Multimode Rayleigh wave profiling by hybrid surface and borehole methods

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Abstract
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Keywords
Fourier analysis, Downhole methods, Controlled source seismology, Surface waves and free oscillations, Site effects, Wave propagation

Disciplines
Geotechnical Engineering

Comments
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SUMMARY
To improve the accuracy of shallow seismic shear wave velocity profiling, we propose a minimally invasive hybrid surface-and-borehole method that enhances the detection of higher modes of Rayleigh wave dispersion data. The new method combines techniques from the multichannel analysis of surface waves and multichannel simulation with one receiver (MSOR) methods to record components of Rayleigh wave motion at the surface as well as at shallow depths within the soil mass. The performance of the proposed method is demonstrated through computational and experimental studies. We show that individual modes of Rayleigh waves can exhibit different dominant depths at which their motion is most significant. This is demonstrated through a numerical study of eigenvectors of layered soil profiles via the stiffness matrix method, and confirmed by a finite element simulation of the apparent dispersion trends recorded at shallow depths using MSOR. Upon superimposing dispersion data recorded via the receivers at various depths, the resulting multimode dispersion data is used in a multi-objective inverse analysis, for which the difference between experimental and theoretical dispersive phase-velocity spectra are minimized for multiple modes simultaneously. In the numerical study, we demonstrate that the resulting inverted profiles and theoretical dispersion data have improved accuracy relative to single-mode inversion. Preliminary field tests are performed using the new hybrid method, and the results are shown to support the conclusions of the numerical study and confirm the feasibility of the proposed technique. Although the use of multiple modes in surface wave testing is not new, the proposed hybrid method can provide more accurate and complete multimodal dispersion data than achieved with surface-only Rayleigh wave methods. As a result, errors because of misidentification or partial measurement of higher modes may be minimized, thus reducing statistical uncertainty in the inverted profiles.

Key words: Fourier analysis; Downhole methods; Controlled source seismology; Surface waves and free oscillations; Site effects; Wave propagation.

1 INTRODUCTION
For surface wave methods, the quality of experimental dispersion data is of critical importance to infer accurate site profiles in terms of layer thicknesses and shear wave velocities. Layered soil profiles inherently possess multimode dispersion characteristics, which include complete information on the soil profile. However, in the analysis of dispersion data from surface wave testing, if one selects only the Rayleigh wave component that is dominant at each frequency, then a single ‘apparent dispersion curve’ will be obtained. The apparent dispersion curve is comprised of a fundamental-mode curve for ‘regular’ soil sites for which velocity increases gradually with depth, or a combination of several modes for irregular profiles which contain velocity inversions or fast over slow layers (e.g. see Nazarian 1984; Gucunski & Woods 1992; Stokoe et al. 1994a; Park et al. 1999a; Xia et al. 1999; Louie 2001; Ryden 2004; Lu et al. 2007; Wong et al. 2011). The single apparent dispersion curve contains only a fraction of the available information on the soil profile contained in the data, and thus limits the resolution and accuracy of the inversion results.

Previous studies have demonstrated that higher mode Rayleigh waves not only provide information for greater depths than the fundamental mode, but also improve the accuracy of the inverted shear wave velocity ($V_s$) profile and improve the stability and resolution of the inversion calculations (e.g. Tokimatsu et al. 1992; Xia et al. 2000, 2003; Beaty et al. 2002; Supranata 2006; Song et al. 2007; Luo et al. 2007). However, noninvasive measurement of multimode dispersion data from surface waves is challenging for a number of reasons. First, wave trains can be very close together and can even overlap (Crampin & Bath 1965), and different modes may have approximately equal group velocities (Nolet & Panza 1976). Second, the presence of a rigid stratum or stiff layer can cause a higher
Rayleigh mode to become dominant at low frequencies, shifting the apparent dispersion curve from the fundamental to the higher mode (Karray & Lefebvre 2010). Even when the fundamental mode appears to be clearly captured, its use in a fundamental-mode inversion can fail to accurately determine the velocity of bedrock (Casto et al. 2010). Analysis of higher modes is thus crucial for accurate determination of bedrock depth as well as identification and isolation of the fundamental mode in general.

