SURFACE WAVE EXPERIMENTS AND GROUND PENETRATING RADAR TOMOGRAPHY FOR INVESTIGATING SUB-SURFACE SOIL CONDITIONS IN HATAY AREA, HANOI

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ABSTRACT: NGI and VNU have jointly carried out geophysical investigations in the Hatay area east of Hanoi. The purpose of the investigations was to obtain a better understanding of the sub-surface soil conditions for future development of the area. Surface wave experiments using the MASW method (multichannel analysis of surface waves) was performed to estimate the subsurface shear wave velocity of the soil. This information is required for assessment of the amplification of earthquake waves and earthquake analyses of the planned facilities. The shear wave velocity in the shallowest layer ranged from 100-120 m/s and generally increases with depth to values in the order of 350 m/s at a depth of about 45 meters. Ground penetrating radar tomography for two sections was also performed in the same area to scan the subsurface soil conditions. The tomograms from these investigations showed that the wave attenuation from one soil section was larger than the other section. This is due to the fact that a high attenuating wave section has higher water content than the other section due to a nearby lake on the surface. Such investigations are useful for planning infrastructure development in the area.

INTRODUCTION

Planning and design of infrastructures is often influenced by the ground conditions at the development site. The ground's stiffness and strength properties together with other parameters such as water content, non-homogeneities, depth to bedrock and susceptibility to liquefaction are important elements in this consideration. For example, depth to bedrock and stiffness parameters of the soil govern to a large extent the level of earthquake shaking on the ground surface at the site. Sites with shallow depth to bedrock tend to amplify high frequencies of the earthquake motions and deep sites amplify low frequencies which are damaging to mid and high rise buildings. The site conditions thus have great influence on the characteristics of the earthquake motions and their effects on constructed facilities. This explains the role of site characterizations in microzontation studies which attempt to map the level of earthquake across a large area. One of the fastest growing methods in site characterization is geophysical methods which use among other seismic and electromagnetic wave measurements. With the ultimate objective of developing efficient site characterization techniques for future development sites in Hanoi both measurements have been employed in this study.

One of the studies performed in Vietnam was surface wave experiment, in order to delineate sub-surface shear wave velocities (1D) at given locations. The technique is based on the geometrical dispersive nature of surface waves, meaning that their phase velocity changes as a function of frequency.

Surface waves are seismic waves that propagate along or at the interfaces between two physical media, as opposed to body waves that travel through media. In conventional seismic exploration, surface waves are often referred to as ground roll, and removed by filtering (Yilmaz, 2001). However, surface waves are of particular interest for geotechnical applications, as their behavior can be used to assess sub-surface shear wave velocity as well as its lateral variability in a non-invasive way (small-strain approximation). Sub-surface characterization of a site using surface wave methods consists of observing a wavefield, derive its propagation characteristics and translate this into sub-surface properties that affect propagation at very low strains (Socco and Strobbia, 2004). Surface wave velocity largely depends on shear wave velocity, which is directly related to shear modulus, one of the fundamental geotechnical parameters. The fundamental relationship between shear wave velocity V_S, maximum (small-strain) dynamic shear modulus G_O and bulk density ρ is given by:

$$V_S = \sqrt{\frac{G_0}{\rho}} \tag{1}$$

One important difference between body and surface waves is that the latter show geometrical dispersion, i.e. their propagation velocity depends on frequency or wavelength. This dispersive nature of surface waves contains important information about near-surface soil conditions in potentially high resolution. This dispersive nature of surface waves can be easily understood considering superposition of waves with different wavelengths (or frequencies). Surface waves penetrate about half a wavelength (shear waves) into the sub-surface. Therefore, waves with longer wavelengths penetrate deeper, thus sense a larger part of the sub-surface compared to surface waves having shorter wavelengths. For dispersive surface waves, phase velocity differs from group velocity and is frequency dependent. Phase velocity can be expressed as a function of temporal frequency f and angular wavenumber k (spatial frequency), or temporal frequency and wavelength λ,, as:

$$v_{phase} = 2\pi \frac{f}{k} = \lambda \cdot f \tag{1}$$

There are two different types of surface waves, i.e. Rayleigh and Love waves, having their own specific particle motion, which has implication on their generation and recording. Rayleigh waves are a combination of P-waves and vertically-polarized S-waves, guided by an elastic layer. Particle motion takes place in the vertical plane of propagation (Figure 1). Love waves are horizontally-polarized S-waves, which particle motion transverse with respect to propagation direction. When a vertical impact is used as seismic source, then only Rayleigh modes will be generated.

