The paper was published in the proceedings of the 11th Australia New Zealand Conference on Geomechanics and was edited by Prof. Guillermo Narsilio, Prof. Arul Arulrajah and Prof. Jayantha Kodikara. The conference was held in Melbourne, Australia, 15-18 July 2012.

Pseudo-N-value from the S-wave velocity: a proposal for communication between engineers and geophysicists

K. Suto[1]

[1]Terra Australis Geophysica Pty Ltd., 52 Nestor Avenue, Bardon, Queensland, 4065, AUSTRALIA;
PH (07) 3876-3848; email: koya@terra-au.com

ABSTRACT

The S-wave velocity is a one of the physical parameters to describe competence or hardness of the ground. It is estimated by the seismic survey particularly Multichannel Analysis of Surface Waves (MASW). In geotechnical engineering, competence of the ground is traditionally described by the *N*-value directly measured by the standard penetration test (SPT). While the physical significance of the *N*-value is tenuous, it has long established in the geotechnical field. Soil classification is based on this parameter and authorities use it as a standard means of description of strength of soil.

While the SPT provides point data at a drilling location measured with a large rig, the seismic survey can achieve data collection from the surface along a line; and cover an area by several lines. This allows mapping of S-wave velocity distribution in the 2-dimensional and 3-dimensional spaces. If the S-wave velocity is converted to the *N*-value, soil classification map can be generated easily with much higher sampling density.

Nearly thirty authors in the past attempted to relate the S-wave velocity and the *N*-value in great details. However, these attempts inevitably had considerable error bars. This paper propose a simple formula: $Vs = 60N^{0.4}$ or its reciprocal $N = (Vs/60)^{2.5}$ and to call it "*pseudo-N-value*". The validity of this formula is examined in reference to the actual measurements.

The *pseudo-N-values* are expressed in the 2-dimensional cross sections or 3-dimensional data volumes. These displays help geotechnical engineers understand geophysical data.

Keywords: S-wave velocity, N-values, Seismic Survey, MASW, Ground competence.

1. INTRODUCTION

The multichannel analysis of surface waves (MASW) method (Park, *et al*., 1999) is a seismic method to investigate the competence of the ground. It utilises the surface waves and estimates distribution of S-wave velocity. This is a physical property of the ground material with the dimension metres per seconds (m/s) in the SI unit. It is closely related to Young's modulus, an elastic parameter commonly described in mega-Pascal (MPa).

The S-wave velocity distribution obtained by MASW method is useful in many aspects in the geotechnical investigation. Recent applications of the MASW method in Australia include: estimating the depth of the natural surface and bedrock under tailings dam (Suto *et al*., 2006), rippability study for excavation for pipeline (Suto, 2007); monitoring ground improvement for construction site (Suto and Scott, 2009) and estimating the depth of the natural surface and bedrock in a rubbish dump (Suto and Lacey, 2011).

The standard penetration test (SPT) is a traditional method to estimate the competence of the ground. Although it is expressed in digits, the N-value is essentially an analogue qualitative indicator with little analytical relationship with "real" physical property of the soil. However, the N-value is well established its position among the geotechnical engineers and it is often referred to in assessing the ground characteristics for building sites by the soil classification schemes.

Relationship between the SPT N-value, the "traditional" hardness indicator, and the S-wave velocity from physical measurements has been attempted by a number of authors (Imai, *et al*., 1975 for example). Bellana (2009) compiled about 30 empirical formulas from the various studies. All of these empirical formulas are expressed in the form of:

$$V_s = aN^k \ , \qquad (1)$$

where *a* and *k* are constants empirically determined by fitting a line to the cross plots of the N-values (*N*) and the S-wave velocity (*Vs*) in the log-log space.

S-WAVE VELOCITY AND YOUNG'S MODULUS

The MASW seismic survey is developed for and increasingly used in the ground investigation in construction projects. It outputs subsurface distribution of the S-wave velocity. The S-wave velocity is indicative of the competence of the ground.

