POLITECNICO DI TORINO
Repository ISTITUZIONALE

Deformation of landfill from measurements of shear wave velocity and damping - Discussion

Original
Deformation of landfill from measurements of shear wave velocity and damping - Discussion / Foti, S.; Lai, C. G.; Rix, G. J.. - In: GEOTECHNIQUE. - ISSN 0016-8505. - STAMPA. - 52:6(2002), pp. 465-467. [10.1680/geot.2002.52.6.465]

Availability:
This version is available at: 11583/2882657 since: 2021-04-02T14:14:23Z

Publisher:
ICE

Published
DOI:10.1680/geot.2002.52.6.465

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

02 May 2026

Abbiss, C. P. (2002). *Géotechnique* **52**, No. 6, 465–467

DISCUSSION

Deformation of landfill from measurements of shear wave velocity and damping

C. P. ABBISS (2001). *Géotechnique* **51**, No. 6, 483–492

S. Foti, *University of Western Australia, Perth*
C. G. Lai, *Studio Geotecnico Italiano, Milano*
G. J. Rix, *Georgia Institute of Technology, Atlanta*

The author presents a method for using in-situ seismic test results to estimate the short-term deformations of geomaterials. The effort to introduce rational algorithms for the evaluation of settlements of shallow foundations on the basis of measured physical quantities is noteworthy, considering that current geotechnical design, especially on small-scale projects, is often based on empirical correlations between settlements and penetration test results that rarely reflect the actual site conditions. In this context the development of simple procedures based on the results of relatively inexpensive in-situ tests including seismic tests is of paramount importance.

Nevertheless it is important to account properly for the physics of wave propagation when inferring material parameters from seismic test results. In this respect, the writers would like to make some observations related to the methods used to evaluate the shear wave velocity and material damping ratio of the solid waste from surface wave measurements. This discussion is focused on and restricted to the aspects of the paper related to the use of surface wave methods to estimate the waste properties.

Shear wave velocity

The empirical approach to inversion used by the author to estimate the shear wave velocity profile on the basis of the Rayleigh wave dispersion curve is based on energy considerations, and it is applicable whenever the site is normally dispersive (that is, the modulus of the soil increases with depth so that the phase velocity is always greater than the group velocity) and no large contrasts in mechanical impedance are present between adjacent layers. Indeed the approach is based on the assumptions that most of the energy propagating via the fundamental mode Rayleigh wave is confined to a depth of approximately one third or a half of the wavelength, and that for a homogeneous half-space V_R ranges between 0·89 and 0·96 V_S.

When the soil is not normally dispersive, or strong contrasts in mechanical impedance are present, the empirical approach can lead to erroneous results. In such situations higher modes of propagation play an important role (Sànchez-Salinero, 1987; Gucunski & Woods, 1991; Tokimatsu, 1995; Foti, 2002) and the distribution of energy with depth can be quite different. As an example, Fig. 13 shows the displacement mode shapes for the first three Rayleigh modes for a layered system.

The experimental dispersion curve obtained for the Calvert landfill (Table 4) clearly corresponds to a situation in which a stiff cap overlies the softer waste material. In such a situation the site is inversely dispersive, and the shear wave velocity profile should be evaluated with more rigorous, theoretically based inversion algorithms that account for the multimodal nature of Rayleigh wave propagation (Roesset *et al.*, 1991; Tokimatsu, 1995; Lai, 1998). An example of the use of this approach for surface wave tests performed on municipal solid waste landfills has been presented by the writers (Rix *et al.*, 1998).