In vertically heterogeneous media, wave equations for dispersive surface waves have multiple solutions at given frequencies. In other words, multiple propagation modes will exist, which should be taken into account in inversion in order to obtain a more accurate geophysical model of the shallow sub-surface. Recording higher-order surface wave modes typically requires longer offsets, but yields the advantage of deeper penetration.

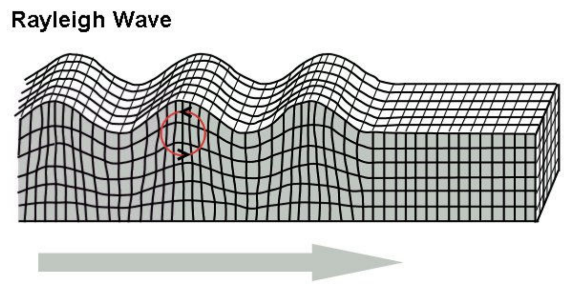

Figure 1 Particle motion of Rayleigh waves in isotropic media. The bold grey arrow represents the propagation direction, whereas the red circle marks retrograde elliptic particle motion normal to the surface and parallel to the direction of propagation (source: Wikipedia).

SURVEY DETAILS

Two sites were investigated with surface waves. At each site, a total of 12 vertical geophones (4.5 Hz corner frequency) were used for the survey. The geophones were repositioned after a number of shots were successfully recorded. For each configuration, the shots were repeated in order to allow (i) selecting the highest-quality traces for analysis and (ii) improve signal-to-noise ratio through stacking. At both sites, the water table lies close to the surface.

VN-Site l

The first target location lies along a small embankment near a village (Figure 2).

Figure 2 Small embankment near a village

A total of 60 shots were generated at site 1. Of these, 50 were acquired using a 60 kg drop weight. The other 10 shots were generated using a small hammer, at a given configuration for which drop weight data were acquired as well. Geophone separation was 6 m, and the offset between the source and the nearest receiver was 15 m throughout the survey. After each sequence, both the geophone array and the source position were moved over a distance of 2 m, thus keeping a fixed distance/offset between source and receivers throughout the acquisition. The layout of the experiment at the first site is presented in Figure 3.

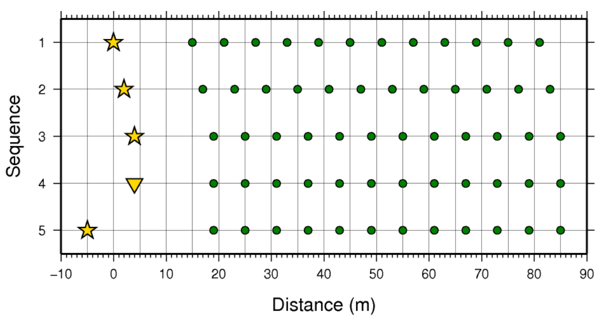

Figure 3 Survey design details for site 1, consisting of 5 different recording sequences. Golden Stars and triangle mark source positions for weight drop and small hammer respectively. The geophones are shown as green circles. Acquisition was done along a single line.

VN-Site2

The second target site lies along a small pavement/street adjacent toa house that collapsed.

At this site, a total of 26 shots were generated, all by dropping a 60 kg weight on the ground. The source remained fixed throughout the experiment at this site, at initially 20 m offset from the nearest geophone. Distance between geophones during recording was 4 m. Geophones were then shifted over 2 m, yielding an effective receiver spacing of 2 m for the final stacked and interleaved shot gathers. The layout of the experiment at the second site is presented in 4.

Results for Site 1

For VN-Site 1, only 12 traces are available within shot gathers, and five different sequences were acquired with multiple shots at each source-receiver configuration. Data quality is highly variable for the different sequences, but also within one and the same sequence the data quality varies. The distal traces often suffer from noise and poor repeatability/coherency. The fact that only 12 traces with 6 m receiver spacing are available within the shot gathers further implies significant under sampling in wave number domain. To circumvent this to some extent, a 10-fold zero-padding was applied in the space domain prior to analysis.

Reasonable results are obtained from the first recording sequence, for which the trace display is shown in Figure 5.

