# A Comparison of Surface- and Standard Penetration Test-Derived Shear-Wave Velocity

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**Key Terms:** ***Geophysics, Geotechnical, Seismic, Engineering***

## ABSTRACT

**Shear wave velocity ($V_s$) values calculated from Standard Penetration Tests (SPTs) and from multichannel analysis of surface waves (MASW) are consistent in their prediction of $V_s$. This analysis was based upon SPT and MASW data from 10 localities representing four different depositional environments across North America. Homogeneous deposits tend to produce the closest agreement between MASW- and SPT-derived $V_s$. Poorly sorted deposits can predict less consistent agreement between MASW- and SPT-derived $V_s$. Further, at depths of greater than 20 m below grade, based upon the testing geometry within this work, the prediction of $V_s$ between the two methods can differ.**

## INTRODUCTION

Engineered structures rely on geotechnical studies of sheer wave velocity ($V_s$) data to properly calculate the design basis for construction. Recently, design basis in earthquake-active areas has driven many researchers to characterize dynamic soil properties (Hvorslev, 1949; Imai, 1977; Ohta and Goto, 1978; Fumal and Tinsley, 1985; Kayabali, 1996; Chien et al., 2000; Andrus et al., 2004; and Hanumantharao and Ramana; 2008). The application of Rayleigh (surface) wave analysis (SWA), introduced in late 1980s to evaluate the stiffness of near-surface material (i.e., $V_s$), is gaining popular acceptance in geotechnical studies. This article addresses one of the methods for calculating $V_s$ from surface waves, the multichannel analysis of surface waves (MASW) method.

Standard Penetration Test (SPT) data have been used for approximately 100 years and are considered the standard by which engineers can convert penetration resistance to dynamic soil moduli (Ohsaki and Iwasaki, 1973; Ohta et al., 1978; and Sykora and Koester, 1988). Further, international standards have codified SPT data into the engineering design basis realm (for example, ASTM, 2008).

SPTs are conducted using the shell and auger method pursuant to ASTM Standard Method D1586 (ASTM, 2008). SPT values are measured in 1.5-m depth intervals by connecting a split spoon sampler to drill rods. A 63.5-kg dead weight is dropped freely from a height 0.76 m and used to drive the split spoon 0.457 m into the subsurface. The number of blows for each 0.152 m of penetration of the split spoon sampler is recorded. The blows required to penetrate the initial 0.152 m of the split spoon are ignored as a result of the presence of possible loose material or cuttings. The SPT value or *N*-value is derived from the cumulative number of blows required to penetrate the remaining 0.305 m of the 0.457-m sampling interval.

The energy generated by the hammer blow in the SPT test is principally shearing energy and can be used to model the shear strain modulus. This article will demonstrate that MASW data are comparable to SPT data, the engineering standard. One of the strongest aspects of MASW testing is that MASW data are digitally recorded. Consequently, MASW data are equally sensitive from the low velocity range (i.e., 10 m/s) to the high velocity range (i.e., $>$5,000 m/s), whereas SPT data are less sensitive in the low blow count range (for the predicted $V_s$ of $<$100 m/s) and saturate in the high blow count range (for the predicted $V_s$ of $>$350 m/s). Furthermore, the strongest aspect of MASW testing is that it does not require a borehole, so cost per test is much less than that associated with SPT testing.

Measurement of $V_s$, performed *in situ*, using geophysical methods can be one of the best methods for measuring the low strain shear modulus (Rollins et al., 1998a). Geophysical seismic methods are based on the velocity of propagation of a wave in an elastic body as a function of the modulus of elasticity, Poisson's ratio, and density of the material (Hvorslev, 1949).

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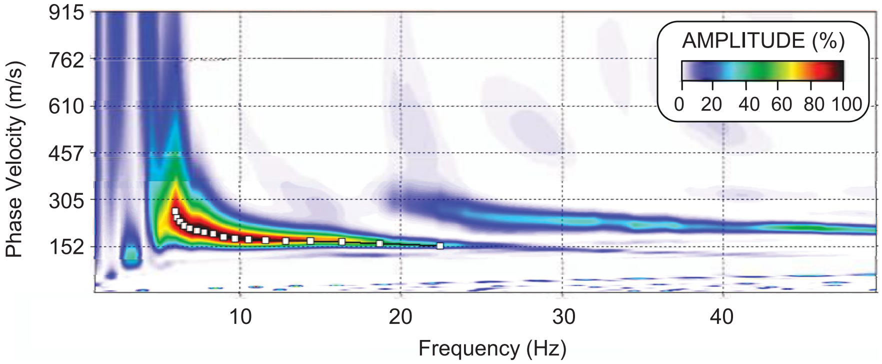


Figure 1. An example of a MASW dispersion curve from south-central Puerto Rico of the fundamental mode of the frequency (Hz) versus phase velocity (m/s). Amplitude intensity is shown in color. The dotted white line represents the fundamental mode. Processed using KGS SurfSeis 3.06 computer program (KGS, 2010).

