

LASER-DOPPLER VIBROMETER MEASUREMENTS OF ACOUSTIC-TO-SEISMIC COUPLING IN UNCONSOLIDATED SOILS

N.D.Harrop

Department of Environmental and Mechanical Engineering, Open
University, Walton Hall, Milton Keynes, MK7 6AA.

K.Attenborough

School of Engineering, University of Hull, Hull.

ABSTRACT

Measurements of acoustic-to-seismic coupling ratio can be made in poroelastic materials to determine both elastic and structural properties. The function can be described as the ratio of the pressure exerted by an acoustic wave at a point on the surface to the acoustic particle velocity generated at the surface at that point. The sound pressure is measured using a microphone whilst particle velocities are usually measured using geophones. Problems with geophone sensors have been shown to include mass loading of the soil and coupling resonances within the frequency range of interest which can lead to inaccurate amplitude and phase measurements. In an attempt to overcome these problems, the use of a Laser-Doppler Vibrometer (LDV) has been investigated. LDV's have several advantages over more conventional vibration sensors, such as geophones, in that they have a flat amplitude and phase response and are non-invasive. We report good agreement among geophone and LDV measurements of vertical particle velocity for a continuous wave sound source. Problems with poor LDV signal-to-noise ratio in unconsolidated materials have been overcome using ground treatment. Subsequent modelling shows reasonable agreement between the data and the predicted values of material properties.

INTRODUCTION

Over the past fifty years, there has been considerable effort, in both civil and agricultural engineering, into the development of techniques to determine soil properties. Shear box or triaxial tests have long been the standard techniques for soil strength determination (Smith, 1994). Direct characterisation of the structural properties of soils has been developed using image analysis techniques (Ringrose-Voase, 1991), whilst indirectly there are several techniques that use liquid or gas flow measurements for characterising pore properties (Stinson and Daigle, 1988).

Most of these techniques involve the removal of a soil packet to be tested later in a laboratory. This removal either alters or totally destroys the in-situ soil structure, making the results difficult to interpret. These tests are also labour and time intensive and since many of the soil parameters of interest vary continuously with time, there is a need for continuous monitoring in a tolerably non-invasive manner. Wave propagation techniques can provide a means for determining the physical properties of soils with minimum soil disturbance. The measurement techniques align themselves to being portable and so suitable for field sites. Furthermore, measurements can be performed continuously without sample alteration once the source and receivers have been placed.

The propagating waves can be either seismic or acoustic. Seismic waves propagate in the bulk soil and are most sensitive to the macroscopic elastic properties of the soil frame. Seismic waves are primarily excited through direct contact with the soil surface, using mechanical vibrators, drop weights or explosive charges. Seismic investigations are commonly used to obtain information about the depth to the interface separating materials of different properties, and to obtain information about various physical properties of each material (Telford *et al.*, 1976).

Proceedings of the Institute of Acoustics

Acoustic waves propagate predominantly through the soil pore space and are sensitive to the hydrodynamic properties of the soil. Acoustic waves in the pores are excited by insonifying the ground using loudspeakers. Several authors (Moore and Attenborough, 1992; Sabatier *et al.*, 1996) have used acoustic waves to determine the air permeability and porosity of soils.

In principle however, acoustic waves can be used as the principal source of induced ground motion in porous elastic materials. Theoretical models of acoustic and seismic wave propagation in porous elastic materials predict the existence of two types of dilatational wave and one rotational wave. The first dilatational wave is primarily transmitted through the bulk soil and the second is primarily transmitted through the soil pores. This method of excitation has the advantage that the input source energy is non-invasive, especially when compared to the use of explosives in seismic exploration.

In light of this, there have been several studies in recent years that have involved the phenomena of acoustic-to-seismic coupling (Albert and Orcutt, 1989; Bass *et al.*, 1980; Sabatier *et al.*, 1986a). The function can be described as the ratio of the pressure exerted by an acoustic wave at a point on the surface to the acoustic particle velocity generated at the surface at that point. In these experiments, sound pressure at the surface was measured with a microphone, with the vertical seismic motion measured using a geophone.

Fluctuations in measurements of acoustic-to-seismic coupling have been attributed to geophone-ground interactions (Harrop, 1999). Several authors (Krohn (1984); Hoover and O'Brien (1980); Harrop (1999)) have undertaken studies of geophone ground coupling and have shown that there is a bandwidth over which the geophone accurately follows the ground motion, whose lower end is the natural frequency of the geophone and whose upper limit is the coupling resonant frequency. The coupling resonant frequency is independent of the natural frequency of the geophone but has been shown to be dependent upon the compaction of the soil into which the geophone is coupled.

In an attempt to overcome the inherent problems associated with the use of geophones for vertical particle velocity measurements it is proposed to investigate the possible use of a Laser Doppler Vibrometer (LDV) system. The use of the frequency shift of laser light (or Doppler shift) to measure flow velocities was first demonstrated experimentally in 1964 and has since undergone continued development (Bouchard and Bogg, 1985). Various LDVs were built in the late sixties (Massey, 1967; Whitman *et al.*, 1968) and are intended for non-contact vibration measurement from diffuse or specularly reflective surfaces. The LDV measures the moving velocity of an object by detecting the frequency shift of the laser. LDVs have several advantages over more conventional vibration sensors, such as geophones, in that they have a flat amplitude and phase response and are non-invasive.

