



Experimental investigation of critical suction velocity of coarse solid particles in hydraulic collecting

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Abstract

Hydraulic collecting and pipe transportation are regarded as an efficient way for exploiting submarine mineral resources such as the manganese nodules and ores. Coarse particles on the surface of the sea bed are sucked by a pipe during the mining and crushing of the mineral. In this paper, the critical suction velocity for lifting the coarse particles is investigated through a series of laboratory experiments, and the solid–liquid two-phase flow characteristics are obtained. Based on the dimensional analysis, the geometric similarity is found between actual exploitation process and model test with the same kind of material. The controlling dimensionless parameters such as the hydraulic collecting number, the relative coarse particle diameter, the relative suction height, and the density ratio are deduced and discussed. The results show that the logarithm in base 10 of the hydraulic collecting number increases approximately linearly with the increase of the relative suction height, while decreases with the relative particle diameter. A fitting formula for predicting the critical suction velocity is presented according to the experimental results.

Keywords Hydraulic collecting · Critical suction velocity · Coarse particles · Deep sea mining · Dimensional analysis

1 Introduction

The continuous deepening of industrialization invokes the acceleration of exploitation and utilization of the mineral resources in various countries. The deep ocean is rich in mineral, biological, energy and chemical resources, such as the manganese nodules, gas and oil, and gas hydrate, leading to high attention and great interest around the world [1–4].

Solid particles such as manganese nodules can be collected from the surface of the sea bed and transported in pipes of the underwater operating system. These particles generally range from about 1 to 12 cm in longest dimension [5, 6]. Hydraulic collecting is regarded to be a promising technology with the advantages of environmental protection, low

energy consumption and high efficiency. Coarse particles on the sea bed are sucked by a pipe and then transported to a storage bin during hydraulic collecting.

Researchers have begun to investigate the mechanism and efficiency of the hydraulic collecting since 1980s. Hong et al. [7, 8] built a two-dimensional water tank to study the lifting characteristics of hydraulic collecting. The displacement of the water jet, the bottom gap, and the position and shape of the baffle were selected as experimental parameters. A series of experiments were conducted to investigate the relationship between the experimental parameters and the operating conditions. Zhao et al. [9] measured the lifting force of hydraulic collecting on a single particle by fixing the particle on a force sensor. Based on the dimensional analysis, a formula for calculating the coefficient of the lifting force was discussed, the critical condition for the incipient motion of the particle was present, and it was found that the vortex around the particle could strengthen the lifting force. Chen et al. [10] analyzed the flow field around the particle through the particle image velocimetry (PIV) method. A high-speed photography was used to capture the motion behavior of the particles during the lifting process. In addition, the computational fluid dynamics (CFD)-discrete element method (DEM) [10] was applied to simulate the particle motion force distribution and the flow

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field around the particle for understanding the particle lifting mechanism. Chen et al. [11] also studied the interaction between the particle and fluid during the particle's motion in hydraulic collecting. It was found that the particle went around in a spiral. For the collection of large particles, the height from the particles on the sea bed to the collection pipe should not exceed 1.75 times that of the particle diameter.

In actual engineering, it is very useful to know the speed or flow rate of the water which can lift the ore particles on the sea bed in advance. However, there is no theoretical formula or empirical formula for calculating the critical suction velocity so far. The critical suction velocity is the speed of water flow that can lift the solid particle from the surface of the sea bed, which is indeed crucial for engineering design to reduce energy costs and increase mining revenue.

The aim of this paper is to investigate the critical suction velocity for lifting the particles on the sea bed in the hydraulic collecting, and give a formula for predicting it. In Sect. 2, the experimental apparatus is introduced and the controlling dimensionless parameters are deduced by applying the dimensional analysis. In Sect. 3, the effect of the dimensionless parameters on the hydraulic collecting are discussed and a formula for calculating the critical suction velocity is presented based on the experimental results.