There is an analytical relationship between S-wave velocity and Young's modulus (E) with the contribution of density (ρ) and Poisson's ratio (ν):

$$E = 2\rho Vs^2(1+\nu) \qquad (2)$$

Equation (2) evaluates Young's modulus approximately 100MPa and 300MPa for corresponding S-wave velocity 150m/s and 250m/s are considered to be equivalent to the property of a competent ground and a typical bed rock in sedimentary basins, respectively(Suto, 2007).

GROUND COMPETENCE AND N-VALUES

Soil classification systems have been developed in various companies and standards exist in several ways. Typically competence level of the soil is expressed by descriptive words and corresponding SPT N-values. Amongst them one documented in the Department of Main Roads, Queensland Government of Australia is quoted here (Table 1). This seems to be representative of the standard commonly accepted by the industry.

Table 1 Soil Classification by Department of Main Roads, Queensland

Essentially Cohesive Soils		Essentially Non-Cohesive Soils	
Terms	**SPT N Value**	**Terms**	**SPT N Value**
Very soft	0-2	Very loose	0-4
Soft	2-4	Loose	4-10
Firm	4-8	Medium dense	10-30
Stiff	8-15	Dense	30-50
Very stiff	15-30	Very dense	>50
Hard	Hard>30		

From Table 1, SPT N-value about 10 appears to correspond to a level of "reasonably competent" material in both cohesive and non-cohesive soils. However, the property expressed in word is vague and there is a range of the SPT N-values for each descriptive word. The boundaries of these classes appear quite arbitrary and they do not seem to have much quantitative significance: *i.e.* the soil with N=4 is not twice as competent as one with N=2. Therefore, these values and the corresponding descriptive terms cannot be used any more than an indicator of competence.

RELATIONSHIP BETWEEN THE S-WAVE VELOCITY AND THE N-VALUE

Many researchers studied the relationship between the S-wave velocity and the SPT N-value. Imai *et al.* (1975) is among the oldest, and his graph is often quoted in the textbooks and manuals. This paper displays a scatter plot between the N-values and the

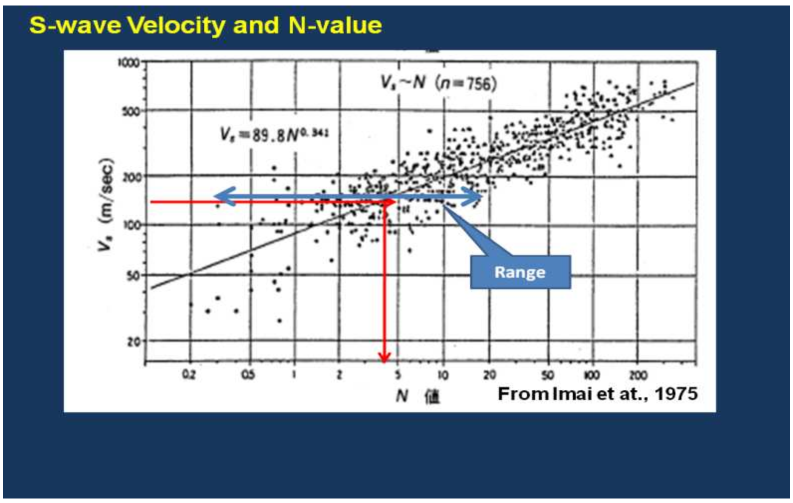


Figure 1. Vs-N plot from Imai et al. (1975), lines superimposed to show error range.

S-wave velocity, and a fitted line with its empirical equation (Figure 1). While there is a clear correlation between the S-wave velocity and N-values, the scatter or deviation from the fitted line is considerable. In Figure 1, the N-value corresponding to *Vs*=150m/s according to the fitted line is about 4, but its possible range is as large as from 0.3 to 20. The scatter diagrams of the *Vs-N* values are biased by the samples the authors dealt with, and it depends on soil type, age, burial depth, and other environmental parameters. Consequently, authors reached various empirical equations. Bellana (2009) collected 28 empirical equations (Table 2). This table again shows a considerable range in *a* and *k* of equation (1).

