Journal of Applied Geophysics 73 (2011) 196–206

Contents lists available at ScienceDirect

Journal of Applied Geophysics

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

Characterization of the sedimentary cover at the Himalayan foothills using active and passive seismic techniques

A.K. Mahajan [a,*], J.J. Galiana-Merino [b,c], C. Lindholm [d], B.R. Arora [a], A.K. Mundepi [a], Nitesh Rai [a], Neetu Chauhan [a]

[a] Wadia Institute of Himalayan Geology, 33, General Mahadeo Singh Road, Dehra Dun, India
[b] Dpto. de Física, Ingeniería de Sistemas y Teoría de la Señal, Universidad de Alicante, Spain
[c] University Institute of Physics Applied to Sciences and Technologies, Universidad de Alicante, Spain
[d] NORSAR, P.O. BOX 53, NO-2027, Kjeller, Norway

ARTICLE INFO

Article history:
Received 16 June 2010
Accepted 5 January 2011
Available online 15 January 2011

Keywords:
Ambient vibrations
Frequency–wavenumber analysis (*f*–*k*)
Active Multichannel Analysis of Surface Waves (MASW)
Passive Remote MASW
Neighbourhood algorithm

ABSTRACT

The characterization of the sediments, down to bedrock, is very important from the seismological point of view in order to study the possible earthquake effects (site effects). Resonance frequency and shear-wave velocity profile are the main features used to estimate the thickness and stiffness of the sedimentary cover. To map these characteristics different geotechnical, geophysical and seismological methods have been developed and applied over a last few years. In this work, different soil investigation methods have been applied around the Himalayan foothills, focusing on three sites with different soil characteristics that span from the Doon valley to the Ganga foreland basin. Active and passive array experiments were carried out: Multichannel Analysis of Surface Waves (active MASW), Passive Remote MASW and *f*–*k* technique. A dispersion curve was estimated for every site covering a wider frequency band rather than if only one method would have been used. Moreover, ambient noise measurements were also recorded in order to apply the H/V method and to estimate the resonance frequencies. Combining the information provided from all methods and using the neighbourhood algorithm, the best suitable shear (S) wave velocity profiles were estimated for each area. In this way, soil sediments were characterized by the resonance frequency, the soil thickness and the mean S-wave velocity. It has been demonstrated that the use of different methods give coherent and more robust results than when only one method is applied. This greatly contributes to the credibility of the results.

1. Introduction

In seismically active area the estimation of the shear wave velocity (Vs) profiles of sediments overlying geological basement is a vital part of site zonation studies for earthquake hazard and more generally for geotechnical studies. The knowledge of the characteristics and thickness of these soils as well as their spatial distribution within a region is of great interest for land use planners and civil engineers. Therefore, site effect studies (microzonation) have become an important part of the seismic risk characterization, and a variety of techniques have been developed to resolve the soil characteristics of a given site (Kramer, 1996). There are two main approaches to determine subsurface structures; one by means of borehole data and the other is based on indirect methods such as geophysical prospecting.

Traditionally, Standard Penetration Test (SPT) was found to be convenient among geotechnical engineers in order to estimate the stiffness of the soil column. Recently, with the advancing technology, geophysical techniques such as downhole or crosshole profiling methods allow in-situ measurements of the shear-wave velocity with depth. However, the performance of these methods for microzonation studies can be difficult and expensive in urban areas (Hunter et al., 2002; Rix et al., 2001). To overcome these problems, non-invasive seismic exploration has emerged as a promising alternative to estimate the shear wave (Vs) profiles and the resonance frequencies. In seismic exploration, the data acquisition process is relatively cheap and fast and can be implemented in urban areas without too much difficulty.

One of the most widely used (and misused) methods for estimating the site response is the Nakamura technique (Nakamura, 1989), where the spectral ratio between the vertical and horizontal components of the records (H/V or HVSR analysis) provides a good estimate of the fundamental frequency of soft soil deposits. It is a cheap and fast technique which allows to obtain a detailed mapping of these frequencies within an urban area (e.g. Mundepi et al., 2010; Parolai and Galiana-Merino, 2006; Parolai et al., 2001; Picozzi et al., 2009).