Third, it can be difficult to measure higher modes because they can be much less energetic than the fundamental mode (Socco et al. 2010). The frequency-wave number (f-k) method can be used to extract multimode dispersion data from measured surface waves, particularly if a long geophone array is used, which aids in separating higher modes with small differences in wavenumber (Gabriels et al. 1987; Stokoe et al. 2004). The f-k method can also be used with conventional arrays (e.g. 24–48 geophones with spacing of a few metres), although wavenumber resolution \( \Delta k = 1/L \) improves with increasing total array length (Foti et al. 2002). If several hundred traces and large receiver spreads of several hundred metres are used, significant lateral variation in material properties may be incurred for the depth scales considered in near-surface profiling (Park et al. 1999b). In addition, it can be seen from various studies that receiver arrays longer than 250 m (Stokoe et al. 2004), 330 m (Gabriels et al. 1987), 600 m (Vanneste et al. 2011) or 2000 m (Klein et al. 2005) can cause the layered profile assumption to become invalid, thus decreasing the reliability of the measurements.

An advantage of more time consuming and costly borehole methods is their greater accuracy, as they involve direct measurement of wave propagation times between two points and do not require an inversion analysis. The primary advantages of surface wave methods are their non-invasive nature and resulting lower cost relative to borehole testing methods, as well as the property of Rayleigh waves to give information well below the sensor elevation, for example to depths on the order of 30–50 m for large impact sources, or 75 to over 200 m for Vibroseis sources. However, solutions for \( V_p \) profiles from surface wave inversion procedures are non-unique (e.g. Calderón-Macias & Luke 2007), and therefore possess statistical uncertainty. Furthermore, if higher modes are not resolved appropriately, they can contribute further to this uncertainty, as they may be mistaken for the fundamental mode. Significant effort has therefore been focused on detecting higher modes in surface wave data to minimize their influence or extract the fundamental mode (e.g. see Park et al. 2000).

The multichannel analysis of surface waves (MASW) method has been employed to measure multimode Rayleigh waves using relatively short geophone arrays of approximately 30 m (e.g. Park et al. 1999b, 2000; Xia et al. 2000, 2003; Song et al. 2007). However, the resulting multimode dispersion data are generally incomplete in the frequency range of interest (e.g. Xia et al. 2003; Bergamo et al. 2011), and are unclear at some frequencies (Song et al. 2007). In addition, including the higher modes in the inversion process can result in an inferior fit of the fundamental mode (Casto et al. 2010). A similar technique named the ‘Modal Analysis of Surface Waves method’ has also been used to measure higher modes, although this method appears to selectively skip many of the higher modes (e.g. Karray & Lefebvre 2010). The practice of manually picking multimode curves from the apparent dispersion data can also yield inaccurate target curves for the inversion analysis, introducing significant errors into the inverted profiles.

As is evident from the studies outlined above, the successful measurement and effective application of higher Rayleigh wave modes is a challenge that requires advances in experimental and analytical techniques. To this end, a hybrid surface-and-borehole method is proposed herein, which combines techniques from MASW testing and borehole or probing methods to limited depths. Using the hybrid method, the accuracy with which higher modes can be measured is improved relative to surface-only methods. The hybrid method can thus be viewed as an enhancement to surface wave methods by the addition of limited-depth borehole measurements, or conversely, as an enhancement of borehole methods by the addition of surface wave data, whereby use of Rayleigh waves extends the profiling depth of borehole methods (such as crosshole tests) or probing methods [such as seismic cone penetration tests (CPT)] well below the maximum depth of the sensor.

### 2 MULTIMODE RAYLEIGH WAVES

Non-invasive surface wave methods employing sensors coupled to the ground surface have been widely used to measure Rayleigh waves since the 1980s. An advantage of surface wave methods is the relative ease with which Rayleigh wave motion can be measured, as this wave type comprises the majority of energy generated from a source on the surface. As depth increases, however, the dominant mode of the surface waves will attenuate quickly, while the other modes may become increasingly dominant, with mode shapes that are strongly dependent on the soil profile. This is demonstrated below by examining the natural mode shapes of Rayleigh waves with depth, that is, the natural mode shapes of vibration of the layered soil structure.