Table 2. Vs-N relationships by various authors

Author(s)	I.D.	All soils
Shibata (1970)	A	-
Ohba and Toriuma (1970)	B	$V_s = 84\ N^{0.31}$
Imai and Yoshimura (1975)	C	$V_s = 76\ N^{0.33}$
Ohta et al (1972)	D	-
Fujiwara (1972)	E	$V_s = 92.1\ N^{0.337}$
Ohsaki and Iwasaki (1973)	F	$V_s = 81.4\ N^{0.39}$
Imai et al (1975)	G	$V_s = 89.9\ N^{0.341}$
Imai(1977)	H	$V_s = 91\ N^{0.337}$
Ohta and Goto (1978)	I	$V_s = 85.35\ N^{0.348}$
Seed and Idriss (1981)	J	$V_s = 61.4\ N^{0.5}$
Imai and Tonouchi (1982)	K	$V_s = 96.9\ N^{0.314}$
Sykora and Stokoe (1983)	L	-
Jinan (1987)	M	$V_s = 116.1\ (N+0.3185)^{0.202}$
Okamoto et al (1989)	N	-
Lee (1990)	O	-
Athanasopoulos (1995)	P	$V_s = 107.6\ N^{0.36}$
Sisman (1995)	Q	$V_s = 32.8\ N^{0.51}$
Iyisan (1996)	R	$V_s = 51.5\ N^{0.516}$
Kanai (1966)	S	$V_s = 19\ N^{0.6}$
Jafari et al (1997)	T	$V_s = 22\ N^{0.85}$
Kiku et al (2001)	U	$V_s = 68.3\ N^{0.292}$
Jafari et al (2002)	V	-
Hasancebi and Ulusay (2006)	W	$V_s = 90\ N^{0.309}$
Ulugergerli and Uyanık (2007)	X	$^{a}V_{SU} = 23.291\ Ln(N)+405.61$
Ulugergerli and Uyanık (2007)	Y	$^{b}V_{SL} = 52.9\ e^{-0.011N}$
Dikmen (2009)	Z	$V_s = 58\ N^{0.39}$
Pitilakis et al. (1999)	AA	-
Hasancebi and Ulusay (2006)	AB	$V_s = 104.79(N_{60})^{0.26}$

From Bellana (2009)

INTEGRATING THESE INFORMATION

As discussed earlier, an approximate correspondence between *Vs*=150m/s, *E*=100MPa and *N*=10 can be postulated for a "competent" material. Even using this relationship as a control point for an empirical equation, many combinations of *a* and *k* are possible: in fact, infinite number of combinations.

From Table 1, the range of *a* is from 19 to 132 and *k* from -0.11 to 0.73; both are large. This perhaps indicates an expectation for a global equation is unreasonable. As the scatter range of the data itself is quite large, fitting a line with several significant digits is not considered appropriate. After several trials, simple conversion formulae between the SPT N-values and S-wave velocity are proposed as:

$$V_s = 60N^{0.4} \qquad (3)$$

and its reciprocal:

$$N = \left(\frac{Vs}{60}\right)^{2.5}. \qquad (4)$$

The line of equation (3) and (4) is plotted with the formulae of previous authors collected by Bellana (2009) and shown in Figure 2, which demonstrates a reasonable agreement with previous formulae.

The N-values thus calculated from the S-wave velocity is subject to a possible range of error. As this calculated N-value is not the value traditionally obtained by the standard in-situ method, it may not be appropriate to call it N-value. So the term "**pseudo-N-value**" is proposed to describe this parameter calculated from the S-wave velocity.

USE OF PSEUDO-N VALUES

Using equation (4), the S-wave velocity from an MASW survey can be converted to the pseudo-N-values, and it can be displayed in the form of a section. Although this value has a considerable error range, it is not any worse than the empirical formulae proposed by the previous authors.

An example of use of pseudo-N-value sections is in Figures 3. The colour scheme for the pseudo-N-value section is made to match the soil classification of the Queensland Government. This enables to express soil classification from S-wave velocity.

