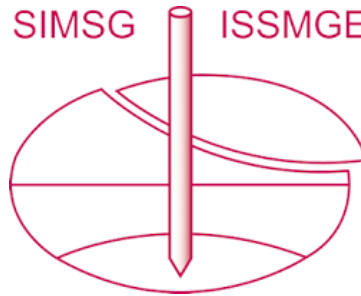


INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING



This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

<https://www.issmge.org/publications/online-library>

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 - 20 June 2019.

Influence of source characteristics on the uncertainties in MASW survey

A.S. Desai

Department of Earthquake Engineering, Indian Institute of Technology Roorkee, India

N. Roy

Department of Civil Engineering, Jadavpur University, Kolkata, India

R.S. Jakka, J.P. Narayan & A. Kranthikumar

Department of Earthquake Engineering, Indian Institute of Technology Roorkee, India

ABSTRACT: Multichannel Analysis of Surface Waves (MASW) method is extremely popular to carry out seismic site characterization. However, certain uncertainties are existent in this technique. One of the crucial factors which contribute to these uncertainties is the source parameters such as source type, energy and position. This study examined how the change in these parameters influences the uncertainties in the MASW method using numerical simulations. The parameters considered in the numerical simulations are the amplitude of impulse load, duration of impulse load and source offset. For the study, the results of full wave-field simulation were compared with those of plane Rayleigh wave simulation. Results indicate that the change in the amplitude of the impulse load doesn't affect the underestimation of the Rayleigh wave phase velocity. Longer the pulse duration, better the dispersion curve observed at lower frequencies. An increment in the source offset reduces the underestimation

1 INTRODUCTION

Seismic site characterization is the procedure of knowing and defining the structure and characteristics of subsurface soil layers. Its results are useful in numerous procedures such as seismic hazard analysis, micro-zonation, seismic site classification, site response studies etc. Hence, it is considered an extremely crucial task in geotechnical earthquake engineering. Currently, the methods which are most commonly employed for site characterization are the surface wave methods, particularly the MASW method. The MASW method is used in geotechnical engineering for the estimation of shear wave velocity (V_s) and then obtaining dynamic soil properties such as soil shear stiffness and damping. It is a non-intrusive geophysical method. Also, it's less time consuming and more economical compared to other conventional methods such as standard penetration test (SPT) and cone penetration test (CPT). To carry out site characterization using surface waves, the first method proposed was the Spectral Analysis of Surface Waves (SASW) test (Nazarian & Stokoe 1986). However, it was found that it had certain shortcomings. Later, an improved method was introduced which was called the MASW method (Park et al. 1999, Xia et al. 1999).

The MASW method utilizes the dispersive nature of Rayleigh-type surface waves. That is, Rayleigh waves of different frequencies travel at different velocities and penetrate to different depths in a layered medium. High frequency (short wavelength) Rayleigh waves propagate in shallow zones close to the free surface and give information about their mechanical properties, whereas low frequency (long wavelength) components involve deeper layers (Figure 1). This property can be used to infer near-surface soil properties, mainly the soil V_s profile and shear modulus.

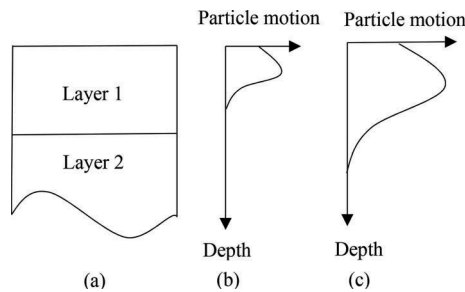


Figure 1. Rayleigh wave propagation in a layered media (a) soil profile (b) high-frequency wave (c) low-frequency wave.

The S-wave velocity (V_s) structure of the near-surface is obtained using the recording of surface waves with an array of receivers/geophones. For this, vertical component geophones are used for recording the vertical component of particle motion at the surface. In this, it's assumed that maximum energy in the recorded motion is from Rayleigh waves. Surface wave methods include 2 types of techniques: 1. Using active sources such as a sledgehammer or weight drop and 2. Using passive source (ambient noise, traffic etc). One of the most widely used active methods uses a linear array of equally spaced receivers and a controlled source such as a sledgehammer, and it is known as multichannel analysis of surface waves. In a MASW test, theoretically, minimum wavelength and depth resolution are governed by the spacing of geophones, whereas the maximum wavelength and depth of penetration are controlled by the geophone resonant frequency and spread length. In most of the active-source (MASW) surveys, dispersion curves can be picked from a minimum frequency of 5–10 Hz to a maximum frequency of 30–50 Hz (Craig & Hayashi 2016). An elaborate literature review on surface wave methods was presented by Socco et al. (2010).

In spite of the fact that the MASW technique is continuously becoming more adopted method for site characterization, it possesses some uncertainties. The values of the source parameters is one of the characteristics which contributes to these uncertainties. It can lead to near-field effects, due to which the Rayleigh wave phase velocity is underestimated (Bodet et al. 2009, Yoon & Rix, 2009, Roy & Jakka, 2017). In the MASW analysis, it's assumed that pure plane Rayleigh wave propagates, which may not be true due to the contamination of Rayleigh wave by body waves. This condition is referred to as near-field effects or sometimes as the model based uncertainty. Hence, there is a need of an illustrative study on how the variations in these parameters affect the uncertainties in the outcomes of the MASW test.

Till now, many studies on MASW method and Rayleigh wave dispersion have been carried out (Miller et al. 1999, Ryden et al. 2004, Dal Moro 2011, Roy et al. 2013, Ayolabi & Adegbola 2014, Jakka et al. 2014, Mahajan et al. 2015). Some studies have been carried out on how the source parameters affect the MASW results using field MASW testing. The effect of the source offset on the value of surface wave phase velocity was studied by Li & Rosenblad (2011). They suggested that till the wavelengths were less than twice the distance from the source to the centre of the receiver array, the near-field effects were insignificant. However, this criteria was less restrictive than that of another study with same conditions using synthetic data which might be due to the difference in the Poisson's ratio considered in both the studies. Chai et al. (2012) worked on how the values of frequency and offset affect the estimation of Rayleigh wave phase velocity. Junior et al. (2012) studied how the MASW results vary with the change in the source offset, geophone frequency and season (dry or rainy). Foti et al. (2017) presented comprehensive guidelines on the acquisition and analysis of surface wave data. They suggested typical values of source offset, receiver spacing and some other parameters. However, these values would be dependent on the site and are to be adapted for each location. Some people have worked on the study of surface wave methods using numerical simulations. Gucunski & Woods (1992) worked on how the SASW test can be simulated numerically. Bodet et al. (2009) carried out physical modelling to evaluate near-field effects on

Rayleigh wave dispersion. Tallavo et al. (2009) used numerical simulations using finite element method (FEM) to support the results of field MASW tests which were carried out to detect buried timber trestles. They found that the surface location of buried timber trestles can be defined using MASW test results. Some others also simulated the surface wave tests using FEM (Aung & Leong 2011, Evangelista & Santucci 2015). However, there is no particular study evaluating the effect of the source parameters on the outcomes of the MASW method using numerical simulations. The uncertainty in the results of the MASW method strongly depends on these parameters. This study investigated how these parameters affect the uncertainties in the outcomes in a MASW survey using extensive numerical simulations.

2 FINITE ELEMENT MODEL GENERATION

In the current work, the study on the source parameters in MASW was done entirely using numerical simulations. The parameters considered in this study which affect the uncertainties were the amplitude of impulse load, duration of impulse load and source offset. These parameters contribute mainly to the model-based uncertainty. ABAQUS (Dassault Systemes 2015) and GEOPSY (Wathelet 2008) software were used for numerical simulations. Also, specifically for modelling the propagation of plane Rayleigh wave, a MATLAB code titled Mat_Disperse and written by Dr. Glenn J. Rix was utilized.

2.1 Generation of Rayleigh wave

The wave propagation for full wave-field in a layered soil during the MASW test was simulated using ABAQUS software which is based on the finite element method. In that, an axisymmetric model was considered. Impulse load was applied and vertical displacements of particle motion at different receiver positions from the source were obtained. In ABAQUS, it is possible to solve a wave equation under impact load in a vertically heterogeneous soil. For a system of N degrees of freedom, the equation of motion under impact load is given as

$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = F(t) \quad (1)$$

In the above equation, M , C and K represent the $N \times N$ mass, damping and stiffness matrices, respectively. The acceleration, velocity and displacement vectors are given as $\ddot{u}(t)$, $\dot{u}(t)$ and $u(t)$ respectively. $F(t)$ denotes the applied impulsive force. At a time $t + \Delta t$, the displacement and velocity at a point can be articulated as

$$u^{t+\Delta t} = u^t + \dot{u}^t \Delta t + ((0.5 - \alpha)\ddot{u}^t + \alpha\ddot{u}^{t+\Delta t})\Delta t^2 \quad (2)$$

$$\dot{u}^{t+\Delta t} = \dot{u}^t + ((1 - \beta)\ddot{u}^t + \beta\ddot{u}^{t+\Delta t})\Delta t \quad (3)$$

Here, Δt = time step; α and β are Newmark's parameters. These parameters check the accuracy of numerical time integration. The prerequisite for a solution to be stable is given as

$$\beta \geq 0.5 \text{ and } \alpha \geq 0.25(0.5 + \beta)^2 \quad (4)$$

Hence, by using the finite element method and employing the axisymmetric model in ABAQUS, a dynamic problem can be solved.

The impulse load was simulated as a half sine pulse load with a peak load of 12 kN acting for 0.025 s and the complete simulation was carried out for 1 s (Figure 2). The time step was kept as 0.002 s. At various locations of receivers at different distances from the source, the displacement time histories were obtained. They were then utilized for subsequent analyses in order to create dispersion spectra.

Figure 3 shows the finite element mesh of the considered model. An axisymmetric model was considered having a size of 400 m * 400 m. On the boundaries at the left and right corners,

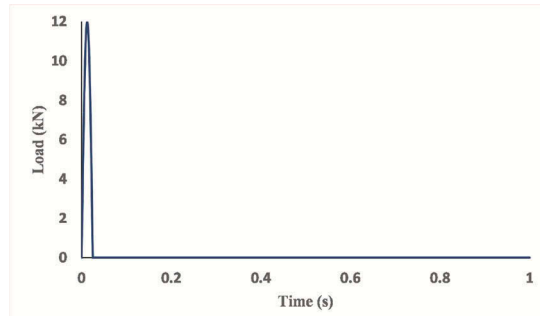


Figure 2. Original load considered for the simulation

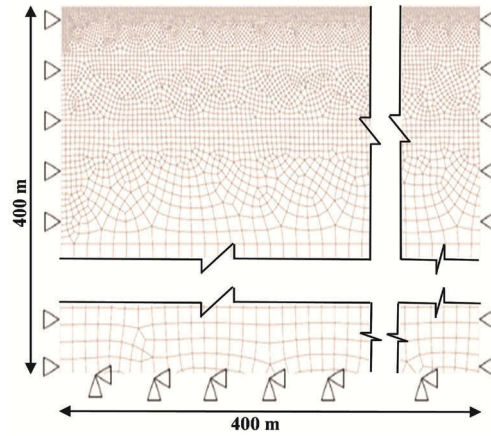


Figure 3. Finite element mesh of the considered model

the horizontal movement was restricted. On the bottom boundary, the horizontal and vertical movement was restricted. Mesh size was kept by considering the criteria given by Kuhlemeyer & Lysmer (1973). They recommended that maximum element size should be one-eighth of the wavelength of the slowest body wave propagating in the elastic material. Mesh was kept finer at the surface with gradual increments in size at higher depths.

2.2 Dispersion calculation

The Rayleigh wave phase velocity was deduced from the procured time histories at various locations from the source. For analyzing these time histories, the frequency-wavenumber (f-k) method was used. The f-k method is a majorly adopted technique to execute the dispersion analyses of an array of surface wave data (Zywicki 1999, Hebel 2001, Yoon & Rix 2009). To perform this, GEOPSY software was used in this study. It utilizes the f-k method for extracting a dispersion curve from a surface wave array data. The basis of this method is the identification of maximum energy peak evolved for a particular wave number in the f-k spectrum. As soon as the peak develops in the f-k spectrum, the wave numbers of dominant modes of propagating Rayleigh wave can be calculated. The calculation of phase velocity can be done using the following equation:

$$V_R = \frac{2\pi f}{|k_{peak}|} \quad (5)$$

Here, V_R = Rayleigh wave phase velocity; f = frequency of the propagating wave and k_{peak} = wave-number associated with the maximum energy peak.

3 NUMERICAL SIMULATIONS

3.1 Soil profile

To assess the influence of different source parameters, extensive numerical simulations were performed. The properties and layering information are given in Table 1. The simulation had two portions: 1. Full wave-field simulation and 2. Plane Rayleigh wave simulation. Full wave-field simulation was carried out in ABAQUS and plane Rayleigh wave curve was calculated by using the MATLAB code by Dr. Glenn J. Rix.