Other common methods are focused on the estimation of the shear-wave velocity, which is considered to be the single best indicator of stiffness (Aki and Richards, 1980; Bullen, 1963). These

* Corresponding author. Tel.: +91 135 2525455; fax: +91 135 2525200.
E-mail address: akmahajan@rediffmail.com (A.K. Mahajan).

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doi:10.1016/j.jappgeo.2011.01.002

methods are based on the dispersion property of the surface waves, which is the most sensitive property to S-wave variations with depth (Zhang et al., 1996). As the wavefield generated by active or passive seismic sources (e.g. weight drop hammer or ambient vibrations) mainly consists of surface waves then the surface wave dispersion curves may be measured and the corresponding Vs profiles may also be estimated (e.g. Milana et al., 1996; Richwalski et al., 2007).

Some of the most popular and standardized procedures used for obtaining the Rayleigh wave phase-velocity dispersion curve are based on the Radon transform (Louie, 2001; Park et al., 1999; Thorson and Claerbout, 1985), the frequency–wavenumber (f–k) transform (Asten and Henstridge, 1984; Capon, 1969; Kvaerna and Ringdahl, 1986; Lacoss et al., 1969; Wathelet, 2005) and the extended spatial autocorrelation (ESAC) analysis (Aki, 1957; Ohori et al., 2002; Okada, 2003).

Once the dispersion curve is obtained, the velocity profile can be estimated through different approaches, as linearized methods (Nolet, 1981; Tarantola, 1987), simulated annealing (Sen and Stoffa, 1991), genetic algorithms (Lomax and Snieder, 1994) or the neighbourhood algorithm (Sambridge, 1999; Wathelet, 2008). Among these methods, the latter three allow to investigate the whole parameter space and to provide all minima in terms of misfit functions.

In this work, we have applied three different array techniques for estimating the dispersion curves: the active multichannel analysis of surface waves (MASW) (Mahajan et al., 2007; Park et al., 1999), the passive remote MASW (Park et al., 2007) and the frequency–wavenumber (f–k) method (Lacoss et al., 1969). The combination of the three techniques allowed us to estimate an average dispersion curve in a frequency band wider than if only one technique would have been used. Moreover, single measurements were taken around the sites under study and H/V analysis was done for estimating the resonance frequencies. Subsequently, the neighbourhood algorithm (Sambridge, 1999; Wathelet, 2008) was used for estimating the shear-wave velocity profiles.

2. Geological characteristics of the study area

The Indo-Gangetic Plains comprise a foreland basin system which is one of the largest in the world (Fuloria, 1996). It is located between the Himalayan Tertiary mountain belt and the Indian main continent. The Indo-Gangetic Plains stretch along the Himalayan arc and are divided into a number of basins by transverse sub-basement ridges (Raiverman et al., 1983; Sastri et al., 1971). The present day geomorphic configuration of the Ganga plain is essentially a product of tectonic forces, climate change and base level changes. Thus the morphology and sedimentary record of the Ganga plain are like an archive of the past tectonic activity in the Himalayan orogen (Sinha et al., 2007). The Ganga plain is separated from the Tertiary mountain belt by the Himalayan Frontal Thrust (HFT) running all along the length of the Himalaya in a NW–SE direction. All along the HFT, there are a number of tectonically controlled valleys, which are filled with the sediments derived from sub-Himalaya and Lesser Himalaya (Fig.1). The Doon valley is one of these (Thakur, 1995), situated north of the HFT in NW Himalaya and bounded by Yamuna Tear Fault in the west and Ganga Tear Fault in the east, India (Fig. 2a). Considering the characteristics of different sites with respect to geology and the HFT, three sites were selected for site characterization (Fig. 1): Nirmal Gyan Ashram (NGA north of the HFT), Roshnabad (just south of the HFT in the Ganga foreland basin) and Dhanauri (Ganga foreland basin).