Previously, Arnott and Sabatier (1990) compared the response of a geophone to a propane cannon burst and to continuous waves from a speaker system. Measurements were in the frequency range 100 to 500Hz. The geophones were positioned in a well-packed consolidated soil, which had been manicured with a straight edge to be horizontal so that the scattered light followed the path of the incident light. They showed that the response of the LDV followed the geophone when the LDV probe beam was focussed on the geophone and that a similar response was seen when the probe beam was focussed directly onto the soil 0.10m away.

A series of experiments have been undertaken using an LDV to assess its suitability for the measurement of induced ground vibration in unconsolidated soils as part of acoustic-to-seismic coupling investigations. The experiments undertaken were designed to show the precision and reliability of vertical ground motion measured using an LDV. In the study, ground motion was excited with atmospheric acoustic sound with a continuous wave speaker source. Vertical particle velocities were measured with geophones and compared with the LDV system. Measurements were taken in an anechoic chamber.

The measured coupling ratio has been compared with theoretical predictions made using a computer program FFLAGS. The FFLAGS program was developed for predicting the seismo-acoustic propagation in horizontally stratified waveguides using wavenumber integration in

Proceedings of the Institute of Acoustics

combination with the Direct Global Matrix solution technique. Wave propagation in the porous elastic medium is based upon the Biot-Stoll formulation. The formulation has been described extensively elsewhere (Tooms (1990); Tooms *et al.* (1992); Taherzadeh (1997)).

EXPERIMENTS

The experimental configuration for the measurements can be seen in Figure 1. A TTi TGA1230 arbitrary wave generator was used to supply the input signal, which was in the form of a sine wave. The output was amplified using an H&H S150 professional power amplifier and was then broadcast using a 30W Tannoy loudspeaker. A 1m brass tube, 0.017m in diameter, was attached to the driver in an attempt to approximate the speaker to a point source. The frequency of the sine wave was swept from 100Hz to 750Hz in 20Hz steps.

Vertical particle velocities were measured using Mark Products L-40A-2, 100Hz, uncased geophones and a Dantec LDV system, whilst sound pressure levels were measured using Brüel and Kjær Type 4191 condenser microphones. Outputs from the sensors were amplified separately prior to recording, using Brüel and Kjær Type 2160 measuring amplifiers.

Several factors can influence the quality of the LDV output. Firstly, any movement of the LDV itself will translate to an overestimation of the velocity of the sample under test, since the optical path length changes between the reflecting surface and the photodiode inside the LDV unit. Induced motion in the LDV can be from background building vibration, or especially in acoustic-to-seismic coupling measurements, motion can be induced through acoustic pressure from the loudspeaker.

The acoustic pressure wave imparts a force on the LDV equal to the product of its mass and acceleration. Thus to minimise LDV motion, the LDV should be massive and rigid. It is important that the LDV is kept stationary, since the impedance of the LDV and its supports should be much greater than the same product for the ground so that the LDV response to atmospheric sound is much less than that of the ground.

As part of the experiments therefore, the LDV was firmly bolted to a high-speed camera stand. The stand was designed so that the laser could easily be moved vertically and horizontally, whilst still keeping its axis vertical and perpendicular to the material under test. The camera stand was placed upon an anti-vibration optical table to reduce the effect of building vibration.

All the signals were recorded on an IBM compatible PC using a National Instruments E-Series AT-MIO-16E-2 I/O acquisition board controlled using a purpose written Labview program.

To evaluate the LDV system, the laser beam was focussed onto a geophone, positioned at the sand surface. To enhance laser reflection back to the photodetector, a piece of 3M reflective tape was applied to the geophone surface. Measurements of the response of the geophone and laser to a series of pure tones produced by the loudspeaker were made.

With the apparatus set-up and the laser reflecting at the geophone surface, a 100Hz tone was broadcast from the loudspeaker. The received signal from the geophone was then amplified and sampled on the PC. The time domain signal was transformed into the frequency domain using a Fast Fourier Transform and the peak frequency amplitude noted. Averaging was employed to enhance the signal-to-noise ratio, whilst a software bandpass filter was also used to reduce the effect of low frequency building vibration and high frequency noise.

The output from the laser was then viewed and again the peak frequency amplitude noted. The frequency was then increased by 20Hz and the procedure repeated, noting the peak frequency amplitude of the laser and geophone in further 20Hz steps up to 750Hz. Sound pressure levels were taken concurrently at all frequencies.

Proceedings of the Institute of Acoustics

All measurements were repeated with a similar L-40A-2 geophone to test reproducibility. To compare the sensor outputs, they were both converted into particle velocities (m/s), having first corrected to remove the effect of the gain used on the amplifiers.