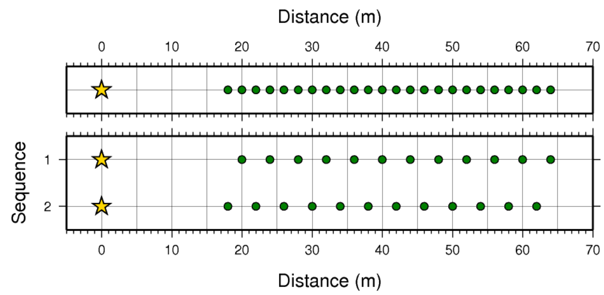

Figure 4 (lower panel) Survey design details for site 2, consisting of 2 different recording sequences. Golden Stars mark source positions for weight drop. The geophones are shown as green circles. Acquisition was done along a single line. (upper panel) Interleaved configuration results in a 24-channel shot gather with 2 m effective geophone spacing.

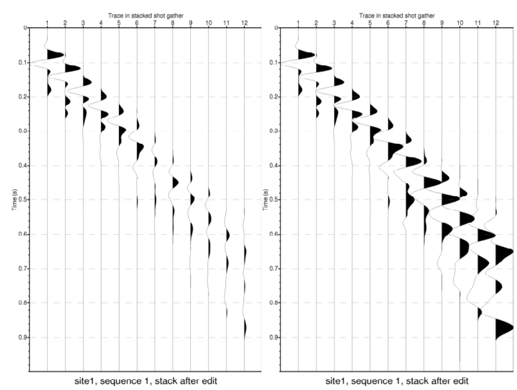

Figure 5 Stacked gather from processed (frequency filtering, top/bottom muting) and edited (removal of ~10% of traces due to poor quality, in particular in the distal part) recorded shot gathers for sequence 1 at VN site 1

Shear wave velocity in the shallowest layers is about 100-120 $m \cdot s^{-1}$ and generally increases with depth to values in the order of 350 $m \cdot s^{-1}$ at depth (around 45 m below the surface, see Fig 6).

Results from Site 2

A similar analysis was done for the second site, with the advantage that more geophone data were available, and that they were more closely spaced, which improves the resolution and dynamic range of the *f-k* domain analysis. The two sites were in close proximity, suggesting that sub-surface soil conditions will most likely not be strikingly different. The shear wave velocities in this site (see Fig. 7) are slightly higher at shallow surface and slightly lower at depth compared to the results from site 1.

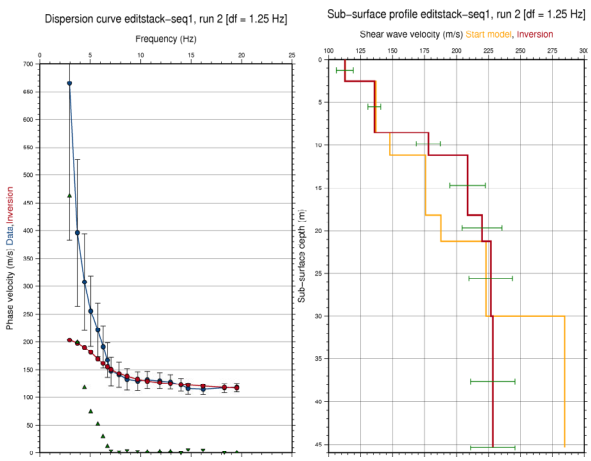

Figure 6 Fundamental Rayleigh mode inversion, using a picking accuracy of 1.25 Hz (f-k domain). The left-hand panel shows picked (blue) and inverted fundamental surface mode (red), with misfit (green triangles). The right-hand panel shows the corresponding sub-surface shear wave velocity profile (red) from the inversion (red). The starting model is shown in dark yellow.

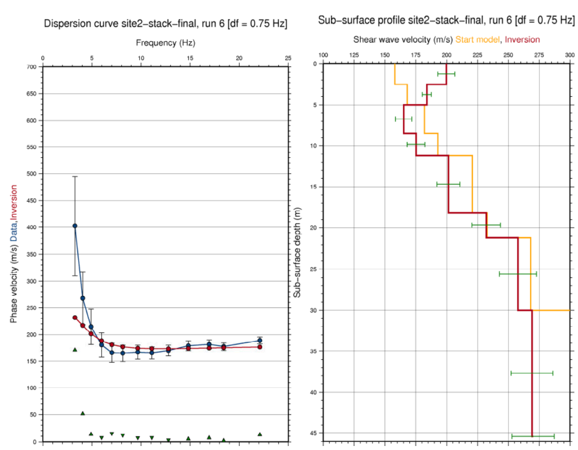

Figure 7 Fundamental Rayleigh model inversion, using a picking accuracy of 0.75 Hz. The left-hand panel shows picked (blue) and inverted fundamental surface mode (red), with misfit (green triangles). The right-hand panel shows the corresponding sub-surface shear wave velocity profile (red) from the inversion (red). The starting model is shown in dark yellow

