NON INTRUSIVE INVESTIGATION IN GEOTECHNICAL ENGINEERING

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ABSTRACT
The shear wave velocity (V_s) is directly related to the elastic shear modulus and constitutes an important characterization parameter in terms of engineering properties. The determination of V_s profiles using surface wave thus appears as a most promising avenue for non intrusive geotechnical investigations. This paper examines the recent developments in surface wave testing and presents numerous examples of geotechnical investigations using surface waves.

RÉSUMÉ
La vitesse de propagation des ondes de cisaillement (V_s) est directement reliée au module de cisaillement dans le domaine élastique et constitue un paramètre de caractérisation important d'un point de vue ingénierie. La possibilité de déterminer un profil de V_s en utilisant les ondes de surface ouvre donc la voie à des méthodes d'investigation non intrusives permettant de caractériser les dépôts de sol sans remaniement et de façon continue. Cet article examine les derniers développements dans l'utilisation des ondes de surface et présente plusieurs exemples d'investigation géotechnique au moyen des ondes de surface.

1. INTRODUCTION

The development of new technologies in recent years has drastically changed and improved the investigation capacities in many fields of human activities. In medicine, for example, non intrusive technologies of investigation allow a look inside the human body in a way unthinkable ten or twenty years ago. While a number of non intrusive techniques of investigation are available in geotechnical engineering, boring, sounding, sampling and laboratory testing remain the main and often the only tools used to characterize soil deposits in geotechnical projects.

Laboratory testing raises the question of samples representativity and of sampling disturbance. In situ measurements of geotechnical properties are also affected by soil disturbance associated with the driving of the sounding tools, and soil properties are most often derived from empirical correlation based on indirect indicators like static or dynamic resistance to penetration. The vast regional expertises which have developed in the various parts of the world allow nevertheless an acceptable geotechnical characterization when the investigation efforts are sufficient. Considering the variability of soil deposits and the cost of quality boring and sounding or of sampling and laboratory testing, any geotechnical engineer cannot but hope for non intrusive methods of investigation which will allow a continuous and detailed characterization of the in-situ soil in its truly undisturbed state and directly in terms of engineering properties.

This paper first briefly reviews available non intrusive techniques for geotechnical investigations to show that the shear wave velocity (V_s) is identified as the parameter which has the best potential for non intrusive characterization of soil deposits. The recent progresses in the determination of shear wave velocity using surface waves are then examined. Several examples of geotechnical investigations using surface waves are finally presented.

2. NON INTRUSIVE GEOTECHNICAL INVESTIGATIONS

For several decades, a number of non intrusive techniques of investigation, globally referred as geophysical methods of investigation, have been available and used generally for detecting anomalies or abrupt changes rather than to characterize the soil in terms of engineering properties.

The resistivity methods, which involve the mapping of subsurface electrical resistivity, are strongly influenced by the pore water salinity, the soil porosity and the degree of saturation. Resistivity methods are thus useful to follow the advance of a saturation front or to detect leakage or similar discontinuities (Abu-Zeid, 1994; Esteves, 1975, 2001).

Ground Penetrating Radar relies on the emission of high frequency electromagnetic waves. The rapidity of ground penetrating radar investigations has made it very attractive to detect anomalies or any change of conditions in the ground which could be associated with a change of electrical properties sufficient to enhance reflection of the electro-magnetic waves (Daniels, 1989).

Resistivity methods and ground penetration radar are good examples of geophysical techniques of investigation which offer a good potential for the detection of anomalies or rapid changes of condition in the ground. The parameters which are measured in these methods are however generally poor indicators of engineering properties.

Seismic testing in general relies on the generation of mechanical waves and presents a particular interest since the propagation velocity of seismic waves is related to the mechanical properties or , in other words, to the engineering properties of the material. The application of a shock at ground surface generates several wave trains as shown on Figure 1. A portion of the energy penetrates in the ground as body waves, compressive and shear waves, and bounces back to surface after reflection or refraction on rigidity contrasts. The largest portion of the applied energy travels however as surface waves (Lefebvre et al., 1981).

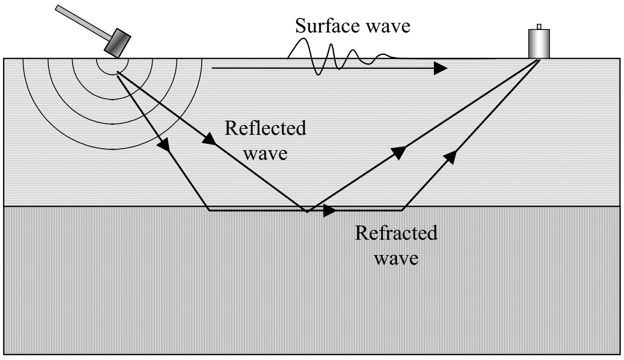

Figure 1. Seismic waves travel path

In seismic testing, surface wave are consequently easy to generate as compared to body waves.

Seismic testing usually refers to seismic reflection or refraction of body waves and has been routinely used on large projects for many years, in particular for bedrock profiling. While seismic testing is primary used for the detection of reflection or refraction boundaries, it offers a certain potential for material characterization in terms of wave propagation velocity.

Compressive wave tends to induce change of volume (Fig. 2) and its propagation velocity (V_P) in a saturated soil is practically identical to V_P in water. V_P is not consequently a good parameter for the characterization of saturated soil. Shear waves, on the other hand, impose only an elastic shear deformation (Fig. 2) without volume change and its velocity (V_s) is, in fact, a direct measure of the rigidity or stiffness of the material which can be expressed as the elastic shear modulus (G_{max}) :

$$G_{max} = \rho V_s^2$$

where ρ is the density of the material.

The generation of shear wave thus offers an interesting potential for soil characterization in terms of engineering properties as compared to other geophysical methods. V_s or G_{max} indeed express a basic engineering property which can be used directly in some analyses, a dynamic response analysis for example, or as a good indicator for geotechnical properties.

