3-D Numerical Analysis on Soil -Pile Interaction of Liquefied Ground Considering Large Deformation

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1. Introduction

Soil shows material and geometrical nonlinearities evidently in strong earthquakes, for example, the geometrical nonlinearity due to the large deformation in the liquefaction of soil. The investigation after the 1995 Hyogoken-Nambu earthquake found that the large displacement of the liquefied soil during the earthquake caused the failure of piles[1]. Many research works on the material nonlinearities of soil have been done with the assumption of infinitesimal deformation, but the geometric nonlinearity due to the large deformation in strong earthquake was neglected. For this reason, the dynamic analysis method for liquefiable soil considering large deformation is necessary to developed. Y. Di and T. Sato have developed a 2-D FE-FD method by updated Lagrangian method[3]. On the other hand, in order to fit in the practical cases, the 3D finite element analysis tends to be used in engineering design, because it's more reasonable than a two-dimensional analysis abviosly. The development of computers made it easy to be conduct. In recent years, few 3-D dynamic analysis programs for soil and structure have been achieved. In this paper, a 3-D FE-FD dynamic analysis method for saturated porous medium considering large deformation is presented. Both geometrical and material nonlinearities were taken into account. The updated Lagrangian method was adopted here. It's based on Biot's two-phase mixture theory. The equilibrium equation was discretized by the finite element method and the continuity equation was discretized by the finite difference method in the space domain. A elasto-plastic model was used to describe the soil. A program according to our method was modified on the basis of Liqca-3D. dynamic analysis program was developed according to this method. The advantages of the proposed method were shown in a soil-pile interaction example.

2. Equations based on updated Lagrangian method

According to Biot's theory for tow-phase mixed medium, the equilibrium equations of saturated soil and the pore fuid are given by (1) and (2) respectively.

$$\sigma_{ij,j} + \rho b_i - \rho \ddot{u}_i - \rho_f \left(\ddot{w}_i + \dot{w}_k \dot{w}_{i,k}\right) = 0 \tag{1}$$

$$p_{,i} - \rho_f b_i + \gamma_f k^{-1} \dot{w}_i + \rho_f (\ddot{u}_i + (\ddot{w}_i + \dot{w}_k \dot{w}_{i,k})/n) = 0 \tag{2}$$

The mass conservation equation for the fluid flow is given by

$$\dot{w}_{i,i} + \dot{\varepsilon}_{ii} + (\frac{n}{K_f} + \frac{1-n}{K_s})\dot{p} - \delta_{ij} D_{ijkl} \frac{{}^0\dot{\varepsilon}_{kl}}{3K_s} + n\beta\dot{T} = 0 \tag{3}$$

Neglecting the acceleration of fluid phase and integrating in spatial domain, assumming that the distribution of porosity in the medium is sufficiently smooth, solid particals are incompressible.and the initial strain rate is 0, and neglecting the thermal expansion of the fluid, a simple equilibrium equation can be derived from (1).

$$\sigma_{ij,j} + \rho b_i - \rho \ddot{u}_i = 0 \tag{4}$$

Combining (4) and (5) , the simple form of the continuity equation can be obtained.

$$\rho_f \ddot{\varepsilon}_{ii} - \frac{\partial^2 p}{\partial x_i^2} - \frac{\gamma_f}{k}(\dot{\varepsilon}_{ii} - \frac{n}{K_f}\dot{p}) = 0 \tag{5}$$

Integrating over the porous medium volumn, the weak form of (4) and (5) are given by (6) and (7).

$$\int_{^{t+dt}A} {}^{t+dt}\rho^{t+dt}\ddot{u}_i \delta^{t+dt} v_i d^{t+dt}V + \int_{^{t+dt}V} {}^{t+dt}\sigma_{ij}\delta^{t+dt} l_{ij} d^{t+dt}V = \int_{^{t+dt}A} {}^{t+dt}T_i \delta^{t+dt} v_i d^{t+dt}A + \int_{^{t+dt}V} {}^{t+dt}\rho^{t+dt} b_i \delta^{t+dt} v_i d^{t+dt}V \tag{6}$$

$$-\rho_f [K_V]\{\ddot{U}\} - \frac{\gamma_f}{k}[K_V]\{\dot{U}\} + \int_V {}^{t+dt}p_{,ii} d^tV + \int_V \frac{n\gamma_f}{kK_f} {}^{t+dt}\dot{p} d^tV = 0 \tag{7}$$

Using the updated Lagrangian method, we can refer all stresses, strains and deformations in (6) and (7) to the current configuration at time t and get

$$\int_{^tV} {}^t\rho^t\ddot{u}_i \delta v_i d^tV + \int_{^tV} (\int_t^{t+dt} \dot{S}_{ij} dt)\delta\dot{E}_{ij} d^tV = \int_{^tA} {}^{t+dt}T_i \delta v_i d^tA + \int_{^tV} {}^t\rho^{t+dt} b_i \delta v_i d^tV - \int_{^tV} {}^t\sigma_{ij}\delta\dot{E}_{ij} d^tV \tag{8}$$

$$-\rho_f [K_V]\{\ddot{U}\} - \frac{\gamma_f}{k}[K_V]\{\dot{U}\} + \int_{^tV} {}^{t+dt}p_{,ii} d^tV + \int_{^tV} \frac{n\gamma_f}{kK_f} {}^{t+dt}\dot{p} d^tV = 0 \tag{9}$$

where, v_i is the velocity of the solid skeleton, b_i is body force on the volumn V of porous medium, T_i is traction on the surface A, E_{ij} is the Lagrangian strain tensor and S_{ij} is the second Piola-Kirchhoff stress tensor.

