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Numerical simulation of soft longitudinal joints in concrete-faced rockfill dam

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Abstract

In the construction of high concrete-faced rockfill dams (CFRDs), soft filler is used in the longitudinal joints in order to avoid extrusion damage to the concrete face slab. In this paper, we consider the soft joint contact as an equivalent contact interface to avoid introducing conventional elements. Based on the introduction of a general transformation to obtain fully decoupled contact constraints, a new generalized node-to-segment formulation is developed to solve the multi-body contact problem in CFRDs. The high CFRD of Tianshengqiao-1 in China is numerically analyzed; the results show that soft joints can significantly reduce the axial stress of face slabs.

Keywords: High concrete-faced rockfill dam; Soft longitudinal joint; Transformation; Perturbed Lagrange method; Nonlinear contact

1. Introduction

The development of concrete-faced rockfill dams (CFRDs) has been rapid over the past two decades (Cooke, 1991). CFRDs can be built in different geological environments and climates, and the construction materials can be easily acquired. At present, the construction technologies of CFRDs with a height of 250 m or more are facing great challenges. Engineering experience from existing projects has shown that the main risk of high CFRDs is the potential failure of the concrete face slabs, especially the extrusion damage occurring in CFRDs higher than 150 m (Cao and Zhang, 2001). Fig. 1 is a photo of the extrusion damage to the concrete face slabs in the Tianshengqiao-1 CFRD project.

To prevent extrusion damage, compressible soft filler is generally used to fill the longitudinal joints between the face slabs (Cao and Zhang, 2001; Johannesson and Tohlang, 2007; Cao and Xu, 2009; Li and Yang, 2012). The soft filler can absorb axial extrusion displacement, thus improving the distribution of stress in the compressive region of the face slabs. Fig. 2 shows the schematic of a soft joint. The soft joint between two face slabs is generally narrow, and its stiffness may increase when axial extrusion develops until the joint is nearly closed. To simulate this problem numerically, thin solid elements must be generated to represent the filler, and then the contact relations of the slab–filler–slab and the filler–cushion need to be treated. However, this method is generally too complicated to implement.

A more convenient way to simulate this problem is to represent the filler and the related interface as a composite interface. Generally, an interface element method, such as the Goodman element (Goodman et al., 1968) or Desai's thin-layer element (Desai et al., 1984), can be used to simulate the

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Fig. 1. Extrusion damage to concrete face slabs in Tianshengqiao-1 CFRD project.

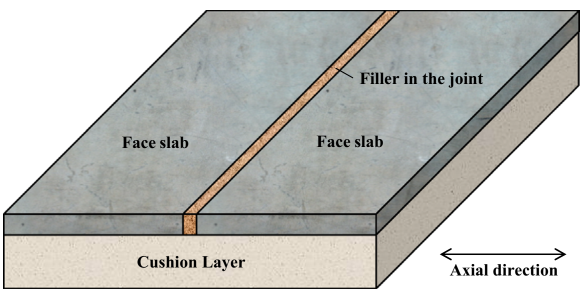

Fig. 2. Schematic of soft longitudinal joint.

interface in a CFRD numerical simulation using the finite element method (FEM) (Zhang et al., 2007; Arici, 2011; Kartal et al., 2012; Xu et al., 2012). However, researchers have indicated that it is difficult to obtain reasonable results with the interface element method when the discontinuous deformation is not small (Zhang et al., 2004; Qian et al., 2013). In particular, the interface element method generally leads to an ill-conditioned matrix system which may greatly influence the computational efficiency.

To overcome the drawbacks associated with the interface element method, the contact analysis method is a promising alternative. The node-to-segment (NTS) approach (Hallquist et al., 1985; Zhang et al., 2004; Sheng et al., 2006) and the segment-to-segment (STS) approach (Zavarise and Wriggers, 1998) are useful for simulating discontinuous deformation and for treating non-conforming meshes, and the NTS approach has been widely applied because of its simplicity. Nonlinear complementary contact constraints are imposed mainly by the penalty method, the Lagrange multiplier method, the perturbed Lagrange method or the augmented Lagrange method (Zavarise et al., 1995; Sitzmann et al., 2014).

In this paper, the interaction between the soft filler and the adjacent slabs is considered as an equivalent soft contact problem. Based on the introduction of a general transformation, we propose a new generalized NTS formulation, which includes the Lagrange multiplier formulation for hard contact problems and the perturbed Lagrange formulation for soft contact problems. The transformation yields fully decoupled contact constraints. Therefore, in the Lagrange multiplier formulation, the Lagrange multipliers are condensed, and this prevents having to solve the saddle-point problem. In the perturbed Lagrange formulation, the penalty factor is only involved in the diagonal position of the matrix system; and thus, the ill-condition is overcome. The proposed generalized NTS formulation was used here to study the effect of soft joints on the extrusion of face slabs in the Tianshengqiao-1 CFRD.

This paper is organized as follows. In Section 2, we briefly introduce the theory of the NTS approach using the Lagrange multiplier method to impose the contact constraints. In Section 3, details of the new generalized NTS formulation are given, and a convenient estimation of the penalty factor is provided. Section 4 outlines the main features of the Tianshengqiao-1 hydropower project (TSQ-1 project) and presents a numerical study on the effect of soft joints on the axial extrusion stress of face slabs. Finally, conclusions are drawn in Section 5.

2. Node-to-segment approach

2.1. Description of contact problem

Fig. 3 shows the contact between two objects with finite deformation. The kinematic description of the contact problem involves domain Ω, which is composed of a master body Ω^m and a slave body Ω^s. The current configuration, $\mathbf{x}$ (at time t), is described by reference configuration $\mathbf{X}$ (at time 0) and a mapping φ:$\mathbf{x}=\varphi(\mathbf{X}, t)$. Thus, displacement $\mathbf{u}$ can be written as $\mathbf{u}(\mathbf{X}, t)=\mathbf{x}(\mathbf{X}, t)-\mathbf{X}$. The current configurations in sub-domains Ω^m and Ω^s are denoted by $\mathbf{x}^m$ and $\mathbf{x}^s$, respectively. The unit vectors in the normal and tangential directions to the master surface are denoted by $\mathbf{n}$ and $\boldsymbol{\tau}$, respectively. Based on the normal vector, Fig. 3 also shows the projection method that yields the definition of the gap function in the normal direction, namely, $g=\mathbf{n}\cdot(\mathbf{x}^s-\mathbf{x}^m)$, where $g>0$ means that the two bodies are separated, and vice versa.

If we denote the Neumann boundary by Γ^N and the Dirichlet boundary by Γ^D, the boundary value problem (BVP) can be

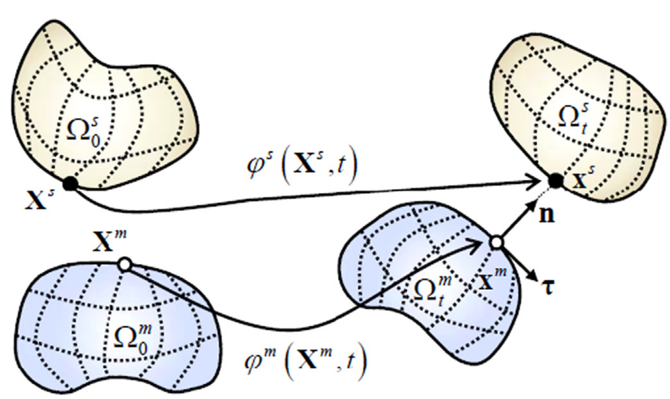

Fig. 3. Contact between two objects, illustrating two sub-domains, Ω^m and Ω^s, and projection method used in modeling.