# **Convolution Quadrature BEM for Wave Analysis in General Anisotropic**

# Fluid-Saturated Porous Solid and its GPU Acceleration

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## Abstract

Rocks under the ground include pores and cracks which produce strong anisotropy. In addition, the pores and cracks are saturated with pore fluid. Therefore, the rocks can be considered as a general anisotropic fluid-saturated porous solid. Boundary element method (BEM) is well known as an effective numerical approach for wave scattering analysis because BEM can treat infinite or semi-infinite domains without any modification. Convolution quadrature boundary element method (CQ-BEM), which uses convolution quadrature method (CQM) for time-discretization, is known as a new time-domain BEM. The CQ-BEM requires Laplace-domain fundamental solutions and can produce stable numerical solutions, even for small time increments. In this research, a CQ-BEM for wave analysis in general anisotropic fluid-saturated porous solids is developed and accelerated by GPU parallelization. The proposed method and the effect of GPU acceleration are verified by solving wave scattering problems by a cavity.

**Keywords:** Boundary element method, Convolution quadrature method, Anisotropy, Pore fluid, GPU acceleration

## Introduction

Wave analysis in rocks has been addressed in earthquake engineering and exploration geophysics. Waves propagating in rocks, especially near the fault fracture zones and reservoirs, have some important properties: anisotropy, dispersion, and attenuation. Anisotropy is generated by crystal preferred orientation of the rocks and aligned cracks in the rocks. On the other hand, dispersion and attenuation result from porous structure of the rocks and existence of pore fluid. Therefore, the rocks can be considered as a general anisotropic fluid-saturated porous solid. A theory of fluid-saturated porous solids has been proposed by [Biot (1956a; 1956b)], and the theory including consideration of general anisotropy was subsequently presented by [Biot (1962)]. The mechanical model proposed by Biot is called Biot's model, and there are various expanded models which have been derived from Biot's original one.

Boundary element method (BEM) is an effective numerical approach for wave analysis. This is because BEM requires boundary discretization only and can treat infinite and semi-infinite domain without any modification. Therefore, BEM can provide accurate numerical solutions compared with other computational methods such as finite element method (FEM), and finite difference method (FDM), which require spatial discretization of analysis zone. In recent years, a novel time-domain BEM, convolution quadrature boundary element method (CQ-BEM), has been proposed by [Schanz, M. and Antes, H. (1997)]. CQ-BEM is the BEM that a convolution quadrature method (CQM) is used for time-discretization. CQM evaluates the Riemann convolution f(t) \* g(t) numerically, and requires Laplace transform of the function f(t). Therefore, in CQ-BEM formulation, time-domain boundary integral equations (BIEs) are solved using Laplace-domain fundamental solutions. Main advantages of CQ-BEM are to produce stable numerical solutions with small time increments, and to deal with waves affected by dispersion and dissipation.

Boundary element method for dynamic poroelastic problems using Biot's model has been presented by a number of researchers. A frequency-domain BEM was proposed by [Domínguez (1992)]. In



Figure 1. Fluid-saturated porous solid.

this research, the frequency-domain BIEs were derived from the analogy between dynamic poroelasticity and thermoelasticity and, described by two kinds of boundary values, i.e., solid displacements, and fluid pressure. On the other hand, time-domain BEMs for this kind of problem have been developed with the advent of the CQ-BEM [Schanz (2001); Saitoh et al. (2012)]. These formulations involved time-domain BIEs with respect to solid displacements and fluid pressure as boundary values. However, these previous BEM formulations can be applied to isotropic fluid-saturated porous solids only, and the research on BEM for wave analysis in general anisotropic fluid-saturated porous solids has not been carried out, as long as the authors know.