2 Methods

The solid particles such as manganese nodules are mainly scattered at the water interface of the sea bed or within the first 10 cm of the deep-sea sediments [12]. The particles have different sizes and shapes, ranging from 1 to 12 cm. Some extremely large particles of 21 cm in diameter have been found in the Peru Basin [13]. As a result, the large particles need to be cut into small sizes first, and then sucked by the suction pipe from the sea bed.

In this paper, it is assumed that the particles are on a flat surface before lifted by the suction pipe during hydraulic collecting. The particles are regarded to have been cut into small sizes, or extracted and separated by jet operation from the relatively soft sea bed sediments. Few deposit sediments exist around the particles according to the engineering test [9, 12].

To investigate the critical suction velocity of coarse mineral particles, an experimental apparatus [10] (Fig. 1) is developed including two main parts—a water tank with a length of 2 m, a width of 1.5 m and a height of 1 m, and a vertical suction pipe with a diameter of 5 cm. The distance between the suction pipe inlet and the bottom of the water tank is adjustable. The water circulation is driven by a HYSB 4/3-AH centrifugal mortar pump, and the volume flow rate of the water is measured by an electromagnetic flowmeter. In addition, the experimental device is also equipped with



Fig. 1 Experimental apparatus

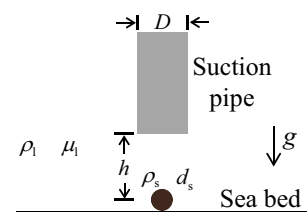


Fig. 2 Factors affecting the critical suction process

a FASTCAM Mini WX50 high-speed camera to record the trajectory of particle motion.

During the experiment, the volume flow rate at which the particle is lifted from the bottom of the water tank is recorded. In order to ensure the accuracy of the data, each experimental case is measured four times. Then, the critical suction velocity is calculated by dividing the volume flow rate by the cross-sectional area of the suction pipe.

The particles on the sea bed such as the manganese nodules have different physical and mechanical properties. Firstly, the dimensional analysis is conducted to obtain the dimensionless controlling parameters of the hydraulic collecting. The particles on the sea bed are affected by the gravity, the buoyancy, the seabed supporting force, the lifting force, and the Magnus force. The factors affecting the critical suction process is shown in Fig. 2. The critical suction velocity (v_{cr}) depends on the diameter of the suction pipe (D), the suction height (h) which represents the vertical distance from the center of the particle to the inlet of the suction pipe, the density (ρ_s) and the diameter of the particle (d_s), the density (ρ_l) and the viscosity (μ_l) of the water, and the gravitational acceleration (g). As a result, the function of the critical suction velocity (v_{cr}) is defined as

$$v_{cr} = f(D, h; \rho_s, d_s; \rho_l, \mu_l; g). \quad (1)$$

The dimensions of these parameters are shown in Table 1.

Table 1 Dimensions of parameters relating to the hydraulic collecting process

Parameters	v_{cr}	D	h	ρ_s	d_s	ρ_l	μ_1	g
Dimensions	LT^{-1}	L	L	ML^{-3}	L	ML^{-3}	$ML^{-1}T^{-1}$	LT^{-2}

Choosing d_s , $\rho_s - \rho_l$, and μ_1 as unit system, the dimensionless expression of Eq. (1) can be written as [14, 15]:

$$\frac{(\rho_s - \rho_l)v_{cr}d_s}{\mu_1} = f\left[\frac{d_s}{D}, \frac{h}{d_s}, \frac{\rho_s}{\rho_s - \rho_l}, \frac{\rho_l}{\rho_s - \rho_l}, \frac{gd_s^3(\rho_s - \rho_l)^2}{\mu_1^2}\right]. \tag{2}$$

Change the form of Eq. (2):

$$\frac{\rho_l v_{cr} d_s}{\mu_1} = f\left[\frac{d_s}{D}, \frac{h}{D}, \frac{\rho_s/\rho_l}{\rho_s/\rho_l - 1}, \frac{1}{\rho_s/\rho_l - 1}, \frac{gd_s^3(\rho_s - \rho_l)\rho_l}{\mu_1^2}\right]. \tag{3}$$

Because the dimensionless parameters $\frac{\rho_s/\rho_l}{\rho_s/\rho_l - 1}$ and $\frac{1}{\rho_s/\rho_l - 1}$ in Eq. (3) are related to ρ_s/ρ_l , Eq. (3) can be rewritten as:

$$Re_{cr} = f\left(\frac{d_s}{D}, \frac{h}{D}, \frac{\rho_s}{\rho_l}, Ar\right), \tag{4}$$

where $Re_{cr} = \rho_l v_{cr} d_s / \mu_1$ is the critical Reynolds number that characterizes the ratio of the inertia effect to the viscous effect, d_s/D is the relative particle diameter, h/D is the relative suction height, ρ_s/ρ_l is the density ratio, and $Ar = gd_s^3(\rho_s - \rho_l)\rho_l/\mu_1^2$ is the Archimedes number which represents the settling effect of the particles.

At the critical condition, the lifting force (F_L), the buoyancy (F_B), and the particle gravity (mg) meet the following relationship:

$$F_L + F_B = mg, \tag{5}$$

where $F_L = \frac{\pi}{8} C_L \rho_l v_{cr}^2$, $F_B = \frac{\pi}{6} g \rho_l d_s^3$, C_L is the lifting force coefficient. As a result, Eq. (5) can be written as:

$$\frac{1}{8} \pi C_L \rho_l v_{cr}^2 d_s^2 = \frac{1}{6} \pi g (\rho_s - \rho_l) d_s^3, \tag{6}$$

$$\frac{1}{8} \pi C_L \left(\frac{\rho_l v_{cr} d_s}{\mu_1}\right)^2 = \frac{1}{6} \pi \frac{gd_s^3(\rho_s - \rho_l)\rho_l}{\mu_1^2}, \tag{7}$$

$$C_L \frac{(Re_{cr})^2}{Ar} = \text{const.} \tag{8}$$

According to Eq. (8), the critical Reynolds number Re_{cr} and the Archimedes number Ar are not independent of each other at the critical condition. In the process of hydraulic collecting, the particles on the sea bed are exerted lifting force by the water. The velocity used in the critical Reynolds number is the critical suction velocity. Therefore, the lifting effect of the water are represented by the critical Reynolds number,

while the Archimedes number represents the settling effect of the particles. When the lifting effect is stronger than the settling effect, the particles are lifted upward from the sea bed and sucked into the suction pipe. However, when the lifting effect is weaker than the settling effect, the particles stay still or move on the sea bed without leaving the surface of the sea floor. Therefore, whether particles can reach the incipient upward motion state is determined by the two effects, namely the lifting effect and the settling effect. Based on this physical mechanism, Eq. (4) is rewritten as:

$$H_c = \frac{Re_{cr}}{Ar} = f\left(\frac{d_s}{D}, \frac{h}{D}, \frac{\rho_s}{\rho_l}\right), \tag{9}$$

and $H_c = Re_{cr}/Ar = v_{cr}\mu_1/[gd_s^2(\rho_s - \rho_l)]$ is called hydraulic collecting number (H_c) which is the ratio of the critical Reynolds number and the Archimedes number. The H_c represents the ratio of lifting effect to the settling effect of the particles during hydraulic collecting. As mentioned above, H_c determines when the particles reach the incipient upward motion state. If the particle material used in the experiment are the same as the actual ones, there is geometric similarity between the laboratory experiment and the actual production process according to Eq. (9).

Based on the dimensional analysis, a series of laboratory experiments have been carried out to investigate the relationship between the hydraulic collecting number and the relative particle diameter, the relative suction height as well as the density ratio. The detailed experimental design can be seen in Table 2.

3 Results and discussion

3.1 Force analysis of particles at incipient motion state

When the pump is not turned on, the particles are initially in static state on the sea bed which are affected by the gravity, the buoyancy, and the sea bed supporting force. Once the pump starts working, a suction-induced flow field is formed below the suction pipe, and the particles begin to move in an irregular circle and self-rotate (Fig. 3). Therefore, the particles are also subjected to the lifting force and Magnus force in addition to the three forces mentioned above. At the low fluid flow velocity, the lifting force is too small to lift the particles. The lifting force increases, and the seabed supporting force decreases as the increase of the flow velocity. When the sea bed supporting force decreases to zero, the particles reach a critical status at which the particles are going to be sucked into the suction pipe.

Table 2 Detailed experimental design

Cases	D/m	h/m	d_s/m	$v_{cr}/(m \cdot s^{-1})$	$\rho_s/(\text{density}^{-3})$	$\rho_l/(\text{density}^{-3})$	ρ_s/ρ_l	h/D	d_s/D
1	0.1	0.065	0.01	2.59 ± 0.09	2450	1000	2.450	0.65	0.1
2	0.1	0.060	0.01	2.37 ± 0.06	2450	1000	2.450	0.60	0.1
3	0.1	0.055	0.01	1.98 ± 0.03	2450	1000	2.450	0.55	0.1
4	0.1	0.050	0.01	1.70 ± 0.11	2450	1000	2.450	0.50	0.1
5	0.1	0.060	0.02	2.87 ± 0.11	2450	1000	2.450	0.60	0.2
6	0.1	0.055	0.02	2.35 ± 0.12	2450	1000	2.450	0.55	0.2
7	0.1	0.050	0.02	2.13 ± 0.05	2450	1000	2.450	0.50	0.2
8	0.1	0.045	0.02	1.70 ± 0.12	2450	1000	2.450	0.45	0.2
9	0.1	0.030	0.02	1.28 ± 0.06	2450	1000	2.450	0.30	0.2
10	0.1	0.055	0.03	3.06 ± 0.10	2450	1000	2.450	0.55	0.3
11	0.1	0.050	0.03	2.60 ± 0.13	2450	1000	2.450	0.50	0.3
12	0.1	0.045	0.03	2.30 ± 0.06	2450	1000	2.450	0.45	0.3
13	0.1	0.040	0.03	1.80 ± 0.07	2450	1000	2.450	0.40	0.3
14	0.1	0.030	0.03	1.44 ± 0.08	2450	1000	2.450	0.30	0.3
15	0.1	0.060	0.04	3.07 ± 0.13	2450	1000	2.450	0.60	0.4
16	0.1	0.050	0.04	2.25 ± 0.13	2450	1000	2.450	0.50	0.4
17	0.1	0.045	0.04	2.09 ± 0.04	2450	1000	2.450	0.45	0.4
18	0.1	0.040	0.04	1.75 ± 0.05	2450	1000	2.450	0.40	0.4
19	0.1	0.035	0.04	1.45 ± 0.04	2450	1000	2.450	0.35	0.4
20	0.1	0.030	0.04	1.43 ± 0.06	2450	1000	2.450	0.30	0.4
21	0.1	0.050	0.05	2.56 ± 0.07	2450	1000	2.450	0.50	0.5
22	0.1	0.045	0.05	2.17 ± 0.10	2450	1000	2.450	0.45	0.5
23	0.1	0.040	0.05	1.80 ± 0.03	2450	1000	2.450	0.40	0.5
24	0.1	0.035	0.05	1.54 ± 0.04	2450	1000	2.450	0.35	0.5
25	0.1	0.030	0.05	1.30 ± 0.05	2450	1000	2.450	0.30	0.5
26	0.1	0.050	0.01	0.45 ± 0.01	1145	1000	1.145	0.50	0.1
27	0.1	0.055	0.01	0.46 ± 0.07	1145	1000	1.145	0.55	0.1
28	0.1	0.060	0.01	0.63 ± 0.06	1145	1000	1.145	0.60	0.1
29	0.1	0.065	0.01	0.71 ± 0.02	1145	1000	1.145	0.65	0.1
30	0.1	0.045	0.02	0.60 ± 0.06	1145	1000	1.145	0.45	0.2
31	0.1	0.050	0.02	0.71 ± 0.03	1145	1000	1.145	0.50	0.2
32	0.1	0.055	0.02	0.76 ± 0.05	1145	1000	1.145	0.55	0.2
33	0.1	0.060	0.02	0.78 ± 0.05	1145	1000	1.145	0.60	0.2
34	0.1	0.040	0.03	0.64 ± 0.02	1145	1000	1.145	0.40	0.3
35	0.1	0.045	0.03	0.74 ± 0.02	1145	1000	1.145	0.45	0.3
36	0.1	0.050	0.03	0.82 ± 0.02	1145	1000	1.145	0.50	0.3
37	0.1	0.055	0.03	0.88 ± 0.04	1145	1000	1.145	0.55	0.3
38	0.1	0.050	0.04	0.52 ± 0.02	1145	1000	1.145	0.35	0.4
39	0.1	0.045	0.04	0.63 ± 0.03	1145	1000	1.145	0.40	0.4
40	0.1	0.040	0.04	0.72 ± 0.01	1145	1000	1.145	0.45	0.4
41	0.1	0.035	0.04	0.86 ± 0.01	1145	1000	1.145	0.50	0.4

