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Efficient 3D boundary element dynamic analysis of discontinuities

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ABSTRACT

In the present study, a nonlinear joint element model with a coupled shear-tensile behavior for multi body boundary element frictional contact problems is presented. The analysis is carried out by discrete crack model using the multi-region 3D boundary element method including material damping. To account for the decay of joint strength parameters at intermediate courses of deformation, the simplified discrete crack joint model (SDCJ) has been used. The nonlinear nature of contact problems demands an iterative technique development to determine the actual contact conditions (opening and sliding with bonding and friction) at arbitrary points of the contact boundaries. Through several analyses, it is demonstrated that the proposed method is robust, as it does not require to solve the whole system simultaneously. As a particular case, the influence of foundation inhomogeneity on the seismic response of concrete arch dam has been studied in order to illustrate the accuracy and efficiency of the present approach in a complicated case.

1. Introduction

The boundary element method (BEM) is a very effective numerical tool for dynamic analysis of linear elastic bounded and unbounded media. Its main advantage is that the discretization is applied only on the boundary, yielding much fewer numbers of degrees of freedom and equations. However, with the conventional boundary element method only elastic and homogeneous domains can be analyzed.

Mainly if nonlinear material behavior is to be modeled with boundary elements, then a volume discretization is needed. Coupling techniques in which BEM equations are combined with other numerical methods are the alternative approach to solve nonlinear practical problems. In this way, the main advantages of both methods could be retained while their respective disadvantages are avoided.

The first idea of coupling BEM and FEM was published by Zienkiewicz et al. [1] for the analysis of solids, which was followed by the works of Brebbia and Georgiou [2] for elastostatics and Beer and Meek [3] for elasto-plasticity [4]. Since then, numerous investigators have contributed to this subject. However, the work of Romero et al. [5], von Estorff and Firuziaan [6] and Soares et al. [7] seem as the most general and whilst considering nonlinear behavior in the FEM domain.

In recent years, many researchers have solved the contact problem using the boundary element method. Man et al. [8,9] have dealt with the contact problem using an incremental loading procedure, with which the solution of the contact and of the friction conditions is mainly carried out for two solids. Takahashi and Brebbia [10] have reduced this problem to a problem defined on the interface with a flexibility approach. Moreover, his method permits to execute the computation for the boundary elements and the contact surface separately.

Abascal [11] and Antes and Steinfeld [12] have both developed iterative time-stepping direct BE techniques to solve realistic, frictional contact problems for the analysis of soil-foundation interaction. Tabatabai-Stocker and Beer [13] have extended the method used by Beer [14] in statics to transient dynamics modeling disconnecting and connecting degrees of freedom for fracture propagation and crack sides interaction. Bangyong and Yijun [15] propose two algorithms for solving 3-D elastostatics frictional contact problems by the BEM with non-conforming discretization dealing with the point-on-surface approach. Leahy and Becker [16] have focused on a generalized numerical scheme to form a deduced set of determinate simultaneous equations that can deal with any relative orientation of the contact element pairs, and stick-slip contact status. Leonel and Venturini [17] propose a nonlinear BEM formulation using tangent operator to deal properly with contact problems using implicit formulation. This operator uses the derivate of the set of algebraic equations to construct the corrections on the non- linear process.

However, there are very few papers dealing with the realistic features of geological faults and cracks which may close and reopen with interactive shear-tensile natures during failures. Nevertheless, using discrete crack models, a versatile and easy to implement algorithm is proposed here to trace the probable

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cracking wherever it might happen such as in contraction joints of a concrete dam body, or in its corresponding foundation.

The present paper is in essence a further development of the strategy originally proposed by Beer [14,18] for static problems. This idea is extended to dynamic problems by applying contact joints using an appropriate discrete crack joint model, i.e., the Simple Discrete Crack Joint (SDCJ) model; where contact surfaces points are assumed to be in one of the three situations of bounding, separation and sliding while shear-tensile damages are accounted for. The implicit formulation is based solely on the use of singular integral equations, to model the possible conditions of contacts that may arise along the boundaries of adjacent bodies as presented in [19].

As only interface variables are involved in nonlinear behavior in the contact mechanics, the proposed method allows an even more efficient and straight forward treatment of multiple regions (in particular, comparing with the BEM-FEM coupling techniques) and is also amenable to parallel computing [18].

2. Joints and contact modeling

The present method is based on non-associated plasticity model named SDCJ model to account for the coupled shear-tensile failure as well as for joint damage concept using BEM. The model assumes alternative joint cohesion values depending on joint opening extent and structural shear key dimensions. The latter is especially crucial in modeling arch dam vertical contraction joints.

In the proposed method of modeling cracks a domain is divided into different sub-regions along a pre-existing fault or along the line where a crack is supposed to develop. Thus it is possible to set up the same boundary equations for co-incident nodes of different crack sides without making the algebraic system of equations singular. Boundary element equation is generated for each region separately and in a standard manner. The system is thus solvable after including the additional relations, determining the status of all interface node pairs corresponding to the boundary of adjacent BE regions.