Within the past 10 years, however, SWA data have proven to offer a more effective and economical alternative to the use of SPT data for the prediction of soil dynamic properties. SWA is generated from a high-amplitude surface wave front initiated through induced elastic energy (i.e., hammer blow).

Initially, non-intrusive surface wave method using a single pair of receivers, Spectral Analysis of Surface Waves (SASW), was introduced (Nazarian and Stokoe, 1984; Dennis et al., 1998). The SASW method produced results that were within 10–15 percent of measured $V_s$ values (Nazarian and Stokoe, 1984; Stokoe et al., 1988; Dennis et al., 1998; and Brown et al., 2002).

The use of multiple channels, as with the MASW method, records higher resolution, more consistent, more repeatable and higher amplitude energy than does the SASW method (Park et al., 1999). Furthermore, dispersion curves based upon MASW produce more readily interpreted data (Xia et al., 1999).

MASW data are recorded using a series of low-frequency geophones (4.5 Hz) in a linear array. A source (sledgehammer, propelled energy generator, etc.) is used to initiate the surface wavefront. The geophones receive the vertical component of the elliptical Rayleigh wave or "ground roll" and convert the mechanical movement to an electrical signal, which is recorded by the seismograph. The depth of surface wave penetration is limited to half of the surface wavelength, and the survey geometry must be chosen accordingly. However, there are limitations to the accuracy of the $V_s$ values, especially in the depth ranges greater than 20 m (Hutchinson et al., 2008).

The surface wave data are post-processed subsequent to the field data collection. Data are displayed in the frequency versus phase velocity format in the form of a dispersion curve. A fundamental mode is derived from the dispersion curve (phase velocity versus the frequency) and is inverted to produce a $V_s$-depth curve (Miller et al., 1999; for example, see Figure 1).

MASW analysis diverges from other seismic methods of $V_s$ data collection and processing because MASW does not, in most cases, attenuate from velocity inversions with depth (Park et al., 1999; Miller et al., 2001; and Ivanov et al., 2008). The MASW method of measuring $V_s$ is quite robust because this method is insensitive to the presence of subsurface utilities; to the occurrence of standing structures; to buried boulders, rocks, and concrete; and to conductive soil (Hutchinson and Beird, 2011).

## DISCUSSION

Many authors have attempted to predict the $V_s$ from SPT data. For example, the NovoSPT program provides more than 260 formulas and methods for correlating geotechnical engineering soil properties from SPT blow counts ($N_{60}$ or $N_{100}$) (NovoTech, 2010).

The generic regression formula for the prediction of $V_s$ from SPT data is:

$$V_s = AN^B, \quad (1)$$

where shear wave velocity is a function of the blow count ($N$) raised to a power ($B$) times a constant ($A$). Hanumantharao and Ramana (2008) collected over 50 formulas within the literature that used this basic regression equation. Their work showed quite a variation in formulas from a low extreme (from Rollins et al., 1998b),

$$V_s = 222.0\,(N)^{0.06}, \quad (2)$$

To a high extreme (from Jafari et al., 2002):

$$V_s = 19.0\,(N)^{0.85}. \quad (3)$$

Consequently, there is quite a bit of variability at the low and high range of $N$-values for predicting $V_s$ (Table 1). Further, $N$-values of $<5$ and $>50$ show

Table 1. *Comparison of regression formulas for the derivation of* $V_s$ *from SPT* N-*values using formulas 2 and 3, respectively.*

| $N$ | $222.0\ (N)^{0.06}$ | $19.0\ (N)^{0.85}$ |
|---|---|---|
| 5 | 75 | 244 |
| 20 | 242 | 266 |
| 50 | 528 | 280 |

$V_s$ values in m/s.

Table 2. *Comparison of Imai and Tonouchi (1982) and Inazaki (2006) formulas based upon the* N-*values provided in Table 1.*

| $N$ | $91(N)^{0.337}$ | $99(N)^{0.3448}$ | Average |
|---|---|---|---|
| 5 | 156 | 173 | 164.5 |
| 20 | 250 | 280 | 265 |
| 50 | 340 | 384 | 362 |

$V_s$ in m/s.

a large calculated $V_s$ range between the two formulas and demonstrate the weaknesses with using the SPT method for the prediction of dynamic soil properties (Figure 2). Further, Inazaki (2006) states "… that it is hopeless to estimate S-wave velocity from generally incorrect [i.e., low or high] $N$-values."