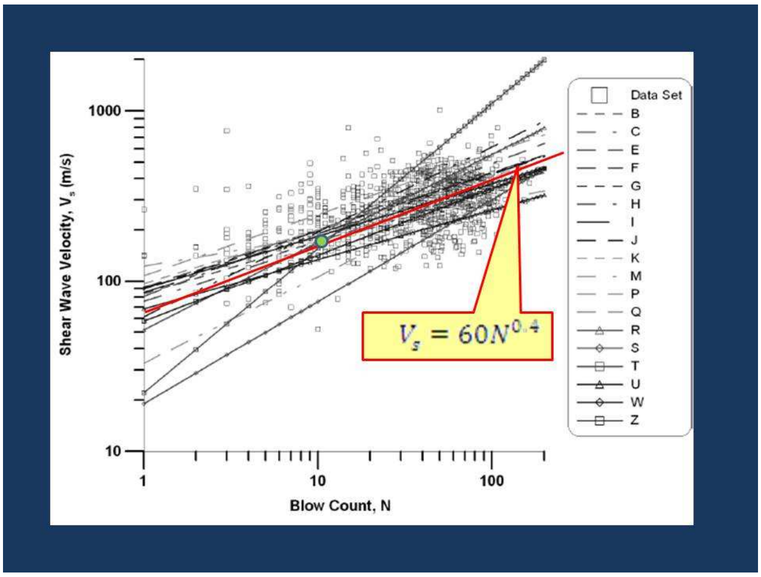
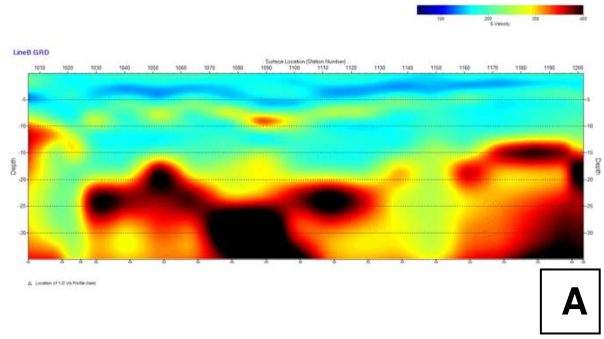
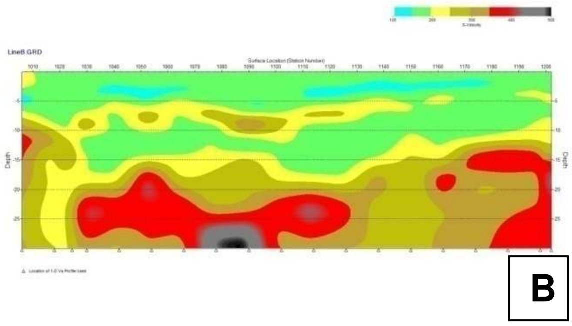
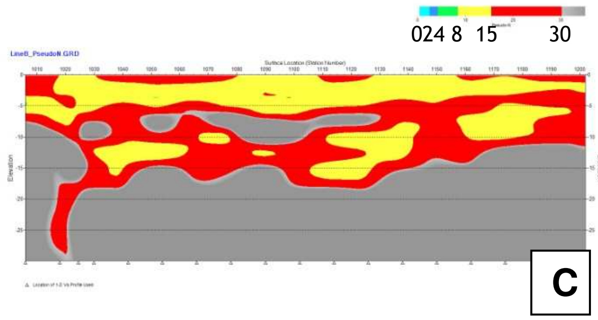


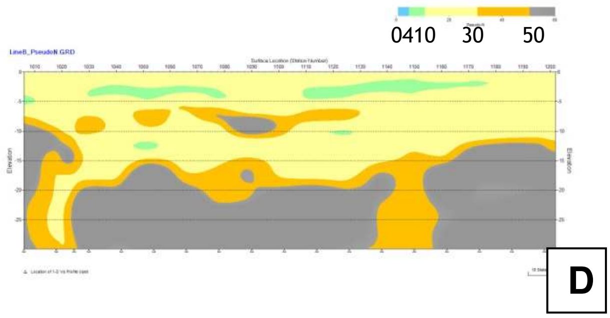
Figure 2. Vs-N plot Bellana (2009) Superimposed with line of the proposed equation in red.







