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Earthquake responses of near-fault building clusters in mountain city considering viscoelasticity of earth medium and process of fault rupture

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ABSTRACT

A new algorithm is proposed to implement viscoelastic wave propagation in earth medium with surface topography by introducing history variables into integral type GZB constitutive equations and by using the recursive formulae of these history variables. Combining the proposed algorithm with the flexural wave algorithm for frame structure and the algorithm for bidirectional wave propagation, a new type of integrated method is developed for earthquake response analyses of near-fault building clusters in mountain city due to rupture of causative fault. The earthquake responses of building clusters of frame structures situated at different sites of a mountain in Chongqing city, China, are studied during a hypothetical M_w 6.2 near-fault earthquake. The numerical results show that, for the multi-story buildings, the maximum peak value of beam-end bending moments appears in the building on the hill top and the earthquake risk positions are mainly at the bottom and/or the top of the buildings. For the high-rise buildings, the maximum peak value of beam-end bending moments appears in the building on the mountainside and the earthquake risk positions are mainly at the bottom and/or the middle of the buildings.

1. Introduction

The computational model of considering together the earthquake source mechanism, earth medium and buildings in a city is a rational model for studying the near-fault earthquake responses of buildings in the city. To the best of our knowledge, by now, a few researchers [1–5] adopted such type of integrated computational model to study the earthquake response of city. Taborda [1] used a double-couple seismic source, and Guidotti et al. and Isbiliroglu et al. [4,5] used the finite-fault seismic source to study the earthquake responses of building clusters. However, the building they used in the building clusters was idealized as an equivalent low-velocity block, which is not very suitable to be used to obtain the actual earthquake response of structure. Liu et al. [2] used the finite-fault seismic source to study the near-fault earthquake responses of building clusters. They adopted the elastic flat-surface model of earth medium without considering the attenuation of real earth medium and adopted the simple shear model (lollipop model) for the multi-story building. Liu and Zhong [3] studied the earthquake responses of near-fault building clusters of frame structures situated on the flat surface of earth medium due to rupture of thrust fault. They adopted the viscoelastic constitutive equations of the Generalized Zener Body (GZB) with memory variables [6] to implement attenuation of seismic waves. A wave-based method was proposed for simulating flexural wave propagation in frame structures and a type of investigated lump used for structure-soil connection was introduced to implement bidirectional wave propagation between the structure and the earth medium.

Many near-fault mountain cities suffered severe damage of building structures during earthquakes, for example, Santa Monica city (during the 1994 Northridge earthquake) [7], Kobe city (during the 1995 Hyogo-ken Nanbu earthquake) [8], and Beichuan city (during the 2008 Wenchuan earthquake) [9]. But up to now, the near-fault earthquake responses of building clusters in the mountain city by considering the topography surface have not been studied by using the integrated computational model.

The aim of this article is to study the earthquake responses of the building clusters of frame structures in near-fault mountain city during an earthquake. In Section 2, a new type of integrated method is developed for studying earthquake responses of near-fault building clusters in mountain city. The history variable type GZB constitutive equations is given. Instead of the memory variable type GZB constitutive equations used in our previous work [3], the history variable type GZB constitutive equations is used for implementing attenuation of seismic waves in earth medium. In Section 3, one numerical test has

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been performed to verify the validity and accuracy of the simulating algorithm proposed in Section 2 for viscoelastic wave propagation in earth medium. In Section 4, the integrated method presented in this article is applied to study the near-fault earthquake responses of building clusters located at different sites of the mountain in Yuzhong district of Chongqing city, China, during a M_w 6.2 hypothetical earthquake.

2. Integrated method for simulating near-fault earthquake responses of building clusters in mountain city considering viscoelasticity of earth medium

2.1. Simulating algorithm for viscoelastic wave propagation in earth medium

The dynamic equilibrium equations of the typical investigated lump i in earth medium with mass M_i are as follows [3,10]

$$M_i\ddot{u}_i = \sum_{n=1}^{n_{i3}}(\sigma_x)_n(a_i^*)_n - \sum_{n=1}^{n_{i3}}(\tau_{xz})_n(b_i^*)_n + \sum_{n=1}^{n_{i4}}(\sigma_x)_n(c_{ir}^*)_n - \sum_{n=1}^{n_{i4}}(\tau_{xz})_n(d_{ir}^*)_n \tag{1}$$

