Drag Coefficients on Razor Clams in Slightly Fluidized Granular Media

by

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ABSTRACT

Razor clams are able to burrow deeply into granular media with only a small fraction of force required by traditional anchoring devices. It is hypothesized that the collapse of their shell and subsequent localized fluidization of the media is responsible for a large reduction in drag, thereby allowing the clam to burrow. A test setup comprised of a fluidized bed connected to a pump with an attached ball valve for flow regulation is constructed which allows testing of drag force in conditions similar to that the clam experiences, as well as in an environment void of wall effects. Testing is done using a dead clam attached to a stainless steel rod which is passed through the fluidized bed to obtain accurate data for the razor clam. The result is that a slight fluidization to a void fraction between 40-45% gives a drag reduction which is more than sufficient for a clam to burrow at velocities seen in nature.

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Introduction

Background on Razor Clam Digging

The razor clam is a species of clam which burrows into sand by locally fluidizing the particles around it to achieve a reduction in the force required to burrow. This process of local fluidization is achieved by a quick collapse of the clam's shell[1]. Due to the small size of the clam, the local particles are only very slightly fluidized, increasing the void fraction by no more than 20%. The force with which the clam pulls does not exceed 10N[2], although this force allows the clam to burrow at speeds and to depths which would require much greater forces if the local medium were not fluidized[3]. Results from testing done on the a blunt body in granular media show that for the same depth of burrow it would require roughly twenty five times more force than the clam is able to exert.

Particle image velocimetry (PIV) was conducted on a clam burrowing in a bed of granular media similar to its natural environment. The results of the PIV showed that particles near the clam (within a few body lengths) are fluidized between 5 and 20%. For this reason it we hypothesize that the local fluidization of particles is responsible for a reduction in the drag force for the clam. The purpose of this thesis is to determine how drag force is related to void fraction in a fluidized bed for low values of void fraction. Confirmation of the drag reduction could prompt development of burrowing and anchoring devices which are able to take advantage of this drag reduction to reduce energy costs of digging. In addition, anchors which are more deeply burrowed are able to provide a greater anchoring force.

Previous work on the subject, such as that done by Mostoufi and Chaouki[4], presents equations which claim to be valid for void fractions higher than 50%. Since the clam can only fluidize the surrounding environment to a void fraction of roughly 40-45%, it is essential that an experiment be set up to test the drag reduction in this regime of fluidization.

Background Theory

Fluidized Bed Theory

A particle falling in fluid has three forces acting upon it: the force of gravity, the force of buoyancy, and a drag force. The force of gravity combined with the buoyancy force is the effective weight of the particle

$$w_e = V_p(\rho_p - \rho_f)g \tag{1}$$

[1] A. Winter, *Biologically inspired mechanisms for burrowing and anchoring in soft undersea substrates.* Group Meeting presented at Hosoi Research Group. (2008, March 31)
[2] E.R.Trueman, *Proc Roy Soc Lond B Biol Sci.* (1967)
[3] A. Winter, Test Results presented at Hosoi Research Group. (2007, November 30)
[4] N. Mostoufi and J. Chaouki, *Prediction of effective drag coefficient in fluidized beds.* (1998, August)

where V_P is the volume of the particle, ρ_p is the density of the particle, and ρ_f is the density of the fluid. The inertial drag force on the particle is equal and opposite to this force, and is given by the equation

$$F_D = \frac{1}{2}\rho_f v^2 A C_D \tag{2}$$

where v^2 is the velocity of the particle, A is the cross sectional area, and C_D is the coefficient of drag.

When the forces from equations 1 and 2 equally offset each other, the particle is in equilibrium, falling at its terminal velocity. In a fluidized bed, it is often the case that fluid is pumped vertically through a bed of packed particles. In this situation, the particles are stationary, but the velocity of the fluid is changed in order to fluidize the bed. The bed will become fluidized once the pressure of the bed is supported by the water flowing past it. The pressure across the bed is given as[5]

$$\Delta P_B = (\rho_p - \rho_p) L_B (1-\varepsilon) g \tag{3}$$

where L_B is the length of the bed, and ε is the void fraction in the bed. Since this pressure drop is constant, the void fraction in the bed can be calculated at any time if the height and initial conditions are known. The pressure that the fluid supports can be given by the Ergun equation[6]:

$$\Delta P = 150 \cdot \frac{\mu_f L v}{d_p^2} + 1.75 \frac{\rho_f L v^2}{d_p} \cdot \frac{(1-\varepsilon)}{\varepsilon^3} \tag{4}$$