The first site, NGA, is located almost 40 km SE of Dehra Dun, and is characterized by young sedimentary basins filled with sediments of Doon gravels derived from the Sub-Himalaya (Siwalik sediments) and Lesser Himalaya (Singh et al., 2001). The other two sites, Roshnabad and Dhanauri, are located in the Ganga foreland basin. According to the geological section of the area from Lesser Himalaya to Ganga basin, these sites are underlain by Tertiary rock which comprises Siwalik Conglomerates with varying thickness of soft sediments. In the Doon valley, the Siwalik strata are folded from south to north into the large Mohan anticline, the Doon syncline and the Santaurgarh anticline (Karunakaran and Rao, 1979; Raiveman et al., 1994). The valley is tectonically separated from the Indo Gangetic Plains in the south by Himalayan Frontal fault (HFT) dipping at 30° in a NE direction (Fig. 2b). The attitude of the HFT was established on the basis of its substructure position derived from the seismic profiles and drill wells (Rao, 1986).

According to the seismic cross sections, Middle Siwalik are exposed only in the northern part of Dehra Dun Fan and are overlain by boulder conglomerate of Upper Siwaliks toward south due to tectonic disposition (Power et al., 1998). Both the sites i.e. NGA and Roshnabad are located north and south of HFT respectively. The seismic section given by Power et al. (1998) shows the presence of Siwalik conglomerate bedrock below all the sites overlain by varied thickness of sediments from the Doon valley to Ganga basins (Fig. 2b).

The seismic hazard analysis carried out for NW Himalaya shows a high seismic potential which can have a peak ground acceleration of the order of 0.15 g to 0.2 g with 10% probability of exceedance in 50 years (Mahajan et al., 2010). Since the studied sites are located in the frontal Himalayan belt underlain by thick soft sediments so, various techniques have been tested for site characterization.

3. Methodology

3.1. H/V method

The H/V method was developed by Nakamura (1989, 1996, and 2000), who demonstrated that the ratio between the Fourier spectral amplitude of the horizontal to vertical component of ambient noise records (microtremors) is related to the fundamental frequency of the soil beneath the site and hence to the amplification factor. However, the theoretical basis of HVSR is still debated and different explanations have been given. More widely accepted is the 'surface waves' explanation that HVSR is related to the ellipticity of Rayleigh waves which are frequency dependant (Bard, 1998; Bonnefoy-Claudet et al., 2006; Kudo, 1995; Lachet and Bard, 1994).

Many experiments (Beauval et al., 2003; Di Giacomo et al., 2005; Fäh, 1997; Gitterman et al., 1996; Gosar, 2007; Guillier et al., 2007; Lermo and Chávez-García, 1993; Mundepi and Kamal, 2006; Panou et al., 2005; Parolai and Galiana-Merino, 2006; Seekins et al., 1996) supported by several theoretical 1-D investigations (Bonnefoy-Claudet et al., 2006; Chatelain et al., 2008; Field and Jacob, 1995; Guillier et al., 2008; Lachet and Bard, 1994; Tokeshi and Sugimura, 1998; Wakamatsu and Yasui, 1996) have shown that ambient noise H/V spectral ratio is sharply packed around the fundamental S-wave frequency if the upper layers have a sharp impedance contrast with the underlying stiffer layers.

3.2. Active MASW and passive remote MASW techniques

Active MASW (Park et al., 1999) and passive remote MASW (Park et al., 2007) techniques utilize a similar analysis, based in the p-tau transformation (Thorson and Claerbout, 1985). This analysis converts the recorded seismograms to power spectrum amplitudes, as a function of the frequency and the apparent phase velocity. In this representation, the maximum values in the power spectrum are identified as the surface wave dispersion curve and then picked automatically. The main difference between both techniques is the source type required for data acquisition. The application of the MASW technique requires an active source, e.g. a weight drop, allowing the discrimination between various surface wave modes (Beaty and Schmitt, 2003). In contrast, the passive remote MASW