In this paper, a CQ-BEM for two-dimensional wave scattering problems in general anisotropic fluidsaturated porous solids is developed, and the validity of our presented method is confirmed. In general, BEM considering general anisotropy requires much computational time because the computation of fundamental solutions involves integration over the unit circle in two-dimensional problems. Therefore, GPU parallelization is applied to the proposed CQ-BEM and effect of GPU parallelization is confirmed. In the following sections, the theory of Biot's model is summarized and CQ-BEM formulation for Biot's model is subsequently presented. After these expressions, numerical examples and effect of GPU parallelization are illustrated.

## **Biot's Model for General Anisotropic Fluid-Saturated Porous Solids**

In this section, Biot's model, a mechanical model for general anisotropic fluid-saturated porous solids proposed by [Biot (1962)], is described. The presented model shown here involves effects of anisotropy. The Biot's model is based on the following assumptions:

- 1. Fluid-saturated porous solid consists of solid skeleton and pore fluid as shown in Fig. 1.
- 2. Infinitesimal transformations occur between the reference and current states of deformation.
- 3. The wavelength is large compared with the dimensions of macroscopic values.
- 4. The conditions are isothermal.
- 5. The fluid is viscous.
- 6. The fluid flows through the porous skeleton according to Darcy's law.

In this model, anisotropy is due to a preferential alignment of the pores or cracks. Therefore, anisotropic effects of both elasticity of the solid skeleton and permeability of pore fluid can be considered.

The linear stress-strain relations of the Biot's model are given by the following equations:

$$\sigma_{ij} = A_{ijkl} e_{kl} + \alpha_{ij} M \zeta, \tag{1}$$

$$p = \alpha_{kl} M e_{kl} + M \zeta \tag{2}$$

where  $\sigma_{ij}$  and p represents the total stress of the porous solid and the fluid pressure, respectively.  $e_{ij}$  is the strain components of the porous solid, and  $\zeta$  is the increment of the fluid content. In addition,  $A_{ijkl}$  represents the elastic tensor of undrained porous solid. M is Biot's elastic modulus, and  $\alpha_{ij}$  is

Biot's effective-stress coefficients in general anisotropic case. In Eqs. (1) and (2), the strain component  $e_{ij}$  is expressed, using the displacement components of the porous solid  $u_i$ , as follows:

$$e_{ij} = \frac{1}{2} \left( u_{i,j} + u_{j,i} \right)$$
(3)

where ()<sub>*i*</sub> =  $\partial/\partial x_i$ . Moreover, the elastic tensor of undrained porous solid  $A_{ijkl}$  is expressed as follows:

$$A_{ijkl} = C_{ijkl} + \alpha_{ij}\alpha_{kl}M \tag{4}$$

where  $C_{ijkl}$  represents the elastic tensor of drained porous solid (solid skeleton).

Equations of motion of the Biot's model are expressed as follows:

$$\sigma_{ij,j} + \rho b_i = \rho \ddot{u}_i + \rho_f \ddot{w}_i, \tag{5}$$

$$p_{,i} + \rho_f c_i = -\rho_f \ddot{u}_i + m_{ij} \ddot{w}_j - \eta r_{ij} \dot{w}_j \tag{6}$$

where  $(\dot{}) = \partial/\partial t$ , and  $w_i$  represents the flow of the fluid relative to the solid in the unit section.  $\rho$  and  $\rho_f$  are the densities of the porous solid and pore fluid.  $b_i$  and  $c_i$  represent body force components of the solid and the pore fluid, respectively. In addition,  $\eta$  is the viscosity of the fluid.  $m_{ij}$  is the mass matrix which depends on the pore geometry. Moreover,  $r_{ij}$  represents the flow resistivity matrix which is the inverse matrix of the permeability matrix based on Darcy's law. Note that the third term of the right hand side in Eq. (6) is dissipation term. Therefore, dissipation depends on the viscosity of the pore fluid and the relative motion between the solid and the fluid.

Characteristics of wave propagation in general anisotropic fluid-saturated porous solids have been studied by several researchers [Carcione (1996); Sharma (2005)]. According to these previous studies, anisotropic fluid-saturated porous solids generate four body waves; i.e., quasi-fast longitudinal wave (qP1), quasi-slow longitudinal wave (qP2), and quasi-transverse waves (qS1 and qS2). In addition, phase velocities of the waves depend on the propagation direction and the frequency. The viscosity  $\eta$  effects great changes on the behavior of qP2 wave.

