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Modeling of particle flow due to ultrasonic drilling

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ABSTRACT

In-situ sampling and analysis is one of the major tasks in future NASA exploration missions. It is essential that the samples acquired on other planets including Mars are free of contaminations from the earth. Recently, a novel drilling technology that is actuated by a piezoelectric drive mechanism was developed and it is called Ultrasonic/Sonic Driller/Corer (USDC). This drill has an inherent capability to extract the formed drilling powder and thus addresses the critical issue of contamination. A modification of this USDC in the form of an Ultrasonic Rock Abrasion Tool (URAT) allows for the formation of pristine rock surface for analysis. An algorithm is being proposed for the reduction of the contamination that may be generated during the acquisition of the samples. The algorithm could be used to control the flow of particles using programmed vibration characteristics and thus allows for smart flow of particles. The hypothesis is that the probability of a contamination left on the ground surface is exponentially inverse-proportional to the volume of the core ground into dusts. To support this hypothesis, we need to understand the flow pattern of the particles. A model proposed by Savage [1988] is used to develop a computer program using finite difference method. Some preliminary results have been derived.

Keywords: Ultrasonic/sonic driller/corer (USDC), particle flow in-situ sampling, ultrasonic drilling, planetary exploration, piezoelectric devices, Active Materials.

1. INTRODUCTION

One major concern of NASA's Mars in-situ sampling effort is the biological contaminations that are carried by space vessels and/or instruments from earth. The samples could easily be contaminated during the acquisition process, and lead to false conclusion about the existence of life on Mars. It is critical to develop a technique that can remove the contamination attached to the samples. Recently the Non-Destructive Evaluation and Advanced Actuator (NDEAA) group at JPL and Cybersonics, Inc. developed a novel drilling technology (Bar-Cohen etc., [2001]). The new technology is the Ultrasonic/Sonic Driller/Corer (USDC) actuated by a piezoelectric driving mechanism, and the Ultrasonic Rock Abrasion Tool (URAT) modified from USDC. It is found that the drill, vibrating vigorously, has the tendency to expel the powder generated under the drill head. This characteristic of the USDC/URAT provides a tool for removing the contamination. The hypothesis is that the probability of a contamination left on the ground surface of a core sample is exponentially inverse-proportional to the volume of the core ground into dusts, expelled and sent away. In order to support this hypothesis, a computer program using finite difference method was developed to investigate the flow pattern of the particles under the pounding force from the USDC/URAT.

As early as in 1787, Chladni observed motion of sand grains on a vibrating flat plate. The vibrated sand grains tend to collect along the nodal lines, which is now known as Chladni patterns. He further observed that when the sand grains were replaced by a finer and lighter material, the vibration caused the powder to collect at the anti-nodes. The explanation for this phenomenon is that the vibration generates acoustic streaming effect in the air, which moves the finer and lighter powder to the anti-nodes. Walker [1982] did a similar experiment with the focus on the circulation patterns developed within the powder itself. He found that the particles at the bottom moved horizontally towards the center of the pile, rose upwards to the peak of the pile, finally rolled down the slopes on the sides and re-joined the pile at the bottom. This phenomenon of particle circulation due to bottom vibration is the key to the problem under investigation, shown in Fig. 1. The pounding from the bit of URAT generates vibration in the rock sample. The pounding also breaks the rock sample and introduces new particles

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into the pile. Details of the vibration-induced particle circulation are needed for assessing the feasibility of the proposed contamination-cleaning algorithm using USDC/URAT. If, for example, there is a local circulation at the center of the bit where particles never travel to the edge, the contamination may be trapped there and the hypothesis stated earlier is no longer valid. On the other hand, by knowing the details of the circulation, we may modify the design of the bit accordingly, so as to create a more uniform flow of the particles.

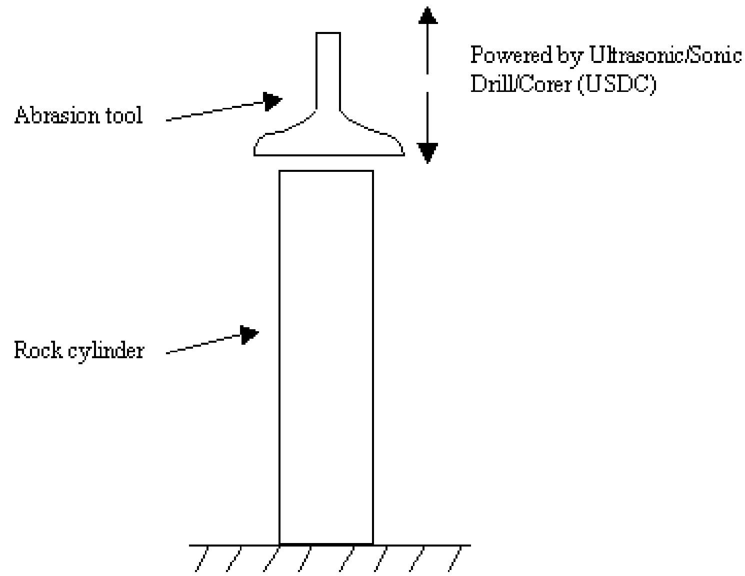


Fig. 1. A rock cylinder ground by URAT.

Theoretical analysis on the granular flow problem was pioneered by Bagnold [1954]. Haff [1983] studied the behavior of granular material in motion from a continuum point of view. He treats individual grains as “molecules” of a granular “fluid”. Unlike in a real fluid, the collision between two grains is inelastic. Haff took care of the inelastic collision by introducing an energy equation into the governing equations. He presented a set of nonlinear and coupled equations for a general grain flow problem. Savage [1988] studied vibration-induced granular flow both experimentally and theoretically. He performed the tests on rounded polystyrene beads contained in a rectangular box having transparent front and back walls, and the bottom vibrating at various frequencies and amplitudes. Slow circulating flow was observed in the form of two vortices in which the velocity was upwards at the vertical centerline and downwards along the vertical sidewalls. Savage derived an approximate solution by using a modification of the constitutive theory of Jenkins and Savage [1983]. The general flow patterns of the particle motions were predicted, but the amplitudes of the velocities were overestimated as a result of the simplifying assumptions.

The problem authors of this paper tried to solve, depicted in Fig. 1, is more complicated than the problem of circulation in a closed container. Particles flow to the edge of the rock sample fly away, and the impact of the drill bit creates new particles. We have an in-flow to and an out-flow from the control volume. In this paper, as a preliminary study of the problem, the authors employed the algorithm developed by Savage and solved a two-dimensional granular flow problem. A computer code using finite difference method was developed base on the algorithm.

2 MODELING

Governing equations derived by Savage are the mean continuity for steady streaming motions and the mean linear momentum equations in the x- and y-directions,

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \qquad (1)$$

$$\varepsilon^2 M\left(U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}\right)=-\frac{\partial T}{\partial X}+\varepsilon^3\mu\frac{\partial^2 U}{\partial X^2}+\frac{1}{2}\varepsilon\mu\frac{\partial^2 U}{\partial Y^2}+\frac{1}{2}\varepsilon^3\mu\frac{\partial^2 V}{\partial X\,\partial Y} \tag{2}$$

$$\varepsilon^4 M\left(U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}\right)=-1+\frac{1}{2}\varepsilon^5\mu\frac{\partial^2 V}{\partial X^2}+\frac{1}{2}\varepsilon^3\mu\frac{\partial^2 V}{\partial Y^2}-\frac{\partial}{\partial Y}\left[T+\frac{1}{2}M\{1+\varepsilon N Cos(\pi X)\}^2 e^{-2\delta hY}\right] \tag{3}$$

where U and V are the dimensionless mean velocities in the x- and y-directions, X and Y are the dimensionless x- and y-coordinates, T is related to the fluctuation specific kinetic energy.

$$M=\frac{v_0^2}{gh} \tag{4}$$

$$\varepsilon=\frac{h}{b} \tag{5}$$

where g is the gravitational acceleration, h and b are the thickness and the width of the layer of particles, respectively. The velocity of the base vibrations is assumed to be in the form of

$$v_b(x)=v_0\left[1+\varepsilon N\cos\left(\pi\frac{x}{b}\right)\right] \tag{6}$$

where v_0 and N are constants to be determined empirically.

