Wave Propagation Problems in Soil Media by BIEM

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1. INTRODUCTION

This paper presents the results of authors concerning different wave propagation problems in soil media by Boundary integral equation method (BIEM) obtained in the last years. Solutions, algorithms and results of the next two-dimensional wave propagation problems are obtained and shown:

•according to the type of the incident wave: SH-seismic waves (anti-plane problems) in multi-layered soil region; P- and SV-seismic waves (in-plane problems) in multi-layered soil regions; steady state and different transient problems

•according to geometry of the geological region: half-space; multilayered region with parallel and nonparallel boundaries; region with relief on the free boundary; dipping layers overlying a half-space.

•according to physical soil properties: pure elastic case; nonelastic case accounting the damping mechanism in soil and dispersion of the seismic waves due to the existence of elasto-relaxational deformation far from the wave source; elasto-viscouse-plastic behaviour of the soil by the generalised Maxwell-Gourevich model.

The methods used are: direct BIEM together with finite difference procedure or Fourier transformation applied to the time variable in the transient problems. The comparison of the obtained results with exact analytical solutions, FEM solutions and other BIEM results are shown. FORTRAN package solving the wave problems is created.

2. GOVERNING EQUATIONS OF WAVE PROPAGATION PROBLEMS

2.1 Equation of motion: $\sigma_{ij,j} + f_i = \ddot{u}_i \quad \mathbf{x} \in \mathrm{V}$ **(1)**

Here: σ_{ij} **is stress tensor,** f_i **is body force,** u_i **is displacement vector, V-volume enclosed by a surface** $S = S_1 + S_2$

2.2 Physical equations: $\sigma_{ij} = 2\mu(\nu/(1-2\nu))\delta_{ij}\varepsilon_{kk} + 2\mu\varepsilon_{ij} \quad \mathbf{x}\in\mathrm{V}$ **(2)**

in elastic case,

or: $\varepsilon_{pij} = (T_P R)^{-1} g\mu_P^{-1} \int_{\exp(-R)}^{1} \exp(-(gt/\mu T_P)\zeta) \int_0^t \exp((gt/\mu T_P)\zeta)\sigma_{ij}\,dt\,d\zeta$ **(3)**

in the case of Generalised Maxwell-Gurevich model [1], accounting for the damping mechanism in soil due to the ***elasto-relaxational deformation.*** **Here:** ε_{pij} **is the elasto-relaxational deformation, which develops and damps in time;** T_P **- relaxation time for one molecule, i.e. time**

for transition from one state of equilibrium into another one for one molecule; $R = \ln(T_M / T_P)$; T_M **- time for transition of a group of molecules from one state of equilibrium into another one;** μ, μ_P **- the elastic and relaxation shear module;** $g = \mu\mu_p(\mu + \mu_p)^{-1}$;

or: $\varepsilon_{ij} = e_{ij} + \varepsilon_{ij}^0$ **in *elasto-viscouse-plastic case*** **(4)**

here: ε_{ij}^0 **is elasto-viscouse-plastic deformation of soil described by the Generalised Maxwell-Gourevich model [1] for irreversible deformation;** e_{ij} **- is elastic deformation;**

$$\frac{\partial \varepsilon_{ij}^0}{\partial t} = \frac{f_{ij}^0}{\eta^0} \quad \text{at} \quad i=j$$

and

$$\frac{\partial \varepsilon_{ij}^0}{\partial t} = 2\frac{f_{ij}^0}{\eta^0} \quad \text{at } i \neq j$$

in two - dimensional case (x,z):

$$f_{xx}^0 = \sigma_{xx} - 0.5\sigma_{zz}; \quad f_{xz}^0 = 1.5\sigma_{xz}; \quad \left|\frac{1}{\eta^0} = \frac{1}{\eta_0^0}\exp\left\{\frac{1}{m^0}\left[\frac{1}{3}\gamma^0(\sigma_{xx} + \sigma_{zz}) + (f_{rr}^0)_{\max}\right]\right\}\right.$$

$$f_{zz}^0 = \sigma_{zz} - 0.5\sigma_{xx}; \quad f_{rr} = 0.5\left[(f_{xx}^0 + f_{zz}^0) \pm \sqrt{(f_{xx}^0 - f_{zz}^0)^2 + (2f_{xz}^0)^2}\right]$$

rr-main directions, $\eta_0{}^0$ **[kg.min/mm^2] - coefficient of the initial viscosity;** γ^0 **- the volume coefficient; m^0 [kg/mm^2] - logarithmic module of the velocity of the irreversible deformation**

Equations (1) and (2) (or (3), or (4)) and equation of geometry can be combined into one vector equation for u (x,t), which together with the corresponding initial and boundary conditions present the boundary-value problems solved by BIEM:

- in the case of steady-state SH seismic waves in *elastic soil region* (anti-plane case):

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2} + k^2 u(x,z) = 0 \qquad (5)$$

in the case of steady-state SH seismic waves in *non-elastic soil region with accounting of damping mechanism* using eq. (3) (anti-plane case):

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2} + (k^*)^2 u(x,z) = 0; k^* = k + i\alpha \quad \text{where } \alpha \text{ is the damping coefficient} \qquad (6)$$

- in the case of transient SH-waves in elastic soil region:

$$\rho\frac{\partial^2 u}{\partial t^2} - \Delta u = f(x,z,t) \qquad (7)$$

- in the case of two-dimensional P- and SV- transient wave propagation problem in elastic soil media (in-plane problem):

$$(C_p^2 - C_v^2)u_{p,pi} + C_v^2 u_{i,pp} - \ddot{u}_i = -\rho^{-1} f_i(t) \qquad (8)$$

- in the case of two-dimensional P- and SV-transient wave propagation problem in *elasto-viscouse-plastic soil media*:

$$(C_p^2 - C_v^2)u_{i,ij} + C_v^2 u_{j,ii} + f_j(t)/\rho - 2C_v^2 \varepsilon_{ij,i}^0 = \frac{\partial^2 u_j}{\partial t^2} \quad (9)$$

3. NUMERICAL RESULTS

It is solved the next boundary-value problems: a) Transient SH-waves in an elastic soil region with dipping layers [2]. We suppose that a buried linear source f_z (x,y,t) acts along the line $x=x_I$, $y=y_I$ ($y_I \leq 0$) and generates the SH-waves. The time behaviour of the source excitation is a triangle impulse. The problem solution is based on applying the Fourier transformation; **Transient in-plane problems in elastic and elasto-viscous-plastic soil half-space. The two-dimensional problem of wave propagation in an elasto-viscous-plastic half-space is studied by the DBIEM combined with the finite difference procedure applied to the time variable. The present hybrid formulation employs the fundamental solution depending neither on the frequency nor on the time variable. Time records of surface responses of the half-space are computed and compared with those obtained by the numerical evaluation of exact analytical solutions to elastic problem. ***Steady state SH-waves propagation in a multi-layered region with complex geometry (non-parallel boundaries and relief peculiarities on the free boundary) and with accounting for the damping in soil [3].

The obtained numerical results show seismic wave field sensitivity to:

a) The geometry of the geological region: nonparallel boundaries, relief non-homogeneities, dipping layers existence;

b) Physical properties of soil and the choice of the constitutive equation describing them

c) Dissipation of seismic energy and damping mechanism in soil

d) The type of the incident waves

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