The value of V_s at a certain depth in a soil deposit depends essentially of the void ratio (e) and the effective stress (σ') and the numerous empirical relations which are proposed in literature to relate V_s to the soil state (Hardin and Richards, 1963; Kim and Novak, 1981; Robertson et al., 1995) are generally in the form of:

$$V_s = F(e)\ F(\sigma'_m)$$

where the effective stress function is generally :

$$F(\sigma'_m) = \sigma'^{1/4}_m \ .$$

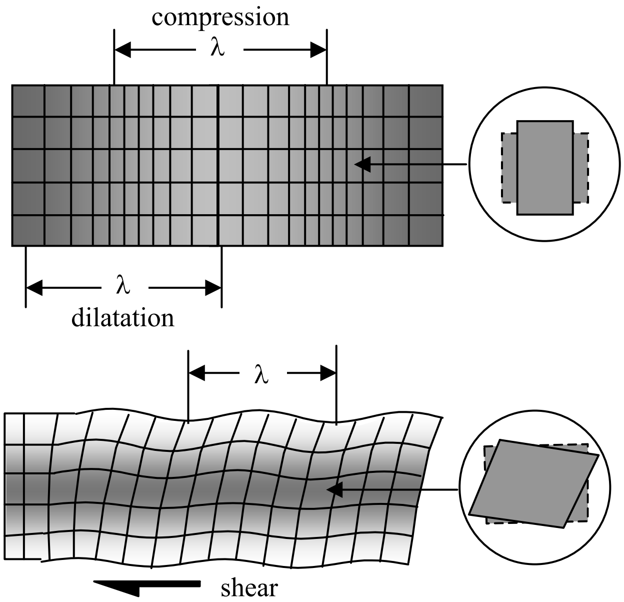

Figure 2. Illustration of seismic waves propagation

V_s can thus be transformed into a V_s normalized for a given vertical pressure, 100 kPa for example, which would express essentially the void ratio or porosity of the material and then constitute a good parameter to express the state of density of sandy deposit. Empirical correlations have indeed been developed to express the liquefaction potential of sandy deposits during earthquakes in terms of V_s just as in terms of Standard Penetration Index or cone penetration resistance (Youd et al., 2001).

3. PROGRESS IN SURFACE WAVE TESTING

The use of surface Raleigh waves has attracted much attention in geotechnical engineering since the early 50's due to its potential to determine V_s profiles entirely from surface (Haskell, 1953; Jones, 1958). The interest of Rayleigh waves lies in its dispersivity or, in other words, on the fact that the penetration in the ground of a Rayleigh wave depends of its wavelength, as illustrated on Figure 3. In a deposit where the stiffness increases with depth, the Rayleigh wave velocity (V_R) would thus increases with wavelength (λ). The relation between V_R and λ referred to as the dispersion curve (Fig. 3) contains in fact all the necessary information to determine a detailed V_s profile. In the early stage of surface wave testing, the dispersion curve was transformed into a V_s profile by assuming that the V_R associated to a given wavelength was equal to V_s at a depth equal to a certain fraction of the wavelength, half the wavelength for example.

The development of the SASW method (Spectral Analysis of Surface Wave) in the 80's (Heisey, 1982; Nazarian, 1983; Nazarian and Stokoe, 1985) has been a major step in the use of surface wave in geotechnical investigations. In SASW, the dispersion curve is determined with an impact and two sensors disposed as on Figure 4 starting with a small spacing between the sensors and repeating the test

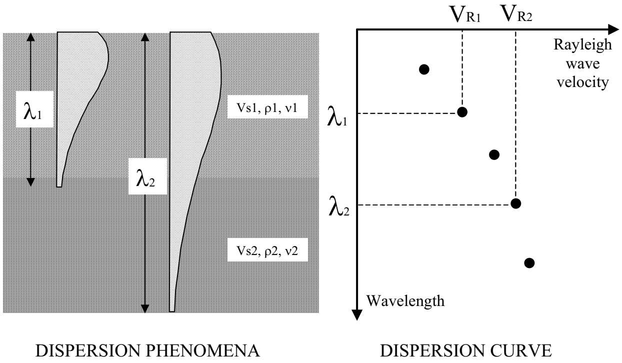

Figure 3. The dispersivity of Rayleigh waves

for larger and larger spacings in order to define a dispersion curve with a sufficient range of wavelengths (Fig. 3). The experimental dispersion curve determined in the field is transformed into a V_s profile by an inversion process. The inversion consists, first to assume a soil stratigraphy with a given number of layers, each layer being characterized in terms of V_s, ρ, and Poisson's ratio and to calculate a theoretical dispersion curve for this assumed stratigraphy. The assumed V_s profile is iteratively adjusted until the theoretical dispersion curve matches the experimental curve. Once adjusted, the assumed V_s profile is then considered identical to the field V_s profile since both V_s profiles have the same dispersion curve. It is important to note that the theoretical dispersion curve is calculated for the fundamental Rayleigh mode, and the inversion process thus assumes that only the fundamental Rayleigh mode has contributed to the dispersion curve.

When a vibration is induced in a body, a rod, a building or a soil deposit for example, the body generally responds by vibrating according to different modes. Deformation patterns for the fundamental and the first higher modes are illustrated for a cantilever rod on Figure 5a and for Rayleigh wave on a soil deposit on Figure 5b. Since in the inversion process, the SASW method assumes that only the fundamental Rayleigh mode contributes to the dispersion curve, the method was designed to minimize the contribution of the higher modes by respecting a certain field configuration (Fig. 4) and by rejecting wavelengths which do not satisfy certain criteria.

The problem of higher Rayleigh mode contribution to the dispersion curve in surface wave testing was identified fairly early but it was believed for a while that the problem should arise only in deposits with irregular V_s profile, i.e. for profile where V_s does not increase regularly with depth (Tokimatsy et al., 1992; Gusumski and Wood, 1992; Ganji et al., 1998). More recently however, detailed numerical analyses of seismic wave propagation in response to an impact at ground surface have shown that higher Rayleigh modes can contribute to the dispersion curve even for deposits with regular V_s profile and even when using SASW criteria. (Karray, 1999).

There is today a consensus that methods of investigation based on surface waves should assume that higher Rayleigh modes could contribute to the dispersion curve

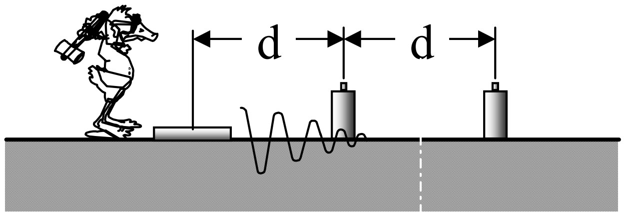

Figure 4. Configuration of the SASW method

and that techniques should be used to separate or eliminate the contribution of these higher modes before proceeding to the inversion (Park, 1999; Foti, 2000; Karray and Lefebvre,1998 and 2000).