## **Convolution Quadrature Boundary Element Method for Biot's Model**

In this section, a formulation of convolution quadrature boundary element method (CQ-BEM) for wave scattering problems in general anisotropic fluid-saturated porous solids is presented. Our formulation is based on that proposed by [Saitoh et al. (2012)]. Firstly, the BEM formulation based on time-domain boundary integral equations (BIEs) is described. Secondly, time- and spatial discretization of the BIEs are expressed. Finally, Laplace-domain fundamental solutions for the target problems are illustrated.

#### CQ-BEM Formulation for Biot's Model

Formulation based on time-domain BIEs is described here. Considering infinite domain *D* and its boundary *S*, time-domain BIEs for Biot's model are expressed as follows:

$$C(\mathbf{x})q_{I}(\mathbf{x},t) = q_{I}^{\text{in}}(\mathbf{x},t) + \int_{S} U_{IK}(\mathbf{x},\mathbf{y},t) * s_{K}(\mathbf{y},t)dS(\mathbf{y}) - \int_{S} W_{IK}(\mathbf{x},\mathbf{y},t) * q_{K}(\mathbf{y},t)dS(\mathbf{y})$$
(7)

where \* denotes the Riemann convolution. For two-dimensional case, the subscript written by capital letter ranges from 1 to 3. In addition,  $q_I(\mathbf{x}, t)$  and  $s_I(\mathbf{x}, t)$  represent generalized displacement and traction at point  $\mathbf{x}$  at time t, respectively, shown as follows:

$$q_I = \{u_1, u_2, p\}^{\mathrm{T}}, \quad s_I = \{t_1, t_2, p_n\}^{\mathrm{T}}$$
(8)

where  $t_i$  (i = 1,2) is the traction component of the solid, and  $p_n$  is normal derivative of the pressure given by  $p_n = \partial p / \partial n$ . In addition,  $q_i^{\text{in}}(\mathbf{x}, t)$  represents generalized displacement for the incident wave, and the free term  $C(\mathbf{x})$  is given by

$$C(\mathbf{x}) = \begin{cases} 1 & : \mathbf{x} \in D \\ 1/2 & : \mathbf{x} \in S \\ 0 & : \mathbf{x} \in D_c \end{cases}$$
(9)

where  $D_c$  denotes complementary domain of the analytical domain D. In Eq. (7),  $U_{IK}(\mathbf{x}, \mathbf{y}, t)$  and  $W_{IK}(\mathbf{x}, \mathbf{y}, t)$  represent time-domain fundamental solutions and its double layer kernels, respectively.

### Time- and Spatial Discretization of BIEs

Algebraic equation which can be solved computationally is derived via time- and spatial discretization of the time-domain BIEs shown in Eq. (7). Time- and spatial discretization is applied by the following manners: Convolution quadrature method (CQM) based on the backward difference formula is used for time-discretization. Collocation method with constant shape function is used for spatial discretization. Approximation formula of the CQM is given by the following equations:

$$f(n\Delta t) * g(n\Delta t) = \sum_{k=0}^{n} \omega_{n-k}(\Delta t) g(n\Delta t)$$
(10)

where  $\Delta t$  represents time increment, and  $\omega_m$  is the weight function as follow:

$$\omega_m(\Delta t) = \frac{1}{2\pi i} \int_{|z|=R} \hat{f}\left(\frac{\gamma(z)}{\Delta t}\right) z^{-n-1} dz \tag{11}$$

where i is the imaginary unit, and  $\hat{f}$  denotes the Laplace transform of f. In the numerical computation, the integration in Eq. (11) is evaluated by *L*-point trapezoidal rule. Therefore, the weight function  $\omega_m$  is expressed as follows:

$$\omega_m(\Delta t) \approx \frac{R^{-m}}{L} \sum_{l=0}^{L-1} \hat{f}\left(\frac{\gamma(z_l)}{\Delta t}\right) e^{-\frac{2\pi i m l}{L}}.$$
(12)