The laser was then moved to a point approximately 0.05m away from the geophone and the response to pure tones noted. It was immediately noticeable that due to the nature of the sand, that it was very difficult to focus the laser (it became very problematical for the laser to attain an adequate lock).

To overcome the difficulty of obtaining sufficient back reflection from the sand to the photodetector, a cylinder with a flat top covered with reflecting tape was pushed into the sand. The laser beam was then reflected off the cylinder instead of the sand surface. The cylinder was manufactured from acrylic. This material was chosen as the most available material with a density close to that of the sand.

Three differing cylinders were made each having a different internal diameter. The dimensions of the three cylinders can be seen in Table 1.

Cylinder	Dimensions (Height x Diameter)
Cylinder 1	26.3mm x 48.5mm
Cylinder 2	24.8mm x 27.1mm
Cylinder 3	23.2mm x 12.1mm

Table 1. Internal diameters of the test cylinders.

In order to assess the effect of the cylinder, the geophone was positioned at the sand surface and the response to the continuous wave over the range 100Hz to 750Hz was noted. Cylinder 1 was then pushed into the sand surface and the geophone firmly attached to the top surface using double-sided tape. The experiment was then repeated, noting the peak frequency amplitude for each test frequency. Repeat measurements were then undertaken using Cylinders' 2 and 3.

Comparisons of the three cylinder tests with the original geophone measurements indicated that Cylinder 3 showed the least effect upon the received signal. Once this had been ascertained, a further set of measurements was undertaken where the laser beam was focussed onto the cylinder top and the response to the pure tones recorded.

Previous experiments to assess the effects of geophone-ground coupling have been carried out by the author (Harrop, 1999). The experiments compared to the amplitude and phase response of a geophone when firmly bolted to a mechanical shaker to the response when inserted into an unconsolidated material.

This experiment was now repeated to assess the possibility of any cylinder-ground coupling occurring. The experimental configuration can be seen in Figure 2.

A TTI TGA1230 arbitrary wave generator was used to supply the input signal, which was in the form of a sine wave, to a Ling Dynamics Model 403 Shaker. The laser was focussed onto the soil box. The amplitude of the sine wave was set by monitoring the RMS output from the Dantec Laser Doppler Vibrometer (LDV) on a Brüel & Kjær 2610 Measuring Amplifier, ensuring that there was always a constant velocity output of 0.26mm/s.

Cylinder 3 was pushed into the sand and the laser beam focussed upon the top using the horizontal adjustment feature of the high-speed camera stand. The output from the laser was amplified using a Brüel and Kjær Type 2160 measuring amplifier and sampled on the PC. The time domain signal was then transformed into the frequency domain and the peak frequency amplitude noted. Averaging was employed to enhance the signal-to-noise ratio.

The frequency of the sine wave was swept from 100Hz to 1000Hz in 25Hz steps with the peak frequency amplitude noted at each frequency. Since the laser was used as both the reference and vibration sensor, only amplitude measurements were taken.

EXPERIMENTAL RESULTS

The results of the initial experiment can be seen in Figure 3. This shows the response of the geophone situated at the ground surface to the acoustic source over a frequency range of 100Hz to 750Hz. The plot also shows the response of the LDV when focused on the top of the geophone.

The plot shows that it is possible to use the LDV system for measurements of ground velocity excited by atmospheric sound sources when the LDV probe beam reflects from the geophone. To be more useful, it would be desirable for the LDV system to work when the laser beam is reflected from the ground surface, rather than the reflective tape on the geophone top.

Figure 4 shows the response of the LDV to a 300Hz tone. Here the LDV has been focussed directly onto the sand surface. The upper plot, which is the time domain signal, shows a large noise component that is mirrored in the frequency spectrum below. The poor response of the LDV is probably due to scattering of the laser beam from the grains. The use of the plastic cylinders, proposed to overcome this problem can be seen in Figure 5. In the upper plot, a sine wave can be clearly seen with very little noise content, and the subsequent frequency spectrum shown in the lower plot shows a strong peak at 300Hz, well above the background levels.

The results of the second series of experiments, undertaken to assess the effect of using the cylinders to enhance the LDV signal, can be seen in Figure 6. The figure shows the response of the geophone positioned at the ground surface to the atmospheric sound source. The three remaining plots are the response of the geophone whilst attached to each of the cylinders that had been inserted into the sand.

It can be seen from the figure that the response of each of the three cylinders shows a reasonable agreement to that of the geophone without the presence of the cylinders. The agreement is improved at lower frequencies (less than roughly 400Hz), with greater variation at the high frequencies. Of the three cylinders tested it appears that Cylinder 3 has least effect on the geophone response, since the response of the geophone only and the geophone coupled to Cylinder 3 shows the most agreement over the frequency range used.

Since it appears that Cylinder 3 shows the least effect on the received signal, it was proposed that its use would provide an effective method for using an LDV for the measurement of vertical ground motion excited with atmospheric acoustic sound. To gauge this, the LDV was focussed directly onto Cylinder 3 and its response to a series of pure tones was compared to the response of a geophone attached to cylinder 3. The results of which can be seen in Figure 7.

It can be seen from Figure 7 that there is a good agreement between the two responses, although the agreement is less so at the higher frequencies. The disparity between the two plots may be due to differences in ground coupling of the cylinder, in a manner observed in geophones. This may be due to the fact that the experiment consisted of attaching the geophone to the cylinder and pushing it into the ground and measuring its response to the acoustic signal, then removing the cylinder and focussing the laser onto the cylinder. The removal of the cylinder and its repositioning in the ground may affect its coupling to the ground.

The results of the experiment to assess the possibility of any cylinder-ground coupling occurring can be seen in Figure 8. This plot shows the velocity of the soil box as measured using the LDV that can be seen as the straight line and the velocity of the cylinder as measured using the LDV.

If there had been perfect coupling between the sand and the cylinder then the second plot would have been a straight line to match the box, however, it can be seen that there is some

Proceedings of the Institute of Acoustics

variation between the two plots. Although it is noticeable that there is no marked frequency, over the range of the test, at which the cylinder response is vastly different. This shows that unlike the geophones tested previously (Harrop, 1999) there does not appear to be a coupling resonant frequency for the cylinder. It seems likely that this is due to the fact that the cylinder has the same density as that of the sand.

It can be concluded therefore that the LDV system can be used for measurements of ground motion in unconsolidated materials when excited by atmospheric sound sources by making use of the cylinder method proposed.

During all the experiments, there was approximately 50dB difference between signal and noise for most frequencies.

Theoretical and Experimental Comparisons

Comparison between the measured acoustic-to-seismic coupling ratio (utilising the LDV) and the FFLAGS model, have been made and can be seen in Figure 9. Table 2 gives a comparison of the soil properties predicted by the FFLAGS model and those values that have been mechanically derived. It can be seen from both Figure 9 and Table 2 that a reasonable agreement has been found between the model and the data.

Soil Parameter	Directly Measured	Acoustically Derived
Number of Layers	1	1
Layer Thickness (m)	0.18	0.18
Flow Resistivity (mks rayls)	16545 ± 726	20000
Porosity (%)	36.0	36.0
Bulk Modulus (MPa)	7.50×10^7	7.50×10^7
Shear Modulus (MPa)	1.30×10^7	1.30×10^7
Soil Density (kg/m^3)	1634	1600

Table 2. Comparison of soil properties determined from acoustic-to-seismic coupling ratio experiments and the FFLAGS prediction.

Conclusions

In an effort to overcome the problem of sensor coupling with the ground, the use of a Laser Doppler Vibrometer has been proposed to provide a completely non-invasive method of measuring motion in soils. This technique has been previously shown to work in consolidated soils. Measurements in unconsolidated soils have shown that poor specular reflection is achieved, resulting in an inaccurate measurement of the induced ground motion.

A solution to this difficulty has been suggested using small cylinders that can be pushed into the ground. The cylinders used have a density similar to the density of the soil into which they are placed. This appears to reduce the effect of the coupling resonant frequency seen in the geophone sensors. The flat surface of the cylinder can be treated to provide a specularly reflective surface.

References

- Albert, D. G. and J. A. Orcutt (1989). "Observations of low-frequency acoustic-to-seismic coupling in the summer and winter." Journal of the Acoustical Society of America **86**(1): 352-359.
- Arnott, P. W. and J. M. Sabatier (1990). "Laser doppler vibrometer measurements of acoustic-to-seismic coupling." Applied Acoustics **30**: 279-291.
- Bass, H. E., L. N. Bolen, D. Cress, J. Lundian and M. Flohr (1980). "Coupling of airborne sound into the earth: Frequency dependence." Journal of the Acoustical Society of America **67**(5): 1502-1506.
- Bouchard, G. and D. B. Bogg (1985). "Experimental measurement of scattered surface waves using a laser doppler technique." Journal of the Acoustical Society of America **77**(3): 1003-1009.
- Krohn, C. E. (1984). "Geophone ground coupling." Geophysics **49**(6): 722-731.
- Harrop, N. D (1999). "The exploitation of acoustic-to-seismic coupling for the determination of soil properties" PhD Thesis The Open University, UK.
- Hoover, G. M. and J. T. O'Brien (1980). "The influence of the planted geophone on seismic land data." Geophysics **45**(8): 1239-1253.
- Massey, G. A. (1967). study of vibration measurements by laser methods, NASA.
- Moore, H. M. and K. Attenborough (1992). "Acoustic determination of air-filled porosity and relative air permeability of soils." Journal of Soil Science **43**: 211-228.
- Ringrose-Voase, A. J. (1991). "Micromorphology of soil-structure: description, quantification, application." Austrian Journal of Soil Research **29**: 777-813.
- Sabatier, J. M., H. E. Bass, L. M. Bolen and K. Attenborough (1986a). "Acoustically induced seismic waves." Journal of the Acoustical Society of America **80**: 646-649.
- Sabatier, J. M., D. C. Sokol, C. K. Frederickson, M. J. M. Rompkins, E. H. Grissinger and J. C. Shipp (1996). "Probe microphone instrumentation for determining soil physical properties: Testing in model porous materials." Soil Technology **8**: 259-274.
- Smith, G. N. (1994). Elements of Soil Mechanics. Oxford, BSP Professional Books.
- Stinson, M. R. and G. A. Daigle (1988). "Electronic system for the measurement of flow resistance." Journal of the Acoustical Society of America **83**(6): 2422-2428.
- Taherzadeh, S. (1997). Sound propagation in inhomogenous media. Engineering Mechanics. Milton Keynes, The Open University.
- Tooms, S. (1990). Acoustic propagation near porous and elastic boundaries. Engineering Mechanics. Milton Keynes, The Open University.
- Tooms, S., S. Taherzadeh and K. Attenborough (1993). "Sound propagating in a refracting fluid above a layered fluid saturated porous elastic material." Journal of the Acoustical Society of America **93**(1): 173-181.
- Telford, W. M., R. E. Sheriff, L. P. Geldert and D. A. Keys (1976). Applied Geophysics. Cambridge, Cambridge University Press.
- Whitman, R. L., L. J. Laub and W. J. Bates (1968). "Acoustic surface displacement measurements on a wedge-shaped transducer using an optical probe technique." IEEE Transactions on Sonics and Ultrasonics **SU-15**(3): 186-189.

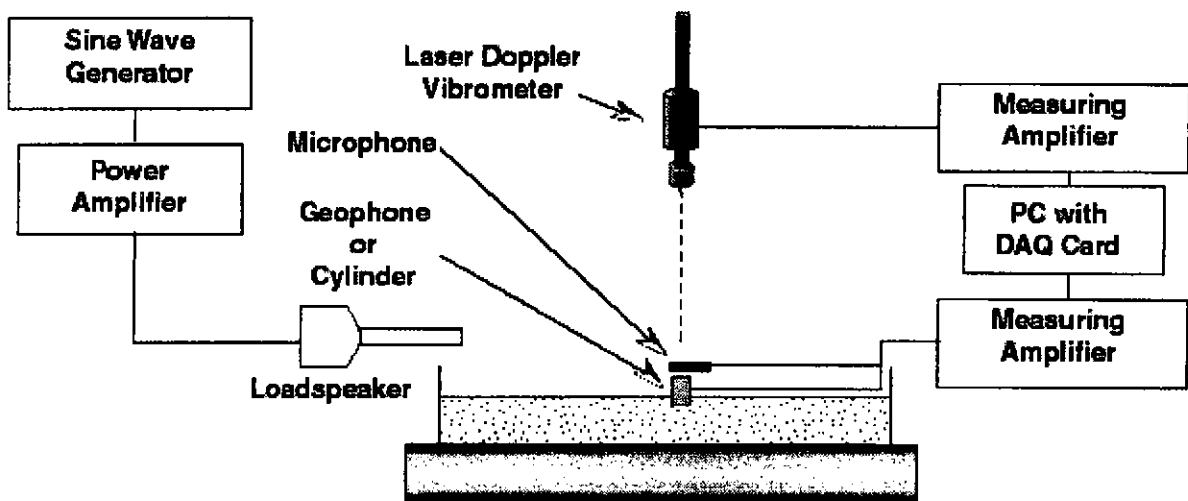


Figure 1. Instrumentation configuration for the LDV assessment measurements.