3.2 Effect of relative suction height

Keeping the density ratio and relative particle diameter unchanged, the relationship between the hydraulic collecting number and the relative suction height is studied. The relative suction height varies from 0.3 to 0.65. Figure 4 shows the

relationship between the logarithm in base 10 of the hydraulic collecting number and the relative suction height. Two materials are used in the experiment, namely glass particles and nylon particles. The densities of the glass particles and the nylon particles are 2450 kg/m^3 and 1145 kg/m^3 , respectively. As can be seen from Fig. 4, although the density ratio is dif-

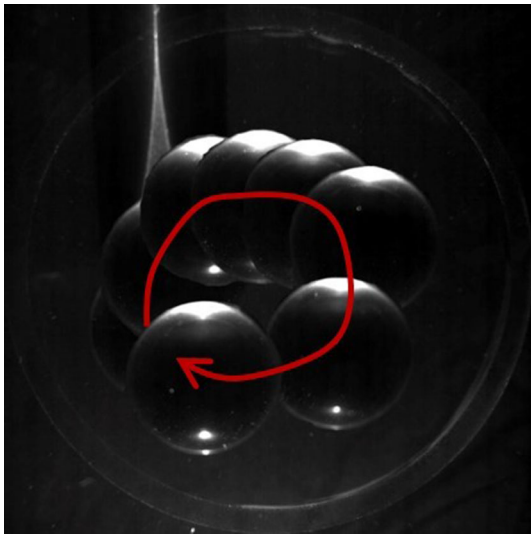


Fig. 3 Particle moves in an irregular circle captured with an interval of 0.2 s. The red line indicates the movement direction of the particle

ferent, the logarithm in base 10 of the hydraulic collecting number increases approximately linearly with the increase of the relative suction height. The larger the relative suction height, the more difficult the particles are to be lifted. This is because when the suction height is larger, the lifting force with the same fluid flow velocity becomes smaller, which causes the lifting force to be less than the critical lifting force. Consequently, the particles cannot be lifted.

3.3 Effect of relative particle diameter

The relationship between the hydraulic collecting number and the relative particle size is investigated by keeping the density ratio and the relative suction height unchanged. The range of relative particle size is 0.1–0.5. Figure 5 gives the

change of the logarithm in base 10 of the hydraulic collecting number with the relative particle diameter. It can be seen from Fig. 5 that the $\log(H_c)$ decreases approximately linearly with the increase of d_s/D .