The CQM parameters  $\gamma(z_l)$  and R, with an error magnitude  $O(\epsilon)$ , are written as follows:

$$\gamma(z_l) = \sum_{i=1}^{k} \frac{1}{i} (1 - z_l)^i, \quad z_l = R e^{-2\pi i \frac{l}{L}}, \quad R = e^{\frac{1}{2L}}.$$
 (13)

Note that Eq. (13) corresponds to the backward differentiation formulas of order k. Using the CQM formula and taking the limit process  $\mathbf{x} \in D \rightarrow \mathbf{x} \in S$ , the following discretized BIEs are obtained:

$$\begin{bmatrix} \frac{1}{2} \delta_{MN} \delta_{IK} + B_{MN;IK}^{(0)} \end{bmatrix} q_{N;K}^{(n)} - A_{MN;IK}^{(0)} s_{N;K}^{(n)} = q_{M;I}^{\mathrm{in}(n)} + \sum_{k=1}^{n-1} \begin{bmatrix} A_{MN;IK}^{(n-k)} s_{N;K}^{(k)} - B_{MN;IK}^{(n-k)} q_{N;K}^{(k)} \end{bmatrix}, (n = 1, 2, \cdots, N_t).$$
(14)

In Eq. (14),  $M, N = 1, 2, \dots, N_e$  where  $N_e$  represents the number of boundary elements. Equation (14) describes the BIEs at *n*-th time step, and  $N_t$  is the total number of time step. Moreover,  $A_{MN;IK}^{(k)}$  and  $B_{MN;IK}^{(k)}$  are the influence functions as follows:

$$A_{MN;IK}^{(m)} = \frac{R^{-m}}{L} \sum_{l=0}^{L-1} \left[ \int_{S^N} \widehat{U}_{IK}(\mathbf{x}^M, \mathbf{y}^N, s_l) dS(\mathbf{y}) \right] e^{-2\pi i m \frac{l}{L}}$$
(15)

$$B_{MN;IK}^{(m)} = \frac{R^{-m}}{L} \sum_{l=0}^{L-1} \left[ \int_{S^N} \widehat{W}_{IK}(\mathbf{x}^M, \mathbf{y}^N, s_l) dS(\mathbf{y}) \right] e^{-2\pi i m \frac{l}{L}}$$
(16)

where  $s_l = \gamma(z_l)/\Delta t$ , and  $\widehat{U}_{lK}(\mathbf{x}, \mathbf{y}, s)$  and  $\widehat{W}_{lK}(\mathbf{x}, \mathbf{y}, s)$  are the Laplace-domain fundamental solutions and its double layer kernels, respectively. Substituting prescribed boundary conditions into Eq. (14) and solving the resulting algebraic equation, unknown boundary values can be obtained.

### Laplace-Domain Fundamental Solutions

Laplace-domain fundamental solutions are required for computation of the influence functions, and given by the following equation:

$$\hat{L}_{PQ}\hat{U}_{QK}(\mathbf{x},\mathbf{y},s) = -\delta(\mathbf{x}-\mathbf{y})\delta_{PK}$$
(17)

where  $\delta(\cdot)$  is Dirac delta function,  $\delta_{IK}$  is Kronecker delta, and

$$\hat{L}_{ik} = C_{ijkl} \frac{\partial}{\partial x_j} \frac{\partial}{\partial x_l} - \tilde{\rho}_{ik} s^2, \quad \hat{L}_{i4} = -\tilde{\alpha}_{ij} \frac{\partial}{\partial x_j}, 
\hat{L}_{4k} = \tilde{\alpha}_{kl} \frac{\partial}{\partial x_l}, \quad \hat{L}_{44} = -\frac{1}{s^2} Y_{jl}^{-1} \frac{\partial}{\partial x_j} \frac{\partial}{\partial x_l} - \frac{1}{M}, 
\tilde{\alpha}_{ik} = \alpha_{ik} - \rho_f Y_{ik}^{-1}, \quad \tilde{\rho}_{ik} = \rho \delta_{ik} - \rho_f^2 Y_{ik}^{-1}.$$
(18)