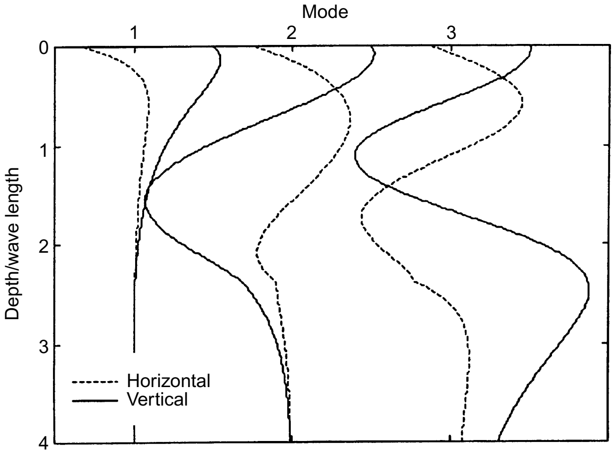

Fig. 13. Normalised displacements eigenfunctions for a frequency of 50 Hz

Moreover, the empirical inversion is conducted using a value of Poisson's ratio deduced from the refraction survey, which employs horizontally polarised shear (V_{SH}) waves, whereas Rayleigh wave propagation involves vertically polarised shear (V_{SV}) waves. This assumption is questionable since the results show that the site is characterised by a high degree of anisotropy, as noted by the author.

Finally, even though in this case it may not have played a major role in the results, in conventional two-station SASW testing frequency of excitation and sequence of receiver spacings and distances from the source are carefully chosen based on the required depth of investigation in order to optimise the resolution depth, minimise spatial aliasing and estimate near-field effects (Stokoe *et al.*, 1989; Tokimatsu, 1995). In the procedure used by the author to determine the experimental dispersion curve these issues seem not to have been addressed.

Material damping ratio

The material damping ratio is measured by the author using the logarithmic decrement of vertical motion caused along the ground surface by a vertical impact source (the stamping of a rubber boot). Near-field effects due to the presence of body waves in the vicinity of the source lead to a complex ground motion that is a function not only of the distance from the source but also of the frequency content of the source signature (Wolf, 1994). As a consequence the attenuation in the proximity of the source is related to different propagation phenomena, and cannot be used in a

Downloaded by [POLITECNICO DI TORINO] on [02/04/21]. Copyright © ICE Publishing, all rights reserved.

straightforward manner to identify the material damping ratio and the associated average strain.

Even in the far field, where Rayleigh waves dominate the motion, the attenuation is frequency dependent as a consequence of geometric dispersion in vertically heterogeneous media. The attenuation of the ground motion at Calvert landfill has quite different values at 20 Hz and at 30 Hz (see Table 5). In the writers' opinion these two values cannot be used directly to evaluate a damping ratio for the whole deposit by simply averaging them. Instead, an attenuation curve for several values of the frequency should have been computed and used in an appropriate inversion process (either coupled or uncoupled with the inversion of the dispersion curve) (Rix *et al.*, 2000; Lai *et al.*, 2001). Rix *et al.* (1998) illustrate this approach to measurements of material damping ratio profiles in solid waste landfills.

It is also important to note that the Rayleigh damping ratio inferred from measurements of the temporal decay of particle motion at a single point differs from the value of Rayleigh damping ratio from measurements of the spatial decay of particle motion with distance in dispersive media: that is, $Q_R^{-1}(\text{temporal}) \neq Q_R^{-1}(\text{spatial})$ (Aki & Richards, 1980).

The use of the damping measurement for the stress–strain relationship calibration is somewhat arguable. Indeed, energy dissipation and material non-linearity should not be identified as the same physical phenomenon. Experimental evidence shows that soils (and geomaterials in general) subjected to cyclic excitations exhibit the ability both to store and to dissipate strain energy. The phenomenon of energy dissipation takes place even at very small strain levels, below the linear cyclic threshold shear strain, where the material response is linear even though inelastic (Ishihara, 1996; Lo Presti *et al.*, 1997). Moreover, the procedure used by the author to determine the strain at which material damping was measured (division of the displacement determined at the geophone by the area of impact) does not reflect, in the writers' opinion, the complex strain history followed by the soil element at the free surface.

