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Determination of Optimum “Multi-Channel Surface Wave Method” Field Parameters

by

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16. Abstract Multi-channel surface wave methods (especially the **m**ulti-channel **a**nalyses of **s**urface **w**ave method; MASW) are routinely used to determine the shear-wave velocity of the subsurface to depths of 100 feet for site classification purposes. Users are aware that the output shear-wave velocity function at a specific site will vary if acquisition parameters (including array orientation, geophone spacing, shot-to-receiver offset) are varied. However, these variations have never been statistically analyzed (quantitatively or qualitatively). As part of this investigation, the researchers will acquire MASW data at multiple study areas in karst terrain with a view to statistically analyzing the extent to which variations in field parameters can affect data quality, data utility, the output shear-wave velocity function and the output site classification.			
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OVERVIEW OF THE MULTI-CHANNEL ANALYSIS OF SURFACE WAVES (MASW) METHOD	Multi-channel analysis of surface waves (MASW) software can be used to transform recorded Rayleigh waves (specific type of surface wave) generated using either an active and/or passive acoustic source into a 1-D shear-wave velocity profile of the subsurface. If MASW data are acquired at multiple sites along a traverse, the output 1-D shear wave velocity profiles can be used to generate a 2-D velocity image of the subsurface. Active Rayleigh wave energy is generated by proximal sources that are discharged by the geophysical survey crew (such as sledge hammers, weight drops and small explosives). Passive Rayleigh wave energy is generated by proximal to distant natural sources of acoustic energy (ambient noise or microtremors) including distal earthquakes and vehicular traffic. In general, active Rayleigh wave energy is higher frequency (typically 10-60 Hz) and provides for higher vertical resolution but significantly shallower depths of investigation (on the order of 100 feet). Passive Rayleigh wave data is generally lower frequency (typically 5-20 Hz) and provides lower vertical resolution in the upper 100 feet but can be used to image the subsurface to depths in excess of several hundreds of feet. Combination active/passive data sets provide both high vertical resolution at shallow depths and greater depths of investigation. Rayleigh wave energy is dispersive meaning that different frequencies travel with different velocities. More specifically, each frequency travels with a phase velocity that is mostly a function of the average shear-wave velocity of the subsurface from the ground surface to the base of particle motion associated with that frequency (wavelength). Active Rayleigh wave data are recorded using a linear array of geophones; passive Rayleigh wave data can be recorded using either a linear array of geophones or a symmetric non-linear array. MASW software analyzes the recorded Rayleigh wave data and calculates the phase velocities of a representative range of frequencies (from highest to lowest frequencies present in data). The phase velocity data are used to estimate the base of particle motion associated with each frequency and to estimate the average shear wave velocity over that depth range of particle motion. The subsurface can then be subdivided into a finite number of layer (one layer for each frequency analyzed; from ground surface to base of lowest most particle motion). Interval shear wave velocities can then be assigned to each layer. The principle output of an MASW survey is a 1-D shear-wave velocity profile of the subsurface. In certain situations, a suite of MASW data sets are collected along the length of traverse and the output 1-D shear-wave velocity profiles are used to generate a 2-D shear-wave velocity profile of the subsurface. The refraction microtremor (ReMi) method is very similar to the multi-channel analysis of surface wave (MASW) method.
ACQUISITION	
Brief overview of field procedure	A linear array of geophones (usually 24) and an engineering seismograph are used to record passive and/or active Rayleigh wave data that propagates along the axis of the array. The geophones are generally spaced such that the length of the array is on the order of the desired maximum depth of investigation. Passive MASW data can also be recorded using a non-linear symmetric array of geophones. Active Rayleigh waves data sets are generated using proximal man-made sources (impulsive mostly, such as a sledge hammer and striking plate) that are discharged off the end of the geophone array. When the active source is discharged, the seismograph is triggered and data is recorded (typically for one second or less). Stacking will improve the signal-to-noise ratio. Passive Rayleigh wave energy (ambient noise) occurs naturally and can be generated nearby proximal to distal earthquakes, highway traffic, construction equipment, etc.