Imai and Tonouchi (1982) and Inazaki (2006) provide regression equations that are more robust than most of the formulas reviewed. Imai and Tonouchi (1982) incorporate a large data set to derive their equation, whereas the Inazaki (2006) equation is based upon a strict data collection regiment.

The Imai and Tonouchi (1982) equation is based upon 1,600 data sets from Japan:

$$V_s = 91(N)^{0.337}; \quad (4)$$

whereas, Inazaki (2006) showed results of 500 $N$-values:

$$V_s = 99(N)^{0.3448}. \quad (5)$$

Both formulas appear to be robust in their approach to the prediction of $V_s$ from $N$-values.

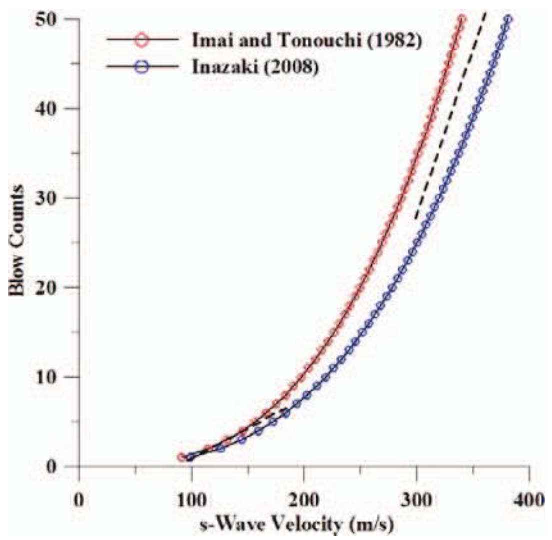


Figure 2. Continuous blow counts converted to $V_s$ using regression equations from Imai and Tonouchi (1982) and Inazaki (2006). Note dashed straight line functions from $N$-value of one to six blows and from 30 to 50 blows.

The formulas from Imai and Tonouchi (1982) and Inazaki (2006) provide a narrow range of S-wave velocities for $N$-values.

Not surprisingly, these equations provide similar results (Table 2). What is interesting is that the first six blow counts ($N = 6$) account for $V_s$ values from 100 m/s to 180 m/s, or 29 percent to 51 percent, respectively, of the predictive range of SPTs.

The majority of engineering sites tested by the authors using the MASW method of $V_s$ prediction have an engineering requirement of a $V_s$ of 180 m/s as a minimum for an effective design basis, and therefore this value is referenced here only as a datum by which to further this discussion of SPT data. Consequently, an acceptable site, using only $N$-values, is one that has a design basis based upon six blow counts. Clearly, any errors in SPT data collection could compromise the analysis and conversion to $V_s$. Further, from an $N$-value of 30 and higher, the curve flattens to a straight line function (Figure 2). Consequently, the top 40 percent of the SPT curve ($N = 30$ to 50) includes a predicted velocity range of only 50 m/s (300–350 m/s).

As with any geophysical method of data collection there are weaknesses. When processing MASW data, the fundamental mode must be selected for the dispersion curve analysis to derive accurate shear wave velocities (Ivanov et al., 2008). Unfortunately, selecting a higher order mode as the fundamental mode for inversion will result in spurious results. This can occur, although rarely, when the fundamental mode blends with the subsequent modes; however, a fully trained interpreter can easily avoid this pitfall.

A high-resolution dispersion curve will lead to a more accurate pick of frequencies and phase velocities. Acquisition factors influencing the dispersion curve resolution are number of channels, spread length, shot offset, and source (Park, 2014). During acquisition it is also beneficial to stack multiple records to diminish the contamination of the shot gather by unwanted data or noise.

Hutchinson and Beird (2011) demonstrated that the active method of MASW data collection is only effective at predicting $V_s$ to a depth of approximately 30 m below grade, consistent with the observations of

Table 3. *A summary of the lithology listed by deposit type and location.*

| Deposit | Locale | Lithology |
|---|---|---|
| Cultural | Western Pennsylvania | Spoil below coal surface mine high wall |
| | Central Arizona | Dynamically compacted construction and demolition debris |
| Glacial | South-central Kansas | Till |
| | Central Saskatchewan | Till; fluvial |
| | Central Ontario | Till, fluvial, lacustrine clay |
| | North-central North Dakota | Till, fluvial, lacustrine clay |
| Fluvial | South-central Puerto Rico | Fluvial, alluvial |
| | Central Pennsylvania | Fluvial |
| Aeolian | Southeastern Washington | Aeolian |
| | Texas Panhandle | Aeolian, fluvial |

Xia et al. (2002). Passive MASW methods of data collection have proven effective at the prediction of $V_s$ to a depth of approximately 70 m below grade (Ivanov et al., 2008).