The first term in the Ergun equation is due to viscous drag, while the second term is due to inertial drag. When the two pressures are equal, the bed will begin to fluidize. In order to calculate the minimum velocity at which the particles will fluidize, first the minimum void fraction must be computed. This has been done experimentally many times, the result being[7]

$$\varepsilon_{mf} = \left(\frac{.071}{\psi}\right)^{1/3} \tag{5}$$

where ψ is the sphericity of the particle. Once the bed has been fluidized, it is possible to study the drag coefficient of objects falling through it.

Taking a force balance on the object falling through the fluidized bed, we once again arrive at equations 1 and 2. Combining equations 1 and 2 gives an expression for the drag coefficient:

$$C_D = \frac{2V_O(\rho_O - \rho_f)g}{v^2 A \rho_f} \tag{6}$$

Where V_O is the volume of the object, and ρ_O is the density of the object.

The terminal velocity for a particle falling in pure water is greater than that for a particle falling in a water fluidized bed. Thus the drag coefficient for a particle falling in

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[5] L. Gibilaro, *Fluidization-Dynamics* (2001)
[6] S. Ergun and A. Orning, *Fluid Flow through randomly packed columns and fluidized beds.* (1949)
[7] C.Y. Wen and Y.H. Yu, *AIChE J. 21,* 610 (1966)

pure water is less than that of a fluidized bed. Similarly, as the void fraction increases, the particles are increasingly spaced out, thereby increasing the terminal velocity of the particle. The relationship between velocity in a fluidized bed and that in pure water without particles was derived by Richardson and Zaki[8]

$$v = v_t \varepsilon^n \tag{7}$$

where v_t is the terminal velocity in pure water, and n is an exponent based on the Reynolds number[9] $\mathrm{Re}_p = \frac{d_p v_f \rho_f}{\mu_f}$ or Archimedes number[10] $Ar = \frac{g d_p^{\,3} \rho_f (\rho_p - \rho_f)}{\mu_f^{\,2}}$.

The relationship used to calculate n was derived by Khan and Richardson:[11]

$$\frac{4.8 - n}{n - 2.4} = 0.043 Ar^{0.57} \tag{8}$$

Calculation of the terminal velocity of the object in pure water is accomplished by relating the Reynolds number to the Archimedes number, and then solving for v_t. Dallavalle gives one such relationship valid for all values of Reynolds and Archimedes numbers[12]

$$\mathrm{Re}_t = \left[-3.809 + (3.809^2 + 1.832 Ar^{0.5})^{0.5}\right]^2 \tag{9}$$

The combination of the above equations will allow the prediction of the required fluid velocity for a given void fraction.

Drag Theory

The drag type considered above was form drag. This type of drag is dominated by inertial effects and occurs at high Reynolds numbers. In the case of the clam, it might also be true that Stokes drag (due to viscosity) is responsible for a significant portion of drag. This will be determined experimentally by calculating the Reynolds number. A Reynolds number on the order of 150 will require the magnitude of the Sokes drag involved to be analyzed.

Experimentation

Experimental Setup

For the experiment, a fluidized bed had to be designed and constructed to mimic the drag reduction that a clam would experience by closing its shell. The first step in designing the bed was to calculate an Archimedes number for the bed. Glass beads 1mm in diameter were used to mimic sand because they were the size of the coarse sand in

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[8] J. Richardson and W. Zaki, *Sedimentation and fluidization.* (1954)
[9] The Reynolds number is a non-dimensional ratio of the inertial forces to the viscous forces on an object
[10] The Archimedes number is a non-dimensional ratio of the gravitational force to the viscous force in fluid motion due to density differences
[11] A. Khan and J. Richardson, *Fluid-particle interactions and flow characteristics of fluidized beds and settling suspensions of spherical particles.* (1989)
[12] J. Dallavalle, *Micromeritics.* (1948)

which clams live and uniform, thus much simpler to use for calculation purposes. With the relevant properties for the water and glass beads known, the Archimedes number was calculated. This was used to calculate a Reynolds number for the bed from equation 9. From this it was possible to calculate the terminal velocity in the bed from the definition of a Reynolds number. Equation 8 allowed the calculation of the exponent n for the Richardson-Zaki equation, which was then used to find the water flow rate in the bed. The void fraction had been observed from PIV to start at around 38% and increase between 5 and 20% to a total void fraction between 40 and 45%. This gave the upper bound for the necessary flow rate for the desired level of fluidization.