#### 2.1 Natural mode shapes of Rayleigh waves with depth

To gain insight into mode shapes of Rayleigh waves with respect to depth, a layered soil system defined by the parameters in Table 1 was analysed using the dynamic stiffness method (DSM) of Kausel & Roesset (1981). Using the DSM, layer stiffness matrices were calculated and assembled to form a global stiffness matrix whose eigenvectors correspond to the mode shapes of the soil system (e.g. see Supranata 2006). Theoretical dispersion curves calculated by the transfer matrix method for the same layered soil system are presented in Fig. 1. The resulting phase velocities \( (V_{ph}) \) of four modes of the dispersion curves were determined at a frequency of 60 Hz, and the corresponding wavelengths were calculated (Table 2). Substituting these frequencies and wavelengths into the global stiffness matrix of the system gives the mode shapes for the fundamental and three higher modes (Fig. 2).

The fundamental mode attenuates exponentially with depth (Fig. 2), as is expected for Rayleigh waves (e.g. Richart et al. 1970). Considering a superposition of all modes, it can be seen that the higher modes will become dominant as depth increases because of the decay of the fundamental mode. Conceptually, depending upon the relative amplitudes of the various modes, a measurement of soil motion at depth may have significant energy contributed by the higher modes and negligible energy from the fundamental mode. Therefore, sensors placed at selected depths in the soil

<table>
<thead>
<tr>
<th>Layer</th>
<th>( V_s ) (m s(^{-1}))</th>
<th>Poisson’s ratio, ( \nu )</th>
<th>Density, ( \rho ) (kg m(^{-3}))</th>
<th>Layer thickness, ( h ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>150</td>
<td>0.30</td>
<td>1800</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>0.30</td>
<td>1800</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>400</td>
<td>0.30</td>
<td>1900</td>
<td>( \infty ) (half-space)</td>
</tr>
</tbody>
</table>

Table 1. Parameters of layered soil model.
profile may be able to record the higher mode Rayleigh waves with improved accuracy because of improved separation from the fundamental mode owing to higher signal-to-noise ratios. In contrast, attempting to measure higher mode contributions at the soil surface for this layered system would typically result in the fundamental mode dominating the response, reducing the accuracy of the higher modes.

The hypothesis of this study is that sensors placed at shallow depths in the soil using a borehole or probe can enable more accurate resolution of higher mode Rayleigh waves, thus improving the accuracy of final inverted $V_s$ profiles. A hybrid method is therefore proposed which combines aspects of surface wave and borehole methods. In contrast to borehole methods such as suspension logging or cross-hole testing, the approach does not limit the depth of profiling to the maximum sensor depth, and only a single borehole or probe sounding is needed. Because Rayleigh waves and concepts of surface wave testing are employed, the maximum sensor depth is only a fraction of the maximum depth profiled, making the hybrid method more efficient and economical than borehole methods, yet possibly more accurate than surface-only methods.

### 2.2 Sensitivity of multimode dispersion images to soil structure

The Jacobian matrix can be used to assess the sensitivity of the dispersion data to soil model parameters (e.g. Xia et al. 1999, 2003; Luo et al. 2007). The magnitude of the Jacobian matrices for the soil model of Table 1 (Fig. 3) demonstrate that the near-surface soil generally has the greatest influence on a given Rayleigh wave mode, with the exception of the fundamental mode between 15 and 20 Hz. However, for any given depth, the higher modes generally show a greater sensitivity to soil model parameters than lower modes.