Essentially Cohesive Soils		
Terms		**SPT N Value**
Very soft	(light blue)	0-2
Soft	(blue)	2-4
Firm	(green)	4-8
Stiff	(yellow)	8-15
Very stiff	(red)	15-30
Hard	(grey)	>30



Essentially Non-Cohesive Soils		
Terms		**SPT N Value**
Very loose	(light blue)	0-4
Loose	(green)	4-10
Medium dense	(light yellow)	10-30
Dense	(orange)	30-50
Very dense	(grey)	>50

Figure 3. An example of S-wave and pseudo-N-value sections. A: Full spectrum Vs section; B: Vs section with step-wise colour. C: Pseudo-N-Value section for cohesive soils. D: Pseudo-N-Value section for non-cohesive soils

In this example, Figures 3C and 3D are pseudo-N value sections in terms of essentially cohesive and non-cohesive. These are indicative of the N-values which are more familiar to the geotechnical engineers than the S-wave velocities presented in Figures 3A and 3B. By displaying the S-wave velocity converted to the pseudo-N values, the engineers can visualise the nature of the soils in their familiar terms. Then it is readily useable in their own projects. However, it is important to understand the pseudo-N values are not *exactly* the same as the N-values actually measured by SPT, but it is an estimate subject to an error range.

CONCLUSION

A simple formula to relate the S-wave velocity and N-value is proposed and the N-value thus calculated is to be called "pseudo-N-value". The properties of the pseudo-N-value are summarised as:

- Pseudo-N-values are not measured by the penetration test, but calculated from the S-wave velocity. It is an indicator of the N-value, although it is not *exactly* the same as the SPT N-value.
- There is one-to-one relationship between the pseudo-N-value and the S-wave velocity.
- Young's modulus can be calculated from the pseudo-N-value for combination of density and Poisson's ratio (Table 6).
- With pseudo-N-value, more quantitative analysis of the ground competence is possible, which cannot be achieved with the conventional SPT N-value.
- Pseudo-N-value is a parameter for communication with the engineers who are familiar with the N-value. The primary indicator of competence is the underlying S-wave velocity.

ACKNOWLEDGEMENTS

The author thanks to Mr James Tayler of EarthSolve, Mr Craig Johnson of SKM and Dr Jun Sugawara of Golders Associate for discussion during this study. A part of this work has been presented in the 73rd Conference of the European Association of Geoscientists and Engineers in Vienna 2011 (Suto, 2011).

REFERENCES

Bellana, N. (2009): Shear wave velocity as function of SPT penetration resistance and vertical effective stress at California bridge sites, Master's Thesis, UCLA.

Imai, T, Fumoto, H and Yokota K: Elastic wave velocity and mechanical properties of soil in Japan (*in Japanese)*, Proc.5th Japan Earthquake Engineering Symposium.

Park, C B, Miller R D and Xia, J (1999): Multichannel analysis of surface waves, *Geophysics* **64,** pp 800-808.

Suto, K (2007): Multichannel Analysis of Surface Waves (MASW) for investigation of ground competence: An introduction. *Proceedings of the Sydney Chapter 2007 Symposium,* Australian Geomechanics Society, pp71-81.

Suto, K (2011): Pseudo-N-value from the S-wave Velocity – A proposal for Communicating with the civil engineers, *Proceeding of the 73rd EAGE Conference & Exhibition incorporating SPE EUROPEC 2011Vienna, Austria, 23-26 May 2011* (CD)

Suto, K and Lacey, D (2011): An Application of multi-channel analysis of surface waves (MASW) to a landfill site: A case history, *Proceedings of the 10th SEGJ International Symposium, Kyoto, 2011.*

Suto, K and Scott, B (2009): 3D treatment of MASW data for monitoring ground improvement at an uncontrolled fill site, *Proceedings of 20th ASEG Conference and Exhibition, Adelaide, February 2009,* (CD)

Suto, K, Wake-Dyster, K and Li, H (2006): A search for distribution of competent layers under tailings by Multi-channel Analysis of Surface Wave (MASW): A case history, *Proceedings of the Australian Earth Sciences Convention 2006, Melbourne, Australia 2-8 July 2006* (CD)