Tunnelling and Underground Space Technology 79 (2018) 250–262

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Earthquake input for finite element analysis of soil-structure interaction on rigid bedrock

Yang Li, Mi Zhao*, Cheng-shun Xu, Xiu-li Du, Zheng Li

Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing 100124, China

ARTICLE INFO

Keywords:
Seismic soil-structure interaction
Finite element method
Rigid bedrock
Viscous-spring boundary
Free-field loading

ABSTRACT

When using the finite element method to analyze seismic soil-structure interaction (SSI) problem on rigid bedrock, several methods have been developed to input earthquake on the lateral boundary of finite element model. These boundary conditions include the free boundary, the viscous-spring (VS) boundary, the tied degrees of freedom (TDOF) boundary and the free-field loading combined viscous-spring (FFL-VS) boundary. Their accuracy and location should be investigated. In this paper, the formulations and ABAQUS implementations of these boundaries are given. The accuracy properties of these boundaries are then compared by numerical examples including the free-field and SSI problems. The comparison studies indicate that the free and VS boundaries failed to reproduce the free-field and SSI responses when a relatively small size SSI model is employed. The TDOF and FFL-VS boundaries can simulate the exact free-field response and have good performances in seismic SSI analyses. The FFL-VS boundary is more accurate than the TDOF boundary. The appropriate locations for the TDOF and FFL-VS boundaries depend on the SSI model. A simplified approach is developed for appropriate boundary location. This approach is applicable to the FFL-VS boundary but not to the TDOF boundary due to the former more accurate than the latter.

1. Introduction

When the finite element method (FEM) is utilized to solve the seismic soil-structure interaction (SSI) problem, an artificial boundary should be introduced to transform the domain from infinite to finite. Earthquake input is required at the artificial boundary of the finite element model. It consists of the site response analysis to obtain the free field and the artificial boundary condition to absorb the scattered waves. The framework of the direct FEM for the seismic SSI analysis has been proposed in Wolf (1985) and Wolf (1988).

Artificial boundary conditions have been studied by many researchers. The early artificial boundary conditions include the viscous boundary (Lysmer, 1969), the viscous-spring boundary (Deeks and Randolph, 1994; Du et al., 2006; Liu et al., 2006; Du and Zhao, 2010), the extrapolation boundary (Liao and Wong, 1984), the infinite element method (Zhao, 2009), the boundary element method (Hall and Oliveto, 2009; Galvín and Romero, 2014) and the boundary element and infinite element coupling (Zhang et al., 1999). The further developments include the perfectly matched layer (Berenger, 1994), the Dirichlet-to-Neumann method (Givoli, 1999; Du and Zhao, 2010; Zhao, 2011), the high-order local non-reflecting boundary condition (Givoli, 2004), and the scaled boundary finite element method (Song and Wolf, 1997; Birk and Behnke, 2012; Chen et al., 2015). Among these artificial boundary conditions, the viscous-spring boundary can simulate the radiation damping and elasticity recovery of the infinite or semi-infinite medium, with the good stability, acceptable accuracy and easy implementation into commercial FEM codes such as ABAQUS and ANSYS.

The bedrock under soil layer can be usually assumed elastic or rigid in seismic SSI analyses. The SSI model with elastic bedrock is a 'fully-open' energy system since the scattered wave can transmit downwards and laterally. Similar to the lateral boundaries, the bottom boundary of the model truncated elastic bedrock belongs to the artificial boundaries. The seismic input has been implemented by loading the equivalent nodal force on the artificial boundary and combining with the artificial boundary conditions such as the viscous or viscous-spring boundary (Liu and Lu, 1998; Wang et al., 2014; Neilsen, 2006; Li and Song, 2015).