4. A MULTI-MODE SURFACE WAVE METHOD OF INVESTIGATION

The MASW (Modal Analysis of Surface Wave) developed at the Université de Sherbrooke at the end of the 90's (Lefebvre and Karray, 1998; Karray, 1999) was specifically designed not to eliminate higher modes contribution but, on the contrary, to make use of the information contained in every available modes. The modal analysis in the MASW system has indeed the purpose to treat the field dispersion data to extract a dispersion curve for each of the contributing Rayleigh modes, as illustrated on Figure 6, to be used at the inversion stage.

The separation and use of the higher Rayleigh modes has an important impact on how the dispersion data are acquired in the fields. There is no need for criteria to reject certain wavelength; all the recorded dispersion data are processed and used. As important, there is no need to impose a field configuration to minimize the contribution of higher Rayleigh modes. In MASW, all the necessary signals are recorded at once by disposing 16 sensors generally with a 1 m spacing, as illustrated on Figure 7. The standard energy source is a 60-kg SPT hammer dropped from a 2 m high. This energy and this configuration covering a distance of only 15 m between the first and last sensors is sufficient to determine V_s profiles to depth of 30 to 60 m depending of soil conditions, due to the fact that no information is rejected based on wavelength or mode contribution.

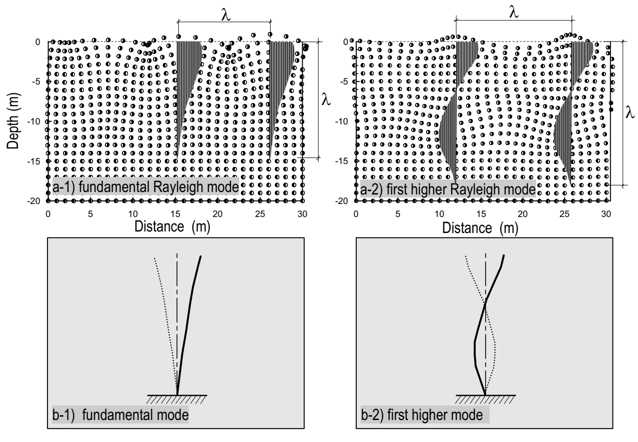

Figure 5. Deformation patterns for the fundamental and first higher modes a) for a cantilever rod, b) for a soil deposit

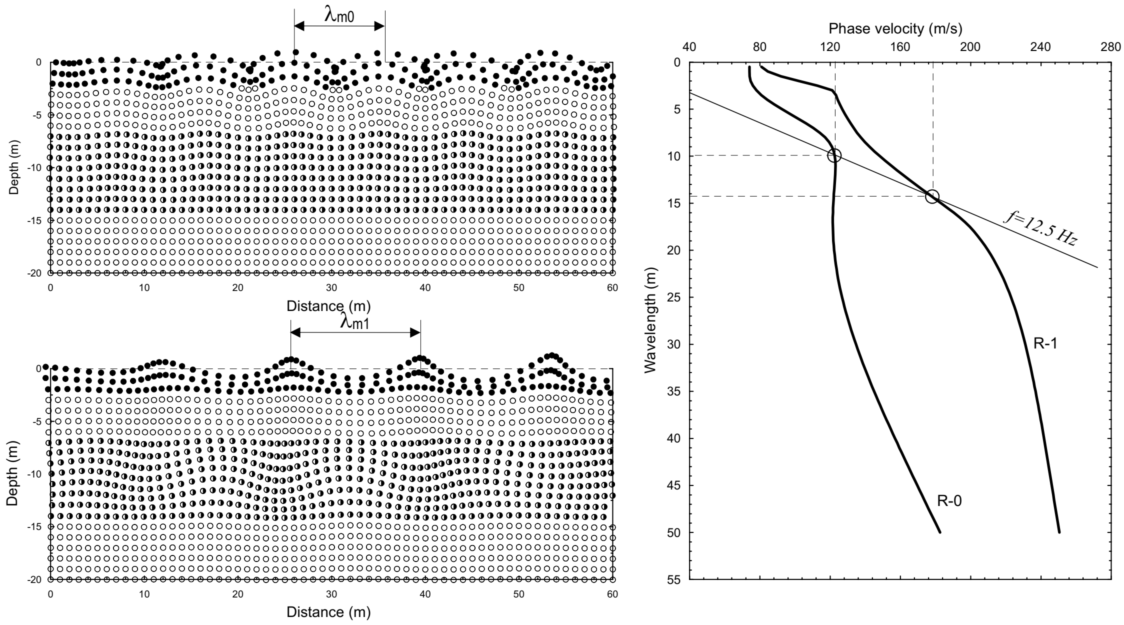

Figure 6. Illustration of dispersion curves associated to different Rayleigh modes (Karray, 1999)

In the MASW method, the recorded signals are interpreted in series of 16 by carrying out an analysis in time-space domain using a wavelet technique (Karray, Lefebvre and Faure, 2004). For each frequency, an energy spectrum is established in the phase travel time and the group travel time plane. The presence of more than one peak of energy indicates the existence of different wave groups. The phase velocity and the group velocity of each peak of energy are then computed for each frequency and the dispersion curves of the different Rayleigh modes are established. Figure 8a shows an example of dispersion curves for different Rayleigh modes.

The automated mode separation illustrated on Figure 8a leads first to the definition of an accurate and completely objective dispersion curve for the fundamental Rayleigh mode since there is no need for the user to draw a curve through, often, a cloud of dispersion data. As important, it also leads to the definition of a dispersion curve for at least one higher Rayleigh mode, in addition to the fundamental mode, to be used in a multi-mode inversion process.

A multi-mode inversion has proven to be an important aspect in the reliability of surface wave testing. The match between the theoretical and experimental dispersion curve for at least one higher mode in addition to the fundamental mode constitutes indeed a verification of the results. In fact, it has been demonstrated (Lefebvre and Karray, 1998; Karray, 1999) that the use of more than one Rayleigh mode in the inversion process allows the determination of the Poisson's ratio (ν) in addition to the shear wave velocity profile, which then corresponds to a unique solution, since there is only one set of ν and V_s profiles which satisfies two different modes at the same time. The first inversion is

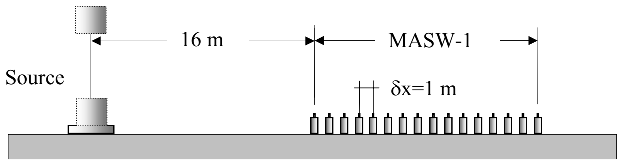

Figure 7. Standard MASW field configuration

carried out by considering an hypothetical Poisson's ratio profile. Once this first inversion is carried out, the theoretical dispersion curves for the different Rayleigh modes are compared with those obtained experimentally. If the higher modes do not match, their profile is adjusted and the inversion process is reinitialized until a best agreement for the various Rayleigh modes. Figure 8 presents an example of a multi-mode inversion.