Solving Eq. (17) using Radon and Fourier transform, the following fundamental solutions are obtained:

$$\widehat{U}_{ik}(\mathbf{x}, \mathbf{y}, s) = \frac{1}{4\pi^2} \int_{|\mathbf{p}|=1} \sum_{\alpha=1}^{4} \Lambda_{ik}^{\alpha}(\mathbf{p}) \Phi^{\alpha} dL(\mathbf{p}),$$

$$\widehat{U}_{i3}(\mathbf{x}, \mathbf{y}, s) = \frac{1}{4\pi^2} \int_{|\mathbf{p}|=1} \sum_{\alpha=1}^{4} \Lambda_{i4}^{\alpha}(\mathbf{p}) \Psi^{\alpha} dL(\mathbf{p}),$$

$$\widehat{U}_{3k}(\mathbf{x}, \mathbf{y}, s) = \frac{1}{4\pi^2} \int_{|\mathbf{p}|=1} \sum_{\alpha=1}^{4} \Lambda_{4k}^{\alpha}(\mathbf{p}) \Psi^{\alpha} dL(\mathbf{p}),$$

$$\widehat{U}_{33}(\mathbf{x}, \mathbf{y}, s) = \frac{1}{4\pi^2} \int_{|\mathbf{p}|=1} \sum_{\alpha=1}^{4} \Lambda_{44}^{\alpha}(\mathbf{p}) \Phi^{\alpha} dL(\mathbf{p}),$$
(19)

where







Figure 3. Time histories of the displacement  $u_1$  around a cavity at several times.

$$\Lambda_{IK}^{\alpha}(\mathbf{p}) = k_{\alpha} \frac{\left(\operatorname{adj}\left[\tilde{\tilde{\mathbf{L}}}\right]\right|_{k=k_{\alpha}}\right)_{IK}}{\frac{\partial}{\partial k} \operatorname{det}\left[\tilde{\tilde{\mathbf{L}}}\right]_{k=k_{\alpha}}},$$
(20)

$$\Phi^{\alpha} = e^{-ik_{\alpha}|\mathbf{p}\cdot\mathbf{r}|} E_{1}(-ik_{\alpha}|\mathbf{p}\cdot\mathbf{r}|) + e^{ik_{\alpha}|\mathbf{p}\cdot\mathbf{r}|} \{E_{1}(ik_{\alpha}|\mathbf{p}\cdot\mathbf{r}|) + i\pi\},$$
(21)

$$\Psi^{\alpha} = \operatorname{sgn}(\mathbf{p} \cdot \mathbf{r}) [-e^{-ik_{\alpha}|\mathbf{p} \cdot \mathbf{r}|} E_{1}(-ik_{\alpha}|\mathbf{p} \cdot \mathbf{r}|) + e^{ik_{\alpha}|\mathbf{p} \cdot \mathbf{r}|} \{E_{1}(ik_{\alpha}|\mathbf{p} \cdot \mathbf{r}|) + i\pi\}].$$
(22)

In Eq. (20), () and () denotes Radon and Fourier transform. Moreover, in Eqs. (21) and (22),  $E_1(\cdot)$  is the exponential integral, and  $\mathbf{r} = \mathbf{x} - \mathbf{y}$ .  $k_{\alpha}$  is obtained by solving the following equation:

$$\det\left[\tilde{\mathbf{L}}\right] = C_1 k_{\alpha}^8 + C_2 k_{\alpha}^6 + C_3 k_{\alpha}^4 + C_4 k_{\alpha}^2 + C_5 = 0, \quad \operatorname{Im}[k_{\alpha}] > 0.$$
(23)

where  $C_1, C_2, \dots, C_5$  are coefficients.