$$M_i\ddot{w}_i = \sum_{n=1}^{n_{i3}}(\tau_{xz})_n(a_i^*)_n - \sum_{n=1}^{n_{i3}}(\sigma_z)_n(b_i^*)_n + \sum_{n=1}^{n_{i4}}(\tau_{xz})_n(c_{ir}^*)_n - \sum_{n=1}^{n_{i4}}(\sigma_z)_n(d_{ir}^*)_n \tag{2}$$

where the meanings of the n_{i3}, n_{i4}, a_i^*, b_i^*, c_{ir}^* and d_{ir}^* are the same as those in the literature [3]. The summations on the right-hand side of Eqs. (1) and (2) are respectively the horizontal and vertical interior forces acting on the investigated lump i.

In order to calculate the interior forces acting on the investigated lumps in viscoelastic earth medium, the stresses should be calculated. In this study we introduce history variables into the integral type GZB constitutive equations and derive the recursive formulae of these history variables in order to obtain the calculating formulae of stresses.

The convolution integral type GZB constitutive equations can be given by [6]

$$\sigma_{ij}(t) = \frac{1}{3}\dot{\psi}_1(t)\delta_{ij}*\varepsilon_{kk} + \dot{\psi}_2(t)*e_{ij} \tag{3}$$

where the relaxation function $\psi_v(t)$ $(v = 1, 2)$ for GZB is [6]

$$\psi_v(t) = M_v^R(1 + \frac{1}{L}\sum_{l=1}^{L}\chi_{vl}\, e^{-\omega_l t})\ H(t), \quad v = 1, 2 \tag{4}$$

with the coefficients $\chi_{vl} = \tau_{\varepsilon l}^{(v)}/\tau_{\sigma l} - 1$ and relaxation frequency $\omega_l = 1/\tau_{\sigma l}$, where $\tau_{\sigma l}$ and $\tau_{\varepsilon l}^{(v)}$, denote respectively stress relaxation time and strain relaxation time corresponding to dilatational ($v=1$) and shear ($v=2$) of the l th attenuation mechanism, L is the number of relaxation mechanisms, M_v^R is the relaxed modulus (elastic modulus) and $M_1^R = \psi'_1(\infty) = 3K$, $M_2^R = \psi'_2(\infty) = 2\mu$. Where K and μ correspond to bulk modulus and shear modulus, respectively.

Introduce the history variables

$$b_l^t = \int_0^t e^{-\omega_l(t-\tau)}\frac{\partial\varepsilon_{kk}(\tau)}{\partial\tau}d\tau, \quad l = 1, \ldots, L \tag{5}$$

and

$$c_{ijl}^t = \int_0^t e^{-\omega_l(t-\tau)}\frac{\partial e_{ij}(\tau)}{\partial\tau}d\tau, \quad l = 1, \ldots, L \tag{6}$$

Substituting Eq. (4) into Eq. (3) and noticing Eqs. (5) and (6), the history variable type GZB constitutive equations is given as follows:

$$\sigma_{ij}(t) = \frac{1}{3}(M_1^R\varepsilon_{kk} + \frac{M_1^R}{L}\sum_{l=1}^{L}\chi_{1l}b_l^t)\,\delta_{ij} + M_2^R e_{ij} + \frac{M_2^R}{L}\sum_{l=1}^{L}\chi_{2l}c_{ijl}^t \tag{7}$$

Assuming $t = t_0 + \Delta t$ in Eqs. (5) and (6) and using the middle point rule in interval $[t_0,\ t_0 + \Delta t]$, and then we have the following recursive formulae of history variables

$$b_l^{t_0+\Delta t} = \exp(-\omega_l\Delta t)b_l^{t_0} + \exp(-\frac{1}{2}\omega_l\Delta t)(\varepsilon_{kk}^{t_0+\Delta t} - \varepsilon_{kk}^{t_0}) \tag{8}$$

and

$$c_{ijl}^{t_0+\Delta t} = \exp(-\omega_l\Delta t)c_{ijl}^{t_0} + \exp(-\frac{1}{2}\omega_l\Delta t)(e_{ij}^{t_0+\Delta t} - e_{ij}^{t_0}) \tag{9}$$

