The paper was published in the proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering and was edited by Mizanur Rahman and Mark Jaksa. The conference was held from May 1st to May 5th 2022 in Sydney, Australia.

Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)
© 2022 Australian Geomechanics Society, Sydney, Australia, ISBN 978-0-9946261-4-1

Prediction of shear wave velocity Vs from PMT

Prévision de la vitesse des ondes de cisaillement Vs à partir du PMT

Philippe Reiffsteck
Université Gustave Eiffel, France, philippe.reiffsteck@ifsttar.fr

Catherine Jacquard, Eric Jandel, Eric Petitjean
Fondasol, France

Jean Benoît
UNH, New Hampshire, USA

ABSTRACT: Shear wave velocity is a dynamic soil property commonly used for dynamic site response and site classification for seismic design. The paper examines the correlations to obtain reliable estimates of the shear wave velocity V_S from pressuremeter testing (PMT) compared to other correlations. While the direct measurement of Vs is obviously preferable, these correlations can be useful in various circumstances. Experimental results from many international research sites and real construction projects suggest that pressuremeter predictions of Vs from the Menard modulus is reliable, and some formulas are proposed, as well as a proposal of site classification for seismic design is given.

RÉSUMÉ : La vitesse des ondes de cisaillement est une propriété dynamique du sol couramment utilisée pour la réponse dynamique du site et la classification pour la conception sismique. La communication examine les corrélations pour obtenir des estimations fiables de la vitesse de l'onde de cisaillement V_S à partir des essais au pressiomètre Ménard. Bien que la mesure directe de V_S soit évidemment préférable, ces corrélations peuvent s'avérer utiles dans diverses circonstances. Les résultats expérimentaux obtenus sur de nombreux sites de recherche internationaux et des projets réels suggèrent que les prédictions de V_S par le pressiomètre à partir du module Ménard sont fiables (PMT); des formules de corrélation sont proposées ainsi qu'une classification des sites à partir des valeurs pressiométriques pour la conception sismique.

KEYWORDS: seismic design, PMT, Vs, geotechnical feedback.

1 INTRODUCTION.

This paper examines the correlations developed to estimate the shear wave velocity, V_s, from pressuremeter tests (PMT). While the direct measurement of V_s is preferable, such correlations are useful tools in seismic design.

The pressuremeter test is the only conventional in situ test that provides a full stress-strain relationship from an expanding cylindrical cavity in soils. Other tests such as the DMT provide a unique value at a standard displacement while other tests such as the CPT or the SPT offer fully empirical correlations. This PMT relationship is obtained whether the probe is inserted in a prebored hole, is self-bored and or pushed-in. The insertion methods only impact the initial stage of the test.

This paper presents the most widely used relationships between shear wave velocity obtained from various soil investigation techniques and compares their prediction against results at well-documented sites and studies. More specifically, the comparisons involve direct measurements of V_s via Cross-hole or MASW type tests and correlations from SPT and PMT. Based on these comparisons, new correlations using two databases are proposed.

2 V_S DERIVED FROM IN SITU TESTS

2.1 Wave propagation tests3

Several techniques are available to measure the velocity of shear waves of subsurface deposits. The reference test for measurement of shear wave velocity is the cross-hole. In this test, measurements are determined between two or three boreholes 4 to 10 m apart, where the compression (V_p) and shear (V_s) wave velocities are obtained directly between a transmitter and a receiver located at the same depth in the boreholes. These seismic geophysical tests induce shear strains lower than about 3.10^{-4} %, and thus the measured shear wave velocities can be used directly to compute G_{max}, the shear modulus at a very small strain level, for the analysis of the dynamic behavior of structures (Figure 1).

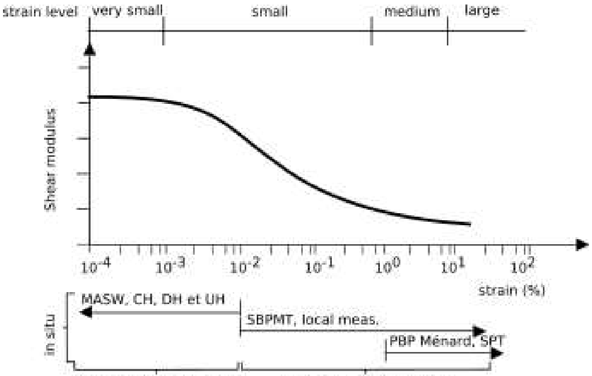

Figure 1. Strain range of the different tests

The following relationship from elastic theory is used to derive the shear modulus from the shear wave velocity:

$$G_{max} = \rho . V_s^2 \tag{1}$$

with G_{max} the shear modulus (Pa or kg.m/s²), ρ the soil density (kg/m³) and Vs the shear wave velocity (m/s).