On the other hand, the SSI model with rigid bedrock is 'semi-open and semi-closed' energy system since the scattered wave is not allowed to escape from the bottom boundary but only escape from the lateral boundaries, where the bottom boundary does not belong to the artificial boundary. For the rigid bedrock case, the SSI problem can be formulated in terms of either the absolute motion or the motion relative to the rigid bedrock. In the absolute motion formulation, the rigid bedrock

* Corresponding author.
E-mail address: zhaomi@bjut.edu.cn (M. Zhao).

https://doi.org/10.1016/j.tust.2018.05.008
Received 26 June 2017; Received in revised form 10 March 2018; Accepted 10 May 2018
0886-7798/

motion is applied as the motion boundary condition on the bottom boundary of SSI model. In the relative motion formulation, the bottom boundary of SSI model is fixed and the inertial force with respect to the bedrock motion is applied to the SSI model. Such treatment is similar to that for a vibration problem in structural dynamics. Therefore, the SSI model with rigid bedrock is widely used in engineering practice. However, the seismic input on the lateral boundary is sometimes simplified in several forms, such as the free boundary (Parra-Montesinos et al., 2006; Wu and Liu, 2008), the roller boundary (Saxena et al., 2011; Torabi and Rayhani, 2014; Rui et al., 2015), the tied degrees of freedom boundary (Tsinidis et al., 2014), and only the artificial boundary condition without consideration of seismic input (Nakamura, 2009; Hatzigeorgiou and Beskos, 2010; Amorosi and Boldini, 2009; Asheghabadi and Matinmanesh, 2011; Li et al., 2014). Such treatments on the lateral boundary may result in the inaccurate solution especially when the lateral boundary is close to structure.

In this paper, for the rigid bedrock case, the accuracies of seismic input methods mentioned above are compared and the appropriate location of artificial boundary is discussed. The outline of this paper is as follows. In Section 2, the theoretical formulations of the seismic input methods are given and they are implemented into ABAQUS. In Section 3, the seismic input methods are compared by numerical examples including the free-field and SSI models. In Section 4, the location of the lateral artificial boundary is discussed. Conclusions are summarized in Section 5.

2. Formulations and implementations of seismic input methods

The formulations of the seismic input methods and their implementations into ABAQUS are given in this section.

2.1. Formulations of seismic input methods

The seismic SSI model on rigid bedrock is schematically shown in Fig. 1. Lateral artificial boundaries are introduced to divide the soil-structure model into the finite and infinite domains. The finite domain contains the artificial boundaries (subscript B), the rigid bottom boundary (subscript G), and the structure and its adjacent soil (subscript I). The finite element equation of the finite domain can be expressed with respect to the absolute motion as

$$\begin{bmatrix} \mathbf{M}_{BB} & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{M}_{II} & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & \mathbf{M}_{GG}\end{bmatrix}\begin{Bmatrix}\ddot{\mathbf{u}}_B\\ \ddot{\mathbf{u}}_I\\ \ddot{\mathbf{u}}_G\end{Bmatrix} + \begin{bmatrix} \mathbf{C}_{BB} & \mathbf{C}_{BI} & \mathbf{C}_{BG}\\ \mathbf{C}_{IB} & \mathbf{C}_{II} & \mathbf{C}_{IG}\\ \mathbf{C}_{GB} & \mathbf{C}_{GI} & \mathbf{C}_{GG}\end{bmatrix}\begin{Bmatrix}\dot{\mathbf{u}}_B\\ \dot{\mathbf{u}}_I\\ \dot{\mathbf{u}}_G\end{Bmatrix} + \begin{bmatrix} \mathbf{K}_{BB} & \mathbf{K}_{BI} & \mathbf{K}_{BG}\\ \mathbf{K}_{IB} & \mathbf{K}_{II} & \mathbf{K}_{IG}\\ \mathbf{K}_{GB} & \mathbf{K}_{GI} & \mathbf{K}_{GG}\end{bmatrix}\begin{Bmatrix}\mathbf{u}_B\\ \mathbf{u}_I\\ \mathbf{u}_G\end{Bmatrix} = \begin{Bmatrix}\mathbf{f}_B\\ \mathbf{0}\\ \mathbf{0}\end{Bmatrix} \quad (1)$$

where $\mathbf{u}$, $\dot{\mathbf{u}}$ and $\ddot{\mathbf{u}}$ are the absolute displacement, velocity and acceleration vectors, respectively; $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the mass, damping and stiffness matrices, respectively; $\mathbf{f}_B$ is the reaction forces of the infinite domain to the finite domain; and $\mathbf{u}_G = \mathbf{I}u_g$ with the unit vector $\mathbf{I}$ and the rigid bedrock motion u_g.