## ANALYSIS

The data utilized within this article were derived from many studies that specifically addressed a depth range of at least 30 m below grade. Consequently, some of the disparities at depth can be attributed to lithologic attenuation of Raleigh waves, from too tight a survey geometry, and from the magnitude of the source.

Four different depositional environments were used for this study. Changes in geometry and magnitude of the elastic shock wave will produce deeper data. The cultural deposit consists of anthropogenic fill, whereas the other three units—glacial, fluvial, and aeolian deposits—represent *in situ* conditions. Several examples from each deposit are used to compare and contrast the $V_s$ values as derived from *N*-values and from MASW.

The regression equations from Imai and Tonoughi (1982) and Inazaki (2006) were used to convert *N*-values to $V_s$ for 10 sites in North America (Table 3). These two values for $V_s$ were then averaged and compared to MASW-derived $V_s$ for borings at two sites at 10 locales.

### Cultural Deposits

Cultural deposits are an important part of urban development. As brownfields are brought back into use, on-site buried waste material can be a challenge for the developer. Construction and demolition debris (C&D) and mining spoil are common urban deposits encountered during development; however, municipal solid waste landfills are often used after closure as parks and other low-impact facilities (Hutchinson and Spieler, 1998; Hutchinson and Barta, 2003).

In general, C&D and mine spoil consist of a bimodal distribution of particle sizes. These deposits can contain cement or rock fragments that are several meters across mixed with sand-sized particles and multi-dimensional wood waste. Representative blow counts in C&D waste can be difficult to collect as buried concrete and brick can induce abnormally high blow counts. A well log, reviewed by the authors, documented the presence of a thick concrete slab at 15 m below grade with concomitant elevated SPT-generated $V_s$ (Figure 3 A). MASW images the cultural waste as a unit and does not respond to discrete large objects in its analysis; consequently, no spike in the $V_s$ is observed at 15 m below grade (Figure 3A).

The $V_s$ derived from the MASW is in general higher than that derived from SPT for mine spoil and C&D waste (see, for example, Figure 3A through C). The lower SPT values can be attributed to the split spoon tendency to find its way through the softer material (i.e., low *N*-values) until encountering rock or large refractory material. The MASW measurements in both coal mine spoil examples are roughly 300 m/s, showing that the readings represent inter-particulate contact (i.e., cement, rock, abandoned machinery, etc.) and may be more representative of the spoil dynamic properties.

After dynamic compaction of C&D waste, SPT-derived $V_s$ values can be consistent with MASW data (Figure 3C and D). In this example, the pre-compaction SPT-derived $V_s$ (Figure 3C) is lower than that derived from MASW measurements prior to dynamic compaction. After dynamic compaction the SPT- and MASW-derived $V_s$ track closely until about 10 m below grade, where the two readings diverge (Figure 3D). Greater than 10 m below grade (Figure 3C), the SPT-derived $V_s$ is consistently less than the MASW-derived $V_s$, suggesting that dynamic compaction impacted the material to a depth of 10 m below grade (Figure 3D).