For the plane strain problem, by discretizing the Eq. (7) at time $t_0 + \Delta t$ and using Eqs. (8) and (9), we can obtain the calculating formulae of stresses as follows:

$$\sigma_x^{t_0+\Delta t} = \frac{1}{3}(M_1^R + 2M_2^R)(\frac{\partial u}{\partial x})^{t_0+\Delta t} + \frac{1}{3}(M_1^R - M_2^R)(\frac{\partial w}{\partial z})^{t_0+\Delta t} + \frac{1}{L}\sum_{l=1}^{L}q_{11l}^{t_0+\Delta t} \tag{10}$$

$$\sigma_z^{t_0+\Delta t} = \frac{1}{3}(M_1^R - M_2^R)(\frac{\partial u}{\partial x})^{t_0+\Delta t} + \frac{1}{3}(M_1^R + 2M_2^R)(\frac{\partial w}{\partial z})^{t_0+\Delta t} + \frac{1}{L}\sum_{l=1}^{L}q_{22l}^{t_0+\Delta t} \tag{11}$$

$$\tau_{xz}^{t_0+\Delta t} = \frac{1}{2}M_2^R(\frac{\partial u}{\partial z})^{t_0+\Delta t} + \frac{1}{2}M_2^R(\frac{\partial w}{\partial x})^{t_0+\Delta t} + \frac{1}{L}\sum_{l=1}^{L}q_{12l}^{t_0+\Delta t} \tag{12}$$

where

$$\begin{aligned} q_{11l}^{t_0+\Delta t} \ &= \ q_{11l}^{t_0}\exp(-\omega_l\Delta t) + \frac{1}{3}[M_1^R\chi_{1l}(p_1 + p_2) \\ &\quad + M_2^R\chi_{2l}(2p_1 - p_2)]\exp(-\frac{1}{2}\omega_l\Delta t) \end{aligned} \tag{13}$$

$$\begin{aligned} q_{22l}^{t_0+\Delta t} \ &= \ q_{22l}^{t_0}\exp(-\omega_l\Delta t) + \frac{1}{3}[M_1^R\chi_{1l}(p_1 + p_2) \\ &\quad + M_2^R\chi_{2l}(2p_2 - p_1)]\exp(-\frac{1}{2}\omega_l\Delta t) \end{aligned} \tag{14}$$

$$q_{12l}^{t_0+\Delta t} = q_{12l}^{t_0}\exp(-\omega_l\Delta t) + \frac{1}{2}M_2^R\chi_{2l}(p_3 + p_4)\exp(-\frac{1}{2}\omega_l\Delta t) \tag{15}$$

where $p_1 = (\partial u/\partial x)^{t_0+\Delta t} - (\partial u/\partial x)^{t_0}$, $p_2 = (\partial w/\partial z)^{t_0+\Delta t} - (\partial w/\partial z)^{t_0}$, $p_3 = (\partial u/\partial z)^{t_0+\Delta t} - (\partial u/\partial z)^{t_0}$, and $p_4 = (\partial w/\partial x)^{t_0+\Delta t} - (\partial w/\partial x)^{t_0}$. The coefficients χ_{1l}, χ_{2l} and relaxation frequency ω_l in Eqs. (13) through (15) can be obtained from constant-Q by means of the least squares technique. We use $L=3$ in this study. $\partial u/\partial x$, $\partial w/\partial z$, $\partial u/\partial z$ and $\partial w/\partial x$ in Eqs. (10) through (15) can be determined by using the spatial derivatives of displacement for the triangular grid and quadrangular grid [10].

The algorithm implementation for viscoelastic wave propagation in earth medium with surface topography is a recursive evaluating procedure in time domain as follows:

Step 1. Evaluate $\ddot{u}_i$ and $\ddot{w}_i$ at time t_0 by using Eqs. (1) and (2).
Step 2. Evaluate u_i and w_i at time $t_0 + \Delta t$ by doing time integration [10].
Step 3. Evaluate σ_x, σ_z and τ_{xz} at time $t_0 + \Delta t$ by using Eqs. (10) through (12) and then go back to step 1 to evaluate $\ddot{u}_i$ and $\ddot{w}_i$ at time $t_0 + \Delta t$.

Calculating in cycle from step 1 to step 3, finally the numerical algorithm for simulating viscoelastic wave propagation is obtained by using the history variable type GZB constitutive equations.

2.2. Integrated method for earthquake response analysis of near-fault building clusters

Combining the algorithm proposed in Section 2.1 for viscoelastic wave propagation in earth medium with the algorithm for flexural wave propagation in frame structure [3] and the algorithm for bidirectional wave propagation between the earth medium and the building structure [3], a new type of integrated method is developed for analyzing near-