SIMULATION OF DYNAMIC CONTACT BEHAVIORS OF SATURATED POROUS MEDIA INVOLVING LARGE DEFORMATION WITH THE COUPLING CONVECTED PARTICLE DOMAIN INTERPOLATION METHOD

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Summary The coupling convected particle domain interpolation (CCPDI) method is extended to simulate the dynamic contact behaviors of saturated porous media involving large deformation. The convected particle domain interpolation technique is used to eliminate the numerical artifact noises due to material points crossing computational grid boundaries and a new contact condition is proposed to avoid unrealistic contact. Numerical results demonstrate the accuracy and efficiency of this newly developed method.

INTRODUCTION

Many natural and artifical materials can be modeled as saturated porous media, such as soils, soft tissues, ceramics and many others [1]. The dynamic analysis of these materials involving large deformation and contact has attracted much attention since the performances of many structures composed of these materials may be greatly altered [2]. Over the past few decades, the finite element method (FEM) has been widely applied to perform this analysis. However, FEM may encounter mesh distortion problem when the deformation is too large and the accuracy of FEM may decrease extremely. To overcome this deficiency, many meshless/particle methods have been developed, among which the material point method (MPM) is one of the promising methods [3]. Recently, a coupling MPM method (CMPM) for the dynamic analysis of saturated porous media has been proposed [4]. In the previous work [5], we further developed the CCPDI method for the dynamic analysis of saturated porous media involving large deformation. In this work, a new contact condition is proposed and combined with the contact algorithms proposed in [4] and [6], which is then implemented in the CCPDI to simulate the large deformation dynamic contact problems of saturated porous media.

CCPDI FOR DYNAMIC CONTACT ANALYSIS OF SATURATED POROUS MEDIA

Governing Equations of Saturated Porous Media

Based on the Biot's theory, the u-p governing equations of saturated porous media can be written as follows [1, 4],

$$\sigma_{ij,j} + \rho g_i - \rho \ddot{u}_i = 0 \quad \text{and} \quad \dot{p} = -Q\left(k\gamma_f^{-1} R_{i,i}^e + \alpha \dot{u}_{i,i}\right), \tag{1}$$

where $Q = [(\alpha - n)/K_s + n/K_f]^{-1}$ and

$$R_i^e = -p_{,i} + \rho_f g_i - \rho_f \ddot{u}_i . \tag{2}$$

In the above equations, $\sigma_{ij} = \sigma''_{ij} - \alpha p \delta_{ij}$ is the total stress, σ''_{ij} the effective stress tensor, p the pore pressure, u_i the displacement of solid skeleton, g_i the body force, α the Biot's constant, k the fluid permeability, γ_i the fluid bulk weight, n the porosity, K_s and K_f the bulk moduli of solid skeleton and fluid, respectively, ρ_s and ρ_f the densities of solid skeleton and fluid, respectively. The boundary conditions for solid skeleton are $u_i = \bar{u}_i$ on $\partial\Omega_u$ or $\sigma_{ij} n_{j,\tau}^b = \tau_i$ on $\partial\Omega_\tau$, in which $\bar{u}_i$ and τ_i are the prescribed displacement and traction, respectively, $\boldsymbol{n}_\tau^b$ is the normal to the boundary $\partial\Omega_\tau$. The boundary conditions for pore fluid are $p = \bar{p}$ on $\partial\Omega_p$ or $q_n = n_{i,q}^b R_i^e \cdot k/\gamma_f$ on $\partial\Omega_q$, in which $\bar{p}$ and q_n are prescribed pressure and fluid flux, respectively, $\boldsymbol{n}_q^b$ is the normal to the boundary $\partial\Omega_q$.

Discretization Equations

The corresponding discretization equations are derived in the framework of GIMP [7], which can be written as [5],

$$m_I \ddot{u}_{iI} = f_{iI}^{\text{int}} + f_{iI}^{\text{ext}} \quad \text{and} \quad V_I R_{iI}^e = R_{iI}^{\text{int}} + R_{iI}^{\text{ext}} , \tag{3}$$