The shape of the bed was designed based off of solid-fluid beds made by other authors[13]. Water was pumped into a cone shaped distributor below the bed which was designed to uniformly disperse the flow of water, such that the flow entering the bed was uniform across the bed. This was achieved by filling a cone with 5/8in marbles, and adding a screen to the top of the bed to keep the glass beads from entering the distributor. An important aspect of the distributor was that the pressure drop be significant compared to the pressure drop across the bed. To calculate this pressure drop, equation 4 was used. This equation relates the pressure drop in a stationary packed bed to operating parameters. The pressure drop in the bed was then calculated from equation 3. The height of the bed was chosen to be at least 3 characteristic lengths of the clam so that a steady state velocity could be achieved before measuring the velocity. Additionally, there was a pressure drop associated with the vertical orientation of the bed due to hydrostatic pressure, which was calculated as

$$\Delta P = \rho_f g L_B \tag{10}$$

Before selection of a pump, it was determined that testing should be done for two different cylinder sizes. In the PIV it was noted that the deformation of sediment was limited to about 3 body widths, thus we chose a 3in diameter pipe to mimic these conditions. The second pipe was to be large enough so that edge effects were no longer an issue, or 8in. The second was chosen to that the type of drag present could be more clearly understood, and so that if the drag were significantly reduced in the larger diameter tank, we would be able to note how much wall effects play a roll in the drag on the clam. With the wall diameters chosen, a pump was able to be chosen by simply multiplying the linear flow rate by the cross sectional area of the tube to get a volumetric flow rate, and matching that flow rate with the pressure drop on a pressure-flow chart provided by pump manufacturers. The sum of the pressure drops in the system was 20kPa, and the flow rate determined for sufficient fluidization was 675 Gallons per hour. These values lead to the selection of the WP5 pump from Aquatic Eco-Systems, which could provide 700 Gallons per hour at 20kPa.

The final important design aspect was to determine the length of the shaft which the clam would ride on. This was crucial because the collection of drag data would only be valid if the clam were moving at steady state. Thus, some portion of the motion of the

[13] N. Mostoufi and J. Chaouki, *Prediction of effective drag coefficient in fluidized beds.* (1998, August), N. Epstein *Liquid-Solids Fluidization* (2000), and others.

clam would need to be neglected until it reached steady state, at which time data collection could begin. A non-linear ODE was setup to calculate the time required. Equations 1 and 2 were summed up and set equal to mass multiplied by acceleration. Numerous time steps were chosen to calculate instantaneous velocity. Below is a graph showing velocity versus time for a shaft weighing .66kg, the same weight as the one chosen.

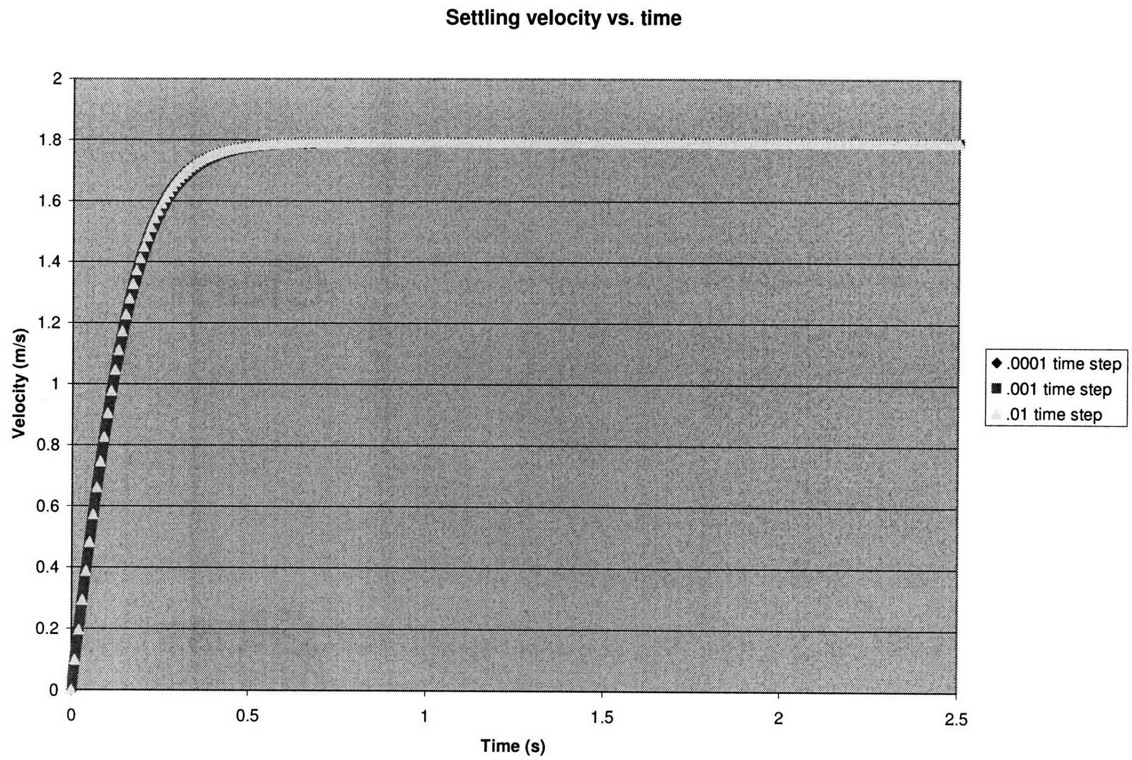

Figure 1: Time to terminal velocity

The shaft was chosen to be 3' so that the clam had sufficient time to travel in the 2.5' fluidized bed of particles before data was collected. For this reason only the last 4.25in were used to collect data.

Water passes from a reservoir into a pump which pumps the water through a series of hoses. It flows through a ball valve to regulate flow, and control void fraction. Water then flows up a distributor consisting of a 4in tall cone packed with 5/8in marbles, past a fine mesh screen to separate the distributor from the fluidized particles, and into the fluidized bed. The fluidized bed is made of .85-1.0mm glass beads with a density of 2500kg/m^3 which rest in a cylinder of either 7.75in or 3in inner diameter. Both cylinders rise a total of 3', and overflow into a 2in hose which returns the water to the reservoir. A plate caps the top of both cylinders and contains a hole in the center into which a bushing is placed. A clam on a polished steel shaft runs inside this bushing, and has a shelf for additional weight to be added. To collect data, two limit switches are attached to a shaft which is attached to the capping plate. They are located 4.25in apart from each other and are triggered by the plate on which the weight rests. Below is a picture of the setup.