In addition, the Poisson ratio □□can be derived from the measurement of compressive and shear wave velocities:

$$\nu = \frac{V_p^2 - 2 \times V_s^2}{2(V_p^2 - V_s^2)} \tag{2}$$

Hence the maximum Young modulus is obtained using:

$$E_{max} = 2(1+\nu) \cdot G_{max} \tag{3}$$

If possible, the soil density is determined on intact samples from a drill core or empirically using various in situ tests such as the SPT and the CPT. Otherwise, estimates can be made based on soil compactness, between 1 700 and 2 100 kg/m^3.

All other types of seismic ground investigation techniques indirectly determine V_S. The following paragraphs focus on two of those techniques, the standard penetration test (SPT) and the Ménard pressuremeter test (PMT).

2.2 *Standard penetration test (SPT)*

The SPT is a dynamic penetration test carried out from the bottom of a borehole and is used extensively in conventional geotechnical practice. Numerous correlations are available to derive a shear wave velocity from the number of blows, N_{SPT}, needed to drive the sampler 30 cm (one foot) into the ground. Hanumantharo and Ramana, (2008) have collected 45 Vs-N correlation from the literature summarizing Japanese, North American, Greek and other practices. The relationship has the following general form:

$$V_s = \alpha \cdot {N_{SPT}}^{\beta} \tag{4}$$

with correlation coefficients α between 100 and 360, and β between 0.6 to 0.8. Unfortunately, not all N-values are corrected for energy and overburden stress to a normalized value $(N_1)_{60}$.

Theses V_s - N_{SPT} correlations reported in engineering practice and literature are summarized in Table 1. It is important to note that different interpretations of N have been used by some authors: initially the energy ratio of SPT equipment was around 60%, whereas now it is very often between 70 and 80%. Relations gathered by the authors are mostly not normalized for energy and therefore should be used with caution.

Table 1. Correlation coefficients for eq. (4)

Geotechnical material	α	β	Author(s)
Very dense gravel	100	0.29	Sykora et Stokoe, 1983
Loose to medium dense cohesionless soil	100	0.24	Raptakis et al., 1995
Hard clay	357.5	0.19	Raptakis et al., 1995
Soft to firm cohesive soils	132	0.27	Pitilakis et al., 1992
Softs clay, silts	165.7	0.19	Pitilakis et al., 1992

2.2 *Ménard Pressuremeter test (PMT)*

The pressuremeter expansion test results in a complete stress-strain relationship over a wide range of strain. As shown in Figure 1, the intermediate strain modulus obtained from the PMT is proportional to the small strain modulus from S-wave velocity measurements.

A correlation between intermediate strain and low strain moduli has been developed based on geophysical surveys. Several authors have published correlations or charts between G_{max} and pressuremeter tests results obtained in calibration chamber tests or field measurements (Byrne et al., 1991; Amar et al., 1995).

Two types of correlations are currently used:

- a direct correlation linking shear modulus with E_M, the Ménard pressuremeter modulus
- an indirect correlation involving an initial correlation between E_M and N_{SPT}, and then a second correlation between N_{SPT} and Vs.

Ménard and Rousseau (1962) have proposed to link the Ménard modulus to a small strain modulus relationship later improved by Semblat and Pecker (2009 as shown in equation 5).

$$G_{max} = \lambda \cdot E_M \tag{5}$$

with λ a dimensionless parameter. Using eq. (1) and (5) yields eq. (6):

$$V_s = (\rho)^{-0.5} \cdot (\lambda \cdot E_M)^{0.5} \tag{6}$$

Table 2 gives the range of the density ρ, Ménard modulus E_M and λ to estimate the shear wave velocity. The correlations carried out either on very compact soils or rocks, or on soils of low compactness, give very different results. This difference can be explained by the use of the shear modulus decay laws. In the case of very compact soils, a lower strain range is observed. It should be noted that these correlations are only applicable to normally consolidated soils.

Table 2. Concordance between Ménard modulus and range of eq.(6) parameters.