Relative tangential and normal deformations at the joint surfaces cause internal resisting forces or tractions. In the elastic range, constitutive law for the interface surface is given by

$$\{\sigma\} = [D_e]\{\delta\} \tag{1}$$

$$\begin{Bmatrix} \sigma_n \\ \tau_s \\ \tau_t \end{Bmatrix} = \begin{bmatrix} k_{n0} & 0 & 0 \\ 0 & k_{s0} & 0 \\ 0 & 0 & k_{s0} \end{bmatrix} \begin{Bmatrix} v \\ u_s \\ u_t \end{Bmatrix} \tag{2}$$

where σ_n, τ_s and τ_t are the normal and the two tangential (shear) tractions, υ, u_s and u_t are the normal and the tangential relative displacements.k_{n0} and k_{s0} are the properly selected penalty parameters to guarantee the no-slip and no-penetration conditions of the initially undamaged interface surfaces. These parameters have the dimension of force per unit volume and are also called the initial shear and normal joint stiffness coefficients.

Based on engineering intuition, only the more influential parameters such as joint initial tensile strength F_t, joint asperity height D_n, joint cohesion c, and coefficient of friction μ, are adopted and taken into consideration for joint modeling.

Thus, joint normal and resultant shear tractions can be represented as functions of different variables in the following manner

$$\sigma_n = k_n(u,\ v,\ F_t,\ k_n)v$$

$$\tau = k_s(v,\ \mu,\ c,\ D_n,\ \sigma_n,\ k_s)u \tag{3}$$

Table 1
Contact stiffness coefficients in matrix *D*.

Stiffness coefficient	Joint state parameter (ITEN)						
	Intact	Tensile damage			Shear damage		
	0	1	2	3	4	5	6
ks	K_{s0}	K_{s0}	0	nK_{s0}	0	mK_{s0}	0
k_n	K_{n0}	K_{n0}	0	0	K_{n0}	K_{n0}	0

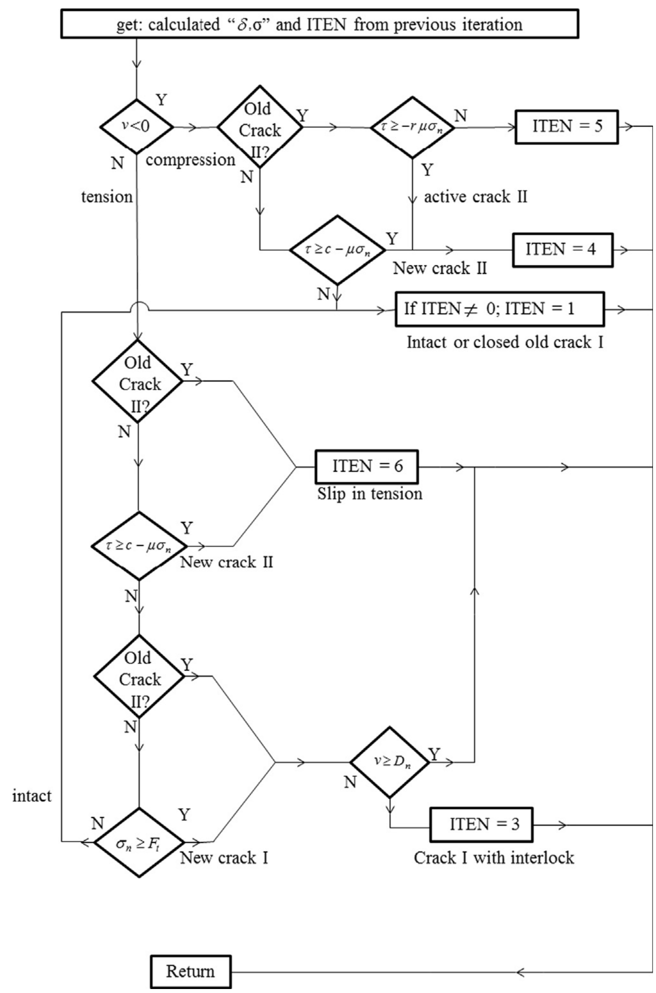

Fig. 1. Flowchart of SDCJ model.

or

$$\{\sigma\} = [\boldsymbol{D}]\{\delta\} \tag{4}$$

The above-elaborated SDCJ model, is especially developed to study the nonlinear joints (such as contraction joints) behavior of arch dams in static and dynamic excitations. The SDCJ model prescribes two types of cracks (or failure modes) defined at each gauss point of joint elements. These are the crack mode-I due to tensile failure, and the crack mode-II due to shear failure. A state parameter (ITEN) describes the joint behavior in the following manner: ITEN=0 for intact joint, ITEN=1 for crack-I in compression, ITEN=2 for crack-I in tension with $\upsilon \geq D_n$, ITEN=3 for crack-I in tension with $\upsilon < D_n$, ITEN=4 for crack-II in compression with $\tau \geq \tau_u$ (τ_u, being the joint shear strength), ITEN=5 for crack-II in compression with $\tau \leq \tau_u$, and finally ITEN=6 for crack-II in tension.