In Eqs. (19), the subscript written by small letter ranges from 1 to 2, and the integrals over the unit circle ( $|\mathbf{p}| = 1$ ) are implemented as a consideration of the interference of the body waves propagating in every direction. Moreover, the summation with respect to  $\alpha$  denotes the superposition of the four body waves. In numerical computation, integrals over the unit circle are evaluated using double exponential formula [Takahasi and Mori (1974)]. The number of sampling points of these integrals is set to 1,400 in this research. Therefore, the computational cost is quite high. On the other hand, the double layer kernels  $\hat{W}_{IK}(\mathbf{x}, \mathbf{y}, s)$  are given by the following equations:

$$\widehat{W}_{IK}(\mathbf{x}, \mathbf{y}, s) = \widehat{B}_{KI}^{\mathbf{y}} \widehat{U}_{IJ}(\mathbf{x}, \mathbf{y}, s)$$
(24)

where

$$\hat{B}_{ik}^{\mathbf{y}} = -C_{ijkl}n_j(\mathbf{y})\frac{\partial}{\partial x_l}, \quad \hat{B}_{i3}^{\mathbf{y}} = \frac{M_{ij}}{M}n_j(\mathbf{y}),$$

$$\hat{B}_{3k}^{\mathbf{y}} = -\rho_f Y_{kl}^{-1}n_l(\mathbf{y}), \quad \hat{B}_{33}^{\mathbf{y}} = \frac{1}{s^2}Y_{jl}^{-1}n_j(\mathbf{y})\frac{\partial}{\partial x_l},$$

$$Y_{ik} = m_{ik} + \frac{\eta}{s}r_{ik}.$$
(25)



Figure 4. Time histories of the fluid pressure *p* around a cavity at several times.

Table 1.	. Effect	of GPU	parallelization.
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	CPU times (s)
CQ-BEM without paral-	23847.59
lelization	
CQ-BEM with OpenMP	2001.67
using 24 threads	
CQ-BEM with GPU par-	940.36
allelization	

In Eqs. (25),  $n_i(\mathbf{y})$  represents the unit normal vector at the point  $\mathbf{y}$  on the boundary S.

#### **Numerical Examples**

### Wave Scattering Analysis by a Cavity

Wave scattering problem by a cavity is solved by the proposed CQ-BEM. Analytical model is illustrated in Fig. 2, and sandstone [Carcione (1996)] which is known as a transversely isotropic fluid-saturated porous solid is used. The boundary *S* is divided into 32 boundary elements, and time increment is given by  $c^*\Delta t/a = 0.05$ . Note that  $c^* = \sqrt{C_{66}/\rho_s}$ ,  $C_{66}$  is the component of elastic tensor, and  $\rho_s$  is density of solid skeleton. The total number of time step  $N_t$  is set to 512. In addition, incident wave is given by the following equations:

$$q_I^{\rm in}(\mathbf{x},t) = -W_{IK}(\mathbf{x},\mathbf{y}^{\rm src},t) * p_K^{\rm src}(t), \qquad (26)$$

$$p_{K}^{\rm src}(t) = \frac{\delta_{1K}}{2} \left\{ 1 - \cos\left(\frac{2\pi t}{T}\right) \right\} \{H(t) - H(t - T)\}$$
(27)

where  $H(\cdot)$  is Heaviside function. Moreover, the source point is set to  $\mathbf{y}^{\text{src}} = \{-2.5a, -2.5a\}^{\text{T}}$ , and the period of source function  $p_{K}^{\text{src}}(t)$  is set to  $T = 16\Delta t$ . The CQM parameters described in Eq. (13) are given as follows:  $\epsilon = 1.0 \times 10^{-12}$ , and k = 1.