Geotechnical material	ρ *(kg/m^3)*	pl^* *(kPa)*	E_M *(kPa)*	λ
Very compact soil and rocks	2100	>5000	> 5.E4	3-6
Sands and Gravels	1700 - 2100	1000- 4000	5000-1.E4	7-9
Soil of very low to low compactness	< 1800	< 500	< 5000	10-18

2.3 *Correlation between SPT, PMT and Vs*

Another approach consists in using two well-known relationships described in details by Gonin et al. (1992) and Akkaya et al. (2019). The first correlation links the SPT blow count with the pressuremeter modulus as shown in equation (7) with coefficients corresponding to different types of soils (Table 3). The second is based on equation (4).

$$N_{SPT} = \alpha \cdot p_\ell * \quad \text{and} \quad N_{SPT} = \beta \cdot E_M \tag{7}$$

Table 3. Correlation coefficients for eq. (7) (after Gonin et al., 1992)

Geotechnical material	α	β
Sand	21	2.9
Silt	32	2.6
Green clay	26	2.3
Plastic clay	18	1.6
Marls	23	1.9
Chalk	6	0.7

We note a relative homogeneity of correlations with a multiplying factor β in a range of 1.6 to 2.9, except for chalk. The low value of the correlation coefficient in chalk is inherent to its thixotropic behavior, so it was not included in our analysis.

Figure 2 gives a comparison of both approaches. Using a pressuremeter modulus of 50 MPa, the relationships for both methods are in very agreement for sands. However, for a value E_M=25 MPa, there is a significant difference for clays. Since the second method is only based on a single correlation it is expected to provide more uncertainty.

Finally, a good match using eq. (8), with a= 98 and b=0.39 can be observed on Figure 3.

$$Vs = a \cdot {E_M}^{\mathrm{b}} \tag{8}$$

This formula may be applied for most of the soils. An average uncertainty of about 20% is shown for this relationship over a wide range of modulus. For stiff soils and rocks, shear waves velocity derived with this formula may be un-conservatives.

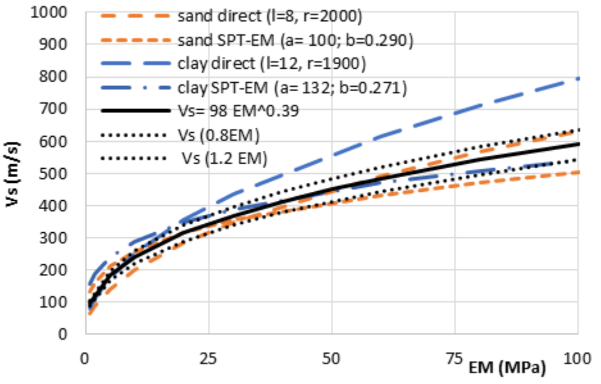

Figure 2. Comparison of direct and SPT-E_M correlations (r=ρ, l=λ, see table 2)

3 COMPARISON WITH DATABASES

3.1 *Data from experimental sites*

The pressuremeter (PMT) results obtained at 20 different experimental sites all over the world where shear wave propagation measurements are available in soils and rocky materials, are plotted on a diagram of shear wave velocity and pressuremeter modulus (Figure 3); the correlation provides estimates of the small strain shear modulus G_0 (hence V_S) from E_M (Ménard modulus) available from the PMT. Observed scattering may be due to the various practice of classifying the ground, preparing the cavity and performing the expansion.

Figure 4 shows the same relationship for stiff soils and rocks. A modulus range up to 1500 MPa is obtained for these materials.

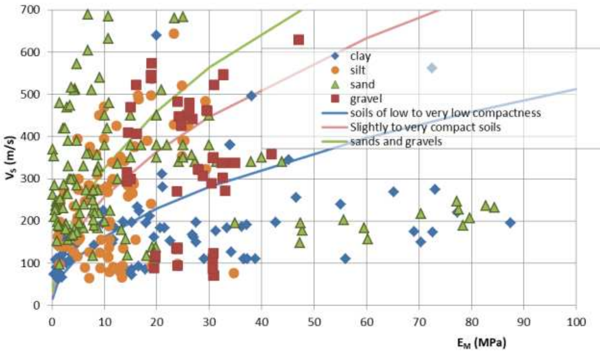

Figure 3. Correlation of the Shear wave velocity and the Ménard pressuremeter modulus (all soils)