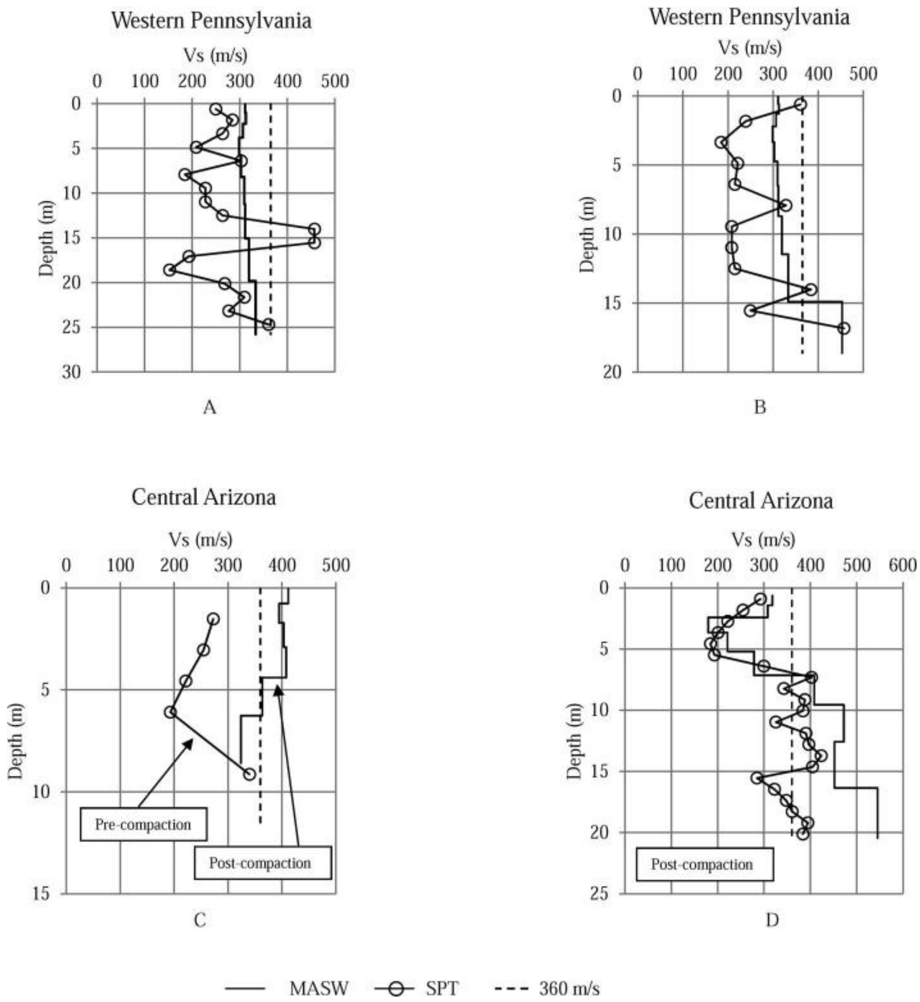


Figure 3. Velocity versus depth profiles for coal mine spoil from western Pennsylvania and C&D waste from central Arizona. Diagram C shows pre-compaction SPT-derived $V_s$ with post-compaction MASW-derived $V_s$. Diagram D shows post-compaction SPT- and MASW-derived $V_s$.

## Glacial Deposits

Glacial deposits consist of poorly sorted till, lacustrine clay, and fluvial sediments. Fine-grained aeolian and loess (i.e., wind-blown) deposits can also be glacially derived; however, this deposit is addressed separately as a result of the homogeneous nature of these sediments. Till with intercalated fluvial deposits are poorly sorted and can contain cobble or large-sized fragments. In general, the $V_s$ derived from SPT measurements are consistent with those derived from MASW measurements (Figure 4A through F).

Several examples of divergence do exist between SPT- and MASW-derived $V_s$ values, however (Figure 4B, C, and F). These differences fall into three categories based upon depth of the measurement (shallow and deep) or lithology. Lacustrine deposits contain a large percentage of water that could be suppressing the MASW-derived $V_s$ measurement in comparison to the $V_s$ derived from SPT: for example, the lake clay found 4 to 7 m below grade (Figure 4B) and that found 8 to 9 m below grade (Figure 4D).

Divergence also tends to occur at depths of greater than 10–15 m, where MASW can be weakest in its prediction of $V_s$ based upon the project-derived MASW data collection methodology (Figure 4B, C, and F). The divergence typically shows the MASW prediction of $V_s$ to be less than that derived by the SPT method (Figure 4C and F). However, MASW can predict a $V_s$ greater than that predicted by SPT methods at depths of greater than 10 m (Figure 4B).

This disparity can be attributed to the geometry of the survey (1.5-m geophone step-out distance), to the magnitude of initiated elastic shock wave (via 3.75-kg sledge hammer), and possibly due to lithologic contrasts. A larger step-out distance and heavier weight source would probably resolve this difference.

In most cases, the $V_s$ values derived from both methods in the shallow portion of each test site are consistent (Figure 4C). In this case, the disagreement

