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Dynamic fracture analysis of the soil-structure interaction system using the scaled boundary finite element method

Denghong Chen[a,*], Shangqiu Dai[b]

[a] *Hubei Key Laboratory of Disaster Prevention and Mitigation, China Three Gorges University, Yichang 443002, China*
[b] *Jiangsu Institute of Building Science Co., Ltd., Nanjing, China*

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ABSTRACT

Dynamic fracture analysis of the soil-structure interaction system by using the scaled boundary finite element method is presented in this paper. The polygon scaled boundary finite elements, which have some salient features to model any star convex polygons, are employed for modelling the near-field bounded domains. A procedure for coupling the bounded domains with an improved continued-fraction-based high-order transmitting boundary is established. The formulations of the soil-structure interaction system are coupled via the interaction force vector at the interface. The dynamic stress intensity factors and T-stress are extracted according to the definition of the generalized stress intensity factors. The dynamic stress intensity factors of the coupled system are evaluated accurately and efficiently. Two numerical examples are demonstrated to validate the developed method.

1. Introduction

Many civil engineering investigations and practices show that cracks commonly appear in the concrete structures and rocks. The presence of cracks has a great influence on the responses of structures under the action of several static and dynamic loads [1]. There are two main numerical challenges in modelling the whole soil-structure interaction system, i.e.

- stress singularity at crack tips and crack propagation;
- modelling of unbounded domain, i.e. accurate description of radiation damping at infinity.

The finite element method (FEM) has been a predominant numerical method in many fields. However, crack propagation modelling with the FEM is still a challenging subject, because it usually requires both fine crack tip meshes and sophisticated remeshing techniques during crack propagation. In addition, when the FEM is employed to study the dynamic soil-structure interaction problem, a finite computational domain should be truncated from the semi-infinite space. If the fixed boundary conditions without special treatment are adopted, the outgoing waves are reflected at the truncated boundaries of the finite element mesh. Another straightforward application of the FEM is the modelling of an unbounded domain using the extended mesh whose outer boundary lies outside the domain of influence. However, the extended mesh requires an extremely large computational region and a tremendous amount of computational cost to analyze the dynamic responses of the soil-structure interaction system. Many global and local procedures, such as the boundary element method (BEM) [2,3], the viscous boundary [4], the viscous-spring boundary [5,6], infinite elements [7], the transmitting boundary [8], etc, have been developed to take into account of the radiation condition of the unbounded domain. Their advantages and disadvantages are referred in a number of review literatures [9–11].

The scaled boundary finite element method (SBFEM), developed by Wolf and Song in 1990s [12,13], is a semi-analytical technique which excels in modelling time-dependent problems in unbounded domains and in modelling bounded domains with singularities. In the SBFEM, the governing partial differential equations (PDEs) of elastodynamics in the circumferential direction are transformed to the ordinary differential equations (ODEs), with the radial coordinate as the independent variable, which can be solved analytically and lead to the following distinguishing features. First of all, for an unbounded domain, the radial coordinate points from the boundary towards infinity. The boundary conditions at infinity (radiation condition) are satisfied exactly in the analytical solution. Secondly, for a bounded domain, the radial coordinate points from the boundary towards the interior. The accurate stress intensity factors (SIFs) can be obtained directly from the analytical stress fields based on the definition.

* Corresponding author.
E-mail address: d.chen@ctgu.edu.cn (D. Chen).

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In the aspect of modelling the unbounded medium, a rigorous solution procedure, which is based on the solution of the acceleration unit-impulse response matrix of the unbounded domain, was commonly utilized in the references [14–17]. It is global in time and space and thus computationally expensive [18,19]. Alternative procedures, which aim at avoiding the convolution integral altogether by developing the scaled boundary finite element method directly in the time domain, have been proposed recently. A Padé approximation for the dynamic stiffness matrix of an unbounded medium in the frequency domain has been proposed by Song and Bazyar [20], which has a large range and high rate of convergence. A high-order local transmitting boundary based on a continued-fraction solution of the dynamic stiffness matrix at high-frequency limit $\omega \to \infty$ has been developed by Bazyar and Song [21]. But it may fail for systems with a larger number of degrees of freedom (DOFs) and for approximations of higher order. A doubly-asymptotic continued-fraction solution of the dynamic stiffness has been proposed [22], in which only the scalar case has been addressed so far. An improved continued-fraction solution for the dynamic stiffness matrix of the unbounded domain has been presented by Birk et al. [23], which yields numerically more robust results and is suitable for large-scale systems and arbitrarily high orders of expansion. A high-order time-domain approach for wave propagation in bounded and unbounded domains has been proposed [24], in which the high-order time-domain formulation representing the bounded domain is coupled to the improved high-order transmitting boundary for unbounded domains proposed in [23]. A FE-SBFEM coupled approach, which is based on the continued fraction solution of dynamic stiffness in [21], has been employed to solve the semi unbounded inclined soil field with bedrock in time domain [25].