<table>
<thead>
<tr>
<th>Mode #</th>
<th>Phase velocity, $V_{ph}$ (m s$^{-1}$)</th>
<th>Wavelength, $\lambda = V_{ph}/f$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>140.7</td>
<td>2.34</td>
</tr>
<tr>
<td>2</td>
<td>197.7</td>
<td>3.29</td>
</tr>
<tr>
<td>3</td>
<td>259.4</td>
<td>4.32</td>
</tr>
<tr>
<td>4</td>
<td>320.7</td>
<td>5.36</td>
</tr>
</tbody>
</table>
If only the fundamental mode is used for inversion (Fig. 3a), the deep soil structure will have very limited influence on the inversion results. That is, the uncertainty of the inverted $V_s$ profile will be expected to be greater for the deeper layers. If the higher modes (Figs 3b and c) are used in the inversion, then the deeper layers will exert a greater influence on the inversion results and $V_s$ will be expected to have lower uncertainty for the deeper layers.

## 3 HYBRID FIELD TESTING

### 3.1 Multichannel simulation with one receiver (MSOR) method

To implement an economical and minimally invasive field-testing approach for measuring higher Rayleigh wave modes, the MSOR method can be used instead of a multichannel one-source method such as MASW. The MSOR method simply reverses the roles of source and receiver in the MASW method, and has been successfully applied to non-destructive testing of pavements (Ryden et al. 2002; Ryden 2004; Ryden & Park 2006; Olson & Miller 2010) and soils (Lin & Ashlock 2011). Compared to the MASW method, the MSOR method has several advantages: (1) greatly reduced instrumentation costs as only one sensor is required; (2) cost savings for data acquisition systems as only two channels are needed (one for the geophone and the other for a trigger); (3) the potential to be faster than MASW if an automated moveable impact source is available, as set-up time for a string of geophones and cables is eliminated; (4) ease in obtaining a 3-D profile as the source can readily be moved along different horizontal lines as shown in Fig. 4, compared to reinstalling an entire string of geophones multiple times to cover the whole testing area for MASW. The primary requirement of the MSOR method is to obtain a repeatable impact source that can generate waves with consistent timing (Park et al. 2002).

### 3.2 Measurement of higher mode Rayleigh wave motion within the soil

For measurement of the vertical Rayleigh wave motion at selected shallow depths in the soil, a borehole geophone may be used. One potential difficulty when using a borehole for such tests is the prospect of collapsing soils such as sands below the water table, which would normally require hollow-stem auguring or installation of casing. This problem might be avoided if a sensor were inserted in the soil by a probe and used measure the unimpeded free-field Rayleigh wave motion within the soil. A standard seismic CPT probe would not likely be usable, as the stiffness of CPT rods would attenuate the motion and alter the dispersion data. However, a retractable CPT tip with embedded accelerometer or geophone which can be temporarily uncoupled from the CPT rods may be a useful alternative.

In the proposed hybrid method, a sensor is used to measure the ground motion at the surface, then at selected depths within the soil, under the action of surface impacts performed over a range of offsets. Alternatively, a string of borehole geophones could be used to measure the motion at several depths simultaneously to reduce testing time. The initial configuration with the sensor at the surface (before creating a borehole) is the same as an MSOR test. The resulting recorded ground motion can then be used to construct a dispersion image using standard MASW analysis procedures. The downhole sensor is then lowered to the first selected depth in the soil and the series of impacts repeated, giving another dispersion curve. As the sensor is lowered to greater depths, the higher modes will begin to dominate the dispersion curves (Fig. 2). Detailed in the following sections are numerical simulations of the test procedure described above, followed by results and interpretation of preliminary field tests.

## 4 NUMERICAL SIMULATIONS

### 4.1 Finite element simulation of multimode Rayleigh wave measurement by hybrid approach

To test the hypothesis that multimode Rayleigh waves can be effectively measured using the proposed minimally invasive hybrid approach, the finite element method (FEM) was used to simulate MSOR tests in Abaqus 6.10–1 with geophones embedded at depths of 0, 1.2, 2.4 and 3.6 m (Fig. 5). To model half-space radiation conditions, infinite elements were used on the two lateral boundaries as well as underneath the bottom layer. A transient impact was used to simulate the dynamic loading of a sledge hammer on the free surface at 24 source locations having a horizontal spacing of 1 m and first offset of 2 m, and the resulting vertical velocity was calculated at the embedded geophone locations. Rayleigh waves as well as primary, reflected and head waves can be clearly seen in the displacements (Fig. 5), although the half-space conditions cannot be simulated perfectly by FEM. The resulting MSOR velocity data for the 24 source locations were assembled to form multichannel records for each geophone, from which dispersion data were...
calculated using the wavefield transformation method of Park et al. (1998), which produces images of the dispersion curves (Fig. 6).