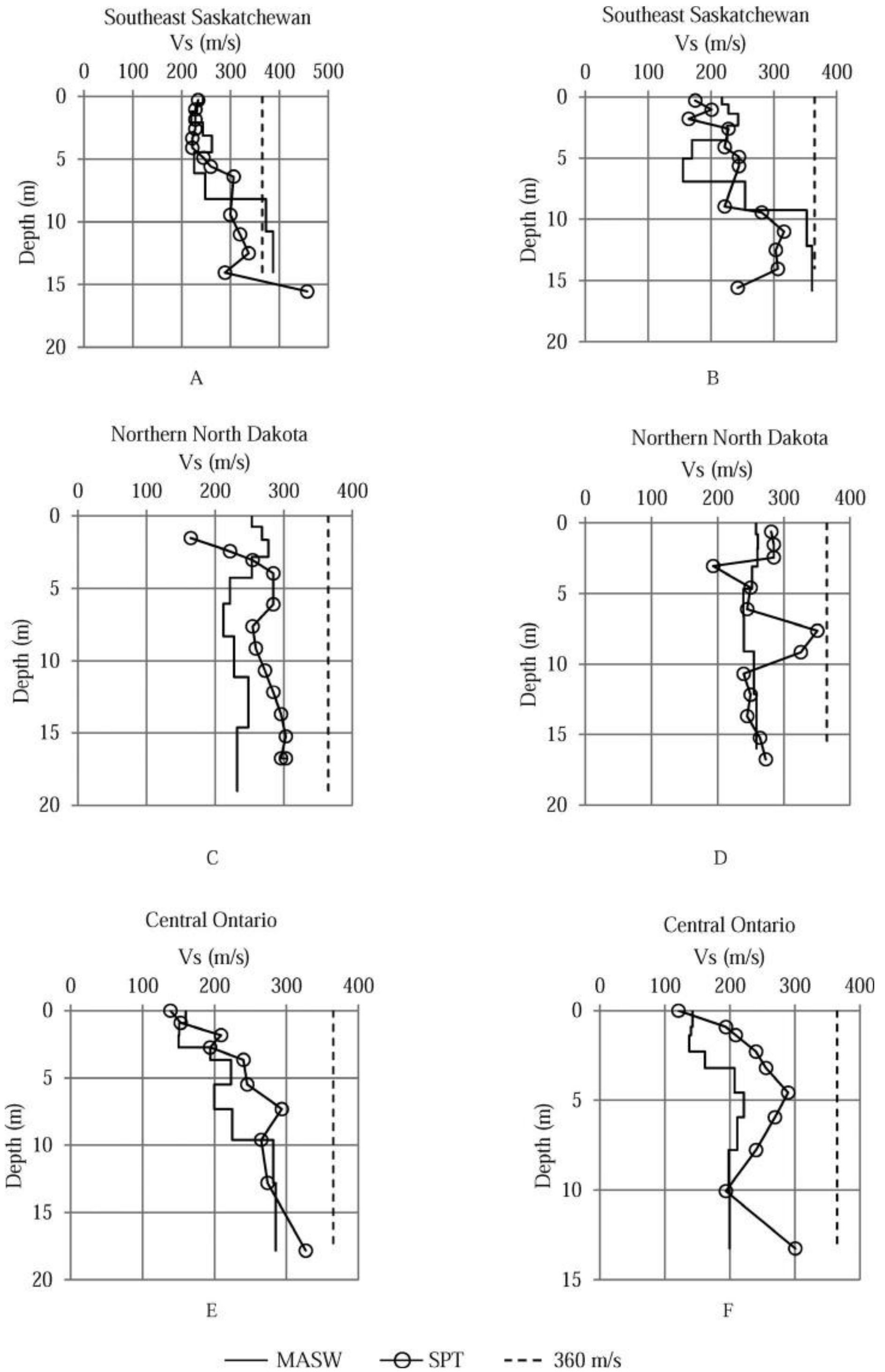


Figure 4. Velocity versus depth profiles of glacial deposits from the United States (North Dakota) and Canada (Saskatchewan and Ontario).

between the two methods is probably related to poor SPT interval measurement (five blow counts) and weight on bit, as near-surface MASW-derived estimates of $V_s$ are usually very reliable indicators of true $V_s$ (Park, 2014).

## Fluvial Deposits

Fluvial deposits are poorly sorted and consist of sand- to cobble-sized particles intercalated with overbank clay and silt. In general, MASW-derived $V_s$ values are equivalent to those derived from SPT