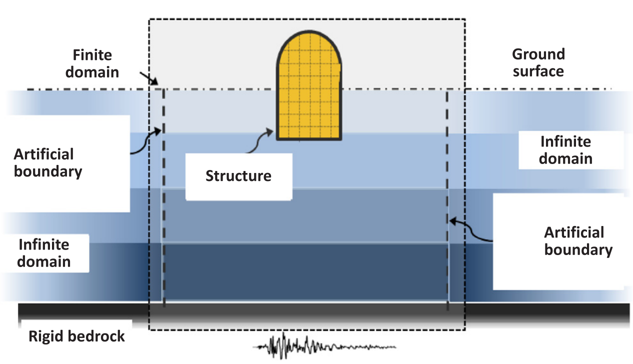

Fig. 1. Seismic SSI model on rigid bedrock.

The response of the infinite domain can be decomposed into the scattered and free fields. It can be written as $\mathbf{f}_B = \mathbf{f}_B^S + \mathbf{f}_B^F$ and $\mathbf{u} = \mathbf{u}^S + \mathbf{u}^F$, where the superscripts S and F denote the scattered and free fields, respectively.

An artificial boundary condition is employed at the lateral artificial boundary of the finite domain to simulate the scattered field. When the viscous-spring boundary is applied, it can be expressed as $\mathbf{f}_B^S = -\mathbf{K}_B^\infty\mathbf{u}_B^S - \mathbf{C}_B^\infty\dot{\mathbf{u}}_B^S$, where $\mathbf{K}_B^\infty$ and $\mathbf{C}_B^\infty$ represent the stiffness and damping matrices, respectively. Considering the viscous-spring boundary and the free-field input, Eq. (1) can be written equivalently as

$$\begin{bmatrix} \mathbf{M}_{BB} & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{M}_{II} & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & \mathbf{M}_{GG}\end{bmatrix}\begin{Bmatrix}\ddot{\mathbf{u}}_B\\ \ddot{\mathbf{u}}_I\\ \ddot{\mathbf{u}}_G\end{Bmatrix} + \begin{bmatrix} \mathbf{C}_{BB}+\mathbf{C}_B^\infty & \mathbf{C}_{BI} & \mathbf{C}_{BG}\\ \mathbf{C}_{IB} & \mathbf{C}_{II} & \mathbf{C}_{IG}\\ \mathbf{C}_{GB} & \mathbf{C}_{GI} & \mathbf{C}_{GG}\end{bmatrix}\begin{Bmatrix}\dot{\mathbf{u}}_B\\ \dot{\mathbf{u}}_I\\ \dot{\mathbf{u}}_G\end{Bmatrix} + \begin{bmatrix} \mathbf{K}_{BB}+\mathbf{K}_B^\infty & \mathbf{K}_{BI} & \mathbf{K}_{BG}\\ \mathbf{K}_{IB} & \mathbf{K}_{II} & \mathbf{K}_{IG}\\ \mathbf{K}_{GB} & \mathbf{K}_{GB} & \mathbf{K}_{GG}\end{bmatrix}\begin{Bmatrix}\mathbf{u}_B\\ \mathbf{u}_I\\ \mathbf{u}_G\end{Bmatrix} = \begin{Bmatrix}\mathbf{f}_B^\infty\\ \mathbf{0}\\ \mathbf{0}\end{Bmatrix} \quad (2)$$

where $\mathbf{f}_B^\infty = \mathbf{K}_B^\infty\mathbf{u}_B^F + \mathbf{C}_B^\infty\dot{\mathbf{u}}_B^F + \mathbf{f}_B^F$.

