 30 m. However, the site classifications using each of the three correlations do not provide a consistent site classification at this site.

Based on the SPT and undrained shear strength measurements, the site would be classified as Class C; whereas using shear wave velocity measurements the site would be classified as Class D. This could have a major implication on the design. However, the NBC states that the shear wave velocity is the fundamental method for determining site classification, and this shows the importance of obtaining shear wave velocity measurements for site classification.

A SCPT program can be incorporated into the field program without a significant increase in cost and can be supplemented by Downhole or Crosshole techniques.

The shear wave velocity of the clay shale/ sandstone bedrock in the Edmonton area was measured between 265 m/s and 485 m/s.

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