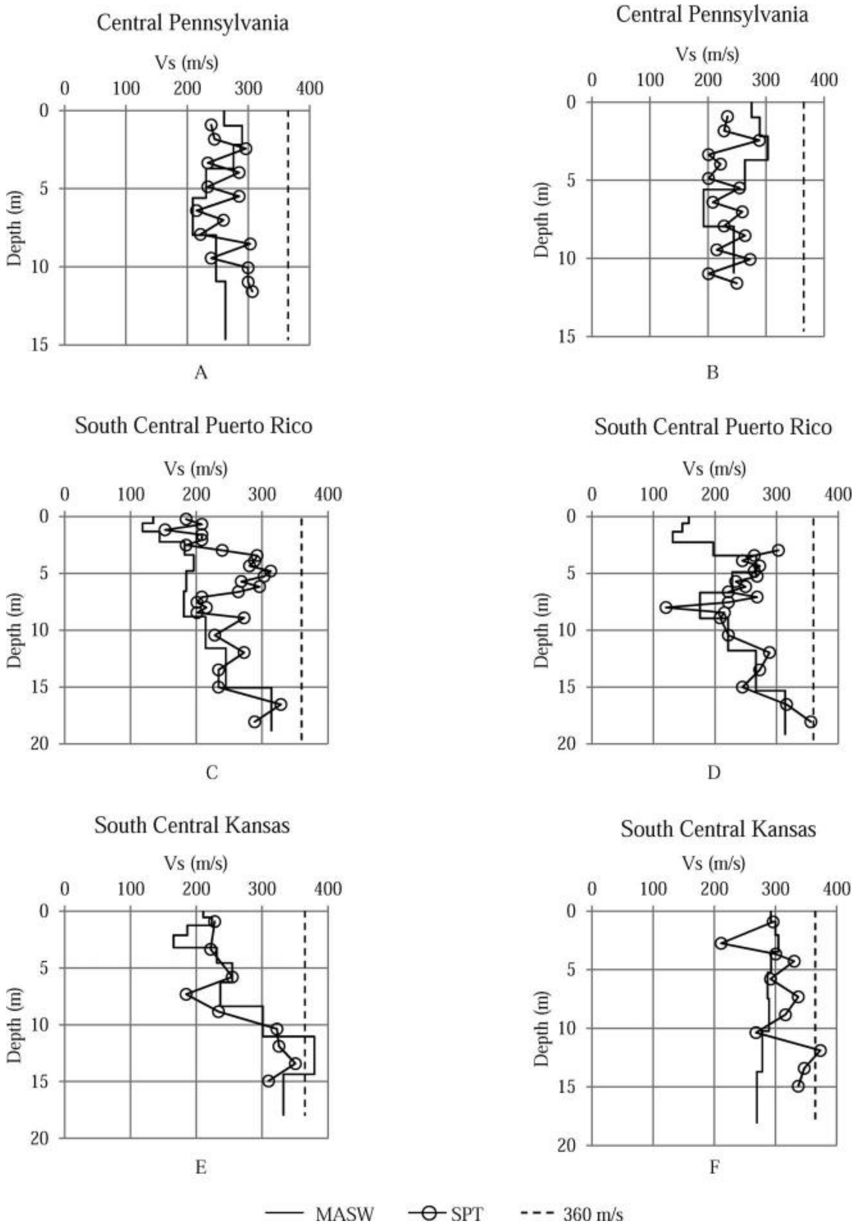


Figure 5. Velocity versus depth profiles of fluvial deposits from central Pennsylvania, south-central Puerto Rico, and south-central Kansas.

measurements (Figure 5A through F). This equivalence can exist to a depth of 20 m below grade; however, agreement can be weak greater than 10 m below grade as a result of lithology, survey geometry, and magnitude of initiated elastic shock wave (Figure 5A and F).

Any variation with the SPT- and MASW-derived $V_s$ values can be attributed to large fragments within poorly sorted units. For example, large cobbles were encountered in an example from Puerto Rico (Figure 5C) between 4 and 6 m below grade. MASW-derived $V_s$ did not reflect the increased $V_s$ due to the bimodal distribution of the sediment size, measured as a unit and not as an individual particle.

## Aeolian Deposits

Aeolian deposits consist of very well-sorted wind-blown sand and silt. Typically the SPT- and the MASW-derived $V_s$ values are very consistent (Figure 6A through D). Similar to the comparison for glacial deposits, there can be divergence between the two measurements in the shallow and deep portions of the site. The shallow divergence is typically not too great, with the MASW-derived $V_s$ slightly higher than the SPT-derived $V_s$ (Figure 6B and D). In addition, the deep divergence is not too great, with the MASW-predicted $V_s$ slightly greater than the SPT-derived $V_s$ (Figure 6D).

