Engineering Geology 123 (2011) 246–258

Contents lists available at SciVerse ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

A mobile multi-depth borehole sensor set-up to study the surface-to-base seismic transfer functions

Edwin A. Obando [a,b,*], Nils Ryden [a], Peter Ulriksen [a]

[a] Department of Engineering Geology, Lund Institute of Technology, P.O.B. 118, SE-221 00 Lund, Sweden
[b] Centro de Investigaciones Geocientificas de la Universidad Nacional Autonoma de Nicaragua, (CIGEO-UNAN), P.O. B. A-131 Managua, Nicaragua

ARTICLE INFO

Article history:
Received 25 August 2010
Received in revised form 16 August 2011
Accepted 4 September 2011
Available online 16 September 2011

Keywords:
Vertical arrays
Borehole transfer function
Site response
Site amplification
Site effect
MASW

ABSTRACT

The best method to evaluate the seismic site response is by means of borehole vertical arrays that use earthquake records from different depths. In this paper we introduce the implementation of a single borehole sensor system (synchronized to a sensor on the surface) that is fixed at variable depths within a single well. This system is used for recording small amplitude earthquake signals at variable stiffness conditions in depth to compute empirical borehole transfer functions. The computed average empirical borehole transfer functions allow the estimation of an S-wave velocity model that is constrained using the frequency peak observed in the H/V ratio curve.

Pairs of surface and borehole earthquake records were obtained with the borehole sensor placed at −10, −20, −50, and −100 m depth in a test site in Managua, Nicaragua. The average velocity of the final model down to −100 m appeared to be in good agreement with the average velocity computed via cross-correlation using the surface and borehole signals. Likewise, an inverted MASW profile and H/V ratio at the same site agree with the S-wave velocity model obtained.

1. Introduction

When earthquakes occur one of the factors that increases the level of damage is the amplification of the ground motion of the soft surface layers overlying hard rock material (Kramer, 1996). In order to minimize the damage during the ground shaking, it is required to evaluate the site response, which is strongly dependent on the local soil characteristics at the site. Several researchers have proposed different techniques to predict the site response (Borcherdt, 1970; Archuleta et al., 1992; Lermo and Chavez-Garcia, 1994) and help to understand the effect of the most influential factor in the ground motion amplification such as S-wave velocity distribution and dynamic parameters. The most accurate method to evaluate the site response is by means of borehole vertical arrays (Archuleta et al., 1992; Steidl et al., 1996; Zeghal and Elgamal, 2000; Bonilla et al., 2002). This system consists of several borehole tri-axial sensors installed in various cased boreholes at various depths and coupled to tri-axial sensors placed on the free surface (Archuleta et al., 1992; Elgamal et al., 1996; Kokusho and Sato, 2008). Vertical array records have been used to evaluate not only the actual ground amplification accurately, but also a number of aspects related to dynamic parameters in a wide range of strain levels (Elgamal et al., 1998; Gunturi et al., 1998; Pavlenko and Irikura, 2002; Kwok et al., 2008). More recently vertical array records have provided the opportunity to estimate the incident wave, as well as the attenuation characteristics of the site (Assimaki et al., 2006; Mehta et al., 2007; Bindi et al., 2010; Parolai et al., 2010). The S-wave velocity distribution can also be estimated via the *waveform deconvolution* method (Mehta et al., 2007) that computes of the travel time of the incident wave from one station to another. This technique is also similar to the cross-correlation technique widely implemented in vertical array data analysis (Elgamal et al., 1996; Assimaki et al., 2006, 2008; Assimaki and Steidl, 2007). S-wave velocity configuration and attenuation characteristics have been evaluated using an inversion technique that uses the input (borehole) and output (surface) ground motions (Assimaki et al., 2006, 2008; Assimaki and Steidl, 2007; Parolai et al., 2010). However, these methods are normally used with data collected in permanent vertical arrays which are not available everywhere. The reason is that vertical arrays are very expensive mainly due to e.g. drilling and equipment acquisition which makes its implementation, in many countries prone to earthquakes, prohibitive.

It is clear that the value of borehole records is that both the input (bottom) and output (free surface) ground motions contain the information of the local site characteristics between the two sensors.

In order to provide an alternative to evaluate the site response from the surface relative to different depths in earthquake prone areas and where a high budget is not available, in this paper we propose the use of a multi-depth single borehole sensor set-up. This system allows obtaining pairs of surface and depth ground motion

* Corresponding author at: Department of Engineering Geology, Lund Institute of Technology, P.O.B. 118, SE-221 00 Lund, Sweden. Tel.: +505 22703983; fax: +505 22770613.
E-mail addresses: edwin.obando@tg.lth.se, edwinobando1981@hotmail.com (E.A. Obando).

0013-7952/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.enggeo.2011.09.001

records with a single borehole sensor that can be placed at different depths within the same well. The collected data are used to compute the borehole transfer functions at multiple depth positions and identify the different resonance modes within a soil column. Based on the fact that in the linear range the observed resonant modes are dependent on the local shear wave velocity configuration, it is possible to approximate a shear wave velocity model using the response of the surface layer relative to multiple depths. The shear wave velocity model is assumed 1D for the computation of the seismic transfer function.

Thus, a simple methodology was developed to estimate an S-wave velocity model whose theoretical transfer function produces the frequency peaks observed on the empirical transfer function from the surface relative to the different depths. For the specific purpose of computing the 1-D linear seismic transfer function, in this paper the use of small amplitude earthquakes is required. A limitation of this set-up is that it does not allow recording simultaneous records at various depths; as a result it will not be possible to evaluate some of the features that vertical arrays normally deal with such as the evaluation of shear stress–strain histories (Elgamal et al., 1996; Gunturi et al., 1998).

