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Soil characteristics in Doon Valley (north west Himalaya, India) by inversion of H/V spectral ratios from ambient noise measurements

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ABSTRACT

Past and recent observations have shown that the local site conditions significantly affect the behavior of seismic waves and its potential to cause destructive earthquakes. Thus, seismic microzonation studies have become crucial for seismic hazard assessment, providing local soil characteristics that can help to evaluate the possible seismic effects. Among the different methods used for estimating the soil characteristics, the ones based on ambient noise measurements, such as the H/V technique, become a cheap, non-invasive and successful way for evaluating the soil properties along a studied area.

In this work, ambient noise measurements were taken at 240 sites around the Doon Valley, India, in order to characterize the sediment deposits. First, the H/V analysis has been carried out to estimate the resonant frequencies along the valley. Subsequently, some of this H/V results have been inverted, using the neighborhood algorithm and the available geotechnical information, in order to provide an estimation of the S-wave velocity profiles at the studied sites.

Using all these information, we have characterized the sedimentary deposits in different areas of the Doon Valley, providing the resonant frequency, the soil thickness, the mean S-wave velocity of the sediments, and the mean S-wave velocity in the uppermost 30 m.

1. Introduction

Doon Valley falls in zone IV of the seismic hazard zonation map of India [1], experimenting several major earthquakes ($M > 6$) in the historical times. The valley is located between the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT), which may be the host fault for future large earthquakes in the region [2]. Along this wide and long valley, we find many of the fastest growing cities in the Himalayan foothills, which are located in areas where the rivers flow becomes gentle and the sediments are deposited in large fans. This fast urbanization process rarely concerns about the future possibility of damaging earthquakes hitting the area, and even less about the dangerous consequences of local amplification.

Past and recent observations have shown that local soil characteristics play a significant role in the damages caused by strong motions. In this way, the effects of the seismic waves generated by an earthquake are more severe in sedimentary basins than on hard rock structures. There are numerous examples of such soil amplifications, three of these are the cases of Mexico [3], Northridge [4] and Boumerdes [5]. The knowledge of the ground dynamic characteristics at one place can help to evaluate the possible seismic effects and minimize the potential damages in the area. Thus, microzonation studies become crucial for the seismic hazard assessment, providing local soil characteristics such as the resonant frequency and the shear-wave velocity profile.

The site amplification can be evaluated by empirical and theoretical methods, and quite often both approaches are used, supporting one each other. Regarding the empirical methods, the subsurface soil characteristics can be estimated through borehole data or by means of geophysical exploration. Among the geophysical methods, the passive seismic survey allows characterizing the soil structure with parameters such as the S-wave velocity, the resonant frequency or the soil thickness.

In urban areas, it can be rather difficult to carry out boreholes, as well as other geophysical surveys, due to the lack of suitable sites to conduct the required experiments and/or by economic constraints. Therefore, microzonation studies based on ambient noise measurements become a suited alternative way to estimate the local soil characteristics in urban areas, through cheap and non-invasive techniques.

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Among the different methods used for extracting the soil properties, one of the most commons is the Nakamura technique [6], which only requires the data recorded by a three-component station. The method is based on the spectral ratio calculation between the vertical and horizontal component of a record (H/V or HVSR curve), which provides a good estimate of the resonant frequency of the studied soft soil deposits. The ease with which the method is applied allows the fast and detailed mapping of the resonant frequencies within urban areas (e.g. [7,8]).

Once the H/V curves are obtained, S-wave velocity profiles can be estimated as the solution of a typical geophysical inverse problem. In this case, the inversion problem is formulated as an optimization process in a finite-dimensional parameter (model) space under some possible constraints. Each parameter in the model space is associated to a set of physical properties of the ground, for example shear-wave velocity and thickness of each layer. A misfit function measures the discrepancy between observations and theoretical predictions from a selected model (determined from the solution of a forward problem).

In this context, stochastic search methods such as uniform Monte Carlo search (UMC) [9–12], simulated annealing [13,14], genetic algorithms [15–17] and the neighborhood algorithm [18,19] are becoming increasingly popular for misfit function optimization in a multidimensional parameter space. Among these methods, the last three allow to investigate the whole parameter space, analyzing many options in parallel at each iteration and providing a huge set of possible solutions in terms of misfit functions.

Nevertheless, without any constrain, the problem is non-unique since there may exist an infinite number of models that satisfy the experimental data. Thus, we follow an approach similar to the one proposed by Casterallo and Mullargia [20] and we use information about the subsoil stratigraphy, obtained from other previous independent geotechnical studies, to constrain the fit of the synthetic H/V curve to the measured one.