Figure 3 and 4 are shown time histories of the displacement components in  $x_1$ -direction and fluid pressure, respectively. In these figures, incident waves generated at the source point are propagating with complex wave surfaces. When the incident waves arrived at the boundary of the cavity, scattered waves are generated.

### Performance of GPU parallelization

In recent years, the use of GPU for general purpose computing, which is often called GPGPU, has received considerable attentions. GPGPU provides a fine-grained parallelization, and the structure of this parallelization is different from a structure using MPI which is coarse-grained parallelization. As mentioned in the previous section, the influence functions shown in Eqs. (15) and (16) require much computational time because these functions include two integrations: integrations over the boundary

element  $S^N$  and the unit circle ( $|\mathbf{p}| = 1$ ). Therefore, in this study, GPU parallelization is applied to the numerical computations of the influence functions. For the numerical computations, TSUBAME 2.5 which is the supercomputer of Tokyo Institute of Technology is used. CPU and GPU of TSUBAME 2.5 are Intel Xeon 2.93 GHz, NVIDIA Tesla K20X, respectively.

Wave scattering problems are solved for evaluating the effect of GPU parallelization. The total number of time step  $N_t$  is set to 128, and other analytical parameters are the same as the previous analysis. Table 1 shows the computational time of three cases: CQ-BEM without parallelization, CQ-BEM with OpenMP parallelization using 24 threads, and CQ-BEM with GPU parallelization. From these results, GPU parallelization can reduce computational time of the proposed CQ-BEM dramatically.

### Conclusions

In this paper, a convolution quadrature boundary element method for general anisotropic fluidsaturated porous solids and its GPU acceleration are presented. The presented Formulation is based on the formulation proposed by [Saitoh et al. (2012)], and CQM and collocation method are used for time- and spatial discretization. Wave scattering problem by a cavity in sandstone is solved using the proposed CQ-BEM. GPU parallelization is implemented to reduce the computational time of evaluations of the influenced functions given by Eqs. (15) and (16). The computational time is reduced compared with both conventional CQ-BEM and that with OpenMP. In near future, CQ-BEM for three-dimensional wave scattering problems in general anisotropic fluid-saturated porous solid will be developed.

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#### References

- Biot, M.A. (1956a) Theory of propagation of elastic waves in a fluid-saturated porous solid. I. Low-frequency range, *The Journal of the Acoustical Society of America*, **28**(2), 168–178.
- Biot, M.A. (1956b) Theory of propagation of elastic waves in a fluid-saturated porous solid. II. Higher frequency range, *The Journal of the Acoustical Society of America*, **28**(2), 179–191.
- Biot, M.A. (1962) Mechanics of deformation and acoustic propagation in porous media, *Journal of Applied Physics*, **33**(4), 1482–1498.
- Carcione, J. M. (1996) Wave propagation in anisotropic saturated porous media: Plane-wave theory and numerical simulation, *Journal of the Acoustic Society of America*, **99**(5), 2655–2666.
- Domínguez, J. (1992) Boundary element approach for dynamic poroelastic problems, *International Journal for Numerical Methods in Engineering*, 35, 307–324.
- Saitoh, T., Chikazawa, F. and Hirose, S. (2012) Large-scale transient poroelastodynamic analysis using convolution quadrature time-domain boundary element method, *4th International Conference on Computational Methods* (*ICCM2012*), CD-ROM.
- Schanz, M. (2001) Application of 3D time domain boundary element formulation to wave propagation in poroelastic solids, *Engineering Analysis with Boundary Elements*, **25**, 363–376.
- Schanz, M. and Antes, H. (1997) Application of 'Operational quadrature methods' in time domain boundary element method, *Meccanica*, **32**, 179–186.
- Sharma, M. D. (2005) Polarisations of quasi-waves in a general anisotropic porous solid saturated with viscous fluid, *Journal of Earth System Science*, **114**(4), 411–419.
- Takahasi, H. and Mori, M. (1974) Double exponential formulas for numerical integration, *Publications of the Research Institute for Mathematical Sciences, Kyoto University*, **9**(3), 721–741.