The determination of both ν and V_s constitutes a complete elastic characterization of the material. The Poisson's ratio was in the past assumed in surface wave testing, considering that the error on V_s should normally be less than 10%. The objective determination of ν constitutes nevertheless an accuracy improvement in the determination of V_s. The Poisson's ratio profile can also constitute a useful information, in particular to detect the water table or, at least, the level where soils are fully saturated (Fig. 8c).

An automated and efficient inversion process has been developed for the MASW system. In the iterative inversion procedure, the minimization of the difference between the theoretical and experimental dispersion curves proceeds not only in terms of phase velocity but also in terms of the shape of the dispersion curves, allowing a more rapid convergence and also a better detection of the weaker or stronger layers at depth (Karray, 1999).

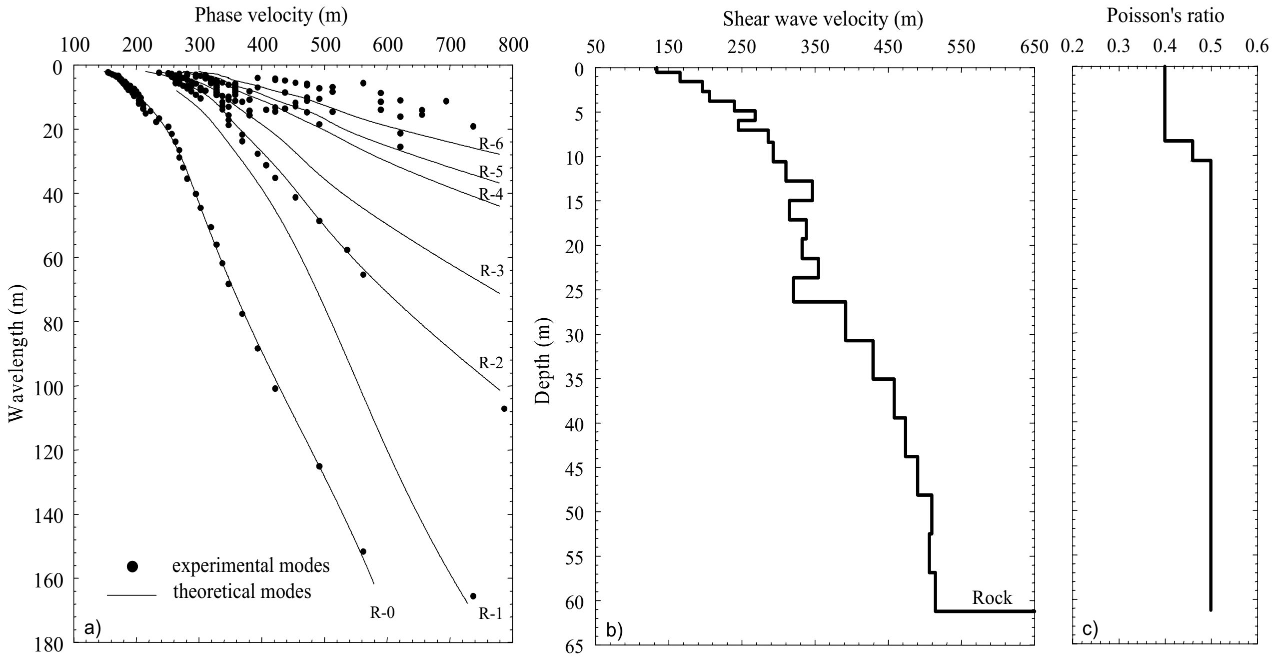

Figure 8. a) Example of dispersion curves for the fundamental and higher Rayleigh modes b) Corresponding shear wave velocity profile and c) Corresponding Poisson's ratio profile theoretical mode

MASW tests are generally performed in series, one test after the other, as illustrated on Figure 9. Successive combinations of 16 signals are then interpreted to determine V_s profiles, generally at 2 m intervals, allowing to present the results as a kind of tomography in terms of V_s contours as illustrated on Figure 10.

5. EXAMPLES OF SURFACE WAVE INVESTIGATION

As mentioned before, V_s can be expressed as the elastic shear modulus. A V_s profile thus expresses the variation of stiffness or rigidity with depth. The elastic shear modulus is a fairly basic engineering property and, with time, better correlation between V_s and various soil engineering properties should become available. This part of the paper presents examples of MASW investigations performed for different purposes.

Figure 10 presents the results of MASW investigations performed to evaluate the liquefaction potential in a deep sandy deposit. One hundred and twenty V_s profiles were determined down to a depth of 70 m over an horizontal distance of 320 m. The results are presented on the form of V_s contours on Figure 10a and as contours of V_s normalized for a vertical pressure of 100 kPa (V_{s1}) on Figure 10b (Hammanji et al., 2004). Field observations at sites where evidence of liquefaction has or has not been observed following earthquakes, are reported in a cyclic stress ratio – V_{s1} space on Figure 11 reproduced from Youd et al., 2001. These empirical correlations indicate a certain risk of liquefaction for sandy soils characterized by a normalized V_{s1} lower than 200 m/s if submitted to relatively strong earthquake. Several zones with V_{s1} lower then 200 m/s are

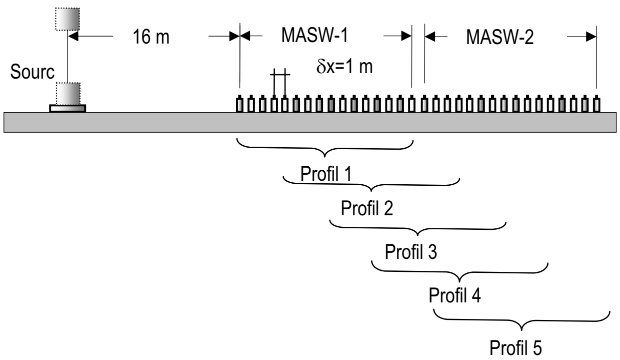

Figure 9. Configuration of the MASW method

detected on Figure 10b between depth of 10 and 20 m and thus indicate a certain potential for liquefaction.