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Discretize (8) and (9) in the space domain by the finite element method and by the finite difference method respectively, we can get the final FEM-FDM coupled formulars for the dynamic analysis of the porous medium. Newmark-β method for the time domain integration is used here to solve the dynamic equations.

The constitutive equation is given by a general linear relationship between the objective stress rate and the deformation rate can be writen in the form.

$$\dot{\sigma}_{ij}^{J} = D_{ijkl} l_{kl} - \dot{p}\delta_{ij} \tag{10}$$

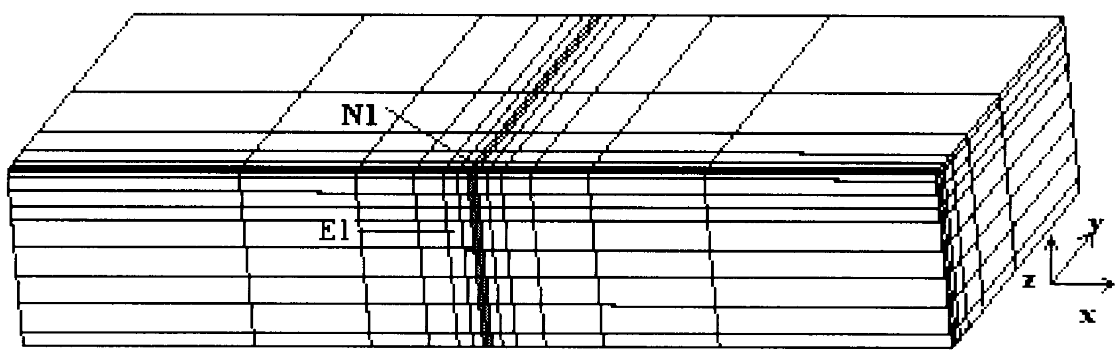
where, $\dot{p}$ is the rate of pore pressure, l_{kl} is the symmetric deformation rate tensor, and D_{ijkl} is the special stiffness of material, σ' is the Jaumann stress obtained by

$$\dot{\sigma}_{ij}^{J} = \dot{\sigma}_{ij} - \sigma_{ik}\omega_{jk} - \sigma_{jk}\omega_{ik} \tag{11}$$

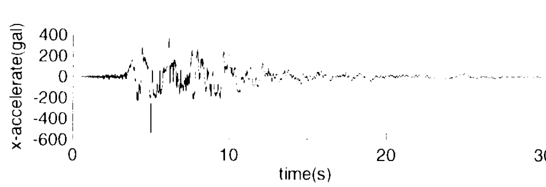
where, $\dot{\sigma}_{ij}$ is the rate of Cauchy stress tensor and ω_{ij} is the skew symmetric spin tensor.

3. Numerical examples

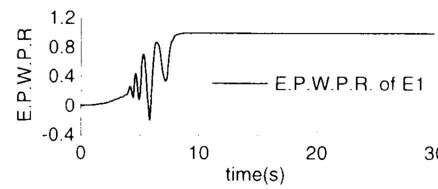
A numerical example is siesmic response of a soil-pile interaction system shown in Fig.1.(a). A concrete pile(shown as the shadow elements, E=2.45e7 kn/m^2) is placed at the center of 23m-deep saturated ground composed of Ensyunada sand(Dr=40%). The selected area of the soil is 128m square, and the diameter of the pile is 1.2m. A half part is analyzed for the reason of symmetry. The soil is described by a cyclic elasto-plastic model based on a non-linear kinematics hardening. The pile is described by an elastic column model. Equi-displacement boundary condition is used. Drainage is only allowed on the top of the soil. The input motion is given in x direction shown in Fig.1.(b) and the excess pore water pressure ratio response of the soil element E1 is shown in Fig.2.(c). The input wave was recorded in the 1995 Hyogoken-Nambu earthquake.



(a)



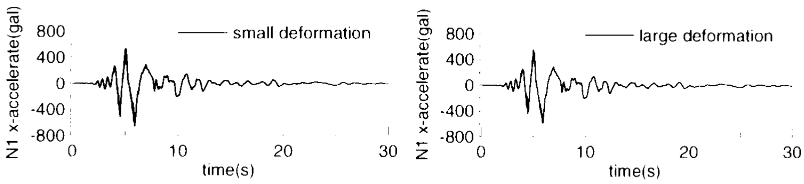
(b)



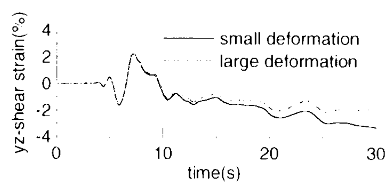
(c)

Fig.1. soil-pile interaction example

Our calculation results are given in Fig.2. where,the x-displacement responses at the head of pile N1 and yz-shear strain responses of soil element E1 are shown in Fig.2.(a) and (b) respectively. The difference between the large deformation and small deformation is obvious.



(a)



(b)

Fig.2. Responses of soil-pile interaction system

4. Conclusion

This paper proposed a 3-D FE-FD dynamic analysis method based on the updated Lagrangian method. The method is applicable to large deformation problem of liquefaction and to seismic response analysis of soil-pile interaction system with liquefiable soil.

References

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