Soil Dynamics and Earthquake Engineering 90 (2016) 250–264

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Anti-plane response induced by an irregular alluvial valley using a hybrid method with modified transfinite interpolation

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ARTICLE INFO

Article history:
Received 24 July 2015
Received in revised form
1 April 2016
Accepted 28 August 2016

Keywords:
SH wave
Irregular alluvial valley
Filling ratio
Hybrid method
Modified transfinite interpolation

ABSTRACT

This paper proposes a novel strategy for the investigation of displacement amplitude ($|u_y|$) near and along an irregular alluvial valley subjected to shear horizontal (*SH*) waves. The irregular alluvial valley in this study comprises a partially filled alluvial valley and a circular-arc-layered alluvial valley. Modified transfinite interpolation (MTFI) was used to obtain the coordinates of nodes and determine the sequence of node numbering in the inner finite region, including the irregular alluvial valley. The proposed hybrid method, comprising finite element method and a Lamb series, was applied in conjunction with MTFI to study the effects of irregular alluvial valley geometry, the incident angle of *SH* waves (θ), a dimensionless frequency (η), and a filling ratio (FR) on $|u_y|$. Semi-circular canyons and semi-circular alluvial valleys were also examined. We describe in detail the amplification of $|u_y|$ at the surface of the alluvial valley and discuss the reasons for the formation of the maximum amplitude ($|u_y|_{max}$) as well as its position. Interestingly, FR was shown to play an important role in determining the value of $|u_y|$, and variations in θ and η dominate the patterns observed in $|u_y|$. Our numerical simulation results help to elucidate site effects in irregular alluvial valleys as well as a wide range of subjects related to geological structures.

1. Introduction

At the site of surface irregularities, such as alluvial valleys, ground motion resulting from earthquakes can increase the amplitude of responses in the frequency domain. This phenomenon can be attributed to the scattering and diffraction of propagating waves, particularly standing waves in fixed regions, such as alluvial valleys. Understanding the mechanisms underlying the scattering of waves by surface irregularities is crucial to engineers in the field of structural design. In the case of a 2-D alluvial valley embedded in an elastic half-space, the scattering of waves created in the half-space and standing waves that develop in the alluvial valley must both be taken into consideration. The wave function expansion method has been proposed to enable analytical analysis of scattering in shear horizontal (*SH*) waves induced by various types of alluvial valley, such as semi-cylindrical alluvial valleys [1], semi-elliptical alluvial valleys [2], shallow circular alluvial valleys [3,4], circular-arc layered alluvial valleys [5,6], partially filled semi-circular alluvial valleys [7,8], and partially filled semi-elliptic alluvial valleys [9], and semi-circular valleys partially filled with an inclined alluvial layer [10].

In the case of a semi-cylindrical alluvial valley, Hankel functions can be used to represent outgoing scattering waves and Bessel functions can be used to represent standing waves. This makes it possible to use wave function expansion method to obtain an analytical solution to problems involving the scattering of *SH* waves. However, this method is applicable only to alluvial valleys with a simple geometric shape [1,2]. As a result, the wave function expansion method must be combined with Graf's addition theorem (or modifying the horizontal free surface using a circular arc) to solve the scattering of *SH* waves by partially filled semi-circular alluvial valleys [7,8,10] (or circular-arc layered alluvial valleys [5,6]) to overcome the difficulties involved in setting the boundary conditions. It should be noted that these analytical methods are useful in the validation of numerical methods.

Numerical methods have been developed to solve problems related to complex anti-plane wave scattering. For example, boundary element method (BEM) is a powerful technique for

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http://dx.doi.org/10.1016/j.soildyn.2016.08.036
0267-7261/

dealing with bounded as well as unbounded problems. Thus, it is commonly used for numerical studies on *SH* wave scattering by semi-circular alluvial valleys [11], semi-elliptical alluvial valleys [12], semi-circular, triangular, and trapezoidal alluvial valleys [13], and multiple alluvial valleys [14]. Finite element method (FEM) has proven highly effective in dealing with irregular inhomogeneous regions; however, it is poorly suited to unbounded problems. Previously, researchers developed a hybrid method combining BEM and FEM to investigate horizontally stratified alluvial valleys [15] and sediment-filled alluvial valleys [16].

Shyu developed a hybrid approach combining FEM and wave functions to solve the scattering of incident waves by irregular objects embedded in an elastic half-space [17]. Shyu et al. used the hybrid method in conjunction with a transfinite interpolation (TFI) [18] to solve anti-plane wave scattering by surface irregularities [19] and an oblique-truncated semicircular canyon comprising an outer infinite region and an inner finite region with an irregular concave surface [20]. TFI makes it possible to eliminate the difficulties in meshing irregularities in a discretized region. The hybrid method requires the ability to number the nodes on the boundary in a particular sequence to ensure compatibility with FEM node numbering.