In this work, we have carried out a microtremor H/V study in the Doon Valley, India. Single station measurements were taken along the valley and then, the H/V analysis has been performed for estimating the resonant frequencies. Once obtained the different H/V curves, we have used the neighborhood algorithm and the available geotechnical information to estimate the V_S profiles at eight sites distributed along the valley. Thus, the accomplished work has contributed to the characterization of the sedimentary basin and the identification of the areas that may be more susceptible to amplify soil shaking during a strong earthquake. In the next sections, the geological and seismic characteristics of the region under study, as well as the methodology, will be exposed. Subsequently, the main obtained results will be presented, showing the resonant frequency, soil thickness and mean S-wave velocity along the Doon Valley.

2. Characteristics of the study area

2.1. Seismicity

The Doon Valley is located between the rupture zone of the 1905 Great Kangra earthquake ($M{\sim}8$) and the 1934Nepal Bihar earthquake (Fig. 1). The general geodynamics and infrequent occurrence of great earthquakes is well summarized by Seeber and Armbruster [21], Khattri [22], and Bilham and Gaur [23]. In case of the 1905 Great Kangra earthquake, the valley experienced an intensity of VIII (MM scale). Similarly, during the 1991 Uttarkashi earthquake and the 1999 Chamoli earthquake, the intensity at Dehradun was VI (MSK scale), a degree higher than the surrounding areas. Considering the relatively small damage of the $M=6.3$ Chamoli earthquake, it is instructive to recall that Ram and Ram [2] estimated the return period for $M=8$ and larger to be around 130 years. According to the data provided by the Global Seismic Hazard Assessment Program, the state of Uttarakhand falls in a region of high to very high seismic hazard. As per the Bureau of Indian Standards (BIS) map [1], Uttarakhand fall in Zones IV and V, and the area of Doon Valley lie in Zone IV, where the maximum intensity expected could reach MSK VIII. Historically, parts of this region have experienced seismic activity in the magnitude of 6.0–7.0 in nearby regions.

2.2. Geological and geomorphological setting

The synclinal trough-shaped Doon Valley is bounded by the Precambrian rocks of the Lesser Himalayan formations (Pre-Tertiary) in the north and Tertiary Siwalik (Mio Upper Pleistocene) in the south. The center of the valley is covered by a thick pile of Quaternary alluvium spread out in fans and terraces. The Tons basin falls in the middle part of the Doon Valley [1,5].

Geologically, Doon Valley can be divided into three major units: Lesser Himalayan Formation, Siwalik Formation and the Alluvium covered valley depression. Proterozoic to Lower Cambrian rocks of Lesser Himalaya are separated from the Cenozoic Siwalik group and the Pleistocene aged Doon gravels by the MBT [3,4]. The rocks in and around the basin consist of the Lesser Himalayan sequence, represented by the older Chandpur Formation, consisting of phyllite, siltstone and graywacke and some volcanic. This is succeeded by the rocks of the Nagthat, Blaini and Infrakrol formations comprised of quartzite and slate, phyllite, siltstone and graywacke, and shale and limestone, respectively. At the top, the thickest Krol Formation composed of limestone and dolomite is found [2,3].

The rocks of the Lesser Himalayan Formation have a thrust contact with the Siwaliks Group represented by the Middle Siwaliks Sandstone. This is turning in overlain by the thick Quaternary alluvium represented by the Old Doon Gravel and the Young Doon Gravel. The Old Doon Gravel is composed of large rounded non-cemented boulders mainly of Quartzite embedded in red soil and is believed to the reworked Upper Siwaliks deposits. Whereas, the Young Doon Gravel consists of less consolidated and weathered gravel beds in sandy clay matrix inter-bedded with sandy clay horizons derived from the older formations including the Old Doon Gravel [2,3].

The southern margin of the Doon Valley is marked by a sudden break in topography defined by the Himalayan Frontal Thrust (HFT), locally known as the Mohand Thrust [24]. Here the rocks from the Siwalik group override the recent alluvial sediments towards the south (Fig. 2). The study area is a broad synclinal depression lying between the Lesser Himalayan hills in the North and the very young topographic relief of the Siwalik ranges in the South. Besides, it is enclosed by the rivers Ganga and Yamuna, located in the East and the West, respectively. Thus, the boundaries of the valley enclose a parallelogram of 72 km long and 20–24 km wide along the NW-SE regional Himalayan strike [25–27].

The collision and merging of the central fan with the western fan result in a higher elevation, which constitutes the formation of a water divide between the Yamuna and Ganga catchments. The Tons River forms the boundary of the western and central fans. The Bindal Nadi, Song and Jakhan rivers drain the central and eastern fans and join the river Ganga. Henceforth, the area lying towards the southeast sector is referred as the Ganga Catchment and that of the north west sector as the Yamuna Catchment.

A variety of soil types have developed on different landforms. The surface soils of Doon fans have formed on mudflow and on over bank deposits in the middle and distal zones of the fans respectively. Particle size data indicate that the Doon soils are mostly medium to moderately fine/textured loamy soils.