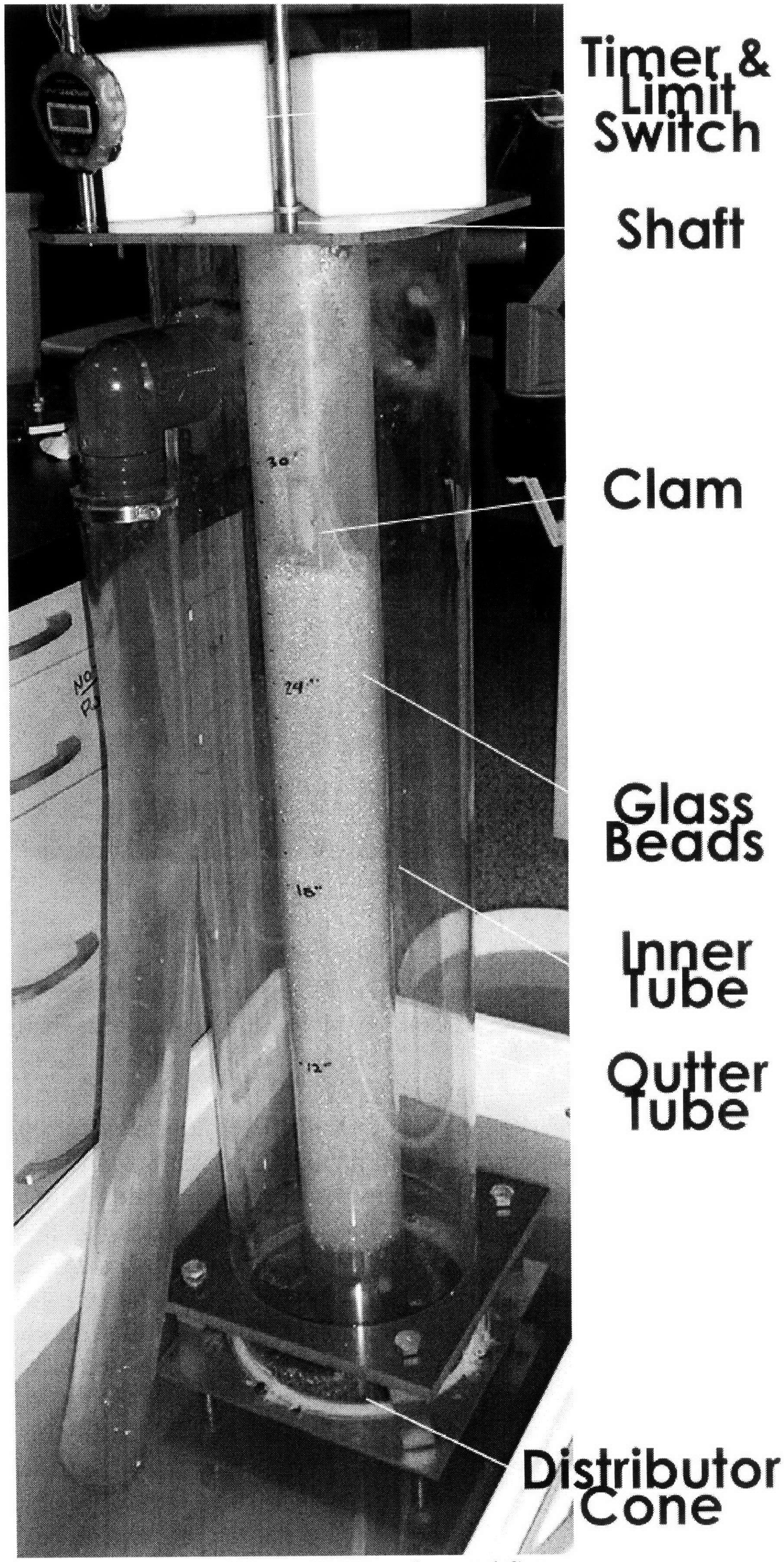

Figure 2: Experimental Setup

Experimental Procedure

Step	Action
1	Glass beads are weighed on a scale
2	Glass beads are inserted into the cylinder until desired height is reached
3	Height recorded
4	Pump is engaged with ball valve closed
5	Ball valve is opened until desired height (thus void fraction) is reached
6	New height recorded
7	Weight is added to top of shaft with clam on it
8	Weight is recorded
9	Clam on shaft is raised so that the top of the clam is flush with the top of the fluidized bed
10	Clam is released, triggering the limit switches
11	Time is recorded

Data collection is repeated using different weights on the top of the clam shaft, so that a plot can be made showing drag force against velocity. This can be used to verify the type of drag which dominates. Additionally, the void fraction of the bed is varied after each set of weights has been tested, so that a relationship between void fraction and drag force can be measured. The initial void fraction is easily calculated based on the weight of the particles which enter the tube and the initial height to which they rise. Finally, all tests are run on both the small and large cylinders so that thorough determination of the dominant type of drag can be achieved.

Results and Discussion

Due to limits in testing, it was only possible to obtain good data for a few different values of weight, .66kg, .78kg and 1.23kg. The clam only barely reached steady state velocity in the 1.23kg weight tests, so any additional weight was not possible. Other weights were not able to be achieved because of material limitations. In addition while testing for the 3in tube, velocity values measured were consistent with Reynolds numbers between 15,000 and 30,000. This clearly proves that the drag effects are due to inertial effects since Stokes drag is only significant in Reynolds numbers below around 150. Below is a graph of drag coefficient against void fraction. The drag coefficient was calculated based on an average of 10 velocities measured for each void fraction. From equation 5, the minimum void fraction for fluidization is roughly 41.4%. The first point on the graph below corresponds with that value.

