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Effect of Surface Unevenness on Non-Contact Surface Wave Measurements Using a Rolling Microphone Array

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Abstract. Surface wave velocity is measured and evaluated along a straight survey line in order to compare two different data acquisition methods. Results from a rolling microphone array are compared to data acquired using a conventional accelerometer. Results from the two different data acquisition methods are shown to be similar. However, it is demonstrated that the results are very sensitive to misalignments between the microphone array and the measured surface. Practices to overcome problems with misalignments are discussed and demonstrated.

INTRODUCTION

Non-destructive seismic testing is today a commonly used method for material characterization [1] and damage detection [2] for various materials. One-sided surface wave testing is used in this study to estimate the Rayleigh wave velocity for material characterization. Non-contact measurements are often preferable to conventional accelerometer measurement since the latter is very time-consuming. A non-contact approach where all needed equipment is mounted on a trolley allows rapid and continuous measurements and also evaluation while moving.

The presented study shows an example of such a trolley specially built for this purpose [3]. The trolley was used for data acquisition over a 0.3 m thick homogenous concrete plate between the basement and the first floor in one of the University buildings at Lund's University, Sweden. Once a proper setup was made, nearly continuous measurements could be performed along a straight survey line. The measurements were performed at normal walking speed and the evaluation was made while measuring. However, it is crucial that the microphone array is perfectly aligned with the measured surface to receive a correct result. It was shown that a rather small misalignment between the receiver array and the measured surface is enough to cause large errors in the results. The results from this non-contact approach were then compared to conventional accelerometer measurements in the same measuring positions.

The calculated results were in this study limited to the estimation of the Rayleigh wave velocity.

THEORY AND METHODOLOGY

Two different types of data sets were collected in this study (Fig. 1). An accelerometer measuring out-of-plane acceleration on the surface was compared to air-coupled microphones measuring air pressure from leaky surface wave energy (explained by Ryden *et al.* [3]).

FIGURE 1. Schematic picture of the equipment setup using the non-contact approach with air-coupled microphones (a) and a conventional accelerometer (b).

Air-coupled receivers were used to achieve data collection while moving. Data were collected using a trolley built for this purpose. The trolley carried the data acquisition equipment and collected data while rolling it at normal walking speed. The non-contact measurements were performed using an array of receivers made out of seven normal audio microphones (ADK SC-1 condenser microphone [10 mV/Pa]) mounted with 0.05 m increments and their tips 0.02 m from the concrete surface. The source was also mounted on the trolley, 0.635 m in front of and 0.085 transverse of the first microphone. A small metal screw (~ 10 g) mounted on a flexible metal stick worked as the source and was triggered automatically every 0.16 m when rolling the trolley forward. All collected air-coupled signals were amplified (SM Pro Audio PR8E) and converted from analog to digital format (DAQ NI USB 6251). Data were collected from 60 different measuring positions along a straight survey line on the concrete surface.

A schematic picture of the survey line is shown in Fig. 2. The plate dimensions are so large that it can be approximated as an infinite free plate without risk of wave reflections from its edges (within the time window of each measurement). Concrete beams under the concrete plate and visible surface cracks are marked in the schematic picture.

To compare the evaluated results from non-contact measurements with traditional contact measurements, data were collected using an accelerometer (PCB model 356A15 [103.3 mV/g]) as receiver. Measurements were performed in 12 different positions along the survey line with equal increments (marked in Fig. 2). In order to achieve equivalent measurements, reciprocity was utilized and an accelerometer was placed in the point of the impact from the microphone setup. Five impacts were averaged in each of the seven positions where the microphones were placed during the corresponding microphone test.

Data were recorded for 5 milliseconds with a sample rate of 125 kHz for all collected signals. All signals, both from accelerometers and microphones, were processed the same way. A high pass filter (10 kHz) was first applied to all data sets to remove low frequencies. A cosine-tapered window was then applied in time domain to suppress the direct air wave from the impact and the surrounding noise. The Rayleigh wave velocity was finally estimated by the Multichannel Analysis of Surface Wave (MASW) method [4]. By maximizing the total amplitude over a frequency range, here chosen to be 10-15 kHz, the Rayleigh wave velocity was found at the asymptotic trend of the fundamental anti-symmetric Lamb mode (A0) [5].