Based on the experiment results, the logarithm in base 10 of the hydraulic collecting number has a linear relationship with the relative suction height and the relative particle diameter as following:

$$\log(H_c) = a \frac{d_s}{D} + b \frac{h}{D} + c, \tag{10}$$

where a , b , and c are constants related to the density ratio. A formula is achieved:

$$\log(H_c) = \begin{cases} -2.760 \frac{d_s}{D} + 1.280 \frac{h}{D} - 3.465, & \rho_s/\rho_l = 2.450, \\ -3.083 \frac{d_s}{D} + 1.235 \frac{h}{D} - 2.870, & \rho_s/\rho_l = 1.145. \end{cases} \tag{11}$$

The results can give the knowledge that when the material of the particles is determined in actual mining, the critical suction velocity and the law of the hydraulic collecting through laboratory experiments can be established based on the geometric similarity. The relationship between the constants and the density ratio will be discussed in the further study.

It can be found that when the relative particle diameter is small, the experimental data point has a larger error from the fitted curve. This is because the particle’s rotation angular velocity is high under the condition of the small relative particle diameter, leading to a larger Magnus force in the experiment.

Similar experiments were conducted by Zhao et al. [9] to investigate the incipient motion of particles in hydraulic collecting. Figure 6 shows the comparison between the calculated value of the critical suction velocity (Eq. (11)) and

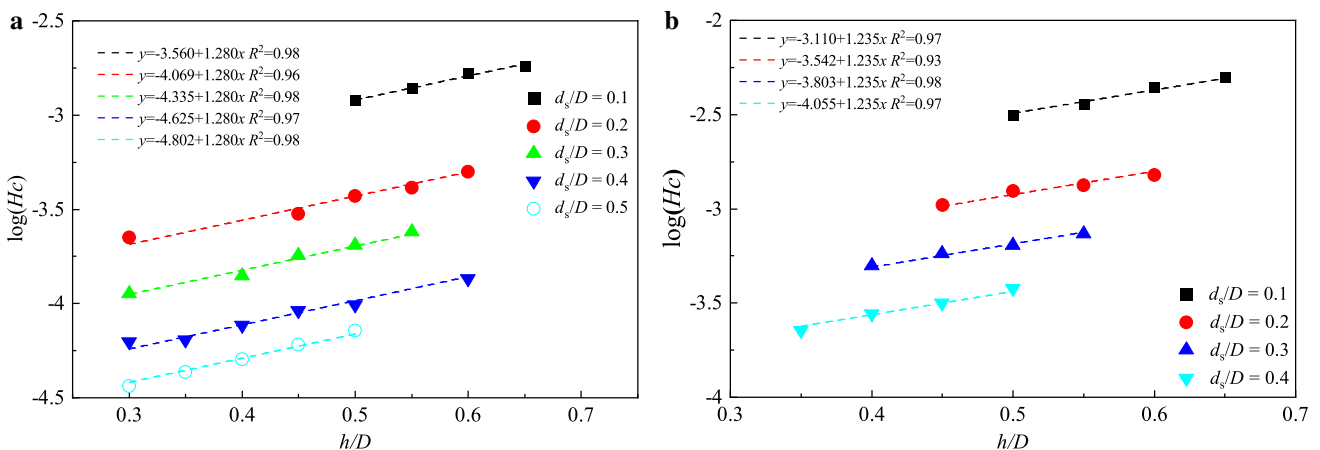


Fig. 4 Relationship between the hydraulic collecting number and the relative suction height: **a** glass particles, density ratio is 2.450 and **b** nylon particles, density ratio is 1.145