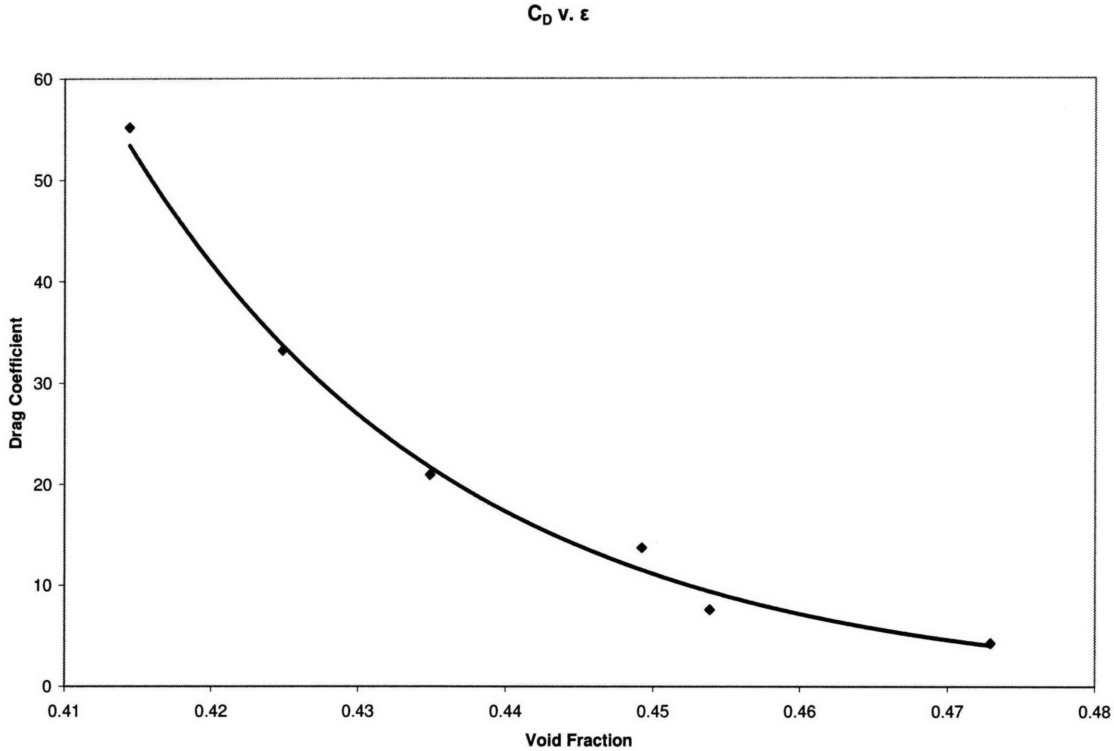

Figure 3: Drag Coefficient v. Void Fraction for the 3in tube

As shown above, drag is greatly reduced upon fluidization. The reduction continues exponentially as the void fraction is increased. Based on this relationship, it is possible to plot a surface on which comparison of force, velocity and void fraction is shown. In order to do this, it is assumed that the drag coefficient does not change with velocity. Below is a plot of the log of the Reynolds number against the log of the drag coefficient.