Expanding the variables U, V, and T in powers of ε as

$$U=U^{(0)}+\varepsilon U^{(1)}+\varepsilon^2 U^{(2)}+\cdots \tag{7}$$

$$V=V^{(0)}+\varepsilon V^{(1)}+\varepsilon^2 V^{(2)}+\cdots \tag{8}$$

$$T=T^{(0)}+\varepsilon T^{(1)}+\varepsilon^2 T^{(2)}+\cdots \tag{9}$$

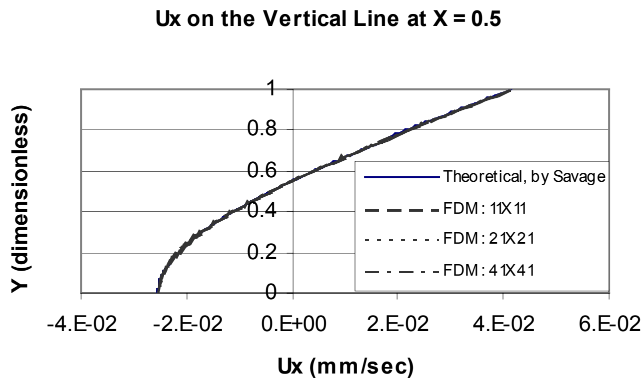
Substituting equations (7), (8), and (9) into equations (1), (2), and (3), applying the boundary condition of the zero normal stress on the top surface, we obtain the following zeroth-order equations

$$\frac{\partial U^{(0)}}{\partial X}+\frac{\partial V^{(0)}}{\partial Y}=0 \tag{10}$$

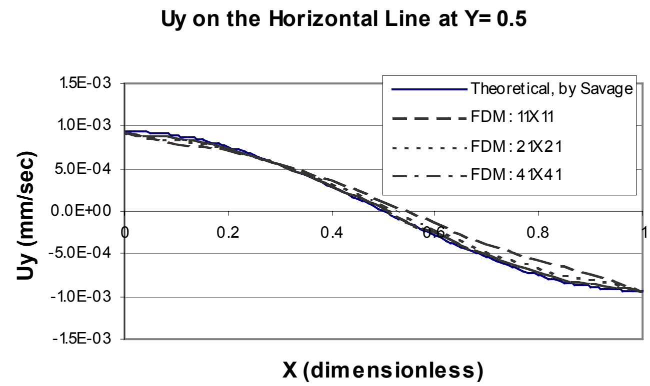
$$\frac{\mu}{2}\frac{\partial^2 U^{(0)}}{\partial Y^2}=M N\pi\sin(\pi X)\left[e^{-2\delta hY}-e^{-2\delta h}\right] \tag{11}$$

$$T^{(0)}=1-Y+\frac{1}{2}M\left[e^{-2\delta h}-e^{-2\delta hY}\right] \tag{12}$$

Solution to the zeroth-order equations stated above reveals the main features of the particle flow problem. As a starting point of the current analysis, the zeroth-order equations were implemented in a computer code using finite difference method. The problem analytically solved by Savage [1988] was used to examine the feasibility as well as the convergence with respect to element size of the computer code. Comparisons of our numerical results and Savage's analytical results are shown below.



(a) Horizontal component of particle flow velocity along a vertical line at X=0.5.



(b) Vertical component of particle flow velocity along a horizontal line at Y=0.5.

Fig. 2 Comparisons of numerical and theoretical results. X and Y are normalized Cartesian coordinates. The 11×11, 21×21, and 41×41 denote the number of nodal points in X and Y direction.

The comparison results shown above verify the validity of the numerical results from the finite difference method. Also shown is the convergence of numerical results with the refinement of the mesh size. Since the 21×21 mesh gives a result close enough to the theoretical one, we stick to this mesh through out our analysis. The flow pattern is shown in Fig. 3 below.

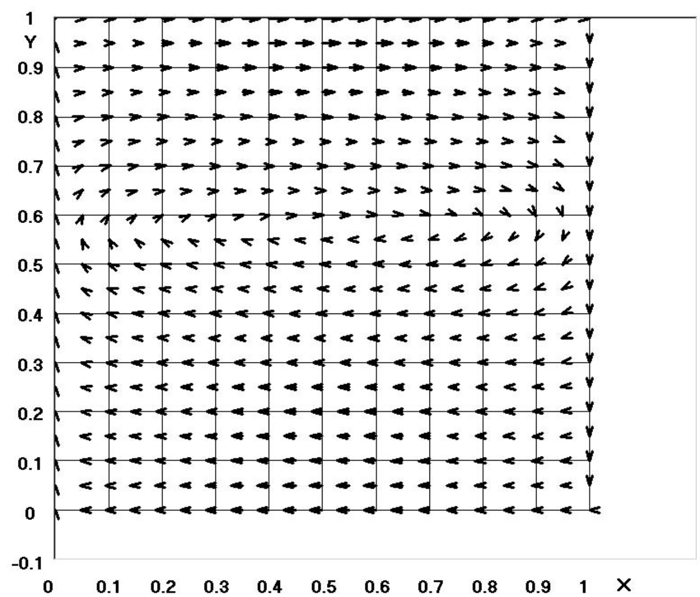


Fig. 3 Flow pattern of the circulation of particles in a closed container. Each arrow points out the direction of particle flow at every nodal point. The length of each arrow represents the magnitude of the velocity, and the length between a pair of adjacent grid-nodes is equivalent to 0.1mm/sec.

