Soil Dynamics and Earthquake Engineering 101 (2017) 162–175

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

SH waves in a moon-shaped valley

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ARTICLE INFO

Keywords:
SH waves in a moon-shaped valley
Focusing by non-parallel interfaces
SH waves in cylindrical coordinates
Discrete Cosine Transform (DCT)

ABSTRACT

The analytical solution of a two-dimensional moon-shaped alluvial valley embedded in an elastic half-space is analyzed for incident plane SH waves, using the wave function expansion and the Discrete Cosine Transform (DCT). A series of solutions with different depth-to-radius ratios have been computed, analyzed, and discussed. It is shown that amplification of incident motions along the thinning valley segment can be significant. The phenomena of combined action of the waves resulting from (a) turning (reversing the direction of propagation), (b) focusing, and (c) diffraction from the half space into the valley have been examined with an emphasis on the significance for surface-motion amplification and the power to damage man-made structures.

1. Introduction

Amplification of strong earthquake ground motion has been studied for simplified site characterizations (in terms of categorical variables: basement rocks versus sedimentary deposits, for example; [27]); site characterization in terms of horizontal layers with various degrees that include the number and depth of the near-surface layers [11,25,26]; regional variations that include the entire sedimentary basins [22,23,32,34,35]; the relationship of site conditions to the observed damage [31,33]; the relationship of site conditions to the measured microtremors [30,36]; and in terms of numerous analytical models involving two and three-dimensional inclusions [20].

Amplification of seismic waves along the sloping alluvial deposits belongs to a more advanced form of site modeling, because it includes complex superposition of amplification within the sloping layer and amplification of refracted and diffracted waves from below the layer, which are amplified by propagation—from harder into softer materials. The complexity of this problem in a realistic setting is further increased by irregular topography, irregular shape of the bottom of the layer [12,13] and by the three-dimensional (3D) geology and geometric complexities. In this paper we examine waves in a simple two-dimensional (2D) version of such a problem, for a sedimentary valley, which is bounded by two circular surfaces. By varying the two radii, our model of the valley can be used to study waves in the sedimentary inclusion with shapes that can range between semi-circular and slender moon-shapes.

Elastic-wave propagation in wedge-shaped layers has been investigated by many authors, such as in the case of a single wedge, and with either stress-free or rigid boundaries [7]. The Kantorovich-Lebedev transformation solution method was reviewed by Knopoff [10]. A wedge bonded to an elastic half-space was studied by [8,9], Hong and Helmberger [5], Wojcik [37], Pao and Ziegler [17], and Sanchez-Sesma and Velazquez [19]. The subject is of considerable interest for earthquake engineering, because the rays of the waves inside the wedge, which propagate towards its apex, are progressively turned to a point where they start to propagate backwards. The focusing of wave energy at the turning point can lead to a large amplification of surface motions, and, as such, becomes important in analyses that aim to interpret the causes of damage to man-made structures.

We introduce the problem of propagation-direction reversal and the associated focusing and amplification of incident wave energy by reviewing two examples, which we believe were the governing mechanisms of the observed surface displacement motions.

2. Two examples

Many settlements are built in valleys surrounded by mountains, where the sediment thickness gradually increases from higher ground toward the valley centers. Typically, those sediments are formed by water and wind erosion and the associated transport of fine particles downhill toward the valley's flat central areas. During strong earthquake shaking, higher-than-average destruction to man-made structures often occurs along the edges of these sedimentary valleys, when wave energy within the sediments is amplified as it progresses toward decreasing layer thickness [18]. In this paper we illustrate such amplification for the Sherman Oaks area in the California San Fernando Valley. We also cite the results of a full-scale shaking experiment during which monochromatic SH waves are amplified by focusing along the

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http://dx.doi.org/10.1016/j.soildyn.2017.06.019
Received 16 May 2017; Accepted 25 June 2017
0267-7261/