From the simulated dispersion data, apparent Rayleigh wave modes are obtained for each geophone measurement depth, and the higher modes clearly become more dominant at higher frequencies as geophone depth increases as a result of the decay of lower mode Rayleigh wave motion. The maxima of the dispersion-image data produced by the wavefield transformation method correspond to the apparent dispersion curves for each geophone depth (Fig. 6). It should be noted that the dispersion data for the surface sensor corresponds to MASW testing by reciprocity with the MSOR method, and does not contain a clear branch of the higher modes (Fig. 6a). The apparent dispersion data were superimposed to construct multimode dispersion curves, which are in good agreement with their theoretical counterparts from Fig. 1 obtained via the transfer matrix method (Fig. 7). This numerical simulation clearly demonstrates that the proposed minimally invasive testing method for measuring multimode Rayleigh waves is feasible, provided that an effective field testing procedure can be developed.

4.2 Multimode inversion via genetic simulated-annealing optimization

The authors recently developed an optimization method for inversion of dispersion data which combines the genetic and simulated annealing algorithms. This inversion program was used to
back-calculate the soil profile in terms of layer thickness and shear wave velocity for the multimodal simulated experimental dispersion curves of Fig. 7. For each inversion trial, the first generation of starting models was randomly produced within a search space obtained by varying the parameters of the same initial model by ±50 per cent. Fig. 8(a) shows inversion results for six trials using only the fundamental mode, whereas Figs 8(b) and (c) show results of using the first two and three modes, respectively, in a multi-objective inversion. The two- and three-mode inversions result in a greater number of $V_s$ profiles close to the real profile in terms of both $V_s$ and layer thickness.

To quantify the inversion accuracy, the inversion error (IR) was calculated in terms of the cumulative relative errors of the inverted profiles as

$$IR = \sum_{i=1}^{2} \sum_{L=1}^{N} \frac{|Inv_{i,L} - Real_{i,L}|}{Real_{i,L}},$$

where $i = 1$ represents layer thickness, $i = 2$ represents shear wave velocity, $L$ represents the layer number and $N$ is the total number of layers. Use of the higher mode dispersion data significantly reduces the IR (Fig. 8; Table 3), whereas a good match of the fundamental mode alone does not ensure a good match for the higher modes. For example, although the root-mean-square (rms) error of 3.85 for the fundamental-mode inversion (Fig. 9a) is slightly smaller than the rms error of 4.17 for the two-mode inversion (Fig. 9b), the corresponding rms errors for the first- and second-higher modes as well as the average IR (Table 3) are nearly twice as high if only the fundamental mode is used. Switching from a two-mode to a three-mode inversion slightly increased the rms error of all three dispersion curves (Fig. 9), but decreased the minimum IR as well as the average IR (Table 3), thus increasing the accuracy of the inverted shear wave velocity profiles (Fig. 8). The multimode inversion

<table>
<thead>
<tr>
<th>Modes used for inversion</th>
<th>Inversion trial</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st</td>
<td>2nd</td>
</tr>
<tr>
<td>Fundamental mode</td>
<td>1.264</td>
<td>0.390</td>
</tr>
<tr>
<td>Two modes</td>
<td>0.303</td>
<td>0.716</td>
</tr>
<tr>
<td>Three modes</td>
<td>0.506</td>
<td>0.676</td>
</tr>
</tbody>
</table>

Note: Underlined values denote the minimum IRs.
provides a good balance between matching the fundamental and higher modes, leading to the more accurate inversion results.