The second example concerns an investigation at a sanitary landfill in order to gain information for dynamic response analyses. MASW investigations were conducted at the top of two closed landfill cells. Each cell had implied an 8 to 10 m excavation in a Champlain clay deposit some 20 or 25 m thick, the placement of municipal waste and of a thick final cover of remoulded clay from the excavation. Figure 12a and 12b present typical V_s profiles at an ancient cell and at a cell recently closed (Karray and Lefebvre, 2001). At both cells, the relatively large stiffness of the compacted municipal waste allows to detect the contacts with the remoulded clay at the top and the natural clay deposits at the bottom, especially for the recently closed cell (Fig. 12b). Due to consolidation, the V_s in the natural clay

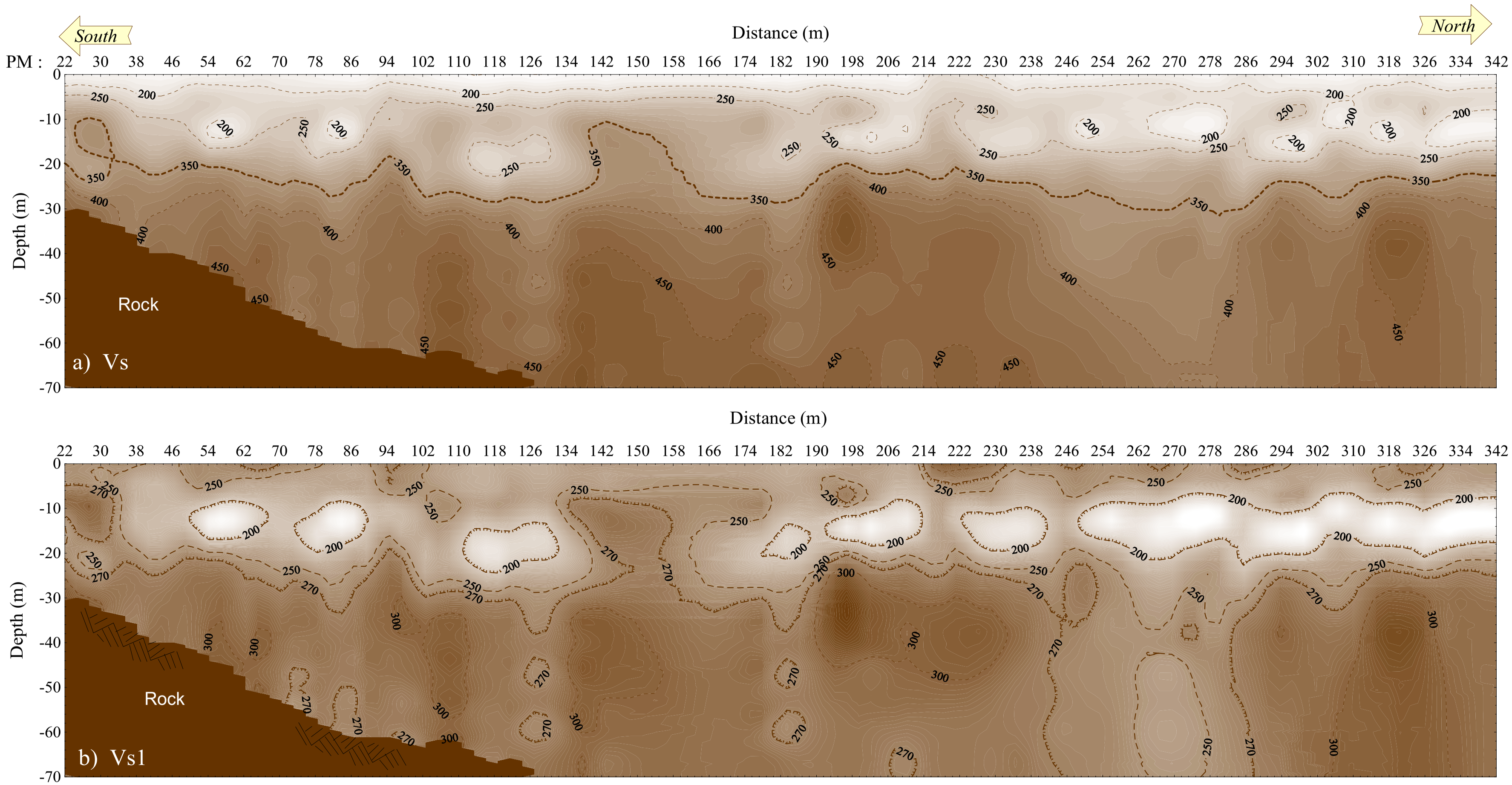

Figure 10. Contours of (a) shear wave velocities (b) and shear wave velocities normalized by an effective stress of 100 kPa

deposit below the waste is significantly higher under the ancient cell (Fig. 12). The Poisson's ratio of 0.3 in the waste layer confirms that the wastes are not saturated.

The next example concerns the investigation of a stiff but very sensitive clay deposit resting on silty and sandy till. A weak clayey silt layer has been identified between the till and the stiff clay layer. The silty soil was so sensitive that it was thought however that routine sounding and sampling could have disturbed the material. Some typical V_s profiles are reproduced on Figure 13 (Karray and Lefebvre, 2003). Each V_s profile (solid line) is also expressed as a V_s normalized for a vertical pressure of 100 kPa (dashed line). A V_s or G_{max} profile is a good indication of the soil layering in terms of stiffness but does not provide any direct information on the nature of the material. Interpretation keys can however be developed confronting V_s profiles with the true stratigraphy positively identified in adjacent borings. Figures 13a and 13b compare V_s profiles with the stratigraphy identified in adjacent borings. The clay layer 8 to 11 m thick is characterised by a V_s increasing with depth to a maximum value of about 300 m/s, confirming the very stiff nature of the clay. In the surficial clay crust, 2 to 5 m thick, the V_s profiles are rather erratic and do not indicate a stiffer condition than in the clay below contrary to the vane profiles which always indicate a maximum stiffness in the crust.