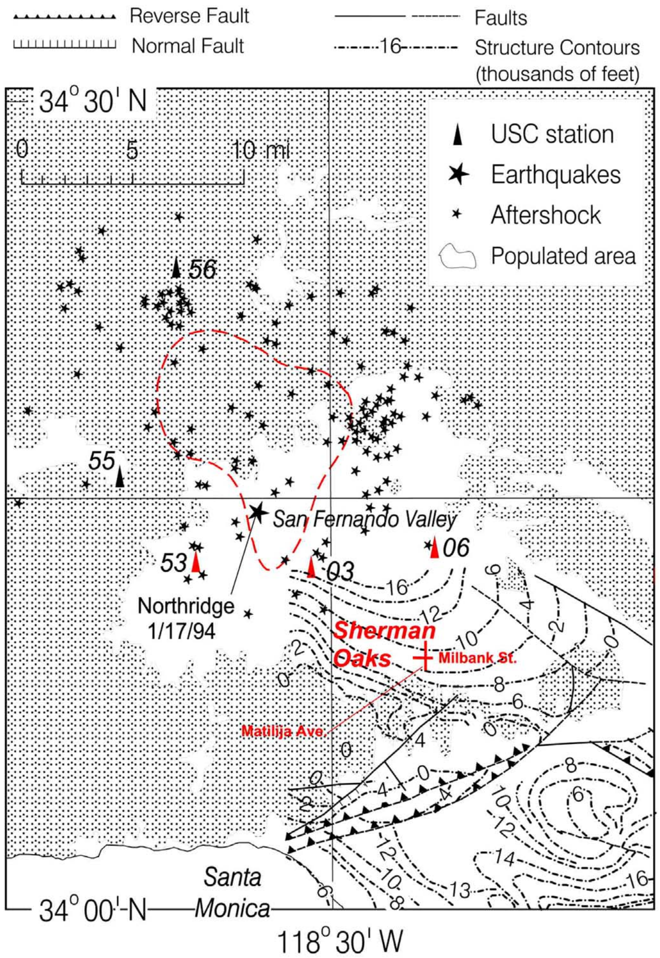

Fig. 1. The San Fernando Valley, northwest of Los Angeles, with a horizontal projection of the fault (dashed line) that slipped during the 1994 Northridge earthquake. Asterisks show the aftershocks, which were recorded at accelerograph stations USC#3, USC#6, and USC#53. The depth to the crystalline basement rocks (from [41]), in thousands of feet, is shown in the southeastern part of the Valley.

shallowing section of a sedimentary layer in eastern Pasadena, California.

2.1. Sherman oaks

The California earthquakes in San Fernando (1971) and Northridge (1994) caused extensive damage throughout the San Fernando Valley, a northwestern segment of the Los Angeles metropolitan area. Fig. 1 shows a horizontal projection of the fault (dashed line) that slipped during the main event on January 17, 1994. The aftershocks, which were recorded by strong-motion accelerographs, are shown by asterisks. Strong-motion accelerograph stations of the Los Angeles strong-motion array [2], which recorded the main event and the aftershocks, are shown by triangles.

The areas in which buildings were damaged by the earthquakes in San Fernando and Northridge are shown in Fig. 2 by gray zones. The location of breaks in the water pipes is shown by black dots (these indicate a large strain in the surface soils). This figure shows that the areas in which buildings were severely damaged (the gray zones) do not overlap with the areas of “high” strain in the soil (areas with high concentration of pipe breaks), where motions were moderate to large. However, in the areas of very severe ground motion, for example, in Sherman Oaks (south of the 101 freeway), buildings were damaged and pipes were broken in the same area, implying a very large nonlinear soil response resulting from excessive input motions and large nonlinearity in the site response [28,29].

In the Sherman Oaks area, the damage was severe, during both the San Fernando 1971 earthquake and the 1994 Northridge earthquake. We interpret this to imply that the wave energy from the deep sediments in the central and northern San Fernando Valley propagated southwards, into progressively shallower surface layers where it was focused and amplified. This amplification was further increased by the waves arriving from below and then amplified by propagation into softer sediments. Together, superimposed, these two amplified motions resulted in excessive peak ground velocity that may have reached 150 cm/s.

The San Fernando Valley is an asymmetric basin that deepens northward from Sherman Oaks (Fig. 1), with the crystalline basin composed of metamorphic and plutonic rocks of the Precambrian and pre-Cretaceous age (Yerkes, 1995; [40]). These rocks are exposed in the San Gabriel, Verdugo, and Santa Monica Mountains. Near the surface, the Matilija and Milbank seismic reflection profiles (Figs. 1 and 2) show Plio-Pleistocene deposits deepening towards the north, with the bottom sloping between 15 and 22 degrees and reaching a depth of about 300 m at the end of the Matilija seismic line [21]. For the purposes of this paper, we will view this complex picture as one in which the overall geology underlying the Sherman Oaks area may be represented approximately by a model consisting of a sedimentary layer that is progressively deepening northwards.

2.2. Forced vibrations of the Millikan Library

Wong et al. [38] describe a forced vibration experiment during which the Millikan Library, a nine-story reinforced concrete (RC) building in Pasadena, California, was shaken in an north-south (NS) direction. During this experiment, shaker baskets were fully loaded with lead weights [6] and, at 1.8 Hz, generated periodic force acting on the ground surface in a NS direction with a maximum amplitude of about 2750 lb. The resulting horizontal force and moment on the soil were approximately 2.8×10^{5} lb and 2.8×10^{7} lb-ft [39]. This type of wave source generated motions whose NS components in the layered half-space consisted of SH and Love waves west of Millikan Library. This occurred because the radiation pattern of SH and Love waves has a maximum in eastward and westward directions for a point source consisting of a harmonic NS force and a harmonic rocking moment acting in the same direction [14].

The central and western portions of Pasadena are underlain by alluvium whose depth ranges from zero to about 1200 ft [4]. The depth of the alluvium underneath the Millikan Library is approximately 900 ft and becomes shallower toward the west and southwest. About 4.5 km west of the Library and north of the Raymond fault, the crystalline basement rocks and deep tertiary become exposed on the ground surface. The variations of measured ground displacements (triangles in Fig. 3) agree with the computed variations for model A. The characteristic pattern of the observed variations of displacement amplitudes versus distance is virtually identical with the pattern predicted by the theoretical model for waves propagating towards a decreasing depth of alluvium.

One of the most important elements in numerous engineering studies that have dealt with the effects of alluvium layers on the variations of strong earthquake ground motions is associated with the assumption concerning the direction and the manner in which the waves enter into the model. Whether seismic energy arrives from below, from the side, from outside, or from within, the body of alluvium layer can lead to remarkably different surface displacement amplitudes even for the same model. Patterns of constructive and destructive interference, as well as the fraction of energy scattered by the material discontinuities in the model, can change dramatically for these different inputs. An initial buildup followed by a rapid decay of observed displacement amplitudes described in Wong et al. [38] results from the focusing as wave energy propagates toward shallower alluvium. The sloping