Journal of the Oceanographical Society of Japan
Vol. 27, No. 4, pp. 158 to 162, August 1971

Settling Velocity and Porosity of Large Suspended Particle*

Masahiro KAJIHARA

Abstract: The settling velocity of large suspended particles which were formed in turbid water due to re-coagulation was measured in the laboratory, and the relation to the particle diameter which was taken as that of a sphere with the same volume, was obtained. This is, however, different from Stokes' law in regard to the relation to the particle diameter, though the Reynolds numbers are almost in the region of Stokes' law. This may be caused by the change of apparent density with the particle diameter. Stokes' law for a porous particle was applied to the settling velocity and the diameter found was compared with the real diameter to obtain an expression for the porosity.

From the result, it is considered that the large suspended particles of "*marine snow*" have a porosity of above 90%.

1. Introduction

It is well known that the large flocculent aggregates, "*marine snow*" are widely recognizable in the sea. Actually, in all our hundreds of dives through using the research submarine "KUROSHIO-II" from 20 m to 100 m in depth, we have always remarked on the considerable amount of "*marine snow*" suspended in the sea. Some particles appeared as vague clusters of several mm in maximum size; also as strings of 2 or 3 cm in maximum length, and others appeared as small points, *in situ*.

The photographic and visual reports of these particles have been published previously (NISHIZAWA *et al.*, 1954, INOUE *et al.*, 1955). In spite of these observations, however, most studies on suspended matter have paid almost no attention to the nature of particle as large aggregates *in situ*. This may be caused by the difficulty of sampling, since the large and fragile particles as they occure *in situ* are disintegrated during the process of water sampling. However, it should be noteworthy that the aggregates are partially composed of dead plankton; thus sea water contained in the porous media of aggregates may be expected to change chemically during the destruction of the plankton by bacteria. This will be important for microbiological and chemical studies, although the exact process has not been demonstrated experimentally. The purpose of the present study is to try to estimate the porosity of large aggregates by some arbitrary means.

2. Materials

The amount of suspended matter in sea water is generally several mg/l. in dry weight and if the sea water samples are set aside to settle, the suspended matter will not tend to re-coagulate. However, sea water near the sea bed off Muroran (where we made two dives using "KUROSHIO-II" on Sept. 3, 1969, depth: 30 m and 42 m, location; 42°19N, 140°55E) was very turbid, and much "*marine snow*" was noticed. This was also apparent from the results of vertical distributions of suspended matter near the sea bed (in preparation).

We fixed "KUROSHIO-II" on the sea bed so as to lie across the current and then lowered a vinyl tube for water sampling using valve released from inside the submarine. An outline of "KUROSHIO-II" and of the arrangement for the sampling tube is shown in Figure 1.

About 100 ml of water was collected from

---

* Received June 9, 1971

** Research Institute of North Pacific Fisheries, Faculty of Fisheries, Hokkaido University, Hakodate, Hokkaido, 040 Japan

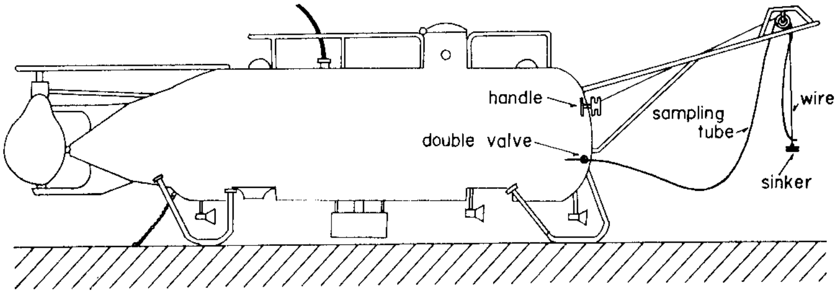

Fig. 1. Outline of the research submarine "KUROSHIO-II" and the arrangement of sampling tube.

each height of 5, 15, 25, 35, 55 and 85 cm above the sea bed. All of the waters were mixed and left for a while, then the suspended matter formed clusters due to re-coagulation. The large clusters obtained with this method had a very similar shape as occured *in situ*. The cluster was composed of dead plankton and detrital matter as well as clay minerals which were recognized as quartz, feldspar, illite and chlorite by X-ray diffraction.