The absolute displacement, velocity and acceleration can be decomposed into the rigid bedrock motion and its relative motion, i.e. $\mathbf{u} = \bar{\mathbf{u}} + \mathbf{I}u_g$, $\dot{\mathbf{u}} = \dot{\bar{\mathbf{u}}} + \mathbf{I}\dot{u}_g$ and $\ddot{\mathbf{u}} = \ddot{\bar{\mathbf{u}}} + \mathbf{I}\ddot{u}_g$. Substituting these into Eq. (2) and neglecting the product of the rigid bedrock motion with the damping matrix yield the formulation with respect to the relative motion as

$$\begin{bmatrix} \mathbf{M}_{BB} & \mathbf{a} & \mathbf{b}\\ \mathbf{0} & \mathbf{M}_{II} & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & \mathbf{b}\end{bmatrix}\begin{Bmatrix}\ddot{\bar{\mathbf{u}}}_B\\ \ddot{\bar{\mathbf{u}}}_I\\ \mathbf{0}\end{Bmatrix} + \begin{bmatrix} \mathbf{C}_{BB}+\mathbf{C}_B^\infty & \mathbf{C}_{BI} & \mathbf{C}_{BG}\\ \mathbf{C}_{IB} & \mathbf{C}_{II} & \mathbf{C}_{IG}\\ \mathbf{C}_{GB} & \mathbf{C}_{GI} & \mathbf{C}_{GG}\end{bmatrix}\begin{Bmatrix}\dot{\bar{\mathbf{u}}}_B\\ \dot{\bar{\mathbf{u}}}_I\\ \mathbf{0}\end{Bmatrix} + \begin{bmatrix} \mathbf{K}_{BB}+\mathbf{K}_B^\infty & \mathbf{K}_{BI} & \mathbf{K}_{BG}\\ \mathbf{K}_{IB} & \mathbf{K}_{II} & \mathbf{K}_{IG}\\ \mathbf{K}_{GB} & \mathbf{K}_{GI} & \mathbf{K}_{GG}\end{bmatrix}\begin{Bmatrix}\bar{\mathbf{u}}_B\\ \bar{\mathbf{u}}_I\\ \mathbf{0}\end{Bmatrix} = -\begin{bmatrix} \mathbf{M}_{BB} & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{M}_{II} & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & \mathbf{M}_{GG}\end{bmatrix}\mathbf{I}\ddot{u}_g + \begin{Bmatrix}\mathbf{f}_B^\infty\\ \mathbf{0}\\ \mathbf{0}\end{Bmatrix} \quad (3)$$

where $\mathbf{f}_B^\infty = \mathbf{K}_B^\infty\bar{\mathbf{u}}_B^F + \mathbf{C}_B^\infty\dot{\bar{\mathbf{u}}}_B^F + \mathbf{f}_B^F$.

The following four seismic input methods, that are different boundary conditions on the lateral artificial boundary and have been used in SSI analyses, are considered in this paper.

(1) Free-field loading combined viscous-spring (FFL-VS) boundary

According to Eq. (3), the springs $\mathbf{K}_B^\infty$ and dampers $\mathbf{C}_B^\infty$ are applied to all of the lateral boundary nodes of the soil layer. The free-field loadings $\mathbf{f}_B^\infty$ are also applied as the equivalent nodal forces at lateral truncated boundary. FFL-VS boundary can both consider free-field loading and wave propagation effect on the lateral boundary.

(2) Free boundary

The springs $\mathbf{K}_B^\infty$, dampers $\mathbf{C}_B^\infty$ and free-field loadings $\mathbf{f}_B^\infty$ presented in Eq. (3) are all neglected. Free boundary considers neither free-field loading nor wave propagation effect.

(3) Viscous-spring (VS) boundary

The springs $\mathbf{K}_B^\infty$ and dampers $\mathbf{C}_B^\infty$ presented in Eq. (3) are applied, while the free-field loadings $\mathbf{f}_B^\infty$ presented in Eq. (3) is neglected. VS boundary considers the wave propagation effect but neglects the free-field loading.

(4) Tied degrees of freedom (TDOF) boundary (Zienkiewicz et al., 1988)