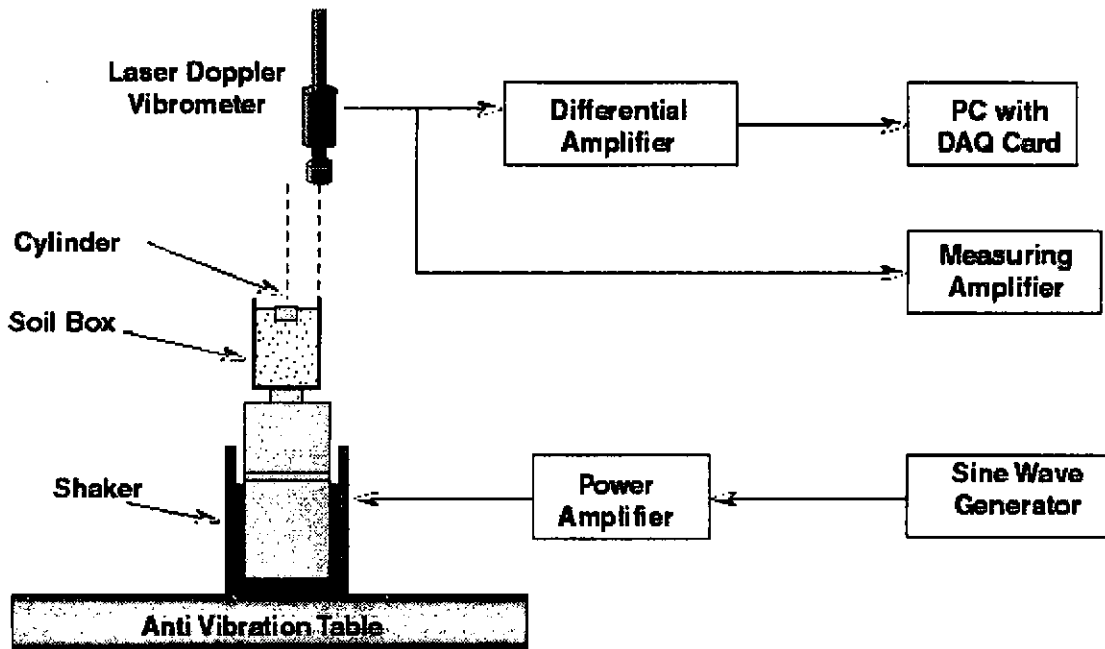


Figure 2. Instrumentation configuration for the LDV-ground coupling assessment measurements.

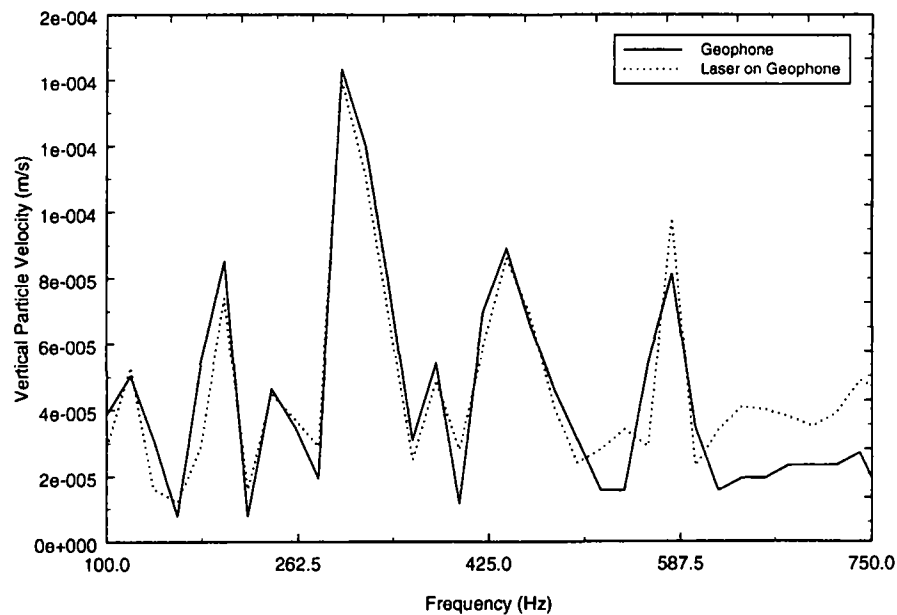


Figure 3. Geophone and LDV response to a series of pure tones. Here the geophone is positioned at the ground surface, with the laser focussed onto the geophone top.

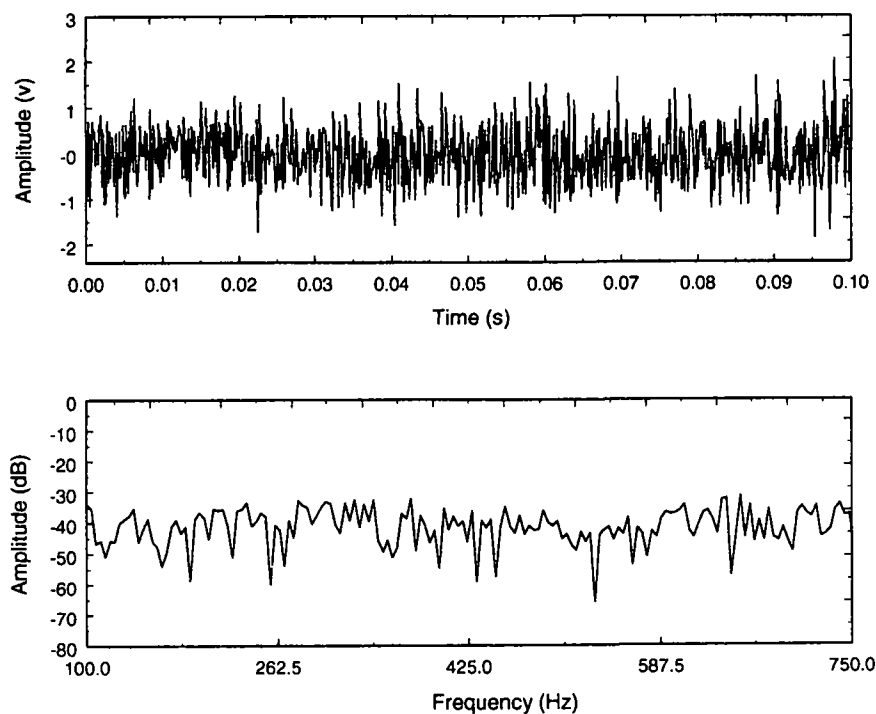


Figure 4. LDV response to a 300Hz pure tone. Here the LDV is focussed directly onto the ground surface.