3. VIBRATION-INDUCED PARTICLE FLOW

For simplicity and utilization of the formulations developed by Savage in terms of Cartesian coordinates, a two-dimensional problem instead of a three-dimensional axis-symmetric one, as depicted in Fig. 1, was solved. The 2D problem is expected to reveal the main features of the 3D axis-symmetric one. Details of the 2D problem is shown in Fig. 3 below

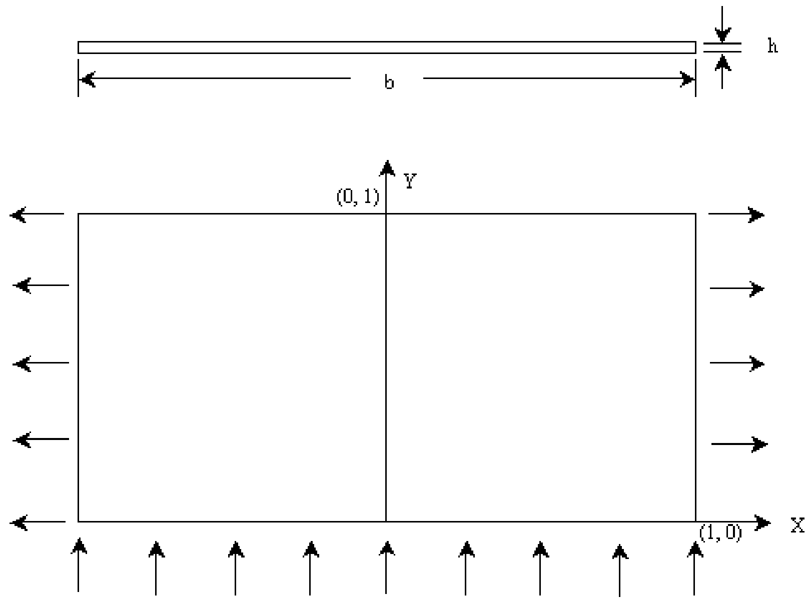


Fig. 4 Top figure shows a thin layer of particles with width b and depth h. Bottom figure shows the mapping of the thin layer to a normalized, dimensionless X-Y coordinate system. The particles generated by the impact from USDC are treated as an inflow to the control volume. Particles are expected to flow out on both sides.

A thin layer of particles is usually found on top of the cylindrical rock sample after it is ground by the USDC. While the impact from the USDC creates more particles, it also generates vibrations on the top surface of the rock. The vibrations, in turn, induce a particle flow in the thin layer and thus move the particles to the edge of the rock sample and send them flying away. The particles generated by USDC are treated as an inflow from the bottom. The thin layer is mapped to a normalized, dimensionless X-Y coordinate system, as shown in Fig. 4, for numerical analysis. Since the problem is symmetric with respect to the Y-axis, only the half on the right side of Y-axis is considered.

A computer program employing the finite difference method was developed base on the zeroth-order equations. The numerical results derived from the program are shown in Fig. 5. Each arrow points out the direction of particle flow at every nodal point. The length of each arrow represents the magnitude of the velocity, and the length between a pair of adjacent grid-nodes is equivalent to 0.1mm/sec. The inflow velocity at the bottom is empirically determined to be 0.001mm/sec. It is shown that the particles flowing into the domain under investigation go out on the right side, and the outflow velocity is uniform. This study shows that there is not a single area under the drill bit where the particles are trapped and stopped from flowing towards the edge of the rock. Next, to find out more details about the flow pattern, the original governing equations (1) to (3) were investigated numerically. Unlike the linear zeroth-order equations, the original governing equations are nonlinear. To solve this problem numerically, the well-known Newton's method for nonlinear systems was employed (refer to, for example, the book by Atkinson [1988]). A computer program combining the finite difference method and the Newton's method is currently under development.

The boundary condition on the right side pretty much dominates the results of the numerical analysis. Yet a proper boundary condition has not been determined, and there may be technical difficulty applying the proper boundary conditions. Fig. 6 and Fig. 7 show the results derived from the nonlinear system by forcing some artificial boundary conditions on the right side. Both assume the component of the granular velocity normal to the right side to be zero. The difference between the two figures is that in Fig. 6 the right side is vertical, while in Fig. 7 the right side is inclined toward the centerline. These preliminary results show that there are local circulations inside the layer of particles. However, more work has to be done before any conclusion can be drawn.