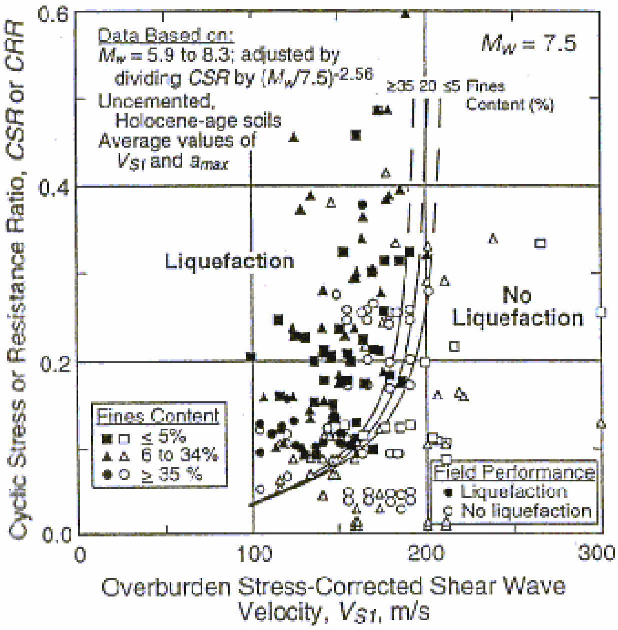

Figure 11. Empirical relations proposed for the evaluation of liquefaction potentiel based on Vs1 (reproduced from Youd et al. 2001)

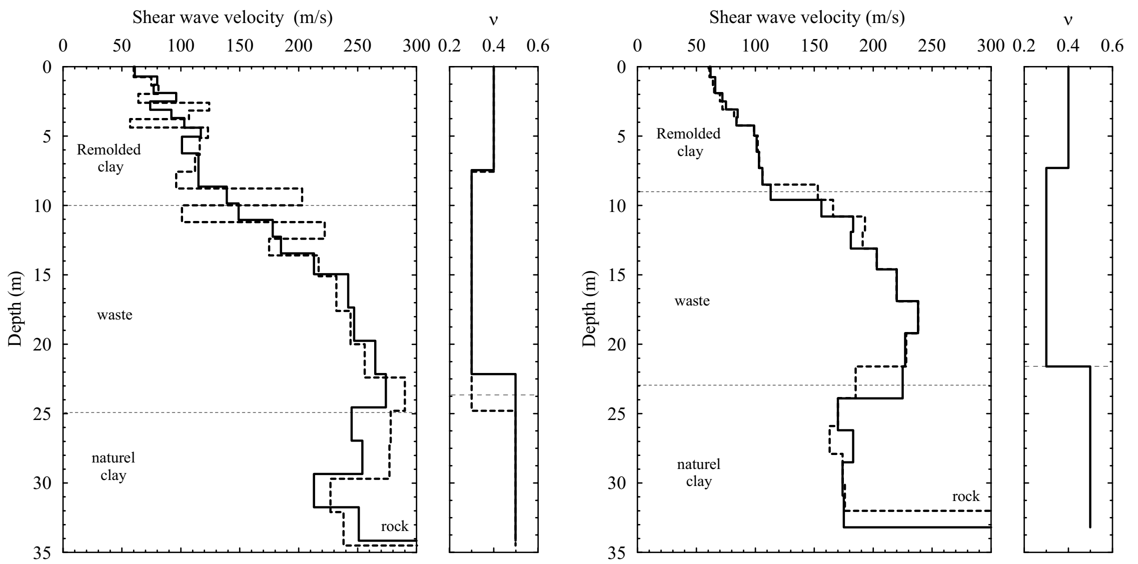

Figure 12. Profiles of Vs and n at a sanitary landfill site a) for an ancient cell and b) for a recently closed cell

The contact between the clay and the silt layer coincides with the end of V_s increase with depth (Fig. 13a and b, allowing to extrapolate this contact at all other V_s profiles. In the silt layer, V_s either remains constant or very slightly decrease. This has been interpreted as an indication that most of the drastic reduction in stiffness observed in routine sampling and sounding was due to soil disturbance. In most profiles, the value of V_s remains fairly constant in the till layer at about 300 m/s as on Figure 13b, indicating a fairly dense condition, as it is generally the case in glacial till. In some V_s profiles however, it was surprising to observe zones in the till appearing fairly loose with V_{s1} as low as 150 m/s (Fig. 13c). Additional borings confirmed that the glacial till deposit at this site occasionally contains zones of alluvionnal clean sand and gravel.

Figure 14 presents an example of MASW investigation carried out in France to detect underground cavities in a chalk deposit (Karray and Lefebvre, 2004). The top of the sound chalk deposit was identified at a depth oh 4 or 5 m by a jump in V_s to values close to 1 500 m/s and increasing very slightly with depth (Fig. 13a). Underground cavities are