GROUND PENETRATING RADAR TOMOGRAPHY

At NGI there has been a continuous activity in developing and testing radars for different subsurface mapping tasks since 1989. The work has included development of hardware and software for data acquisition and algorithms for data processing and interpretation. In parallel with the development work, NGI has carried out more than hundred service jobs, gaining a lot of practical experience.

The NGI Ground Penetrating Radar (GPR) employs an Agilent E5062A Network analyser as the transmitter and receiver. It uses step frequency radar signals instead of the impulse signals that most of the commercial GPR use. The NGI GPR has been successfully used for over 100 field tests in around 20 countries since 1989. The NGI radar systems have been exported to USA, South Korea, France, Taiwan, Malaysia, India, Denmark and Bhutan.

The advantages of using a network analyser based GPR system are:

- The NGI system can work within the frequency band 0.3 MHz to 3000 MHz, which has a wider bandwidth coverage than most of the commercial GPR systems.
- The radar signal bandwidth can be adjusted by software at the test site in order to best match the ground conditions to the antenna resonance frequency. Conventional GPR systems, which use impulse signals, need to change hardware to modify radar signals.
- The frequency step number can be adjusted by software to make the best use of signal power for target detection under different ground conditions.
- The receiver of the NGI system has a higher processing dynamic range than conventional GPR systems.
- The NGI system has a perfect frequency response, flat and non-dispersion within the assigned bandwidth. It is in itself a good tool for measuring ground material parameters and antenna response.
- The NGI system makes it simpler to employ frequency-domain signal processing method such as filtering, deconvolution, Hilbert transform, etc.

DEMONSTRATION OF GPR TOMOGRAPHY TEST

Principle of radar tomography and NGI borehole radar system

Cross hole measurements are conducted with borehole radar systems using separate probes (antennas) for the transmitter and the receiver (Figure 8). In crosshole mode, the transmitter and the receiver are lowered into different boreholes. The investigated section is the media between the boreholes.

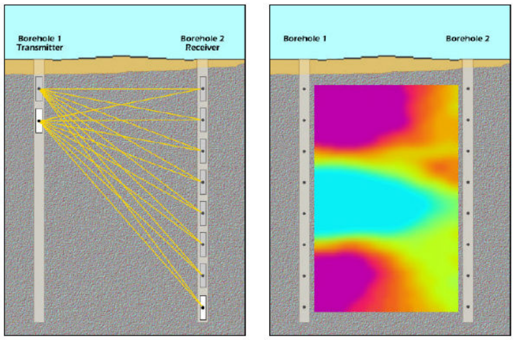

Figure 8 Basic principle of Tomography (borehole radar)

Figure 9 NGI borehole antennas for cross hole measurements

In cross hole surveys, the transmitter is first fixed at one position in one borehole, and the receiver scans the complete length of the other borehole. Then, the transmitter is moved one step and the receiver scans the complete adjacent borehole again. This procedure is repeated until the transmitter has covered the whole length of the first borehole. The cross hole survey mode is also referred to as the tomography mode. Tomography inversion can be made using two types of recorded data, the amplitude of the first arrival and the travel time of the first arrival. Travel time tomography is an excellent surveying and processing method to determine target areas between the boreholes containing high water content (e.g. water filled fractures and cavities). This is because the travel time is heavily affected by the high dielectric constant of water.

The radar signal bandwidth can be adjusted by software at the test site in order to best match the ground conditions. Generally speaking, one uses lower frequency for penetrating difficult ground material (clay etc) and higher frequency for penetrating ‘good’ ground material (sand and sandy soil etc). The only thing we need to do for changing the working frequency is to change the antenna length. Figure 9 shows the NGI borehole antennas for crosshole measurements. From the figure one can see that it is rather easy to change the antenna length by adding additional wires. Crosshole surveys are effective for the case where a target is far from the surface but close to the borehole, and specifically for the case where targets are covered by wet clay layer, which makes it difficult to detect targets from the surface. Figure 10 shows the application for finding cavities in limestone. For this application, it is more effective to use crosshole surveys, when the limestone layer is covered by a thick clay layer. This is because EM wave can propagate in the lime stone layer with less attenuation than in the clay layer.