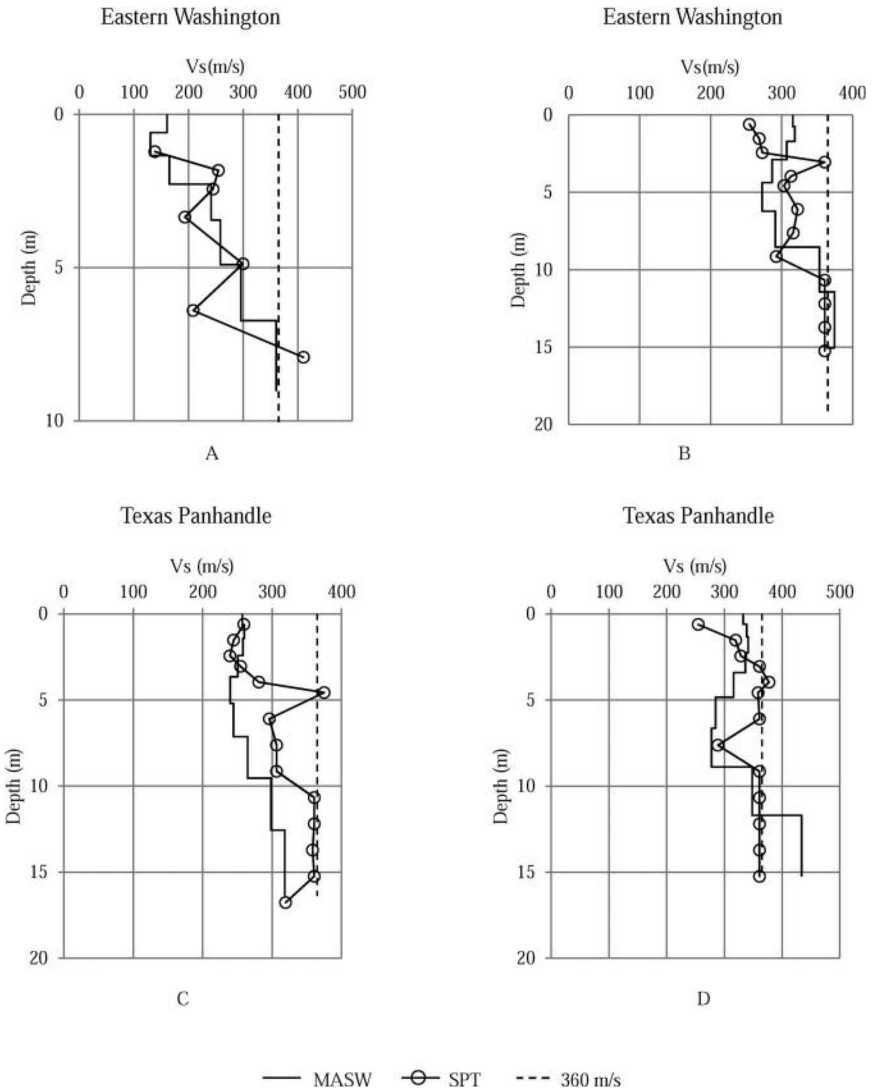


Figure 6. Velocity versus depth profiles for aeolian deposits from the southeastern Washington State and the Panhandle of Texas.

Lithologic and clast size differences have a dramatic effect on the prediction consistency of the two methods. Borehole logs for Figure 6B and C indicate that these borings penetrated a fluvial unit at 3 m and 4.75 m, respectively. The lithologic change from well-sorted aeolian to poorly sorted fluvial deposit, with its concomitant coarse-sized fraction, attributed to the divergence in $V_s$ measurements. Consequently, well-sorted and probably finer-grained deposits produce more consistent $V_s$ predictions between the MASW and SPT methods.

## CONCLUSION

SPT data conversion to $V_s$ encompasses numerous formulas to express the relationship, many of which are not reasonable in predicting $V_s$. Furthermore, the *N*-values are an analog method of data collection, through which continuous information is not collected. Low *N*-values (i.e., $<6$) are very insensitive to $V_s$ prediction where there is a significant change with every blow count. Moreover, *N*-values greater than 30 blow counts produce a narrow $V_s$ range, leading to imprecise data. Large objects are not detected by MASW methods, yet the SPT method can produce spuriously high readings for the depth zone in which the large object is encountered.

The MASW method continuously collects data, providing a digital representation of $V_s$ throughout the entire depth of investigation, which, in the cases presented within this study, are limited to approximately 20 m below grade. MASW- and SPT-derived $V_s$ values tend to diverge at approximately 20 m below grade; however, it is unclear which method produces more accurate readings. The limitation on depth of detection is due to the attenuation of

Rayleigh waves with depth. The attenuation of Raleigh waves can be ameliorated by expanding the survey and increasing the source magnitude. However, lithology is also a factor in the attenuation of Raleigh waves, and there is no adjustment for this.

$V_s$, derived from MASW testing, is more sensitive to subsurface lithologic changes and should be included within every soil dynamic geotechnical study of the subsurface. Homogeneous (and possibly isotropic) deposits within the sand-sized fraction of a deposit produce consistent $V_s$ values between MASW- and SPT-derived methods.

Shear wave velocity measurements from these two methods can show some disagreement in poorly sorted deposits. However, these differences are not that significant and can be minimized by the collection of more MASW tests in the area.

These two test methods are complimentary, and while SPT is the "Engineering Standard," 20–30 MASW tests can be collected for every boring. So in this regard, the two tests are complementary, and each contains strengths and weaknesses, so using both methods is recommended.

## ACKNOWLEDGMENTS

The authors would like to thank all of the engineers and geologists who have contributed well logs for the MASW we have collected. In many cases these data were proprietary to the client and sometimes great effort was applied to obtain approval for the release of the corresponding well logs. We would like to thank the good people of RES-Americas, Pattern Energy, Terracon, CMT Laboratories, and Tulloch. Engineers and geologists who have helped collect well logs include Mohamed Nofal, Jordan Black, Michael Ehss, Richard Gray, Lloyd Pasley, Shad Hoover, and James Dermody, and for this we owe a big debt of gratitude.

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