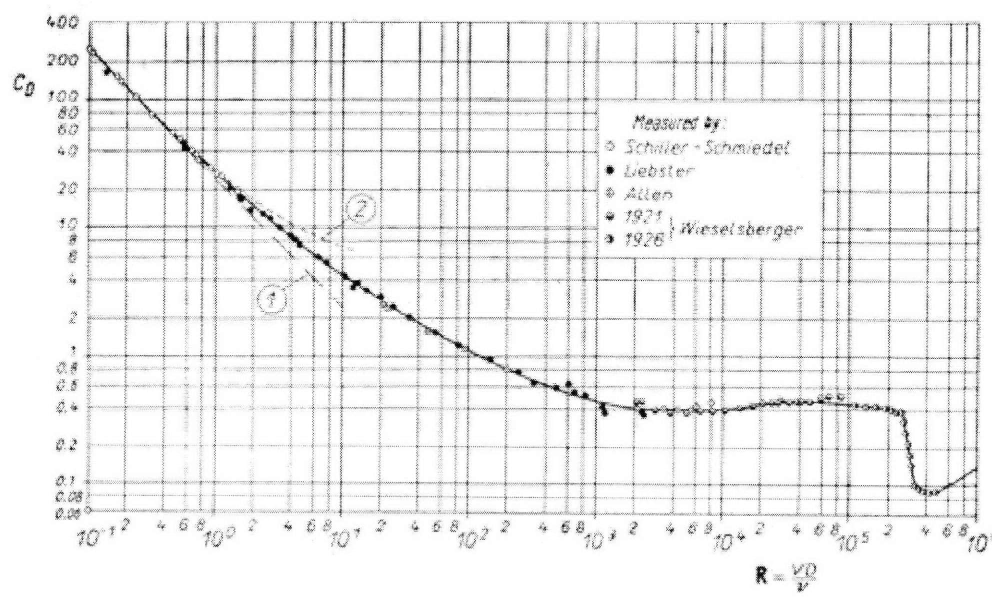

Figure 4: Drag coefficient for spheres as a function of the Reynolds number

As is evident, the coefficient of drag does change with Reynolds number, and hence velocity, although for Reynolds numbers between 10^2 and 10^5 the drag coefficient is constant. Since the operating range of Reynolds numbers is within this range, and furthermore, since the Reynolds numbers calculated change by only a factor of two and not an entire order of magnitude, it is reasonable to assume that the drag coefficient is only a function of void fraction, and not velocity. Thus the surface relating force, velocity and void fraction is constructed below.

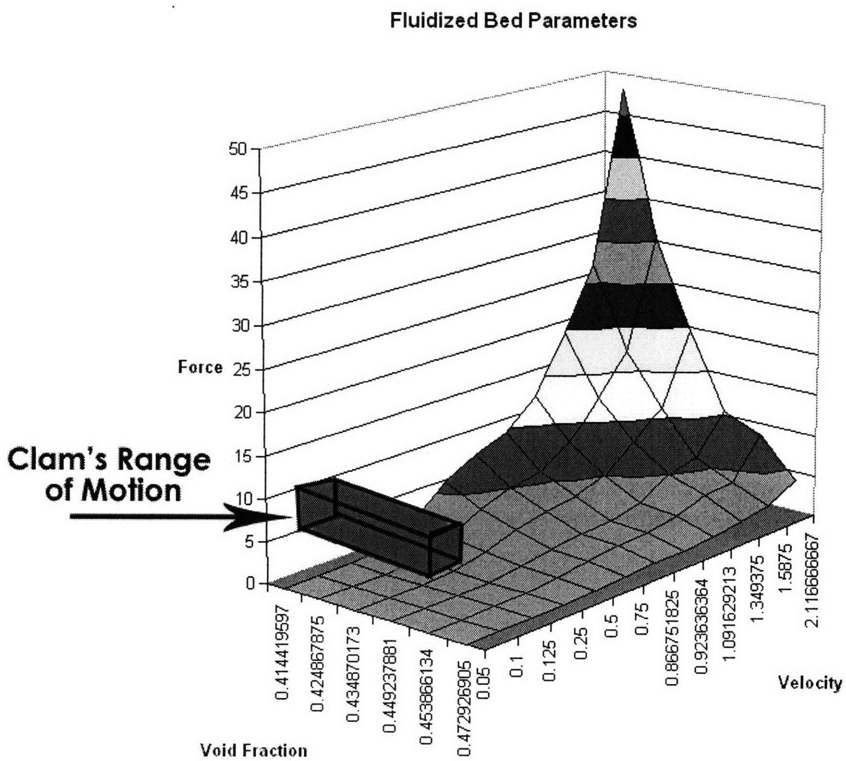

Figure 5: Force plotted against velocity and void fraction

Conclusion

As the results show, drag is significantly reduced by fluidization. This reduction in drag is sufficient to allow a clam to burrow with only a fraction of the force otherwise required. It is recommended that in the future research is conducted to determine the influence of wall effects, as well as to allow for more weights to be tested, so that a surface plot can be created with finer resolution.