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A new analytical approach to reconstruct the acceleration time history at the bedrock base from the free surface signal records

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ABSTRACT

Acceleration time histories of earthquake events are typically measured in seismic stations that are placed close to the soil top surface. These acceleration records are often used as input data for seismic analysis. It may be used for base excitation in seismic analysis of above ground structures with shallow foundations.. However it may not be used for seismic analysis of underground structures, or even for above ground buildings with deep foundations and several underground stories. The required base excitation data of the latter should have been measured below the top surface, at a level that may be determined according to the specific analyzed building geometry or at the bedrock below. If the acceleration time history at the bedrock would have been known, the seismic wave propagation through the soil medium, from the bedrock towards the top surface, could have been carried out and the base excitation of the buried structure could be determined. Since there is no data on the acceleration time history at the bedrock, and the only given data is the acceleration records at the top surface, the goal of this paper is to provide an exact reverse analysis procedure to determine the unknown acceleration time history at the bedrock that would exactly produce the measured acceleration time history at the top surface. Once this goal is achieved, seismic analysis of buried structures may be carried out with the determined acceleration record at the bedrock as input. This paper presents an analytical exact solution of the inverse problem for determination of the acceleration, velocity and displacement time histories at the bedrock base of a layered geological medium that are compatible with the given acceleration record at the soil top surface. This new proposed method is based on analytical solutions of the initial-boundary value problems of the linear wave equation in the case of a layered medium. The relationship between waves in one layer and waves in another adjacent layer is derived considering the continuity of stresses and displacements at the common interface between the layers. The efficiency and accuracy of the proposed method is demonstrated through several examples involving the nonstationary response of the free surface. The case of the San Fernando Earthquake is studied. Excellent agreement is achieved between the recorded free surface time history and the reconstructed signal. This excellent agreement is obtained due to the exact analytical method used in deriving the inverse problem solution. This exact analytical method allows one to obtain an acceleration (velocity/displacement) distribution along all the layers at any time.

1. Introduction

Earthquake ground motions are commonly recorded close to the soil top surface and are available for seismic analyses, while signals at the bedrock base motion are seldom available [1]. The top surface signals may serve as the base excitation data and satisfy the analysis input data for above ground structures with shallow foundations (Fig. 1a) [1,2], however they are inappropriate for the analysis of buried structures (Fig. 1b) [3–6] or even above ground structures with deep foundations and several underground stories. In the latter case, the seismic input must be applied at the base of the analyzed buried structure rather than at the ground surface as is shown in Fig. 1b. The question then arises: which is the appropriate base excitation at the underground base that corresponds to the measured given signal at the soil top surface? Alternatively the corresponding signal at the rock base may be calculated, with aid of which the wave propagation in the soil medium may be analyzed and the predicted signal at the top surface would be identical to the given top surface recorded signal. This matter is significant in order to properly simulate the motion of the underground structure. Clearly, the given top surface records cannot be applied as base

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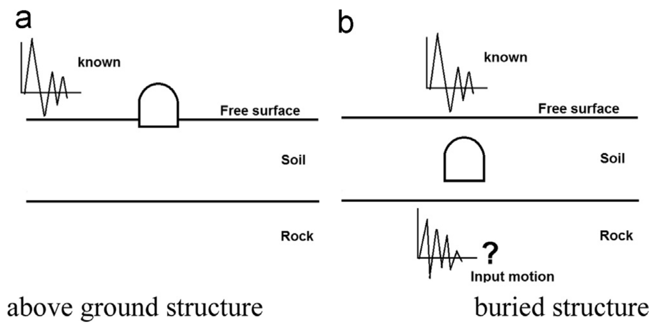

Fig. 1. a) above ground structure. b) Buried structure.

excitation to below ground structures bases and if they are used as such, due to the absence of the below ground corresponding signals at the structures base level, would yield erroneous results that are most often in excess of the physical response. The correct procedure is then to apply the true ground motion records that are unfortunately not available. In order to determine the signal at a requested level below the ground surface, it is required to solve an inverse problem of wave propagation and reconstruct (restore) the acceleration time history at the bedrock base from a given recorded signal at the top free surface.

Therefore, a procedure that inverts the free surface acceleration to obtain the incident velocity at a substrata rock-soil interface is required. An alternative method had been proposed, using one-half the rock surface velocity as the incident velocity at the soil base [7]. This method is very simple but it is not precise.

It is known [8], that there are two powerful tools for the extraction of the subsurface geological information from the surface records: inversion and deconvolution. In the inverse method an initial guess of the model is assumed and its theoretical response is computed. The computation is carried out until the difference between the theoretical and observed responses reach an achievable minimum. Various linearized inversion schemes such as the eigenvector analysis [8], Backus–Gilbert method [9], layer-peeling methods [10] and the so-called non-causal solutions [10] are possible.