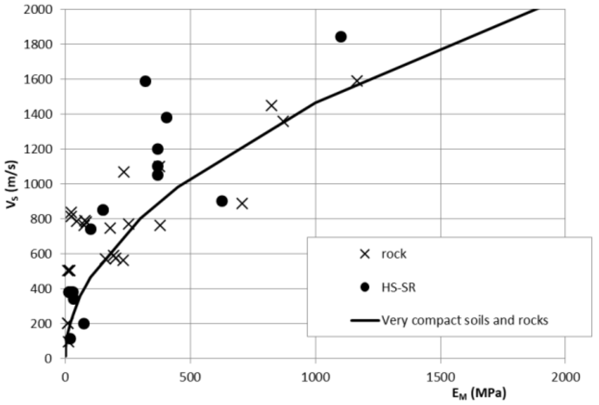

Figure 4. Correlation of the Shear wave velocity and the Ménard pressuremeter modulus (hard soils-soft rocks and rock)

3.2 *Data from sites specific geotechnical investigations*

Among the hundred or so sites combining cross-hole measurements and pressuremeter soundings, the analysis focused on 26 sites involving lithological sets considered homogeneous and for which a pressuremeter sounding less than 30 m away from the cross-hole test is available. Considering the relative dispersion of the values of pressuremeter modulus observed in the same lithology, the analysis was of the mean value of Ménard pressuremeter modulus (mean E_M) and the mean value of velocities (mean Vs) for a given lithological strata, instead of each pair of E_M /Vs values measured at the same depth.

A total of 70 pairs of values (mean Vs; mean E_M) were thus selected, representing 750 measurement pairs (Vs/E_M). From these 70 couples, 5 soil classes were distinguished and represented on Figure 5 and are summarized in Table 4 with a and b coefficients of eq.(8).

Table 4. Correlation coefficients for eq. (8)

Geotechnical material	E_M range (MPa)	*a*	*b*	Curve
limestone and chalk	50-500	168	0.32	1
marl	35-350	189	0.25	2
gravel and dense sand	10-350	125	0.33	3
sand	5-150	116	0.27	4
clay	10-180	98	0.29	5

Three ground facies were treated separately: lacustrine chalk (1 case), Gypsum (Gypsum Masses and Marls) (2 cases). Gneiss type rock (1 case).

