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Dynamic Analysis of the Complete Integrated Deep-Ocean Mining Pilot System Based on Single-Body Tracked Miner and Discrete Element Model of Pipe

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ABSTRACT

The dynamic analysis of the complete integrated deep-ocean mining pilot system is carried out in this paper taking into account the interactions between each subsystem and ocean environment. The self-propelled seafloor tracked miner is modeled as a single-body vehicle with 6 degrees of freedom which allows real-time simulation and can be applied for the dynamic simulation analysis of the complete integrated mining system. The interaction model between the tracked miner and soft cohesive seafloor soil is built based on the theory of terramechanics and considering the principal dimensions of the tracked miner and the mechanical characteristics of seabed soil. The pipe subsystem including the lift pipe, pumps, the buffer and the flexible hose are built as 3-D discrete element models which are divided into rigid elements linked by flexible connectors with 6-DOF stiffness coefficients. External forces such as the hydrodynamic force of seawater, the buoyancy forces acting at discrete locations on the flexible hose, and other forces are considered. The virtual prototypes of each subsystem are modeled and connected to form the complete integrated mining system and the interaction models between mining system and environment are developed, then the dynamic simulation analysis of the complete integrated deep-ocean mining pilot system is performed and discussed.

KEY WORDS: Deep-ocean mining system; tracked miner; single-body model; pipe system; discrete element method; dynamic simulation analysis

INTRODUCTION

Interest in deep-ocean mining of manganese nodules and other metal deposits has developed as a result of rising metal prices, and out of concern for securing supplies of strategic and critical minerals. A typical and may be the most prospective deep-ocean mining system is an integration of self-propelled seafloor miner, miner-to-buffer flexible hose, buffer, pumps, lift pipe, mining ship and ocean transportation system. Fig.1 shows the poly-metallic nodule deep-ocean mining system of China's 1000-m sea trial. Due to the complexity of each subsystem and the coupled interaction between subsystem and ocean environment, the dynamic behavior analysis of the complete integrated mining system is difficult. Various studies and analysis have been carried out about pipe system and seafloor self-propelled miner, which are basic components for the dynamic analysis of the complete integrated mining system. For the pipe system, since 1980 Chung et al. (1981) have done a great deal of work about long vertical pipes by finite element method. For example, a nonlinear finite element code was developed to model 3-D dynamic behavior of long vertical pipes by Chung and Cheng(1994). In addition, a new discrete element method which is somewhat simpler than the finite element method, has been developed by Mustoe, Hettelmaier and Chung (1992) to solve the dynamic coupled bending-axial analysis of two-dimensional pipes. Subsequently, Cheng et al. (1997) proposed an improved discrete element method for linear and nonlinear dynamic analysis of 3D beam structures, and by a DEM model, Cheng et al. carried out a frequency analysis of a 1905m vertical deep-ocean pipe. A lumped parameter method for analysis of 3D nonlinear dynamics of flexible risers and lift pipes of deep-ocean mining systems has been developed in the incremental-iterative formulation (Hong, 1995, 1997), and Hong et al. (2003) developed a novel method for analysis of 3D nonlinear dynamic of marine riser/piles in terms of the four Euler parameters (Hong, 2003). Wang et al. (2005) performed dynamic analysis on 3D motions of deep-ocean mining pipe system for China's 1000m sea trial based on the finite element method. Li et al. (2005) use DEM to model and perform dynamic analysis of the poly-metallic nodule deep-ocean mining system of China's 1000m sea trial, and discussed the motions of the entire mining pipe system under different work conditions.

For the seafloor miner, tracked vehicles are preferred compared to wheeled or legged vehicles due to the larger contact area of tracks with the ground providing better floatation and the larger traction forces, which are required for the extremely cohesive soft deep-seabed soil. In order to investigate the performance of tracked vehicles, a number of studies have been carried out since Bekker's pioneering studies (1969). Wong et al (1989) developed an analytical method for predicting the normal pressure distribution under a moving tracked vehicle, taking into account the response of the terrain to repetitive shear loading. Hong et al. (2002) developed a simplified transient 3D dynamic analysis method for tracked vehicles crawling on extremely soft