FIGURE 2. Schematic picture of the tested concrete plate.

RESULTS AND DISCUSSION

All recorded data sets were processed as described in the previous chapter. While the trolley was rolled, Rayleigh wave velocity was evaluated in every measuring position along the survey line, a total of 60 positions. The survey line was measured and evaluated five times using the microphone array to ensure repeatability in the measurements. Figure 3 shows the Rayleigh wave velocity variation along the survey line for the five measuring sets. The microphone array length is illustrated with horizontal lines as markers in Fig. 3. The Rayleigh wave velocity value marked in the plot is actually an average over the array length. The repeated measurements show that the repeatability of the rolling measurements is very high. The largest difference between a single test value and its mean in a single measuring position is 2 %. However, even though the variability between the five measuring sets is very low, the variation along the survey line is high (ca. 500 m/s). It should be pointed out that the whole survey line is measured in one set, the trolley is thus not pushed back and forth over the same measuring position five times. It is further shown in Fig. 3 that the accelerometer measurements (marked with black squares) correspond fairly well to the mobile microphone measurements.

FIGURE 3. Evaluated Rayleigh wave velocity variation along the tested survey line.

The large Rayleigh wave velocity variation along the survey line may have several explanations. The variation can partly be explained by natural stiffness variations in the material, but it may also have other explanations. A local misalignment between the microphone array and the measured surface affects the velocity significantly.

The surface wave velocity v_R over the array length D can be calculated by Eq. 1.

$$v_R = \frac{D}{t} \quad (1)$$

where t is the travel time of the surface wave. Introducing a linear misalignment between the microphone array and the measured surface, simulating a surface unevenness or a tilted microphone array, will cause errors in the calculations of phase velocities. Increasing the height of the last microphone in the array a distance Δd (according to Fig. 4), adds an additional travel time Δt , given in Eq. 2, to that last signal.

$$\Delta t = \frac{\Delta d}{v_{air} \cdot \cos\left(\sin^{-1}\left(\frac{v_{air}}{v_R}\right)\right)} \quad (2)$$

where $\sin^{-1}\left(\frac{v_{air}}{v_R}\right)$ is the leaky (refraction) angle according to Snell's law.

FIGURE 4. Introducing a misalignment between the microphone array and the measured surface, simulating a surface unevenness or a tilted microphone array, will cause errors in the calculations of phase velocities.

Using trigonometry, the Δt expression is simplified to Eq. 3.

$$\Delta t = \frac{\Delta d}{v_{air} \cdot \sqrt{1 - \left(\frac{v_{air}}{v_R}\right)^2}} \quad (3)$$

Due to the extra travel time Δt the system will evaluate a higher or lower phase velocity according to Fig. 1a. The biased phase velocity is given in Eq. 4.

$$v_{R,new} = \frac{D}{t + \Delta t} = \frac{D}{\frac{D}{v_R} + \frac{\Delta d}{v_{air} \cdot \sqrt{1 - \left(\frac{v_{air}}{v_R}\right)^2}}} \quad (4)$$

Figure 5 shows the calculated relative errors in surface wave velocity when introducing different misalignments (Δd). It is shown that a misalignment of a few millimeters is enough to cause major errors in the evaluation. When calculating the errors an array length of 0.3 m (as in this study) and a wave velocity through air of 344 m/s were assumed.

FIGURE 5. Relative errors in the relevant phase velocity range for concrete. The five lines represent different values of Δd . All errors were calculated using a microphone array length of 0.3 m.