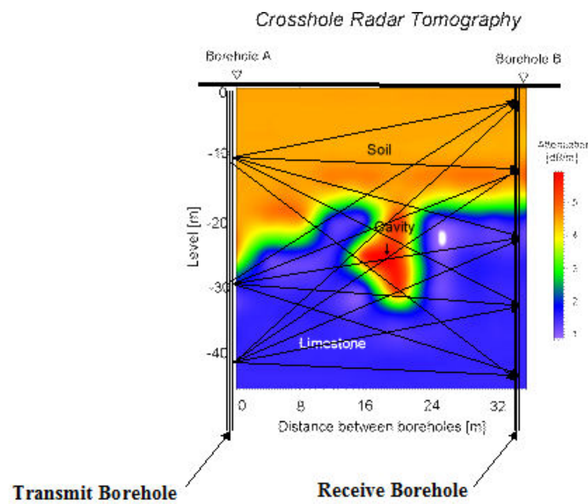

Figure 10 Typical application: checking cavities in limestone covered by thick clay layer

Tomography test results in Hatay area

The radar tomography tests were performed for two sections: one section is between Borehole I and Borehole two near the Site 1, see Figure 11, left) and Borehole II (Figure 11, right), and the other section is between Borehole II and Borehole III. Borehole III is in the other side of the lake. Figure 12 shows a helper carrying a receiver cable swims to Borehole III. The distance between Borehole I and II is 33 m and between II and III is 37 m. The depths of the boreholes are about 50 m.

Figure 11 Borehole 1 (left) and borehole 2 right with a spacing of 33 m

Figure 12 A helper carrying the receiver cable to borehole 3 on the other side of the pond

For performing the tomography test, rather long antennas (5m in length) are used. The center frequency for a 5m - antenna is at 10 MHz.

NGI carried out the tomography inversion and made the tomograms for two sections, using the magnitudes of received signals at 2 MHz. The optimum antenna length for radiating 2 MHz signal could be as long as 25m. The tomogram of the section between Borehole I and II (B12) is shown in Figure 13 (left) and the tomogram of the section between Borehole II and III (B23) is shown in Figure 13 (right). The color of the tomogram represents the material attenuation. The red color means large attenuation and the blue color means small attenuation.

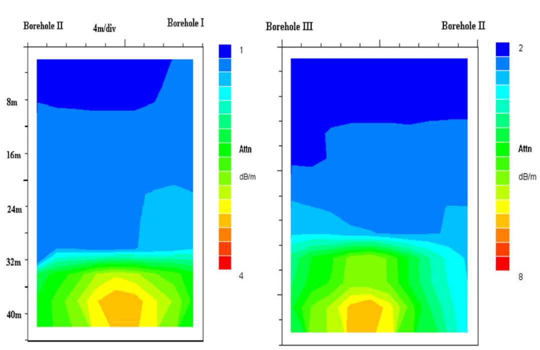

Figure 13 GPR tomograms of the two sections

Since the tomograms are suffered by strong cable wave interference, we hesitate to discuss the results quantitatively in very detail. However we wish to point out the following phenomena:

- The attenuation in the section B23 is larger than the section B12. This is because the clay in B23 has more water content, due to the lake on the surface. Here we should note that the color scales are different for the tomograms of the two sections. The red color in B23 represents a larger attenuation (8 db/m) than the attenuation (4db/m) represented by the red color for B12
- The material changes are generally smooth in both sections. No large targets (cavities) are found. However there seems a sudden change of the material property at the depth about 30 m.

CONCLUSIONS

Multichannel analysis of surface waves (MASW) was performed at two sites in the Hatay area near Hanoi to estimate the sub-surface shear wave velocity of the soil. The results from these tests showed that the shear wave velocity in the shallowest layer ranged from 100-120 m/s and generally increases with depth to values in the order of 350 m/s at a depth of about 45 meters. This information us useful for assessing the amplification of earthquake waves and earthquake analysis of the planned facilities in the area. Ground Penetrating Radar investigations using cross-hole seismic surveys was also performed near the same sites to scan the subsurface soil conditions. The tomograms from these investigations showed that the wave attenuation from one soil section was larger than the other section. This is due to the fact that a high attenuating wave section has higher water content than the other section due to a nearby lake on the surface. Such investigations are useful for planning infrastructure development in the area.

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