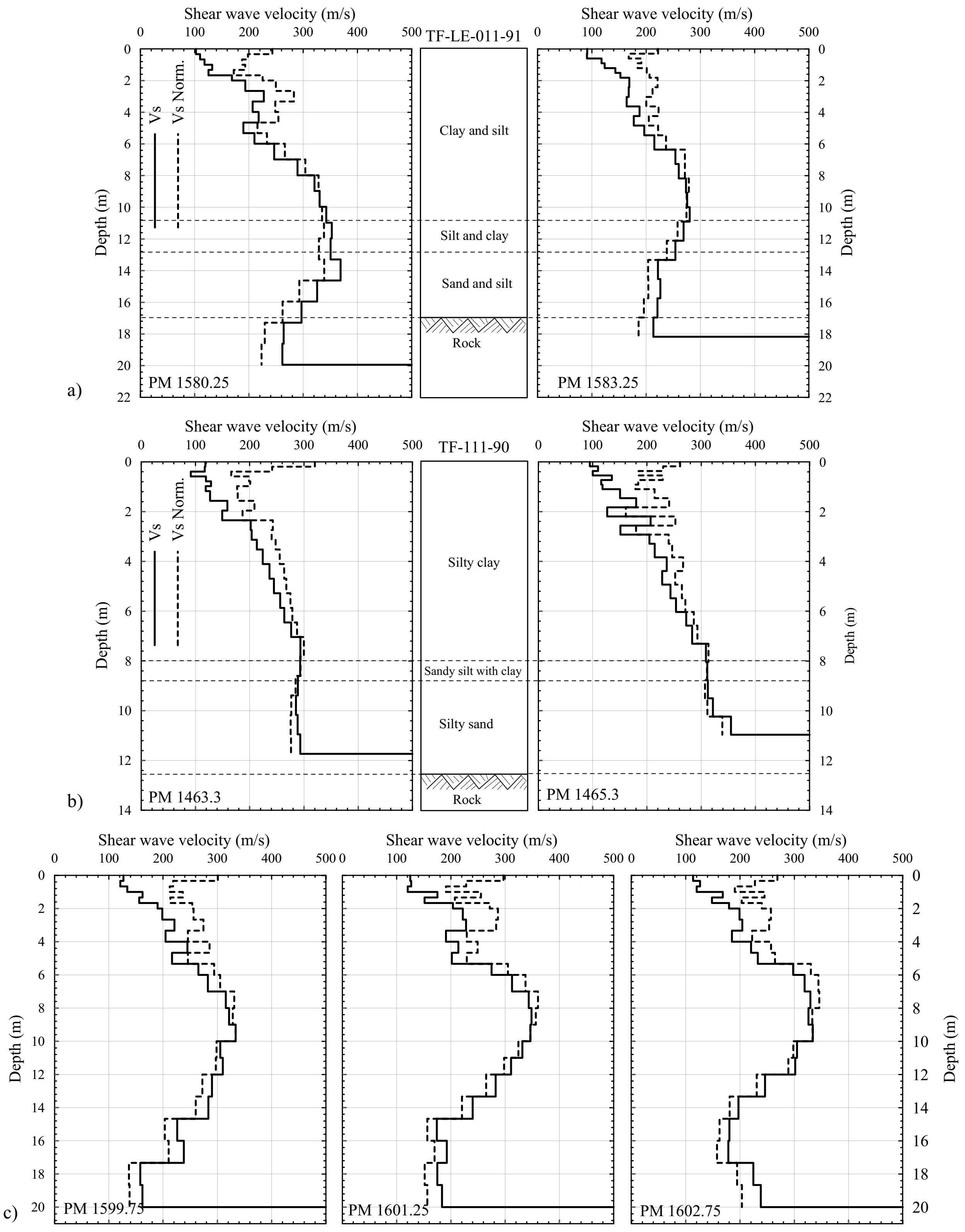

Figure 13. Typical Vs profiles at a clayey site a, b) Compared with adjacent borings logs and b) Showing the presence of a loose zone in the till below the clay deposit.

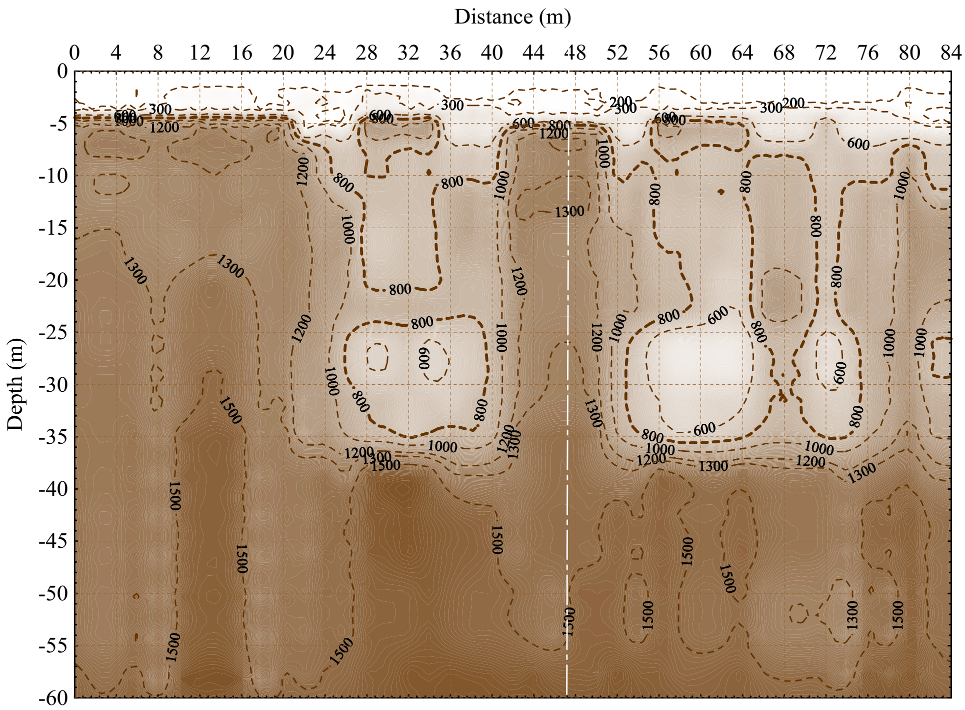

Figure 14. Contours of Vs for the detection of underground cavities in a chalk deposit in Normandie, France

identified between depths of 26 and 35 m on Figure 14. The results indicate, in addition, some degradation of the stiffness in the roof of the cavity. This is a good example to illustrate the fact that a V_s profile determined with surface waves is not a punctual measurement like, for example, a piezocone profile, but rather represents average values for a certain volume of soil. In the present case, the chalk deposit was characterized down to a depth of 60 m with a 1 m spacing between the 16 sensors. The width of the cavities does not exceed 10 m, which means that in the vicinity of the cavities, the 16 sensors in a MASW test were always partly above solid chalk, partly above the cavity, leading to average V_s values significantly higher than the zero value which should characterized a void.

Figure 15 presents examples of MASW investigations of concrete liners in two tunnels in France. Due to the presence of bedrock behind the liners, the surface wave data are interpreted as in the previous examples ("geological model"). The investigation in the Mont Blanc tunnel (Fig. 15a) was carried out after the disastrous 1999 fire to gain information on the extent of damage due to the fire (Karray et al., 2004a). The V_s profiles clearly identified the contact between the bedrock and the concrete liner, the thickness of the liner varying between 0.35 and 0.50 m in the zone of investigation (Fig. 15a). Based on the literature and on MASW testing outside the fire zone, V_s lower than 1 000 m/s was considered to reflect some degradation of the concrete due to the fire. The MASW results indicated that the damage to the concrete due to the fire was generally limited to a layer 10 to 20 cm thick. This was later confirmed by destructive testing (Karray et al., 2004).

The second example of liners investigation (Fig. 15b and c) concerns a new tunnel in France where the liner was made of high performance (HP) concrete, placed on a layer of shockcrete directly on the bedrock (Karray and Lefebvre, 2004b). The shockcrete layer is well-identified on the profiles by a lower V_s zone between the HP concrete and the bedrock. The HP concrete liner was generally about 0.4 m thick as in Figure 15c; local zones with a significantly thicker liner were however identified (Fig. 15b). It is interesting to compare the elastic shear modulus of the HP concrete liner in the new tunnel (Fig. 15b and c) with the one of the Mont Blanc tunnel, built in the 60's.

