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Mesoscopic investigation of the sand particulate system subjected to intense dynamic loadings

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A R T I C L E I N F O

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A B S T R A C T

This paper presents a mesoscale analysis approach to investigate the dynamic response of the sand particulate system. Firstly, a 3D mesoscopic model is developed considering the randomness of sand particles in shape and distribution. Secondly, we put forward an analysis approach to model the mechanical behavior of dry sand under static and dynamic loadings. Simulations are conducted to validate the numerical model and the analysis approach. A good agreement is attained comparing with test data. The presented 3D model can realistically model the grain-level response of the dry sand particulate system under high strain rate loadings. Finally, applications are carried out in the domain of projectile penetration into the sand particulate system. The contact and friction between sand particles are taken into account using the contact algorithm. The effects of mesoscopic configurations (porosity, particle size, contact and friction coefficients) of the specimen are discussed numerically. Simulations focusing on the stress wave propagation, projectile penetration depth and instability are conducted. Results show that impact velocity of projectile is also an important factor for penetration behavior. Porosity, particle size and friction coefficients affect ballistic instability significantly.

1. Introduction

Dry sand is a granular porous medium, which is different from such geological materials as rock, concrete, brick. In the past few years, many studies [1–15] have been conducted to investigate the dynamics of granular materials. However, the response of the sand particulate system under dynamic loading is not well understood yet for such features as shear dilatancy, rate-dependency, non-coaxiality and particle crushing.

Under static loading, sand particulate system is allowed to form shear bands and rearrange itself. Under dynamic loading, the sand particles flow and tumble ceaselessly. Viscous flow occurs as the strength of the sand particles is exceeded, which is sensitive to the rate of loading. Moreover, stress concentration on individual particle and particle-to-particle friction also plays important roles during dynamic compaction. It calls for the insights into the grain-level response of the sand particulate system under dynamic events.

From 1960s, the dynamic responses of projectile penetrating into the sand particulate system have been investigated extensively [16–21]. Allen et al. [16,17], Wang [18], Collins et al. [19], Borg et al. [20], Savvateev et al. [21] carried out a series of experiments of projectile penetration into the sand target. These experimental results indicate that the mesoscopic configurations of the sand specimen (such as initial void ratio, sand particle size, wet or dry) are important to the penetration depth. As is known to all, tests cost highly. And it is difficult to obtain insights into the grain-level response under penetration. Salgado et al. [22], Tolooiyan and Gavin [23], Gavin and Tolooiyan [24], Huang et al. [25] employ empirical and numerical methods to study the penetration into sand and soil materials. These efforts show that the projectile cone resistance is influenced more by the shear modulus and the dilation angle than by the friction angle of sand. Susila and Hryciw [8], Ahmadi et al. [9], Kiousis et al. [26], Kumar et al. [27], Sikora and Gudehus [28] studied the large deformation based on the cone penetration test (CPT) and discussed the influence of friction angle and dilation angle. However, these investigations are based on the homogeneous continuum assumptions. Due to the heterogeneity, it is hard to reveal the mesoscopic response of the sand particulate system. And the process of tumbling and deviation of projectile also cannot be studied realistically. Attention to new methods is extremely important in order to predict the grain-level performance of dry sand.

As an alternative to continuum-based method, mesoscopic approach considering the grain-level response has been developed to resolve heterogeneous variations of dry sand in recent years. Borg and Vogler [29] used the hydrocode CTH and Dwivedi et al. [30] developed the program ISP-SAND to simulate the grain-level response of sand using the mesoscale model respectively. Results were significantly influenced by the mesoscale configurations of dry sand (such as particle size, porosity, contact and friction coefficients).

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Nomenclature

ρ	density
μ	Poisson's ratio
G	shear modulus
P_s	void porosity of sand specimen
D_s	diameter of sand particle
H	penetration depth
V	impact velocity
C_p	specific heat
A	normalized cohesive strength in the HJC material model
B	normalized pressure hardening in the HJC material model
C	strain rate coefficient in the HJC material model
N	pressure hardening exponent in the HJC material model
T	maximum tensile hydrostatic pressure in the HJC material model
S_{max}	normalized maximum strength in the HJC material model
P_c	crushing pressure in the HJC material model
D_1	damage constant in the HJC material model
A_1	static yield stress in the JC material model
B_1	strain hardening coefficient in the JC material model
C_1	strain rate coefficient in the JC material model
m	thermal softening exponent in the JC material model
n	strain hardening exponent in the JC material model
T_m	melting temperature in the JC material model
T_r	room temperature in the JC material model

Ciamarra et al. [31] used molecular dynamics (MD) and Jiang et al. [32] employed discrete element method (DEM) to study the dynamics of sand. In these simulations, the sand particles are modeled using circular disks or sphere. The sand particles are assumed to be rigid body. Their deficiency is the lack of tracking material interface and grain-level deformation. Studies [33–35] have revealed that the sand particles' behavior (such as collisions, friction, deformation and fragmentation) happens continuously during penetration. Therefore, it is needed carefully to take into account the mesoscopic configurations of sand. The mesoscopic configurations (such as the contact of particle to particle and particle to projectile, the deformation of sand particles, the randomness of sand particles in shape and distribution) are critical to the dynamic behavior. Moreover, it may be more realistic based on 3D models than on 2D models.