The proposed set-up is tested in Managua, the capital city of Nicaragua, where small earthquakes are frequent. Thus, from existing geotechnical information it is well known that throughout Managua city in general soft layers are in the first 10 to 15 m depth (Faccioli et al., 1973). Available SPT (Standard Penetration Test) records at the installation site show that the stiff material starts to appear down to the first 10 m depth. Since at the site no S-wave velocity information is available, the maximum depth of the borehole was chosen to be −100 m. At this depth it is expected that a very stiff material exists. To evaluate the stiffness variation along the entire 100 m profile a number of records are obtained with the borehole sensor placed at −10, −20, −50, and −100 m depth. A final velocity model for the site can be estimated by initially fitting the theoretical surface-to-base multiple depth transfer functions to the empirical borehole transfer functions from the surface to each corresponding depth. With this initial velocity model the maximum velocity contrast in identified. The average velocity of the estimated S-wave velocity model is then compared to the average velocity computed using the travel time estimated using cross-correlation technique. A final velocity model is obtained by constraining with the frequency peak observed in the average H/V ratio curve at the site. The response of the final S-wave velocity model is compared to the one obtained from surface wave MASW at the same site.

2. Multi-depth single borehole sensor concept

The mobile multi-depth single borehole sensor set-up consists of one surface tri-axial sensor placed on the free surface and one tri-axial borehole sensor, installed in a single cased well, which are connected to a surface digital recorder. The borehole sensor is installed in such a way that it can be moved to different depths and fixed to record earthquake signals at the surface and different depths in a similar manner as in vertical arrays and evaluate the surface-to-base seismic transfer function at different depths (Figure 1).

The borehole sensor can be moved and fixed at different depths (BH1, BH2, BH3… BHn) using an inflatable (or air-bladder) coupling device similar to the one used in conventional refraction S-wave downhole or cross-hole surveys. By computing the seismic response of the surface relative to variable depths the identification of different resonant modes within the soil profile can be obtained. Then, with this information it is possible to estimate an S-wave velocity model required for the seismic site response evaluation. This is especially useful when a geotechnical S-wave velocity model is not available.

A difference compared to normal vertical arrays is that with the multi-depth set-up the evaluation of the transfer function at the different depths is made with earthquakes of different characteristics. The possible effect on the subsequent transfer function computations due to differences in source distances can be minimized when averaging different transfer functions. For the specific purpose of the linear site response all the earthquake records selected should be of small amplitude, since including large amplitude events (strong motion records) would introduce higher strain levels outside the linear elastic range. However, the systems can also be used to record strong motion records and evaluate nonlinear soil characteristics. A limitation of the data collected with this system is that features such as the shear stress–strain histories and the identification of resonant site characteristics (Elgamal et al., 1996; Zeghal et al., 1996; Gunturi et al., 1998) cannot

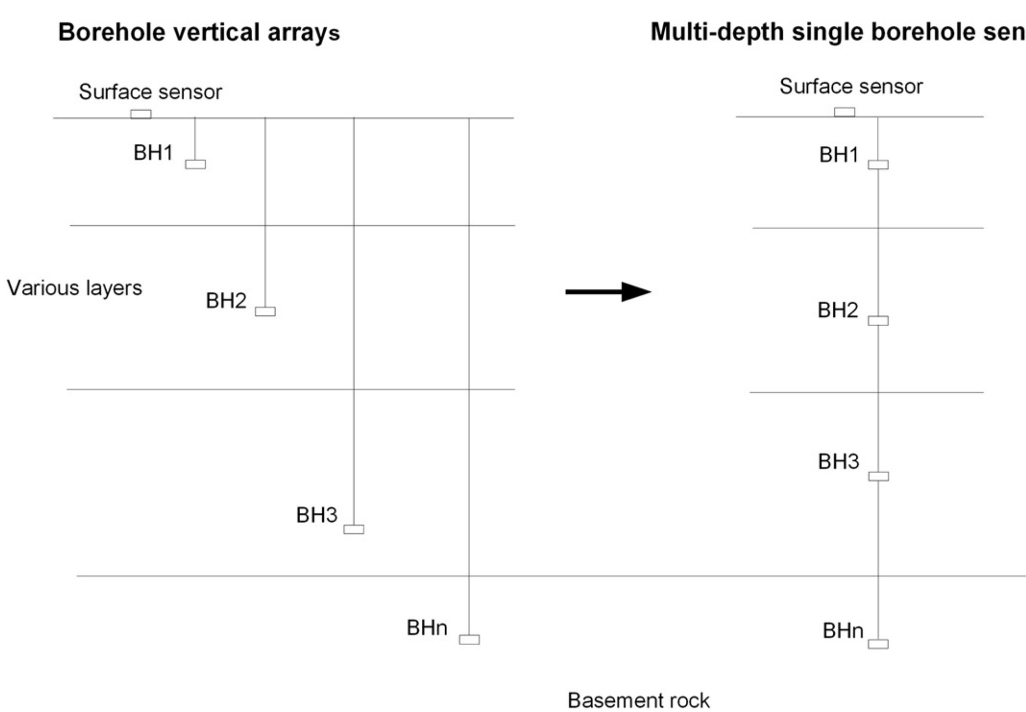

Fig. 1. Conceptual scheme of borehole vertical arrays and mobile multi-depth single borehole sensor set-up.