	Passive data are generated by triggering the seismograph manually and recording "random" data for 30 seconds or more. Data are never stacked, but multiple 30 second records are often recorded at each test location to increase the probability useful Rayleigh wave energy has propagated through the array. If a linear array is used, the Rayleigh wave energy must have propagated through the array and in a direction parallel to the axis of the array. Rayleigh wave energy that propagates parallel to the axis of a linear array will exhibit lower apparent velocities (greater slowness) than energy that propagates through the same array at an angle. If combination active/passive data are required, an active source can be discharged while the 30 second passive data sets are being recorded. Alternatively, active and passive wave data can be recorded separately and combined during processing.
Field equipment	The method utilizes equipment typically employed in conventional seismic refraction surveys. This equipment consists of an engineering seismograph and an array of relatively low frequency geophones (typically twenty-four 4.5 Hz or 14 Hz geophones). If active MASW data are being recorded, an acoustic source is employed. If passive data (only) are being recorded, an operational source is not required.
Field crew	Consists of 2-3 persons.
Considerations	
• **size of test site**	The size of test site has to allow for ease of placement of geophones (and a source if active data are being acquired).
• **Sampling interval**	A 1-D shear-wave velocity profile will be generated at each test location. Generally, the shear-wave velocity profile is assumed to represent the shear-wave velocity profile of the subsurface at the center of the geophone array.
• **Vehicular access**	All equipment can be transported by hand. Usually, the equipment and crew are transported in a single vehicle.
• **topography**	Data can be acquired across undulating ground surface or across steeply dipping terrain. However, elevation changes should be minimized where/if possible as data quality usually decreases as surface topographic relief increases.
• **vegetation**	Data can be acquired in heavily vegetated areas. However, dense vegetation does impede work and slows down field data acquisition.
• **background noise**	Active MASW data can usually be acquired even in acoustically noisy environments (by increasing the size of the source or stacking multiple field records). Highway traffic can constitute a useful source of passive Rayleigh wave energy.
• **anchoring requirements**	The equipment does not need to be physically anchored or coupled to the ground surface; however the geophones do need to be placed in stable, vertical positions on the ground surface.
• **nature of ground surface**	The geophones can be placed on soil, rock, fill, concrete, asphalt, etc. They should be stable and vertical.
• **subsurface lithology or material**	MASW data can be acquired across all types of soil and/or rock. MASW data can also be acquired across pavement, asphalt, fill, etc.
• **depth of investigation**	The maximum depth of investigation is a function mostly of the lowest frequency Rayleigh wave energy recorded and the length of the geophone array. If active data are being recorded, the lowest frequency recorded is a function of the energy generated by the source, as higher energy sources generate lower frequency Rayleigh waves. If passive data are being recorded, the lowest frequency recorded is a function of the magnitude, location and timeliness of naturally-generated acoustic energy. Lower frequencies are more reliably analyzed when recorded using arrays with lengths on the order of the wavelength of those frequencies.

• **proximity to buried structures and buried utilities**	The MASW tool is non-invasive. Active data can be acquired in proximity to buried utilities and buried structures, unless there is concern that the acoustic source could damage built structures such as concrete or pavement. Ambient seismic 'noise' or microtremors, which occur constantly as cultural and natural background noise, can be as source of passive Rayleigh waves.
• **proximity to built structures and utilities**	The MASW tool is non-invasive. Active data can be acquired in proximity to utilities and structures. Ambient seismic 'noise' or microtremors, which occur constantly as cultural and natural background noise, can be as source of passive Rayleigh waves.MASW data can be acquired in proximity to surface utilities and built structures. The only clearance required is sufficient room to swing a sledge hammer. The sledge hammer can damage built structures such as concrete or pavement.
• **permitting requirements**	Generally, only permission from the surface rights holder is required.
• **notification requirements**	Generally, only permission from the surface rights holder is required.
• **other**	Good quality passive MASW data cannot be recorded unless suitable passive energy passes through the array while the seismograph is activated. Similarly, useful active MASW data (coverage to desired depth of investigation) will not be recorded if the active source is too small.
Brief description of field data	The field data (active and/or passive source) are recorded digitally and stored on the laptop connected to the seismograph or to built-in flash memory. Generally, one stacked active record (typically 1 second in length) is generated for each active test location. Generally, multiple non-stacked passive records (each typically 30 seconds in length) are generated for each passive test location.

Estimated cost to acquire field data at one test site	Basic field costs include: a) one hour of crew time plus travel time; b) equipment rental and/or depreciation; c) vehicle rental and/or depreciation plus fuel. It typically takes a 3-person crew about two hour to acquire a single MASW data set (24-geophone array).
Potential for errors	There is little likelihood that field errors will lead to misinterpretation.
• **human**	Human error, leading to misinterpretation, is unlikely because the only critical non-automated processes are the placement of the geophones and the discharge of the source (if active data are being acquired).
• **equipment**	Equipment problems are unlikely to generate errors that will lead to misinterpretation.
Reproducibility of field tests	If good quality data can be recorded, field results can be reproduced with a high degree of consistency.
DATA AND/OR LABORATORY PROCESSING	
Brief overview of data processing	Each MASW field record is transformed into dispersion data (Rayleigh-wave velocity vs. frequency format; standard, established mathematical process that does not require any interactive input from the interpreter). The dispersion data are analyzed qualitatively (processor input is required) and optimum phase velocities are selected (dispersion curve). The dispersion curve is usually inverted without any qualitative input from the interpreter. The output 1-D shear-wave velocity profile is the deliverable.