By comparing the results of the full wave-field simulation and plane Rayleigh wave simulation, the study was done on how the source parameters affect the underestimation of Rayleigh wave phase velocity. However, the underestimation of Rayleigh wave phase velocity might not be purely due to source parameters, they could be due to data acquisition parameters such as frequency of sampling, number of receivers, receiver spacing. These things need to be explored further in future studies. However, in the current study, to study the source parameters' effects, other parameters are kept constant and thereby their effect could be assumed constant. The source offset was kept 2 m and receiver spacing was kept 1 m for all the cases except the cases where the effect due to variation in these parameters was studied. The number of receivers was 30.

3.2 Effect of source parameters

3.2.1 Amplitude of impulse load

The effect of the weight of the source was studied. For that, the amplitude of the input impulse load was varied and the results were observed. Initially, the applied impulse load was kept as 12 kN which was considered the original load (Figure 2). Then, the loads were kept as 24 kN, 36 kN and 60 kN. For the loading, the duration was kept constant for all the cases.

Figure 4 shows the analysis result. As per the figure, for the 4 loads of 12 kN, 24 kN, 36 kN and 60 kN, the results are completely overlapping. Hence, it seems that with the increase in the amplitude of the load, there is no change in the near-field effects. However, in the real scenario, due to internal noise of earth, the signal to noise ratio improves with an increase in the amplitude

Table 1. Details of the soil profile

Layer	Thickness (meter)	shear wave velocity (meter/second)	Density (kg/meter ³)	v (Poisson's ratio)
1	5	180	1800	0.3
2	7	240	1800	0.3
3	12	300	1800	0.3
Halfspace	-	700	1800	0.3

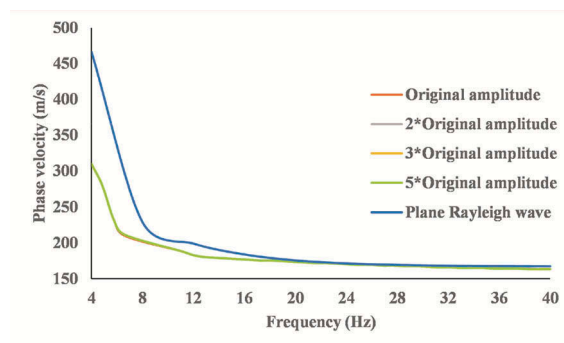


Figure 4. Comparison of dispersion curves for different loads

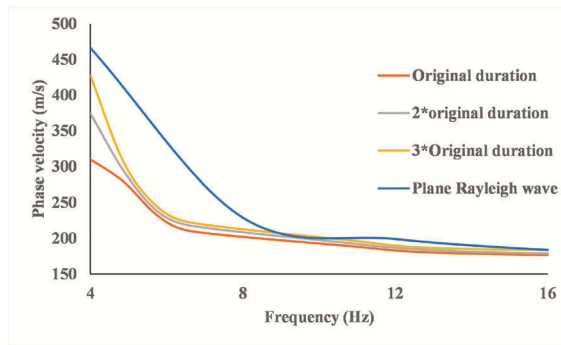


Figure 5. Comparison of dispersion curves for different load durations

of source which is going to improve the results. However, this aspect is not studied here. So, it can't be stated here that the amplitude of impulse load doesn't affect the near-field effects at all.

3.2.2 Duration of impulse load

This effect was studied by varying the duration of load. The original time was kept 0.025 seconds. Later, it was kept 0.05 seconds and 0.075 seconds with the impulse load being kept constant to 12 kN. Then, a comparison was made with plane Rayleigh wave dispersion curve. The results have been shown in Figure 5. It shows that for the impulse duration of 0.025 seconds the values of Rayleigh wave phase velocity are comparatively higher. While moving to the duration of 0.05 seconds and 0.075 seconds, these values are increasing. The % increase in the Rayleigh wave phase velocity at the lowest frequency (4 Hz) while moving from 0.025 s to 0.075 s is 38%. As the Rayleigh wave phase velocity increases, the dispersion curve comes closer to the plane Rayleigh wave curve. Hence, as the duration of loading increases, the near-field effects tend to decrease and the underestimation of Rayleigh wave phase velocity decreases.

3.2.3 Source offset

The distance between the source and the first receiver (source offset) is an important parameter that contributes to the near-field effects in the MASW test. In order to study the effect of this parameter, 3 different values of the source offset were considered: 2 m, 5 m and 10 m. The inter-receiver spacing was kept constant as 1 m. Figure 6 shows the result of this study.