In order to further investigate the results from the survey line, the trolley was turned around and rolled in the opposite direction. Data were acquired while rolling the trolley in the opposite direction in order to try to compensate the unevenness along the survey line [6]. A recorded higher velocity (compared to the true phase velocity) due to a surface unevenness in one direction should be able to be compensated by a recorded lower velocity due to the same unevenness when the trolley is rolled in the opposite direction. Strictly this assumption only holds for unevenness producing the same amount of tilt but with opposite sign for the forward and backward direction of the trolley. When rolling the trolley in the backward direction the microphones were located in the same positions as before but with the source and the microphones in the reversed order. The source was thus located on the other side of the receiver array. Since the microphone array was located in same the position as before the calculated phase velocities from the forward and backward rolling were averaged over the same part of the plate, the 0.3 m covered by the receiver array, and thus to some degree neutralized.

In order to neutralize the unevenness by measuring in opposite directions, three conditions have to be fulfilled.

1. The unevenness has to be shorter than the wheelbase of the trolley, otherwise the trolley will incline together with the surface and a correct phase velocity will be measured.
2. The receiver array must be located exactly in the middle of the wheelbase to ensure that the phase velocities from opposite directions will be equally far from the correct value.
3. The unevenness has to be linear over the receiver array length to ensure that no non-linear errors are introduced.

The evaluated results from the forward and backward rolling direction are plotted together with the accelerometer results in Fig. 6. The backward rolling measurements were repeated five times just as the forward rolling measurements. The results plotted on a synchronized x-axis reveal some differences between the two measuring directions even though the repeatability in each direction is very good.

FIGURE 6. Rayleigh wave velocity measured in ten sets along the survey line, five times measured in each direction.

The mean value was taken from the ten microphone measurements (five in each direction) in each of the 60 different measuring positions resulting in a mean velocity variation line, shown in Fig 7. Under the three conditions mentioned the velocities would theoretically even out each other and be equal to the accelerometer measurements.

FIGURE 7. Mean velocity variation along the survey line.

The results from the mean velocity variation line improved the compliance with the accelerometer measurements so that most of the stationary results matched the ones from the air-coupled microphones.

THEORETICAL SIMULATION

To examine the errors on a surface with realistic unevenness, a simulated surface for a high quality pavement [7-8] was created and shown in Fig. 8 (red line). A synthetic periodic wave with a constant frequency of 12 kHz was

created by Eq. 5 where x is the array vector and k is wave number with a reference phase velocity of 2200 m/s. 15 receivers with 0.05 m increments were simulated perfectly horizontal over the uneven surface. The surface unevenness was considered in the time-dependent term ωt by adding an individual time lag to each signal. The relative phase velocity error from the MASW method applied to the synthetic signal (from Eq. 5) is plotted in Fig. 8 (blue solid line). The same procedure was performed in the opposite direction (blue dashed line) to simulate rolling the trolley in the backward direction. The mean of the two simulations performed in opposite directions is very close (max 0.75%) to the reference velocity (zero relative error).

$$u(x, t) = A \cdot e^{i(k \cdot x - \omega t)} \quad (5)$$

It is reasonable to expect that the errors are unrealistically large due to the assumption that the receiver array is always perfectly horizontal. In field measurements the trolley will be parallel to the surface even in a slope (point 1 in the list above) rather than horizontal as assumed in this simulation and thus the errors may be smaller.

FIGURE 8. Relative phase velocity error (without unit) in calculated Rayleigh wave velocity for a synthetic periodic wave with a fix frequency of 12 kHz and a reference velocity of 2200 m/s.

CONCLUSIONS

The presented study was focused on measuring the Rayleigh wave velocity in a concrete plate.

- It was shown that a rolling microphone array allows rapid measurements with results comparable to conventional stationary accelerometer measurements.
- The results obtained with the rolling microphone array had a high repeatability.
- It was further shown that even small misalignments between the microphone array and the measured surface were enough to cause major errors in estimated Rayleigh wave velocity. However, by performing the rolling measurements in two opposite directions, the misalignments and hence the errors in calculated Rayleigh wave velocity were reduced.

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