Output of data processing	The output from a single test location is a 1-D shear-wave velocity profile. If data are collected at multiple test locations along the length of a traverse, the output 1-D shear-wave velocity profiles can be used to generate a 2-D shear-wave velocity profile. Creating a 2D cross-section will allow the user to image the lateral variations in the shear-wave velocity. These profiles constitute the final deliverable.
Estimated cost to process field data from one test site	Basic processing costs include: a) two hours of processor's time; b) hardware/software rental and/or depreciation.
Potential for error	
• **human**	Two of the three processing steps (the transformation of MASW field data into dispersion data and the inversion of the dispersion curve) do not require interpreter input. The generation of a dispersion curve however, is subjective (although straightforward). In certain instances, it is difficult to "pick" an optimum dispersion curve. Problems can arise for one of a number of reasons: suitable passive Rayleigh wave energy may not have been recorded; the acoustic source may have been too small; the geophone array may have been too long or too short; lateral velocity variations along the length of the array may have resulted in "smoothing" or "smearing"; excessive topographic relief may have caused "smoothing" or "smearing"; geologic conditions (faulting for example) may have been such that surface wave energy of the desired frequency could not be recorded in the study area. If active data (only) are acquired, it is possible for a processor to misidentify higher mode Rayleigh wave energy as fundamental mode Rayleigh wave energy.
• **equipment**	The MASW processing software should not be defective.
Reproducibility of field tests	If the field data are good quality, trained processors will generate consistent 1-D shear-wave velocity profiles over the range of frequencies that were generated by the source in the field.
INTERPRETATION	
Brief overview of interpretation of processed data	The output of data processing is a 1-D or 2-D velocity model of the subsurface. Normally, the interpreter establishes relationships between lithology and acoustic velocity and transforms the output velocity model into a geologic model of the subsurface. This geologic model constitutes the final deliverable.

Deliverable(s)	1-D or 2-D geologic and shear-wave velocity models.
Depth range (top/bottom)	Surface to depths on the order of 100-120 ft. Greater depths of investigation can be achieved if a larger source is employed.
Lateral resolution	In general, active Rayleigh wave energy is higher frequency and provides for higher resolution but significantly shallower depths of investigation (on the order of 100 feet). Passive Rayleigh wave data provide poorer spatial resolution in the upper 100 feet but can be used to image the subsurface to depths in excess of several hundreds of feet. Combination active/passive data sets provide both high at shallow depth and greater depths of investigation.
Vertical resolution	Rayleigh wave data are acquired along the entire length of the geophone array. If the velocity of the subsurface varies laterally along the length of the array, lateral smoothing or smearing will occur. However, some weighting involved as the source/receiver separation is generally selected such that high frequencies are excessively attenuated at the farthest geophones and low frequencies are not be

	recorded on the closest geophones.
Time required to interpret field data (one test site)	If ground truth is available and if velocity/lithologic relationships can be established, the interpretation of the shear-wave velocity data is normally relatively rapid and straightforward.
Potential for error	
• **human**	There is little potential for error, if the interpreter understands that the output shear-wave velocity profile generated at each test location represents the average shear-wave along the length of the array. It does not represent the precise shear-wave velocity of the subsurface at the mid-point of the geophone array.
• **equipment**	There is little potential for error.
Reproducibility of deliverable	If ground truth is available, different experienced interpreters should come up with similar interpretations. If ground truth is not available, unreasonable interpretations are a very real possibility.
DELIVERABLES	
Brief overview of deliverable(s)	1-D or 2-D geologic and velocity models.
Utility of deliverable(s)	Geologic and velocity models provide information about variations in lithology, porosity, engineering properties, ripability of rock, diggability of soil, depth to top of rock, etc. The shear-wave velocity profiles can be used for earthquake site classification purposes.
Accuracy	The final interpretations are generally reliable if good quality field data are recorded and if ground truth is available. Use of an experienced interpreter is essential.
ADVANTAGES	Advantages include relatively low cost, portability of equipment, rapid processing of field data, few restrictions with respect to surface conditions (soil, rock, pavement, etc), non-invasive, limited potential for human error, reproducibility of field data and processing results, and depth penetration (in all types of soil and/or rock) on the order of 100+ ft using only a sledge hammer source. The method has multiple applications (determination of lithology, porosity, rippability, depth to bedrock, location of voids, shear strength). Additionally, permitting is not required, and the tool can be used across and in proximity to utilities and built structures as the method is fairly insensitive to background acoustic noise.
DISADVANTAGES	If passive Rayleigh wave data (only) are acquired, suitable energy may not be recorded at a specific test location. At some sites, such as near a busy highway, passive data may be dominated by a small range of frequencies having a high amplitude. If active Rayleigh wave data (only) are acquired, desired depths of investigation may not be realized if the source is too small given geologic conditions. Reliability of output shear-wave velocity data decreases as lateral and vertical heterogeneity of soil/rock increases.

Tabularized Overview of the MASW Method.