This paper presents a mesoscale analysis approach to model the dynamic behavior of dry sand particulate system. Firstly, a 3D numerical model is set up. In order to describe the particulate features of dry sand, the randomness of sand particles in shape and distribution is resolved. Secondly, an analysis approach is established and validated taking into account the mesoscopic configurations of the target utilizing the hydrocode LS-DYNA. The friction effects are taken into account in the simulation. The deformation of sand particles is considered employing the material model in LS-DYNA. Thirdly, application is conducted to research the projectile penetration into the dry sand specimen. Finally, parametric studies are carried out focusing on the grain-level responses of the sand specimen.

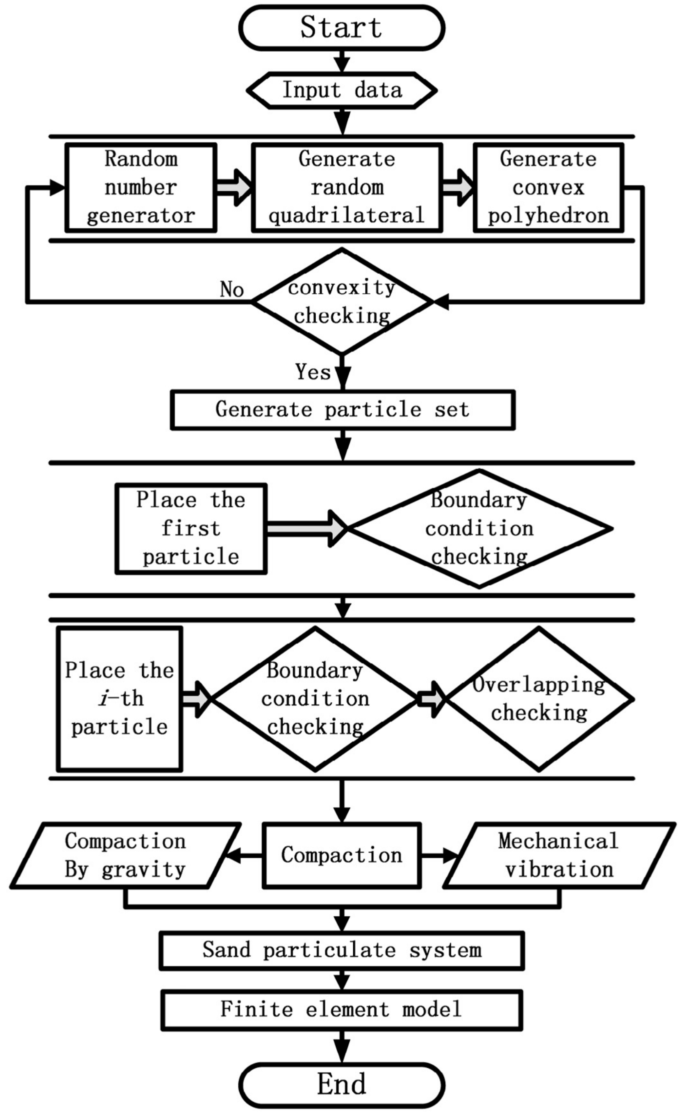

Fig. 1. The algorithm of generating sand particulate system.

2. The mesoscale model for sand particulate system

In this paper, we employ the mixed congruent algorithm to generate random number. The algorithm can be described as [36,37]: if x_i is assumed to be the initial value, the recursive function is $x_{n+1} = (N{\cdot}x_n + C)$ **mod** M. In the function, **mod** is an operator. For example, a **modulo** n (abbreviated as a **mod** n) is the remainder of the division of a by n. M is called modulus, the maximum number of numbers the formula can produce.

Based on the formally proposed 3D mesoscopic model for rock-rubble overlays [38], a new 3D mesoscopic model for dry sand is presented, emphasizing on the randomness of sand particles in size, shape and distribution. The algorithm to generate the mesoscopic model for the sand particulate system is composed of four steps. The first step is to generate individual sand particles. The second step is to take and place the generated sand particles into the specimen randomly. The third is to compact the sand specimen. The last step is to form the finite-element grid of the sand particulate system. The flow chart of the algorithm is shown in Fig. 1. Details of the algorithm can be seen in reference 39. The generated model is shown in Fig. 2.