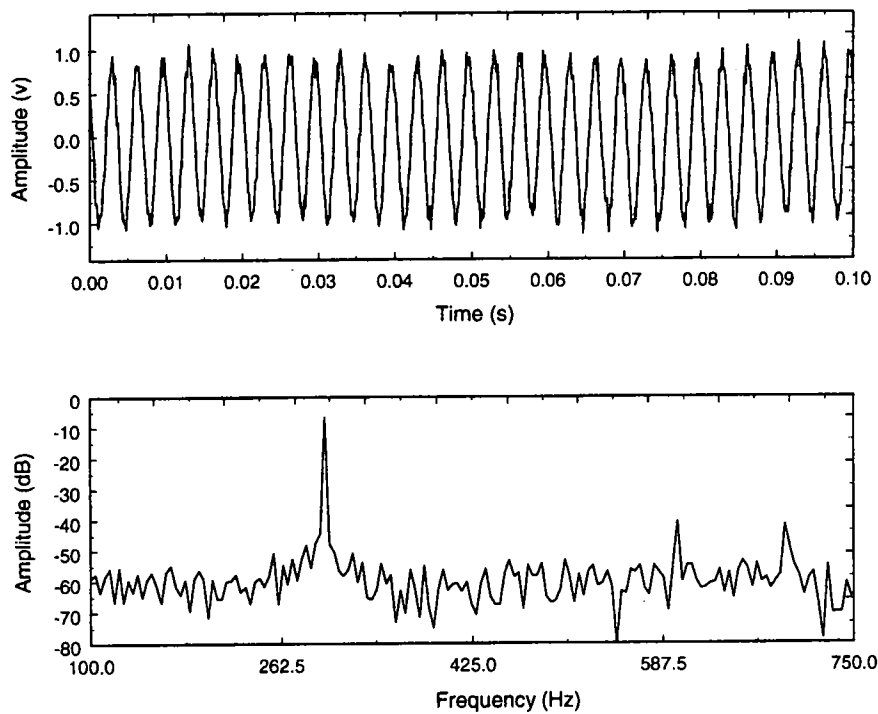


Figure 5. LDV response to a 300Hz pure tone. Here the LDV is focussed onto a plastic cylinder.

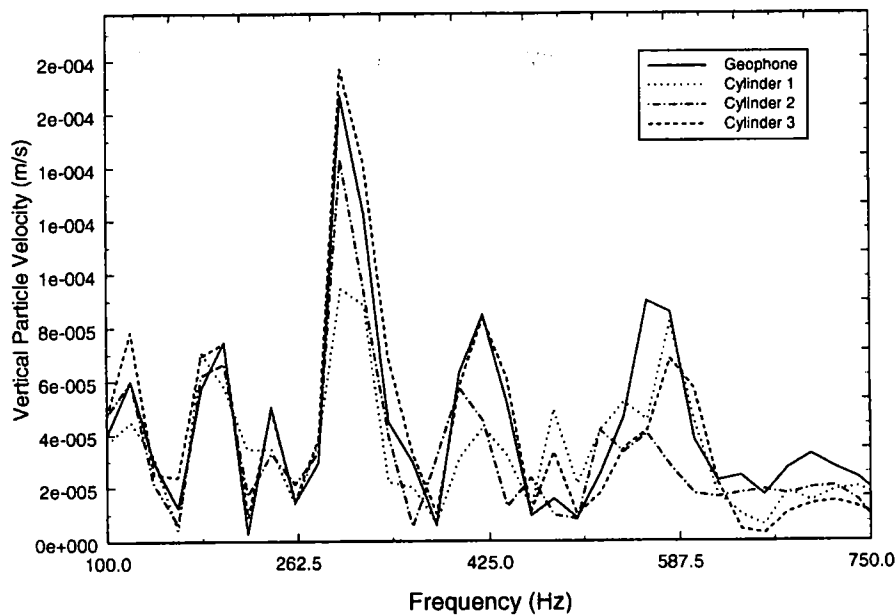


Figure 6. Response of the geophone to a range of pure tones, whilst positioned at the ground surface and the response whilst attached to Cylinders 1 to 3 buried in the ground.