In summary, the writers believe it is no longer necessary or adequate to use empirical methods to obtain shear wave velocity and material damping ratio profiles from Rayleigh wave dispersion and attenuation data. The interpretation of surface wave test data should be based on well-known and established theories of wave propagation in vertically heterogeneous media. Also, the parameters obtained from seismic tests should be used carefully, accounting for the physics of wave propagation.

Author's reply

The discussion and interest is much appreciated, with the comments on new developments in surface wave methods and on the in-situ determination of damping. The original Rayleigh wave measurements at Calvert were made in 1987, when the skip tests were carried out. Improvements in technique and theoretical treatment have taken place since then. A frequency response analyser can now be used instead of a spectrum analyser for phase measurement. This instrument generates the frequency at which it is taking measurements, and averages over many readings. It is compact and relatively inexpensive. Alternatively the signals can be digitised and the phase found by using a fast Fourier transform method with a personal computer (Moxhay *et al.*, 2001). However, these developments do not invalidate the procedure used in the paper. The positions of the geophones were chosen to ensure that the signals being compared were not too dissimilar in amplitude, that they were not being aliased, and that the error in the phase angle was minimised.

Inversion of the Rayleigh wave data

More rigorous analytical methods can also now be used for inverting the graphs of velocity against frequency to produce plots of velocity against depth. The method of forward modelling calculates velocity against frequency from velocity against depth in an iterative procedure. Successively refined trial profiles of velocity are tested against observations (Nazarian & Stokoe, 1986). As a first approximation a profile can be found from the half wavelength rule and then improved by further adjustments. Dynamic finite element programs are becoming available that may be used for this purpose.

Heukelom & Foster (1962) used the half wavelength rule to produce profiles of velocities in pavements, where macadam overlay sand and gravel over clay: see Fig. 1 from their paper, where L is wavelength. The high velocities can be clearly seen above the lower velocities, with the transitions occurring at the right depths. In hindsight we should have recorded more detailed observations around the transition between the velocities, but this was not realised at the time of the measurements.

Poisson's ratio most probably has different values in different orientations in such an anisotropic material. A value in the vertical plane is strictly required for the vertically polarised surface waves. However, a difference of ±0·1 either side of 0·36 produces a change in the ratio of V_R/V_s of 2% at most from the graph in White (1965).

Measurement of damping ratio

The decay of vibration from an impact is due to two factors. Energy is absorbed by the material in which the vibration is taking place, and it is also radiated away into the half-space around. The situation is axisymmetrical, with the vibration of the centre line being similar to a simple harmonic motion in the vertical plane. The central vibration attenuates with time, while the amplitude also attenuates with distance from the source. The geophone was placed as close to the centre as possible without suffering damage, so as to minimise the effects of spatial reduction in signal. However, a correction was applied. Thus the traces on the screen followed the decay of the centre, rather than at some distance from the source. The geophone was spaced at a distance of 0·3 m, compared with the wavelength of 2·8 m.

The experiments reported in Abbiss (1986) suggest that the energy losses in the material of the ground (glacial till in this particular case) outweigh those due to radiation. Damping was still comparable when the period was increased to 10 s and the particle velocity was relatively small. Also, Table 1 from that paper lists the flux fraction flowing away from the vibration at higher frequencies. At 0·8 m the flux had reduced to 4×10^{-5} of that at 0·033 m. The calculation assumes that most of the energy was in the surface wave, which was flowing out over a cylinder of radius equal to the distance, D, from the source, and with a depth of one wavelength, λ. This is probably an overestimate as the displacement falls off with depth. The particle velocity, v, is in m/s and the flux fraction is proportional to Dv^2.

Table 1. Energy flux

D: m	v: m/s	Flux fraction
0·033	$2{\cdot}8 \times 10^{-3}$	1
0·213	$2{\cdot}7 \times 10^{-4}$	0·06
0·413	$1{\cdot}5 \times 10^{-4}$	0·04
0·613	$2{\cdot}8 \times 10^{-5}$	0·0018
0·813	$3{\cdot}5 \times 10^{-6}$	4×10^{-5}

Downloaded by [POLITECNICO DI TORINO] on [02/04/21]. Copyright © ICE Publishing, all rights reserved.