In the deconvolution approach, the geophysical systems are treated as convolution models where the input and the output are connected with the convolution formula. Therefore, the obtained signals are a result of the convolution of many signal components. Various deconvolution approaches such as Wiener filtering and smoothing [11,12], predictive deconvolution [13], minimum entropy deconvolution [14–16], homomorphic deconvolution [17], adaptive deconvolution [18], and L1-norm deconvolution [19], the convolution using Kaiman predictor model [20], zero memory non-linear deconvolution [21], wavelet approach [22] have been developed. A deconvolution approach is given in a special monograph [23]. It is based on a time-domain state variable representation for seismogram model and minimum variance and maximum-likelihood estimation theory.

The acceleration time history at any depth, that may be used as base excitation for a buried structure may be computed through a deconvolution analysis using a 1-D wave propagation code such as the equivalent linear program SHAKE [24]. SHAKE [24] is a widely used 1-D wave propagation code for site response analysis. SHAKE computes the vertical propagation of shear waves through horizontal elastic layers. In [25] the application of SHAKE for adapting design earthquake motions for FLAC input [25] is studied. It should be noted that the SHAKE code deals only with harmonic excitations. The SHAKE solution is formulated in terms of an upward and a downward propagating wave within each layer. The code does not provide solutions of the general nonstationary initial/boundary direct or inverse problem of wave propagation.

Another approximate deconvolution method is the so-called blind deconvolution methodology [26,27] for identification of the local site characteristics that is based on two seismograms recorded on the free surface of a sediment site. The method considers that the surface recordings are the result of the convolution of the "input motion at depth" with transfer functions (channels). The transfer functions represent the characteristics of the transmission path of the waves from the input location to each recording station.

The so-called non-reference site techniques [28] involve a generalized inversion scheme that estimates source, path and site effects, but may require prior parameterization of the source or path characteristics. As for the single-station techniques, based on the horizontal-to-vertical spectral ratio of earthquake recordings ("receiver function" technique [29]) or micro tremor recordings [30], it is generally accepted that they do provide a reliable estimate of the fundamental frequency of soft soils, but their ability to provide information on the amplification level is still questionable [31].

From the above detailed literature review it may be concluded that presently there exist various approximate methods for reconstruction of the signal time history at the bedrock base. These methods require various additional procedures such as the transfer function calculation [24,26], Riemann problem solving [32] etc. As it was shown in [8,33] the deconvolution problem is equivalent to the linear inverse theory problem [8]. The deconvolution operators are designed in such a way that there is a minimum difference between the predicted and the actual observed value. Therefore, in both cases, a minimization problem should be solved.

It is the objective of the present paper, to develop an exact, easy and effective analytical solution of the general inverse problem for reconstruction of the signal time history at the bedrock base of a layered geological medium that is based on a given known signal at the free surface. The new developed method is based on exact analytical solutions of the initial-boundary value problems of the linear wave equation in the case of a layered medium. The developed method does not require the additional procedures that are used in present available techniques as that are described in the above literature review.

The developed new method is described in the following in detail. First, the solution of a single layer inverse problem is given. This solution is a building stone of the solution of the general N-layers inverse problem and therefore it is of major importance. After that, two elastic layers are analyzed, in which an interface between layers is considered and the corresponding inverse problem is solved, using the solution of the single layer inverse problem that is derived earlier. The solution of the general N-layers inverse problem is then derived on the basis of the single layer and the two layers solutions.

2. Definition of the inverse problem

Consider a geological medium containing N soil layers with N+1 interfaces (Fig. 2a). The interfaces are marked from 1, 2 (denoting the interface between layer 1 and layer 2) to N-1, N. The top boundary of the first soil layer is the free top surface, and the bottom boundary of the last soil layer (N) is the interface between the soil medium and the semi-infinite rock marked as the "Bedrock base". Consider a given time history signal (acceleration/velocity/displacement) that was measured at the free top surface of the layered medium (Fig. 2a). The inverse problem requires reconstructing (restoring) the time history signal (acceleration/velocity/displacement) at the "rock-soil" interface (bedrock base) from the given recorded signal at the free surface.

A special case of the general layered medium that is described above is that of a single soil layer on top of the bedrock base as shown in Fig. 2b. In the following, all the indexes may be omitted in this case. It will be shown that the solution of the general inverse problem (Fig. 2a) is obtained using the solution corresponding to this special case (Fig. 2b).