The result implies that as the source offset increases, the level of underestimation decreases. The % increase in the Rayleigh wave phase velocity at the lowest frequency is 21.5% when the source offset is moved from 2 m to 10 m. Hence, the near-field effects decrease with the increase in the source to first receiver distance.

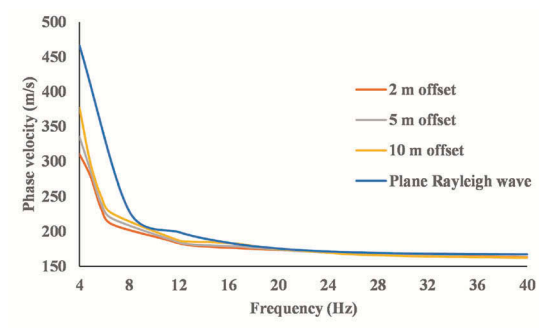


Figure 6. Comparison of dispersion curves for different source offsets

4 SUMMARY AND CONCLUSIONS

This study examined how the source parameters affect the uncertainties in the MASW method. The considered source characteristics are the load amplitude, load duration and the distance between the source and the first receiver. For quantifying the results, the % variation in the phase velocity with the change in the source parameters was considered at the lowest frequency i.e. 4 Hz. The results of this study indicate that an increase in the amplitude of the impulse load leads to no change in the underestimation of the Rayleigh wave phase velocity. When the load duration was increased from 0.025 s to 0.075 s, the phase velocity at the lowest frequency increased by 38%. As the pulse duration increases, a better dispersion curve is obtained at lower frequencies. With the increase in pulse duration, the underestimation of Rayleigh wave phase velocity reduces. Increase in the amplitude of impact alone doesn't have much effect on the resolution of the dispersion curve, while changes in the duration of pulse affect the dispersion curve resolution significantly. Thus, the study is emphasizing the importance of the contact mechanism (coupling) rather than simply increasing the weight of the source. However, in a real scenario, a lower amplitude of impact below a certain level is also going to influence the resolution due to the presence of noise present in the ground. The threshold value of impact depends on the noisy environment. When the source offset was increased from 2 m to 10 m, the phase velocity increased by 21.5%. This proved that with an increase in source offset, the underestimation reduces. However, the underestimation of Rayleigh wave phase velocity might not be purely due to source parameters, they could be due to data acquisition parameters such as frequency of sampling, number of receivers, receiver spacing. These things need to be explored further in future studies. However, in the current study, to study the source parameters' effects, other parameters are kept constant and thereby their effect could be assumed constant. Also, these results are preliminary and a combination of different source parameters should also be studied for different soil profiles and different other source characteristics.

ACKNOWLEDGEMENTS

The authors wish to thank Science and Engineering Research Board (SERB), Department of Science and Technology (DST), Government of India for providing financial support for carrying out the current research (Project Grant Code No. SER-909-EQD).

REFERENCES

- Aung, A.M.W. & Leong, E.C. 2011. Finite element modeling of continuous surface waves tests: Numerical accuracy with respect to domain size. *Journal of Geotechnical and Geoenvironmental Engineering* 137(12): 1294-1298.
- Ayolabi, E.A. & Adegbola, R.B. 2014. Application of MASW in road failure investigation. *Arabian Journal of Geosciences* 7(10): 4335-4341.
- Bodet, L., Abraham, O. & Clorennec, D. 2009. Near-offset effects on Rayleigh-wave dispersion measurements: Physical modeling. *Journal of Applied Geophysics* 68: 95-103.
- Chai, H.Y., Cui, Y.J. & Wei, C.F. 2012. A parametric study of effective phase velocity of surface waves in layered media. *Computers and Geotechnics* 44: 176-184.
- Craig, M. & Hayashi, K. 2016. Surface wave surveying for near-surface site characterization in the East San Francisco Bay Area, California. *Interpretation* 4(4): SQ59-SQ69.
- Dal Moro, G. 2011. Some aspects about surface wave and HVSr analyses: a short overview and a case study. *Bollettino di Geofisica Teorica ed Applicata* 52(2): 241-259.
- Dassault Systemes. 2015. Abaqus. Retrieved from <http://www.3ds.com/products-services/simulia/products/abaqus/>
- Evangelista, L. & Santucci, D.M. 2015. Some limits in the use of the MASW technique in soils with inclined layers. *Geotechnical and Geological Engineering* 33(3): 701-711.
- Foti, S., Hollender, F., Garofalo, F., Albarello, D., Asten, M., Bard, P.-Y., Comina, C., Cornou, C., Cox, B., Di Giulio, G., Forbriger, T., Hayashi, K., Lunedei, E., Martin, A., Mercier, D., Ohrnberger,