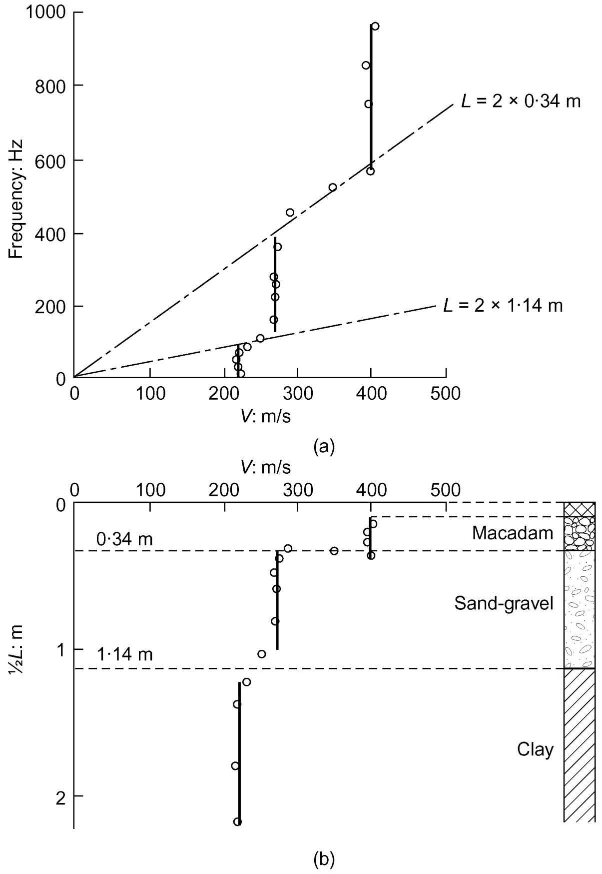

Fig. 14. Wave velocities observed on stratified soil, as a function of (a) frequency and (b) depth (from Heukelom & Foster, 1962)

The main problem is to assign an average strain to the region within which the energy is absorbed. Further work is required on this problem. It may be that the energy is radiated and reabsorbed within this region, where the strains are moderately high.

In an elastic material radiation losses can be calculated analytically (e.g. Miller & Pursey, 1954). This component may explain the difference between equation (3) for the *s* curve observed in the field and equation (13) for the basic non-linear material. However, this additional contribution may not greatly alter the value of the representative strain at the point of inflexion of the curve.

Damping and non-linearity

Damping in the material can be thought of as being due to two main, energy-absorbing components. There is the part due to non-linearity, which is time-independent, and visco-elastic contributions, which may be time-dependent. The latter are characteristic of clays, and are described in Abbiss (1986). The time-dependence is controlled by permeability, with low permeability producing delayed responses and a high Poisson's ratio nearly equal to 0·5. Conversely if the permeability is high then the response is over almost immediately, and one is left with non-linearity. The assertion made in this paper is that the losses in the landfill in question may be considered as frictional in the short term, indicated by a relatively small Poisson's ratio. This is borne out by the flat initial part of the settlement curve. In detail there may be several mechanisms responsible for this behaviour.

Elastic behaviour at very low strains is verified by Clayton & Heymann (2001). Bothkennar clay, London clay and high-porosity chalk all show linear stress–strain laws at strains below 0·002–0·003%.

In conclusion the approximations and assumptions made are intended to be appropriate to the problem and to lead to a reasonable accuracy in the calculation of immediate settlement.

REFERENCES

Abbiss, C. P. (1986). The effects of damping on the interpretation of geophysical measurements. *Géotechnique* **36**, No. 4, 565–580.