In the aspect of fracture analysis, the SBFEM has been well demonstrated by calculating static stress intensity factors (SIFs) for isotropic materials [26], anisotropic materials [27], functionally graded materials [28] and piezoelectric composites [29,30]. After coupling with several simple remeshing methods, such as polygon elements in [31–33], quadtree meshes in [34] and a non-matching method in [35], the SBFEM has been successfully applied to static crack propagation problems. According to these attributes, the SBFEM has also been exploited in coupling with FEM [36], BEM [37] or XFEM [38–40] for calculating parameters in fracture mechanics and crack propagation. For dynamic fracture mechanics analyses, a super-element, represented by the static stiffness matrix and mass matrix, was proposed by Song [41]. The dynamic crack propagation has been modeled based on this super-element method with polygon [42] or quadtree meshes [43]. Although the advantages of the SBFEM in representing stress singularities are retained, the size of the super-element is limited by the highest frequency component of interest, which may lead to considerable computational cost in each time step. Instead of this super-element, a frequency domain method to calculate dynamic SIFs for homogenous materials and bimaterial interface problems are presented by Yang et al. [44] and Yang and Deeks [45]. However, it is not easily amendable to time domain crack propagation. Recently, the dynamic analysis of isotropic and anisotropic materials has been performed efficiently with a novel solution procedure, known as the continued fraction algorithm, in both frequency and time domain [46,47], in which the high frequency response is modeled by the high-order terms [48]. However, the method may fail for systems with a large number of DOFs and for approximations of high-order expansions [24]. To the best of our knowledge, there are few studies on the dynamic fracture analysis for the soil-structure interaction system at present.

This paper aims to combine the two distinguishing features of the SBFEM and solve the crack problems in the soil-structure interaction system in the time domain. The bounded domain is modeled by the polygon elements. The unbounded domain is represented by a high-order transmitting boundary, which is based on the improved continued fraction solution for the dynamic stiffness matrix. The rest of the paper is outlined as follows. In Section 2, some basic equations about the polygon scaled boundary finite element method are briefly described. In Section 3, a high-order approach for the dynamic soil-structure interaction system by using the SBFEM is presented. In Section 4, a numerical procedure to extract the dynamic stress intensity factors and T-stress with the definition of the generalized stress intensity factors is addressed. In Section 5, the application of the proposed coupled method to two numerical examples is demonstrated. In Section 6, some major conclusions from this contribution are summarized.

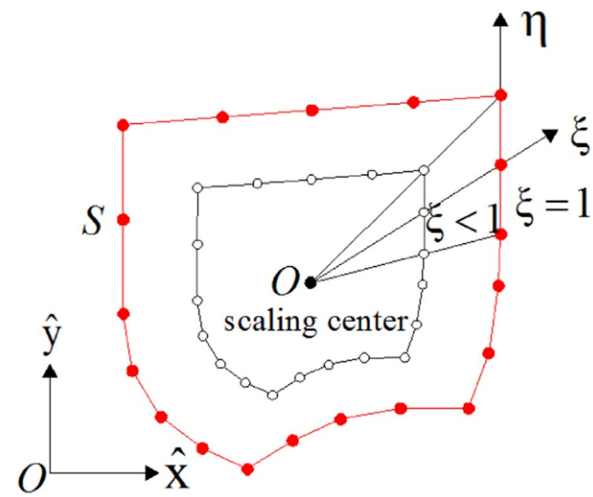

Fig. 1. The basic concept of the SBFEM.

2. Summary of the polygon scaled boundary finite element method

The basic concepts and equations of the scaled boundary finite element method are introduced in detail in the literature [12,13]. For completeness, only some main equations are summarized in this section.

As shown in Fig. 1, the SBFEM is described in a local coordinate system, η on the boundary and the radial coordinate ξ. The whole domain can be divided into several subdomains (also named super-elements [49]) in a manner similar to the FEM and each subdomain is defined by scaling a boundary S relative to its scaling center O. The normalized radial coordinate ξ is a scaling factor, defined as 1 at the boundary S and 0 at the scaling center O. For a bounded subdomain, $0 \le \xi \le 1$; whereas, for an unbounded subdomain, $1 \le \xi < +\infty$.

The displacements at a point (ξ, η) are interpolated as

$$\{u(\xi, \eta)\} = [N(\eta)]\{u(\xi)\} = [N_1(\eta)[I],\ N_2(\eta)[I],\ \dots]\{u(\xi)\} \tag{1}$$

where $[N(\eta)]$ are the shape functions in the circumferential directions. $\{u(\xi)\}$ are the displacements function along the radial lines and are analytical with respect to ξ only.

The strains are derived as

$$\{\varepsilon(\xi, \eta)\} = [B^1(\eta)]\{u(\xi)\}_{,\xi} + \frac{1}{\xi}[B^2(\eta)]\{u(\xi)\} \tag{2}$$

where $[B^1(\eta)]$ and $[B^2(\eta)]$ represent the strain-nodal displacement relationship.

The stresses are derived as

$$\{\sigma(\xi, \eta)\} = [D]\{\varepsilon(\xi, \eta)\} \tag{3}$$

where $[D]$ is the elastic matrix. After expressing the governing differential equations in the scaled boundary coordinates, Galerkin's weighted residual method or the virtual work formulation [50] is applied in the circumferential directions. In the frequency domain, the two-dimensional fundamental equation of the scaled boundary finite element in displacement $\{u(\xi)\}$ is shown to be