- M., Poggi, V., Renalier, F., Sicilia, D. & Socco, V. 2017. Guidelines for the good practice of surface wave analysis: A product of the InterPACIFIC project. *Bulletin of Earthquake Engineering* 16(6): 2367-2420.
- Gucunski, N. & Woods, R.D. 1992. Numerical simulation of the SASW test. *Soil Dynamics and Earthquake Engineering* 11:213-227.
- Hebeler, G.L. 2001 Site characterization in Shelby County, Tennessee using advanced surface wave methods. MS dissertation, Georgia Institute of Technology, Atlanta, USA.
- Jakka, R.S., Roy, N. & Wason, H.R. 2014. Implications of surface wave data measurement uncertainty on seismic ground response analysis. *Soil Dynamics and Earthquake Engineering* 61-62: 239-245.
- Júnior, S.B.L., Prado, R.L. & Mendes, R.M. 2012. Application of multichannel analysis of surface waves method (MASW) in an area susceptible to landslide at Ubatuba city, Brazil. *Revista Brasileira de Geotécnica* 30(2): 213-224.
- Kuhlemeyer, R.L. & Lysmer, J. 1973. Finite element method accuracy for wave propagation problems. *Journal of Soil Mechanics & Foundations Division* 99(SM5): 421-427.
- Li, J., Rosenblad, B.L. 2011. Experimental study of near-field effects in multichannel array-based surface wave velocity measurements. *Near-Surface Geophysics* 9(4):357-366.
- Mahajan, A.K., Chandra, S., Sarma, V.S. & Arora, B.R. 2015. Multichannel analysis of surface waves and high-resolution electrical resistivity tomography in detection of subsurface features in northwest Himalaya. *Current Science* 108(12): 2230-2239.
- Mathworks. 2017. MATLAB. Retrieved from <https://www.mathworks.com/products/matlab.html>.
- Miller, R.D., Xia, J., Park, C.B., & Ivanov, J. 1999. Multichannel analysis of surface waves to map bedrock. *The Leading Edge* 18(12): 1392-1396.
- Nazarian, S. & Stokoe, K.H. 1986. Use of surface waves in pavement evaluation. *Transportation Research Record* 1070, TRB, National Research Council, 132-144.
- Park, C.B., Miller, R.D. & Xia, J. 1999. Multi-channel analysis of surface waves. *Geophysics* 64 (3):800-808.
- Rix, G.J. 1988. Experimental study of factors affecting the spectral analysis of surface waves method. PhD thesis, University of Texas, Austin, USA.
- Roy, N. & Jakka, R.S. 2017. Near-field effects on site characterization using MASW technique. *Soil Dynamics and Earthquake Engineering* 97: 289-303.
- Roy, N., Jakka, R.S. & Wason, H.R. 2013. Effect of surface wave inversion non-uniqueness on 1-D seismic ground response analysis. *Natural Hazards* 68(2): 1141-1153.
- Ryden, N., Park, C.B., Ulriksen, P. & Miller, R.D. 2004. Multimodal approach to seismic pavement testing. *Journal of Geotechnical and Geoenvironmental Engineering* 130: 636-645.
- Socco, L.V., Foti, S. & Boiero, D. 2010. Surface-wave analysis for building near-surface velocity models—Established approaches and new perspectives. *Geophysics* 75(5):75A83-75A102.
- Tallavó, F., Cascante, G. & Pandey, M. 2009. Experimental and numerical analysis of MASW tests for detection of buried timber trestles. *Soil Dynamics and Earthquake Engineering* 29(1): 91-102.
- Wathelet, M. (2008). An improved neighborhood algorithm: parameter conditions and dynamic scaling. *Geophysical Research Letters* 35:L09301, doi:10.1029/2008GL033256.
- Xia, J., Miller, R.D. & Park, C.B. 1999. Estimation of near-surface shear-wave velocity by inversion of Rayleigh wave. *Geophysics* 64(3):691-700.
- Yoon, S. & Rix, G.J. 2009. Near-field effects on array-based surface wave methods with active sources. *Journal of Geotechnical and Geoenvironmental Engineering* 135:399-406.
- Zywicki, D.J. 1999. Advanced signal processing methods applied to engineering analysis of seismic surface waves. PhD thesis, Georgia Institute of Technology, Atlanta, USA.