5 PRELIMINARY FIELD TESTING WITH SHALLOW BOREHOLE MEASUREMENTS

5.1 Case study at East River Valley

The hybrid testing method described above was successfully employed for preliminary tests at the East River Valley recreational site in Ames, Iowa. A 4.5 Hz vertical geophone was coupled to the soil surface using a ground spike and a triggered 10 lb sledgehammer source was used to generate Rayleigh waves by impacting an aluminium plate resting on the ground surface. A four-channel LDS Photon II dynamic signal analyser was used for data acquisition, with a sampling interval of 0.78125 ms, sample size of 2048 points and anti-aliasing filtering for a maximum alias-free frequency of 500 Hz. A 3.66 m (12 ft) station separation was used over an offset range from 3.66 to 43.89 m (12 to 144 ft), and ten impacts were performed at each station for signal stacking. As mentioned above, the dispersion data for the geophone depth of 0 m is theoretically equivalent to what would be obtained in an MASW surface wave test with 12 receivers. However, the source and geophone locations are reversed in the MSOR testing method. An 8.3 cm (3.25 inch) borehole was hand-augured to a depth of 0.91 m (3 ft) and the geophone was inserted into the bottom surface of the borehole using the ground spike and a specially constructed insertion and retrieval device. Similar tests were then performed with geophone depths of 1.83, 2.74 and 3.35 m (6, 9 and 11 ft), giving a total of five test depths.

The experimental dispersion data for depths of 0 and 0.91 m show a consistent fundamental mode from 6 to 35 Hz (Figs 10b and d). As anticipated, with an increased geophone depth of 1.83 m, Fig. 10(f) clearly shows the appearance of a higher mode around 30 Hz which becomes more prominent as sensor depth is increased, and is also accompanied by possible additional higher modes (Figs 10h and j). By superimposing the five dispersion images shown in Fig. 10, multimode experimental dispersion curves were obtained similar to those from the FEM simulation, as shown in Fig. 11. Although the tests detailed herein are preliminary, it should be noted that the near-surface resolution may be improved by reducing the 3.66 m (12 ft) receiver spacing. This would minimize spatial aliasing and far-field effects, and improve the quality of dispersion data above 30 Hz. In addition, dispersion data at frequencies below 8–10 Hz could
Figure 10. Stacked, normalized velocity traces from field tests and dispersion images obtained using the waveform transformation method of Park et al. (1998): (a) and (b) geophone at depth of 0 m, (c) and (d) geophone depth 0.91 m, (e) and (f) geophone depth 1.83 m, (g) and (h) geophone depth 2.74 m, (i) and (j) geophone depth 3.35 m. White dots are the maxima.

be a result of ambient sources, which can result in high apparent
phase velocities if originating off-line from the receiver spread. For
simplicity, the clear trend from 6 to 35 Hz in Fig. 10 will be referred
to herein as the fundamental mode, but this might not be the true
fundamental-mode dispersion trend for the site. This issue will be
examined in future studies.

As expected, the presumed fundamental and possibly two higher
modes were obtained using the embedded geophone (Fig. 11),
whereas the higher modes were less clearly defined in the surface
wave test with the geophone at a depth of 0 m (Fig. 10b). How-
ever, the simple approach of inserting the geophone spike into the
bottom of a borehole does not provide optimal coupling with the
soil, which may reduce the signal-to-noise ratio. It is anticipated
that proper coupling of the geophone with the soil using either a
pneumatic bladder, a commercially available borehole geophone or
a modified seismic CPT probe as described above will increase the
measurement quality of the higher modes.

To determine the near-surface shear wave velocity profile of
the test site, the first two modes of Fig. 11 were used in the
genetic-simulated-annealing inversion program with a frequency
range of 6–30 Hz. Two analyses were performed; the first using the
fundamental mode as the optimization objective function and the

second using the first two modes. The two-mode inversion yielded final converged velocity profiles with a smaller scatter than the fundamental-mode inversion (Fig. 12a). A statistical analysis of the depth-averaged shear wave velocities was also performed for the profiles of Fig. 12(a), as the average shear wave velocity in the upper 30 m \( (V_{s30}) \) is used in the AASHTO (2009) specifications for bridge design and in building codes for classification of sites according to soil type. The results show that the two-mode inversion gives a smaller standard deviation in average velocity than the fundamental-mode inversion (Fig. 12b). The multimode inversion from the proposed hybrid test method thus has the potential to reduce the ambiguity and uncertainty of shear wave velocity profiles used for seismic hazard assessment.