where, $m_I = \sum_p m_p \bar{\phi}_{Ip}$, $f_{iI}^{\text{int}} = -\sum_p m_p \sigma'_{ijp} \bar{\nabla}\phi_{Ip}$, $f_I^{\text{ext}} = \sum_p m_p g_i \bar{\phi}_{Ip} + \int_{\partial\Omega} \sigma_{ij} n_j S_I(\boldsymbol{x}) dS$, $V_I = \sum_p V_p \bar{\phi}_{Ip}$, $R_{iI}^{\text{int}} = \sum_p V_p p_p \bar{\nabla}\phi_{Ip} - \rho_{fp} f_{iI}/\rho_p$ and $R_{iI}^{\text{ext}} = \sum_p V_p \rho_{fp} g_i \bar{\phi}_{ip} - \int_{\partial\Omega_\tau} p n_j S_I(\boldsymbol{x}) d\Gamma$. To eliminate the numerical artifact noises due to material points crossing computational grid boundaries as in large deformation cases, the convected particle domain interpolation technique is used here, that is, the interpolation functions are chosen as $\bar{\phi}_{Ip} = \int_\Omega \chi_p(\boldsymbol{x}) S_I(\boldsymbol{x}) / V_p \, d\Omega$ and $\bar{\nabla}\phi_{Ip} = \int_\Omega \chi_p(\boldsymbol{x}) \nabla S_I(\boldsymbol{x}) / V_p \, d\Omega$, in which $S_I(\boldsymbol{x})$ is the standard grid basis functions [8].

Contact Algorithm

In conventional contact algorithm in MPM [4], the contact grid nodes are detected when the nodal velocities calculated based on the common and individual meshes are different. This may introduce significant errors in capturing the contact

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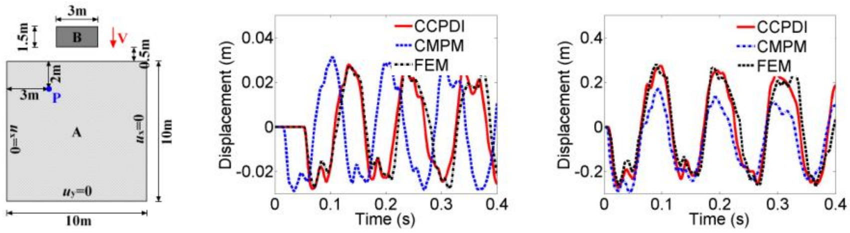
time since two bodies may be regarded as in contact when their material points enter into two neighbouring grids though these bodies are actually separated. In this work, the contact is detected when the particle domains (i.e., the true volume representations) of material points belong to different bodies are overlapped with each other, thus unrealistic contact can be avoided. After detecting the contact, the contact normal and forces can be computed following the usual way [4, 6].

NUMERICAL EXAMPLES

Impact between Solid Bodies

Fig. 1 shows the displacement histories of Point P of a two-dimensional solid foundation A under the impact of a small solid body B. It can be seen that the contact time can be correctly captured by using the proposed contact condition and the present results are in good agreement with those computed by the FEM. These results validate the proposed method.

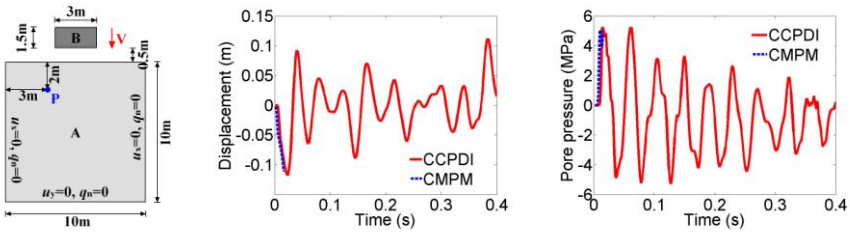


(a) (b) (c)

Fig. 1. (a) Simulation model and (b,c) displacement histories of Point P: (b) small deformation (v_B=10m/s) and (c) large deformation (v_B=100m/s).

Impact between Saturated Porous Media and Solid Bodies

Fig. 2 shows the displacement and pore press histories of Point P of a saturated porous foundation A under the impact of a solid body B. Compared with the results of CMPM, it can be seen that the CCPDI combined with the proposed contact algorithm can not only capture the correct displacement and pore pressure in the initial small deformation stage but also be successfully used to model the dynamic contact responses of saturated porous media involving large deformation.



(a) (b) (c)

Fig. 2. (a) Displacement and (b) pore press histories of Point P of a saturated porous foundation under the impact of a solid body (v_B=100m/s).

CONCLUSIONS

In summary, a new contact algorithm is proposed and integrated into the CCPDI method to simulate the dynamic contact behaviors of saturated porous media involving large deformation. Numerical experiments of several representative examples are carried out to valid the proposed method. These applications imply that this method is applicable to model the nonlinear coupling dynamics contact of the solid skeleton and fluid phase in soft tissue, bone and other saturated porous soft matter.

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