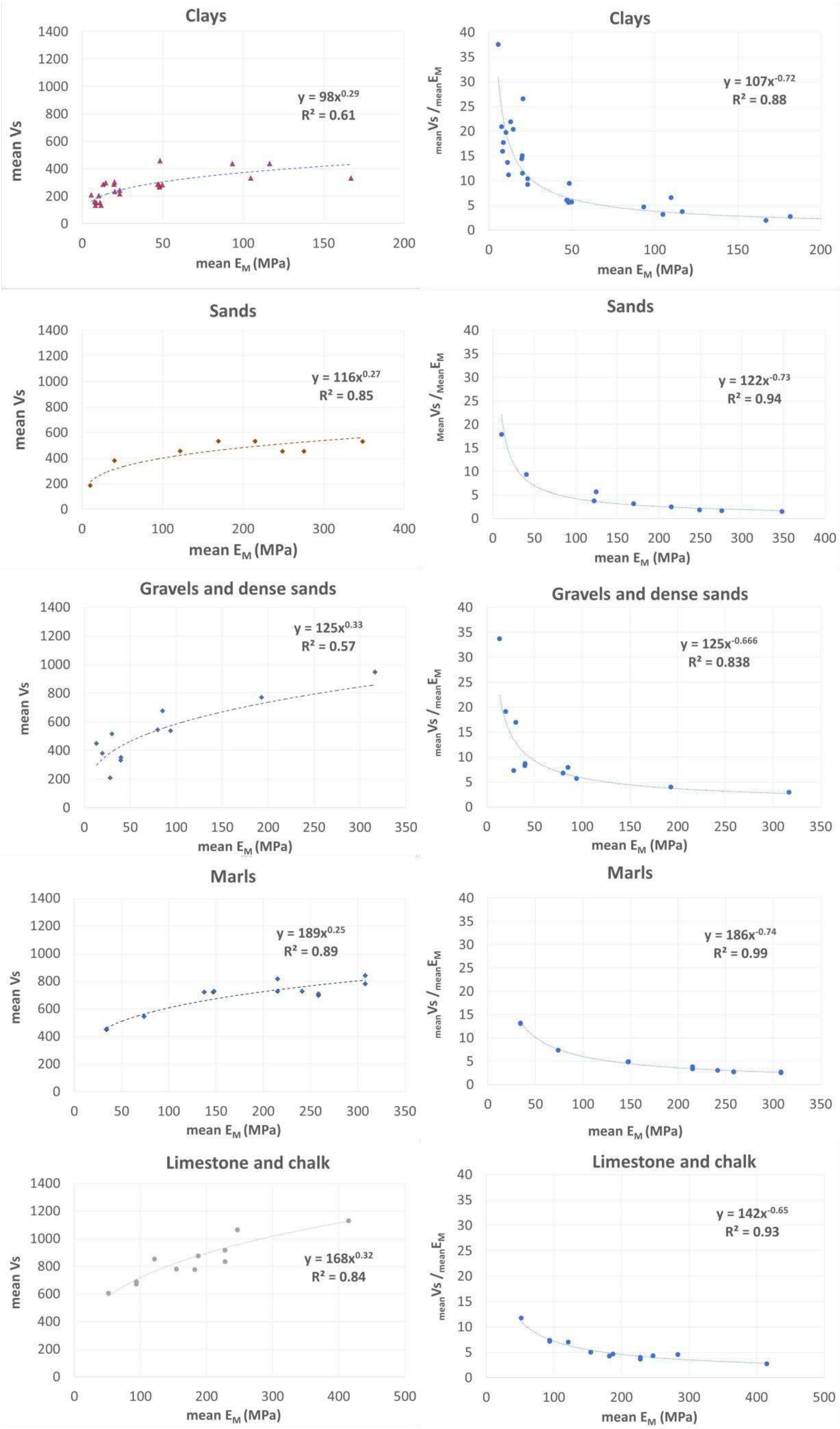

Figure 5. In situ measurement and correlation curves for sites specific geotechnical investigations (French sites)

4 PROPOSED METHODOLOGY

Figure 6 shows a comparison of Vs-E_M direct correlations to the ranges of the soil class limits given in Eurocode 8-1, 2005, adding a corresponding limit of E_M values for all types of soils (upper figure) and for clays (lower figure).

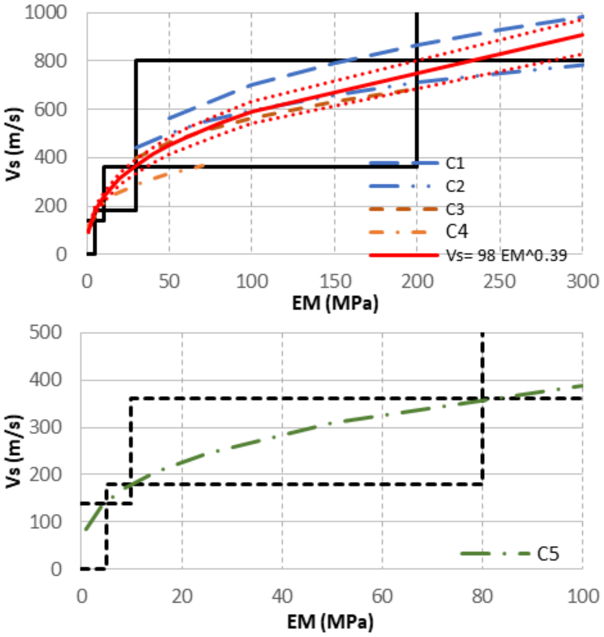

Figure 6. Curves correlations proposed and EC8 ranges for classification

The analysis of correlations proposed in this paper can improve the classification of soils in order to define ground types to characterize seismic action. Considering the good correspondence between Vs measured by cross-holes, and Ménard pressuremeter modulus E_M measured by PMT, a correlation is proposed for Vs=f(E_M) for several types of soils (figure 6). Moreover, a proposition of lower and upper bound for Vs-E_M is given for implementation in Eurocode 8, depending on the type of soils (see table 5).

Table 5. Proposal for correspondence between geotechnical characterization of soil materials, range of shear wave velocities, and ground class

Geotechnical material	*SPT*	*PMT*		Range of	Ground class
	N_{60} *(ER=60%)*	E_M (MPa)	pl_M* (MPa)	Vs (m/s)	
Rock /hard ground	-	>150	>5,0	> 800	A
Very dense sand, gravel	40-60	30-120	2,0-5,0	360-800	B
Dense sand, gravel	15-40	10-30	1,0-2,0	180-360	C
Medium cohesionless soil	8-15	5-10	0,5-1,0	140-180	D
Very loose cohesionless soil	< 8	< 5	< 0,5	<140	S1
Hard clay	-	> 80	> 2,0	360-800	B
Stiff clay	-	10-80	1,2-2,0	180-360	C
Soft to firm cohesive soil	-	5-10	0,4-1,2	140-180	D

5 CONCLUSIONS

New limits are proposed to evaluate the soil classes and to complete the ranges fixed for the other testing techniques currently proposed within the framework of the design rules for structures under seismic loads of Eurocode 8.