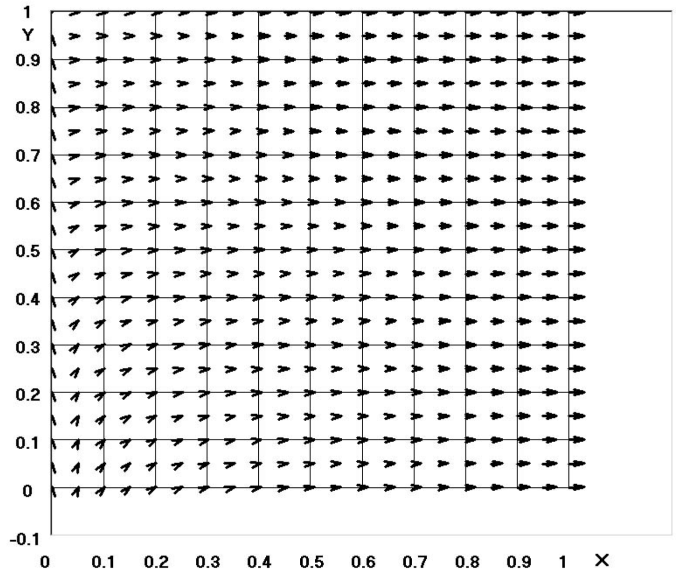
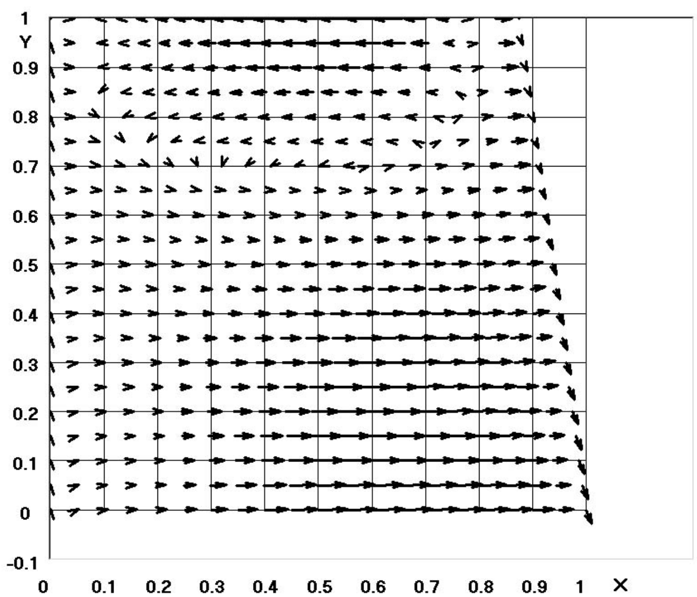


Fig. 5 Results from the computer program implementing the finite difference method base on the zeroth-order equations. Each arrow points out the direction of particle flow at every nodal point. The length of each arrow represents the magnitude of the velocity, and the length between a pair of adjacent grid-nodes is equivalent to 0.1mm/sec.



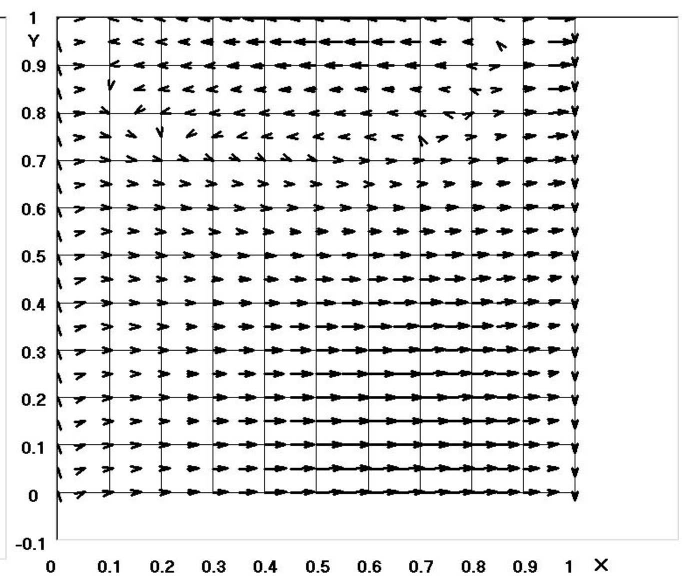


Fig. 6 Results derived from the nonlinear system with a vertical right side.	Fig. 7 Results derived from the nonlinear system with a inclined right side.

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