No previous study has reported that the *SH* wave scattering by a partially filled alluvial valley (PFAV) or a circular-arc-layered alluvial valley (CALAV) can be analytically or numerically solved using the same techniques. This study presents a novel strategy by which to investigate the scattering of *SH* waves induced by a PFAV or CALAV embedded in an elastic half-space. This is an extension our works [20], involving the development of a modified TFI (MTFI) for the mapping of two arbitrary finite domains comprising an alluvial valley and a canyon (physical region) into two unit square domains (logical region). This makes it possible to determine the coordinates of the nodes and the sequence of node numbering in the physical region in a systematic manner. We then developed a hybrid method of FEM and wave functions to obtain numerical solutions to the problems of *SH* wave scattering induced by a PFAV or CALAV. We also investigated how displacement is affected by the type of alluvial valley, the incident *SH* wave angle (θ), the dimensionless frequency (η), and the filling ratio (FR). The proposed method was validated by making two comparisons: (1) In the first comparison, we numerically determined *SH* wave scattering in a simple case, in which the material properties of the CALAV were identical to those of the outer infinite region, and then compared the results with those obtained for a circular-arc canyon, in which the nodal coordinates in irregular regions were calculated using a TFI; and (2) We compared the numerical predictions of a horizontal PFAV to the results reported by Tsaur and Chang [7].

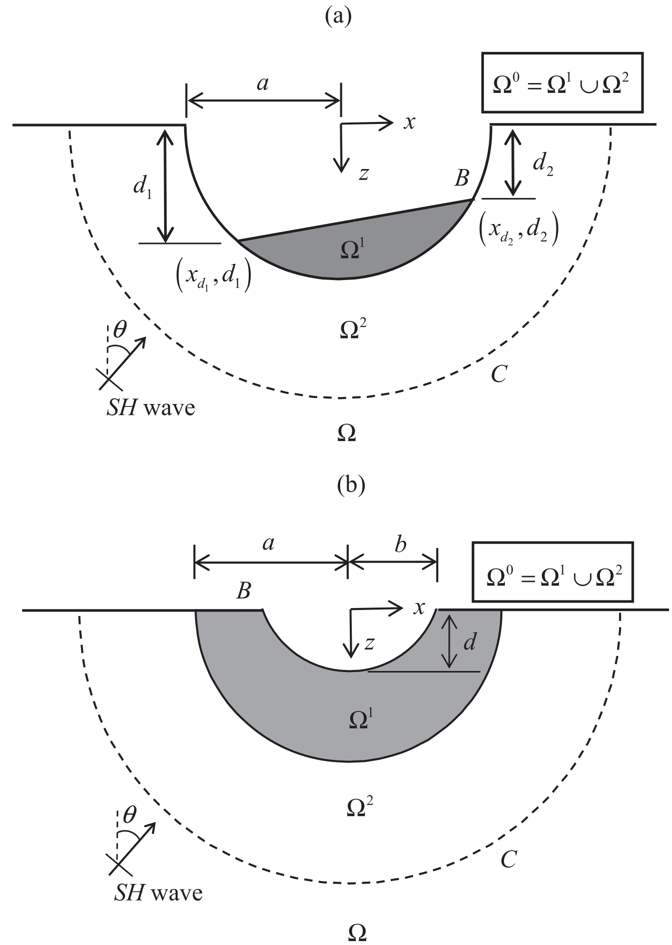

Fig. 1. Schematic illustration of inner finite region: (a) PFAV and (b) CALAV.

Table 1
Test conditions of PFAVs.

	d_1/a	d_2/a	x_{d_1}/a	x_{d_2}/a	Valley area/a^2	Filling ratio (%)
Case P1	0.75	0.75	−0.66	0.66	0.23	14
Case P2	0.75	0.50	−0.66	0.87	0.38	24
Case P3	0.50	0.50	−0.87	0.87	0.63	40
Case P4	0.50	0.25	−0.87	0.97	0.81	51
Case P5	0.25	0.25	−0.97	0.97	1.09	69
Case P6	0.25	0.15	−0.97	0.97	1.16	74
Case P7	0.15	0.15	−0.97	0.97	1.27	81
Case P8	0.15	0.00	−0.97	1.00	1.36	87
Case P9	0.10	0.00	−0.99	1.00	1.43	91

2. Numerical model

2.1. 2-D irregular alluvial valleys

This study investigated alluvial valleys, comprising an irregular soft sedimentary layer settled atop a semi-circular canyon. The entire structure is embedded within an elastic half-space on the *x*-*z* plane excited by an unit-amplitude plane *SH* wave (perpendicular to the *x*-*z* plane) with θ and a circular frequency (ω). This elastic half-space is divided into two regions: (1) an inner finite region Ω^0, which includes a soft sedimentary layer (Ω^1) and a semi-circular annulus (Ω^2); (2) outer infinite region Ω. The boundary (C) between Ω^0 and Ω is a semi-circle.

Two types of alluvial valley were considered in this study: (1) PFAV and (2) CALAV. Symbols a, d_1, and d_2 in Fig. 1(a) represent the semi-width of the semi-circular canyon, the depth on the left hand side, and the depth on right hand side of the PFAV, respectively. Symbols b and d in Fig. 1(b) represent the semi-width and depth of the CALAV, respectively. Table 1 lists the dimensionless parameters for nine types of PFAV, and Table 2 lists the dimensionless parameters for nine types of CALAV. The FR of alluvial valleys is defined by the ratio of the valley area to $0.5\pi a^2$ (area of a semi-circular canyon). The FR can be divided into three groups: (1) low ($\text{FR} \le 33\%$); (2) medium ($33\% < \text{FR} < 66\%$); and (3) high ($\text{FR} \ge 66\%$).

In dealing with the problem of *SH* wave scattering induced by a PFAV or CALAV, researchers generally consider the contributions from free and scattered fields to physical quantity. Accordingly, traction (t_y) and displacement (u_y) in the *y* direction can be described as follows: