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Technical Note

Earthquake responses of near-fault frame structure clusters due to thrust fault by using flexural wave method and viscoelastic model of earth medium

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ABSTRACT

An integrated method for simulating earthquake responses of near-fault structure clusters is developed by considering structure cluster consisting of plane frame structures, half-space viscoelastic earth medium and causative fault simultaneously. The seismic responses of near-fault structure cluster of reinforced concrete (RC) frame are simulated during a M_w 6.0 hypothetical earthquake, considering viscoelastic attenuation and inhomogeneity of earth medium. It showed that the orbit of structure in the cluster located between the epicenter and rupture forward is in anticlockwise motion during the earthquake induced by thrust fault.

1. Introduction

There are mainly three approaches to introduce the buildings on the surface of half-space earth medium when studying site–city interaction or earthquake response of the city. In the first approach, a building or a set of buildings on urban area is simplified as a low-velocity block and then is connected to substratum. By using these building models, some researchers studied analysis of the multiple interactions between soil layers and civil-engineering structures in dense urban areas and the seismic response in an idealized city under incident SH plane waves [1–4]. Taborda [5] applied buildings simplified as low-velocity blocks and a double-couple source to simulate wave propagation in earth media and the homogeneous buildings.

In the second approach, each building in urban area is described by an equivalent oscillator. Guéguen et al. [6] used this model of building to analyze the seismic interaction of the city with soft soil layers when foundations of buildings are subjected to horizontal and vertical seismic input motion simultaneously. Boutin and Roussillon [7] used building model simplified as an equivalent oscillator to study the urbanization effect on seismic motion under a vertical incident SH wave.

In the third approach, each building in a city adopts 3D real building. Lombaert and Clouteau [8] used coupled finite element/boundary element and this city model to study the change of the seismic site response by the presence of a city on the surface of elastic medium due to an incident plane wave.

Many earthquakes have caused the near-fault cities to suffer severe seismic disaster. For example, the Kobe city during the 1995 Hyogo-ken Nanbu earthquake [9], the Tangshan city during the 1976 Tangshan earthquake [10] and the Beichuan city during the 2008 Wenchuan earthquake [11]. So it is neccessary to study the earthquake responses of near-fault structure clusters in the city area.

In our previous work, Liu et al. [12] developed a method of integrated simulation to study the earthquake responses of clusters of building structures caused by a near-field thrust fault. In the previous work, the simple shear models of computation are used for the multi-story buildings and the earth medium adopted half-space elastic body without considering attenuation of earth medium.

In this study, we firstly developed an integrated numerical simulation method for flexural wave propagation in the plane frame structure and viscoelastic wave propagation in earth medium as well as bidirectional wave propagation between the plane frame structure and earth medium during a near-fault earthquake. Then we apply the proposed method to simulate the seismic responses of frame structure cluster during a M_w 6.0 hypothetical earthquake.

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2. Integrated system of frame structure clusters, half-space viscoelastic earth medium and causative fault

Fig. 1 shows the 2D schematic map of the integrated system consisting of frame structure clusters, half-space viscoelastic earth medium and causative fault. We denote the height of structure, width of structure and space interval between structures by using h, w and d. We will apply this integrated system to simulate seismic wave propagation in the frame structures and viscoelastic earth medium for obtaining the seismic responses of frame structure cluster due to rupture of the causative fault.

3. Numerical method for wave propagation in the integrated system

3.1. Algorithm implementation for flexural wave propagation in plane frame structure

As is shown in Fig. 2(c), the whole shaded part is a typical investigated lump, which consists of half-length of every beam or column around the discrete node, for the beam-column connection in plane frame structure.

According to the analysis of forces on the investigated lump shown in Fig. 2(c), if there are n half-lengths of beam element composing investigated lump I and considering the influence of structural damping, the dynamic equilibrium equations for Ith investigated lump with the mass of m_I can be obtained as follows:

$$m_I\ddot{u}_I = \sum_{l=1}^{n}(N_l \cos \varphi_l - V_l \sin \varphi_l) - \beta_1 m_I \dot{u}_I \tag{1}$$

$$m_I\ddot{w}_I = \sum_{l=1}^{n}(N_l \sin \varphi_l + V_l \cos \varphi_l) - \beta_1 m_I \dot{w}_I \tag{2}$$

$$J_I\ddot{\theta}_I = \sum_{l=1}^{n}[M_l - V_l\frac{L_l}{2}] - \beta_1 J_I \dot{\theta}_I \tag{3}$$

where J_I is the moment of inertia of investigated lump I about the horizontal y-axis (pointing towards the inside of paper) through I point. u_I, w_I and θ_I are the horizontal, vertical and rotational angle displacements of investigated lump I, respectively. L_l is the length of element l. The symbol ϕ_l is the angle between x' axis in natural

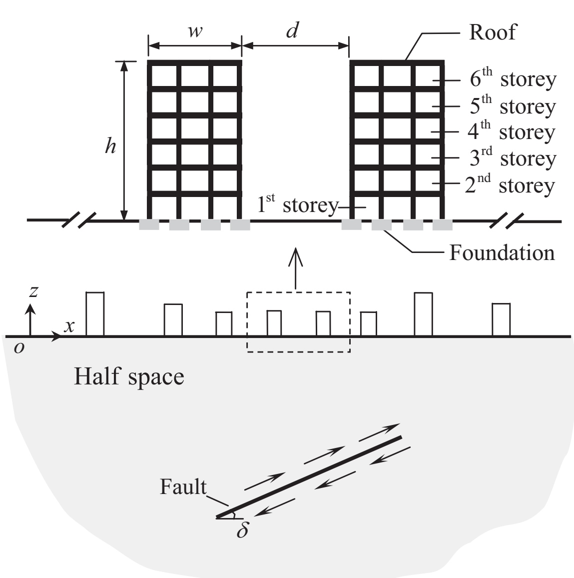

Fig. 1. The 2D schematic map of the integrated system. δ is the dip angle of the fault.

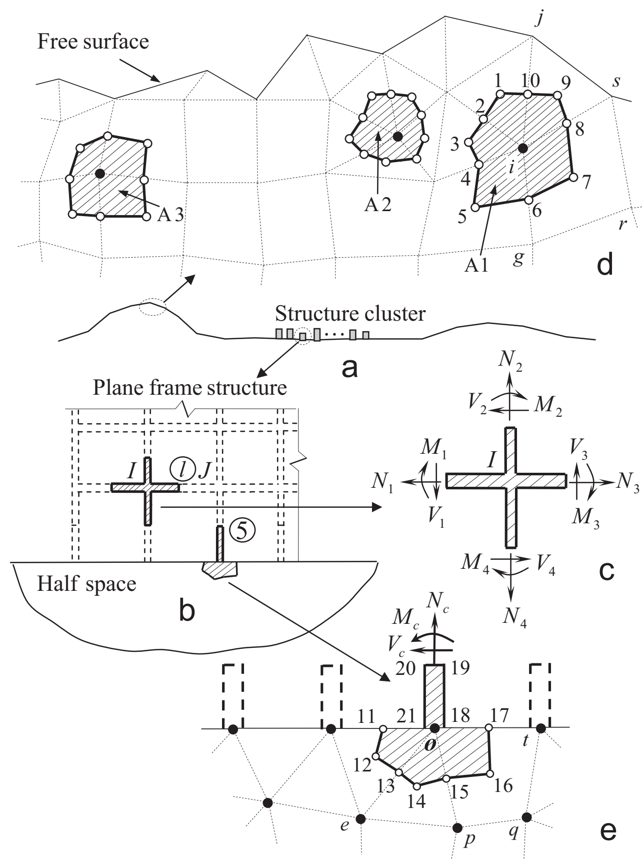

Fig. 2. Schematic illustration of the investigated lumps in the plane frame structure and earth medium as well as structure-soil connection. (a) Simplified diagram of structure cluster and half-space earth medium with irregular free surface. (b) The investigated lumps (shaded parts) in the plane frame structure and at the structure-soil connection. (c) Internal forces on the investigated lump in plane frame. (d) The typical investigated lumps (shaded parts A1, A2 and A3) in the earth medium. (e) The connecting investigated lump (shaded part).

coordinates and x axis in the global coordinates. The internal forces N_l, V_l and M_l acting on the investigated lump are respectively the median axial force, median shear force and median bending moment acting on the median cross-section of element l. These internal forces can be given as follows:

$$N_l = K_{1l}(u'_J - u'_I) + \beta_2 K_{1l}(\dot{u}'_J - \dot{u}'_I) \tag{4}$$

$$V_l = K_{2l}(w'_J - w'_I) + K_{3l}(\theta'_I \theta'_J) + \beta_2[K_{2l}(\dot{w}'_J - \dot{w}'_I) + K_{3l}(\dot{\theta}'_I + \dot{\theta}'_J)] \tag{5}$$

$$M_l = K_{6l}(\theta'_J - \theta'_I) + \beta_2 K_{6l}(\dot{\theta}'_J - \dot{\theta}'_I) \tag{6}$$

where, $K_{1l} = (EA)_l/L_l$, $K_{2l} = 12(EI)_l/[L_l^3(1+2\alpha_l)]$, $K_{3l} = 6(EI)_l/[L_l^2(1+2\alpha_l)]$, and $K_{6l} = (EI)_l/L_l$. $\alpha_l = 6(EI)_l/[L_l^2(GA_s)_l]$ is the coefficient of shear deflection in element l. It means that the contribution of shear deformation to the deflection has been considered. $(EA)_l$, $(EI)_l$ and $(GA_s)_l$ are respectively the axial stiffness, bending stiffness and shear stiffness of element l. u'_I, w'_I and θ'_I are respectively the longitudinal, transverse and the rotational angle displacements for node I of element l in natural coordinates. u'_J, w'_J and θ'_J are for node J of element l. It should be pointed that Rayleigh damping, which is a frequency dependent damping [13], is employed to implement structural damping in this study. β_1 and β_2 are respectively mass-damping parameter and stiffness-damping parameter of Rayleigh damping.

As in most engineering practice we use natural vibration frequencies corresponding to first and second vibration modes of