Aki, K. & Richards, P. G. (1980). *Quantitative seismology: theory and methods*. San Francisco: Freeman.

Clayton, C. R. I. & Heymann, G. (2001). Stiffness of geomaterials at very small strain. *Géotechnique* **51**, No. 3, 245–255.

Foti, S. (2002). Numerical and experimental comparison between 2-station and multistation methods for spectral analysis of surface waves. *RIG*, No. 1, 7–18.

Gucunski, N. & Woods, R. D. (1991). Use of Rayleigh modes in interpretation of SASW test. *Proc. 2nd Int. Conf. Recent Adv. Geotech. Earthquake Engng Soil Dyn., St Louis*, 1399–1408.

Heukelom, W. & Foster, C. R. (1962). Dynamic testing of pavements. *Trans. Am. Soc. Civ. Engrs* **127**, 425–457.

Ishihara, K. (1996). *Soil behaviour in earthquake geotechnics*. Oxford: Oxford University Press.

Lai, C. G. (1998). *Simultaneous inversion of Rayleigh phase velocity and attenuation for near-surface site characterization*. PhD dissertation, Georgia Institute of Technology, Atlanta.

Lai, C. G., Rix, G. J., Foti, S. & Roma, V. (2001). Application of multi-station methods to surface wave testing. *Soil Dyn. Earthquake Engng* (submitted).

Lo Presti, D. C. F., Pallaro, O. & Cavallaro, A. (1997). Damping ratio of soils from laboratory and in-situ tests. *Proc. 14th Int. Conf. Soil Mech. Found. Engng, Hamburg*, 391–400.

Miller, G. F. & Pursey, H. (1954). Field and radiation impedance of mechanical radiators on the surface of a semi-infinite isotropic solid. *Proc. Roy. Soc London Ser. A* **223,** 521–541.

Moxhay, A. L., Tinsley, R. D. & Sutton, J. A. (2001). Monitoring of soil stiffness during ground improvement using seismic surface waves. *Ground Engng,* **34**, No. 1, Jan, 34–37.

Nazarian, S. & Stokoe, K. H. (1986). *In situ determination of elastic moduli of pavement systems by spectral-analysis-of surface-waves method (theoretical aspects)*, Research Report 437-2. Austin: University of Texas at Austin.

Rix, G. J., Lai, C. G., Foti, S. & Zywicki, D. (1998). Surface wave tests in landfills and embankments. *Proc. Specialty Conf. Geotech Earthquake Engng Soil Dyn. III, Seattle*, 1008–1019.

Rix, G. J., Lai, C. G. & Wesley Spang, A. W. Jr (2000). In situ measurement of damping ratio using surface waves. *J. Geotech. Geoenviron Engng, ASCE* **126**, 472–480.

Roesset, J. M., Chang, D. W. & Stokoe, K. H. (1991). Comparison of 2-D and 3-D models for analysis of surface wave tests. *Proc. 5th Int. Conf. Soil Dyn. Earthquake Engng, Kalsruhe* **1**, 111–126.

Sànchez-Salinero, I. (1987). *Analytical investigation of seismic methods used for engineering applications*. PhD dissertation, University of Texas at Austin.

Stokoe, K. H., Rix, G. J. & Nazarian, S. (1989). In situ seismic testing with surface waves. *Proc. 12th Int. Conf. Soil Mech. Found. Engng, Rio de Janeiro*, 331–334.

Tokimatsu, K. (1995). Geotechnical site characterisation using surface waves. *Proc. 1st Int. Conf. Earthquake Geotech. Engng*, 1333–1368

White, J. E. (1965). *Seismic waves: radiation transmission and attenuation*. New York: McGraw-Hill.

Wolf, J. P. (1994). *Foundation vibration analysis using simple physical models*. Englewood Cliffs, NJ: Prentice Hall.

Downloaded by [POLITECNICO DI TORINO] on [02/04/21]. Copyright © ICE Publishing, all rights reserved.