This paper has demonstrated the ability to evaluate the shear wave velocity via PMT values correlations, in order to get a classification of soil in seismic area, when direct measurements are not available.

These correlations are a guide in the absence of V_s measurements, but their use must take into account the geological and geotechnical context.

6 REFERENCES

Akkaya, I., Özvan, A., & Özvan, E.E. (2019). A new empirical correlation between pressuremeter modules (EM) and shear wave velocity (Vs) for clay soils. Journal of Applied Geophysics, 171, 103865.

Amar S., Baguelin F., Frank R. and Jezequel J.F.. 1995. The adimensional pressuremeter curve in clays. The Interplay between Geotechnical Engineering and Engineering Geology. Proc. 11th ECSMGE, Copenhagen, Danemark, DGF, Bull. 11, pp. 1.7-1.11

Byrne, Peter M.; Salgado, Francisco; and Howie, J. A., (1991) G max From Pressuremeter Tests: Theory; Chamber Tests; and Field Measurements, Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri, pp. 57-63.

Gonin H., Vandangeon P. and Lafeuillade 1992, Etude sur les corrélations entre le standard penetration test et le pressiomètre (Correlation study between standard penetration and pressuremeter tests) in French, Revue Française de Géotechnique N°58, pp. 67-78.

Jamiolkowski M.J., Ghionna V.N., Lancellotta R., Pasqualini E. (1988) New correlations of penetration tests for design practice J.D. Ruiter (Ed.), Penetration Testing: Proceedings of the First International Symposium on Penetration Testing, ISOPT-1, Orlando, 20–24 March 1988, A.A. Balkema, Rotterdam; Brookfield, VT, USA (1988), pp. 263-296.

Ménard L., Rousseau J. 1962. L'évaluation des tassements, tendances nouvelles. Sols-Soils, N°1, Paris.

Pitilakis K D, Anastasiadis A and Raptakis D 1992 Field and laboratory determination of dynamic properties of natural soil deposits; Proc. 10th World Conf. Earthquake Engg., Rotherdam, pp. 1275–1280.

Pitilakis, K., Raptakis, D., Lontzetidis, K., Tika-Vassilikou,T., Jongmans, D. (1999). "Geotechnical and Geophysical Description of Euro-Seistests, Using Field, and Laboratory Tests and Moderate Strong Ground Motions." Journal of Earthquake Engineering, 3 (3), pp. 381-409.

Raptakis D G, Anastasiadis S A J, Pitilakis K D and Lontzetidis K S 1995 Shear wave velocities and damping of Greek natural soils; Proc. 10th European Conf. Earthquake Engg., Vienna, 477–482.

Seed H.B. and al. 1986. Moduli and damping factors for dynamic analyse of cohesionless soils, Report No.EERC UCB/EERC-84-14, UC Berkeley, Calif.

Semblat J.F., Pecker A. 2009 Waves and vibrations in soils : Earthquakes, Traffic, Shocks, Construction works, IUSS Press, Institute of Advanced Study of Pavia, 490 pages,

Sykora D W and Stokoe K H-II 1983 Correlations of in situ measurements in sands of shear wave velocity, soil characteristics, and site conditions; Report GR 83-33, Civil Engg. Dept., Univ. Texas at Austin, 484 pages.

Wichtmann T., Triantafyllidis T. (2009) On the correlation of "static" and "dynamic" stiffness moduli of non-cohesive soils, Bautechnik 86, Special Issue S1 "Geotechnical Engineering", pp. 28-39.

Youd, T.L. and Idriss, I.M., (1997). ―Proceedings of the NCEER Workshop on Evaluation of Liquefaction Resistance of Soils‖, Salt Lake City,UT, January 5-6, 1996, Technical Report NCEER-97-0022, National Center for Earthquake Engineering Research, University at Buffalo.

Eurocode 8 — Design of structures for earthquake resistance — Part 1: General rules, seismic actions and rules for buildings NF EN 1998-1- september 2005.