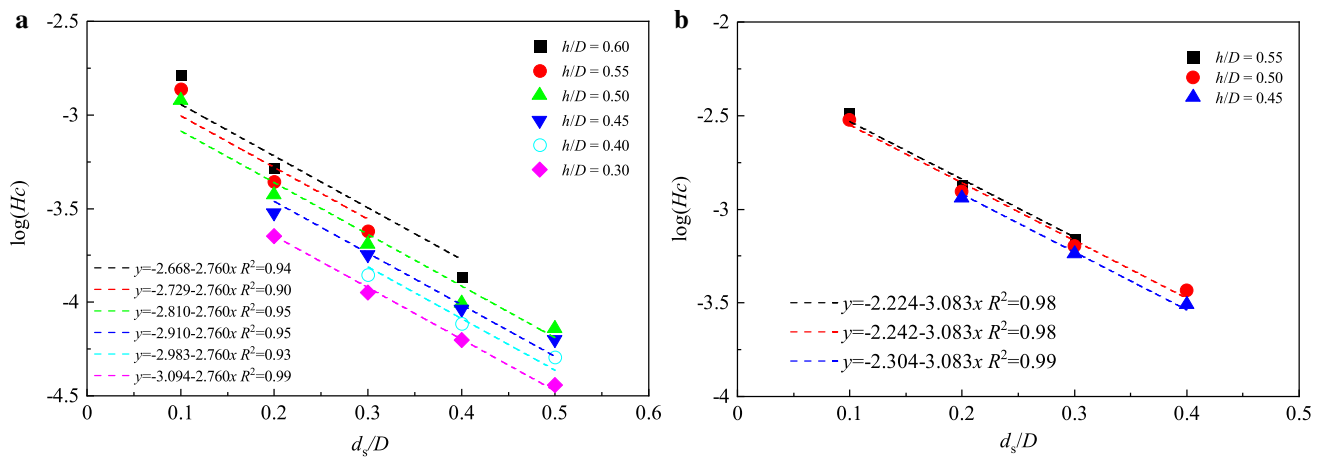


Fig. 5 Relationship between the hydraulic collecting number and the relative particle diameter: **a** glass particles, density ratio is 2.450 and **b** nylon particles, density ratio is 1.145

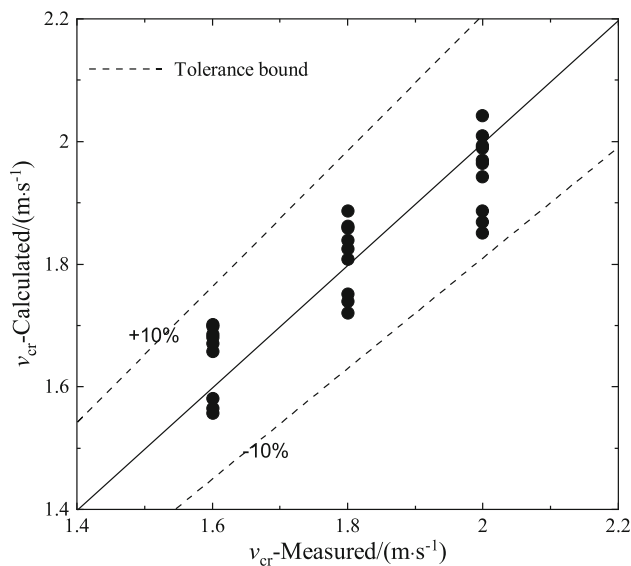


Fig. 6 Comparison between the calculated v_{cr} and measured v_{cr}

the experimental data [9], which shows a good agreement with the experiment results of Zhao et al. [9].

4 Conclusion

A series of experiments are conducted to investigate the critical suction velocity in hydraulic collecting. A geometric similarity is found, which is of great importance for establishing the relationship between the laboratory results and the actual engineering with a same kind of particle material. The controlling dimensionless parameters such as the relative suction height, the relative particle diameter, and the density ratio are obtained. The hydraulic collecting number which is the ratio of the critical Reynolds number and the

Archimedes number is presented for representing the critical suction condition.

The effects of the controlling dimensionless parameters on the hydraulic collecting number is discussed. It is found that the logarithm in base 10 of the hydraulic collecting number increases approximately linearly with the increase of the relative suction height and decreases approximately linearly with the increase of the relative particle diameter. An empirical formula (Eq. (11)) from the experimental results at various relative particle diameter and relative suction height is achieved for calculating the hydraulic collecting number. Based on the experiments, the formula is applicable when the range of the relative suction height is 0.3–0.65 and the range of the relative particle diameter is 0.1–0.5, which is also in the range of the actual engineering.

Generally, the particles on the sea bed such as manganese nodules have different densities. The formula for the critical suction velocity of particles for a specific material can be modified considering the density ratio in the engineering practice.

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