Similar to the FEM simulation results, a two-mode inversion was found to produce a better fit of the experimental first-higher mode than the fundamental-mode inversion (Fig. 13). Furthermore, for both the fundamental and first-higher modes, the two-mode inversion resulted in a lower average rms error and standard deviation than the fundamental-mode inversion (Fig. 14). In particular, the rms error of the first-higher mode is significantly reduced for the two-mode inversion compared to the fundamental-mode inversion, in terms of both the average value and the distribution range (Fig. 14b).

Because the minimally invasive procedure employs sensors embedded in the soil, the attenuation of Rayleigh wave motion with depth is a logical concern. To examine this aspect, the amplitude and signal-to-noise ratio of all field data shown in Fig. 10 was analysed for the range of sensor depths and impact offsets used. As shown in Fig. 15(a), the amplitude generally attenuates with offset and depth, with minor variations that might be attributable to variations in impact energy and ambient noise. Fig. 15(b) shows the signal-to-noise ratio of all field data, which is affected by both the dominant surface waves in Fig. 10, as well as the noise from the tail-end of the signal traces. The signal-to-noise ratio generally decreases with depth and offset distance, but is still significant at the greatest employed geophone depth of 3.35 m. This further indicates that it is feasible to measure the motion of Rayleigh waves within the soil via the hybrid testing procedure presented herein. It should be noted that the 3.35 m depth of the borehole is only 13.4 per cent of the total depth of 25 m of the inverted profile.

As shown in the numerical and physical examples above, a significant advantage of the hybrid method relative to borehole methods...
Figure 12. Fundamental-mode and two-mode inversions of field data: (a) inverted profiles, (b) box plots of average shear wave velocity distributions (central mark is median, box edges are 25th and 75th percentiles, whiskers extend to most extreme data not considered outliers).

Figure 13. Experimental dispersion curves compared to theoretical dispersion curves of final inverted profiles: (a) fundamental-mode inversion (30 trials), (b) two-mode inversion (30 trials).

Figure 14. rms error of inversion for Fig. 13: (a) error of fundamental mode, (b) error of first-higher mode (central mark is median, box edges are 25th and 75th percentiles, whiskers extend to most extreme data not considered outliers, outliers shown as + marks).

is that the sensor needs to be embedded to only a fraction of the total depth profiled. For example, a borehole or probe insertion of roughly 4.5 m would be needed for a profile of the upper 30 m for typical seismic site classification purposes, compared to the entire 30 m for crosshole, downhole or seismic CPT tests. In addition, fewer tests would be required compared to the borehole and CPT methods, as the hybrid procedure gives global soil properties measured over a large receiver-spread area. Finally, the above analyses illustrate the enhanced clarity of multimode experimental dispersion images of Rayleigh waves by the hybrid method compared to surface-only methods, as well as the reduction in variability of the final inverted velocity profiles gained by multimode inversion.

6 CONCLUSIONS

The eigenvector analysis, numerical simulations, and preliminary field tests presented herein demonstrate the feasibility of using embedded sensors at various depths to more accurately measure higher modes of Rayleigh waves in a minimally invasive manner.
As demonstrated in this study, using the resulting additional information offered by the higher modes leads to more accurate models of the measured soil response as evidenced by improved fits of the higher mode dispersion data, more accurate inverted soil profiles in numerical studies and reduced variability in inverted profiles from field data. As in surface wave methods, the use of Rayleigh waves enables measurement of geological properties well below the maximum sensor depth. The advantages of greater accuracy commonly provided by borehole methods are thus combined with the benefit of sounding to depths below the sensor elevations as provided by surface wave methods. With refinements to improve the measurement accuracy of the field-testing technique presented herein, it is anticipated that the proposed method can ultimately contribute to the goal of minimizing seismic hazard by improving the accuracy and reducing the ambiguity of shallow shear wave velocity profiles for site response analysis, seismic site classification and soil–structure interaction analyses.

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