Until recently, concrete slabs or pavements could not be characterized using rigorous surface wave investigation because it was not possible to calculate theoretical dispersion curves for these conditions. A solution has however been developed lately and is being tested. The data acquisition and mode separation are carried out using standard MASW procedures, but new algorithms are used at the inversion stage to calculate the theoretical dispersion curves. Experimental and theoretical dispersion curves are compared on Figure 16a for the MASW testing of a concrete slab. Figure 16b presents the V_s profiles in the concrete slab and compares the thickness obtained with MASW with a direct measurement.

6. CONCLUSION

As compared to other fields of activities, non intrusive type of investigations has developed rather slowly in geotechnical engineering. However, the progresses which have been made in the last 25 years in surface wave testing, starting with the development of the SASW method and more recently the recognition of the multi-mode problem

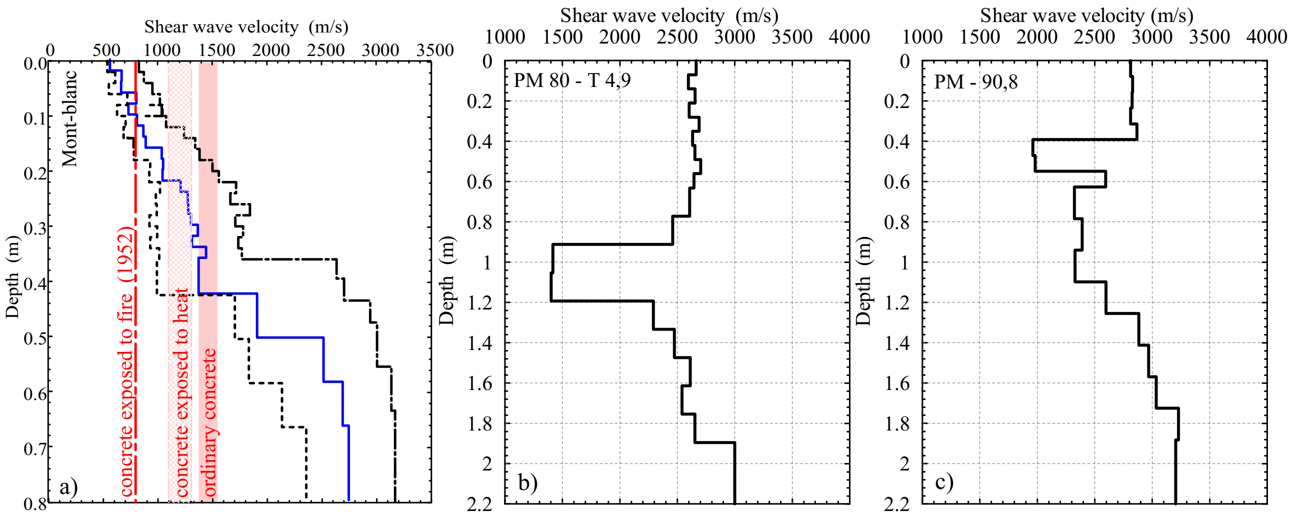

Figure 15. Examples of MASW investigations of concrete tunnel liner a) after the 1999 fire in the Mont-Blanc tunnel b and c) In new tunnel with higher performance concrete liner

have paved the way for non intrusive type of investigations. With the computing facilities which are now available, it is possible today to automate the rather complex data treatment necessary to isolate and determine the dispersion curves for the different Rayleigh modes and to proceed to a multi-mode inversion to arrive at a unique solution in terms of elastic properties. There is no reason why a rigorous treatment of Rayleigh waves acquisition, dispersion and inversion should not lead to reliable and accurate V_s profiling. Confidence should, in addition, rapidly developed as results of investigation performed with surface wave closed systems because available for comparison with other types of geotechnical investigations.

The basic engineering property, determined by surface wave testing, the elastic shear modulus, in addition to be used directly in some types of analyses, dynamic response, elastic settlement or liquefaction potential, would be a most suitable parameter for empirical relations with geotechnical properties related to mechanical competence like density index, bearing capacity, preconsolidation pressure or shear strength for example. But as important, the availability of reliable surface wave investigation methods would address two major concerns in geotechnical engineering. By using non intrusive method like surface wave, the elastic parameters of the soil are measured without any disturbance due to sampling or sounding. Secondly, the surface wave testing easily allows, as demonstrated, a continuous characterization of a deposit, with closely spaced V_s profiles, minimizing the risks of interpolation or extrapolation of soundings and borings.

Non intrusive methods of investigation, like surface wave, cannot evidently totally replace all borings and soundings. Elastic properties profiling can allow the definition of a certain layering in terms of stiffness in addition to the bedrock location. It cannot, however, identify the nature of the materials and positive identification by sampling should remain desirable. And like other geophysical and non intrusive type of investigations, the need for some positive identification should always remain of some importance.

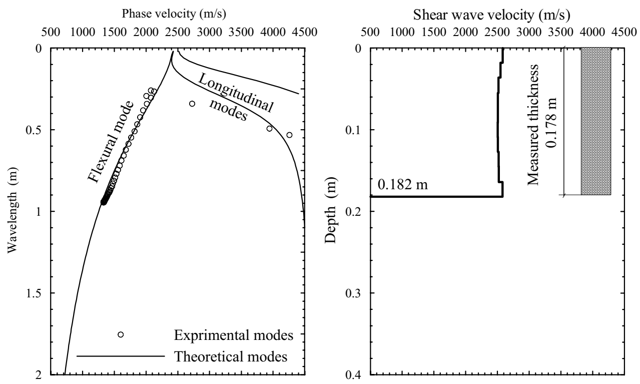

Figure 16. Example of MASW investigations for a concrete slab a) Experimental and theoretical dispersion curves; b) V_s profiles and measured thickness

7. ACKNOWLEDGEMENT

The development of MASW (Modal Analysis of Surface Waves) was initiated in Dr. Karray Ph.D. thesis (Université de Sherbrooke,1999) and has been pursued without interruption to its present state. Geotechnical investigation methods cannot be developed and improved without frequent testing in the field for various conditions and various purposes. Societies like Hydro-Québec, the Ministry of Transport Québec, and in France, the CETU (Centre d'Études des Tunnels) and the Hydro-Géotechnique Group have been instrumental in the development of MASW and their support is acknowledged. The development of surface wave testing has been in progress at Université de Sherbrooke since more than 15 years and the financial support of the National Sciences and Engineering Research Council of Canada funds is acknowledged.

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