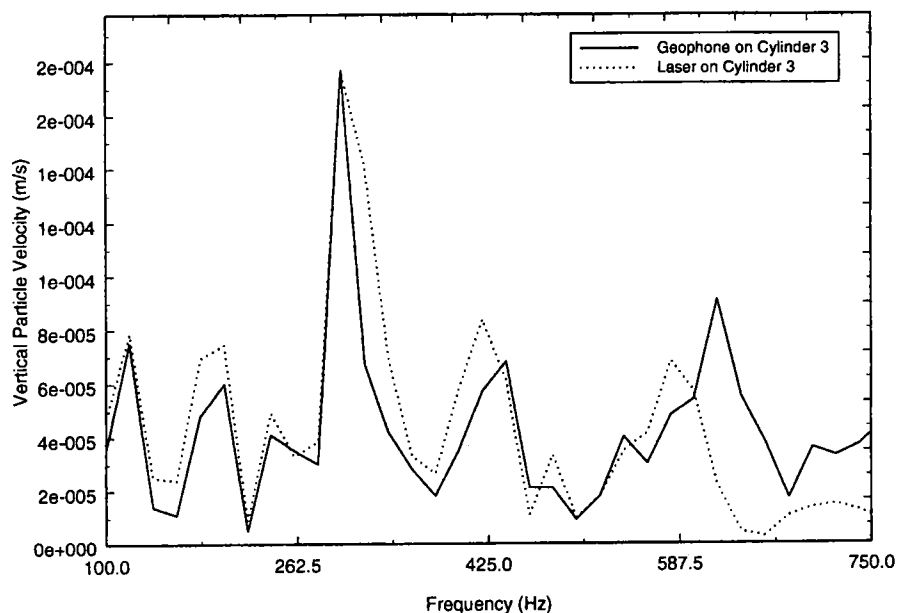


Figure 7. Showing the response of the geophone (coupled to Cylinder 3) and laser (focussed onto Cylinder 3) to a range of pure tones.

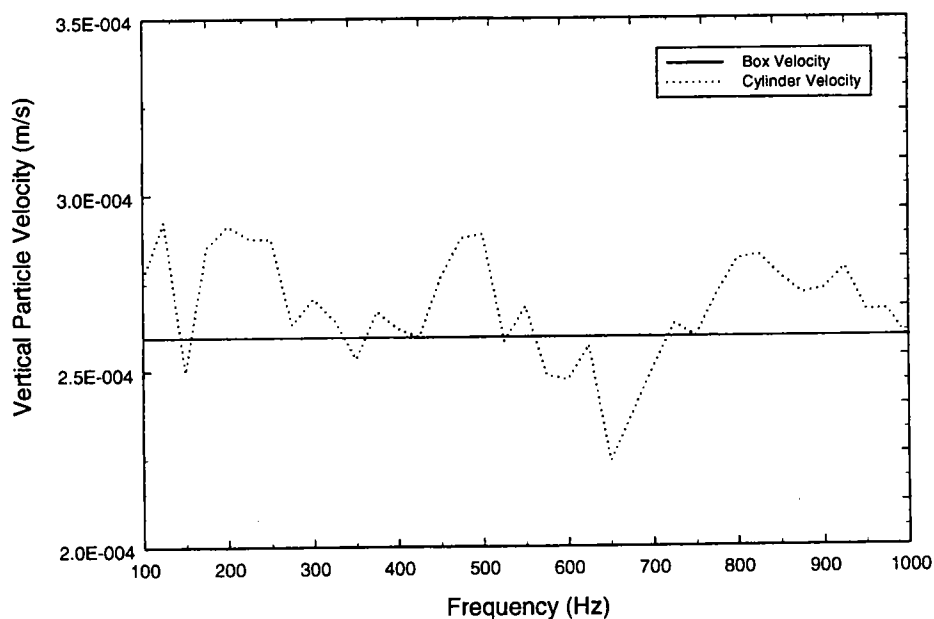


Figure 8. LDV calibration chart using the sand box. This shows the response of laser focussed onto Cylinder 3.

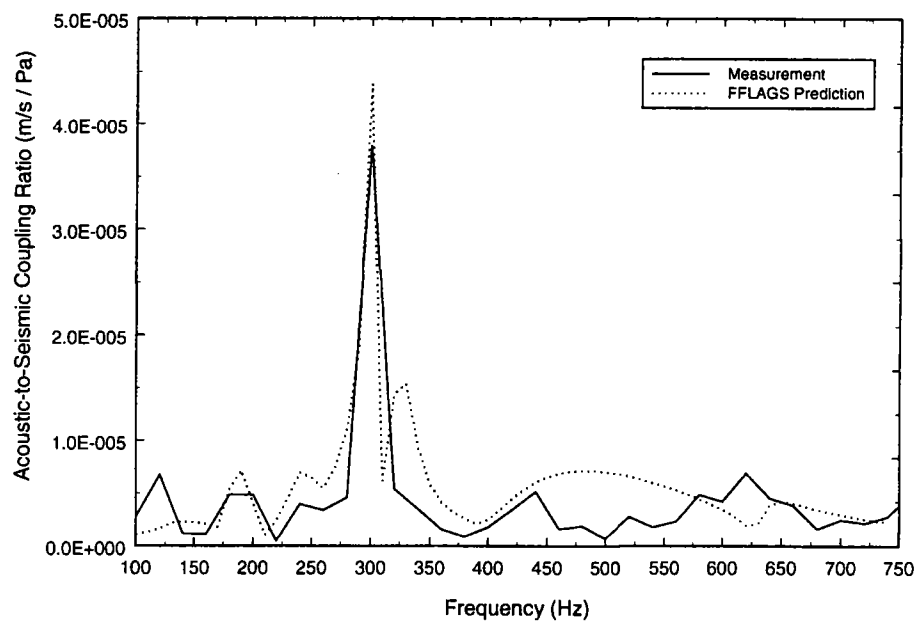


Figure 9. Comparison between measured and predicted acoustic-to-seismic coupling ratio.