3. Apparatus and Procedure

Figure 2 shows a schematic representation of apparatus. A settling tower (4×15×50 cm) was made of transparent acryl plate of 4 mm in thickness. In order to prevent light reflection and also to increase the brightness contrast of a photograph, the back side of tower was blackened. A camera, on which an extension tube was mounted, was placed in front of the tower, and a cylindrical Xenon tube housed in a reflector case was set on one side.

The experiment was carried out in a dark room. The settling tower was filled with the filtrated sea water (Cl; 18.21 ‰) and left for a while untill both the room and water temperature became almost the same (15.8°C). Using a pipette, we sucked up settled particles carefully and poured them from the upper side of tower. Unfortunately most of the large particles were disintegrated during this opperation, so the range of particle sizes were from about 0.1 mm to about 1 mm.

The camera was used shutterless and the Xenon tube connected with a timer circuit was opperated so as to fire intermittently with five flashes for a period of 2.1 or 4.2 sec.; thus settling particles were photographed repeatedly over a specific time-interval.

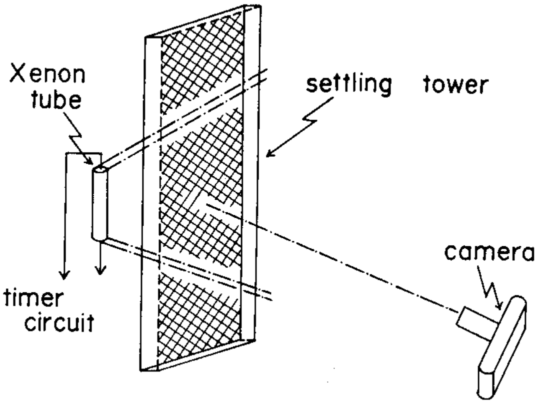

Fig. 2. Schematic view of apparatus for the settling measurement.

4. Result and Discussion

Because of the extension tube mounted on the camera, the depth of a focus was very shallow. Accordingly, it was rare for the photograph to be sharply in focus. As an example, however, we could choose 54 particles which were just settling, from among 50 photographs. Figure 3 shows an example of the photograph and from this the settling velocity can be easily determined.

Particles occured in a great variety of shapes, which tend to be more complicated with their size. Excluding the particles which were a particularly complicated in shape, we classified them into 5 types; a single spherical body, ellipsoidal, cylindrical, conical and multiple body. Each of their volume was computed and the particle diameter was defined as that of a sphere with the same volume. The relation between the settling velocity and the defined particle diameter is shown in Figure 4, where white circles denote either a single spherical body or an ellipsoid, and solid circles denote other shapes. The result shows a somewhat large scatter of points but it is seen that the settling velocity increases in proportion to the particle diameter. Using the least squares method, we obtain the relation as follows,

$$W=0.67\cdot D^{0.57} \qquad (1)$$

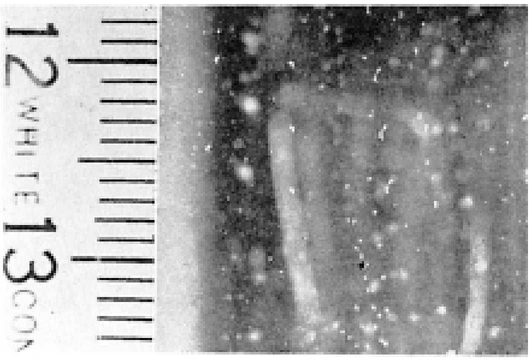

Fig. 3. An example of the photograph.

where W and D are the settling velocity and the particle diameter respectively.

The settling velocity of particle is depended on the density difference between the particle and the fluid, the fluid viscosity, the particle size and the shape. But in the case of a spherical particle and in the region of Reynolds number being approximately smaller than 1, the settling velocity is given as Stokes' law,

$$W=\frac{\bar{\rho}-\rho}{18\mu}\cdot gD^2 \qquad (2)$$

where $\bar{\rho}$, ρ are the density of settling particles and of fluid respectively, g is the acceleration of gravity and μ the fluid viscosity.

On the other hand with a long cylinder, a plate or other non-spherical particles, such as one found among the plankton, there is an appreciable decrease in the settling velocity because of an increase in surface area for the same volume. Thus, a shape correction is necessary for the settling behaviour of such non-spherical particles (HUTCHINSON, 1967). However, it is impossible to assume a coefficient of form resistance for each particle. As mentioned above, we excluded particles of complicated shape, and moreover, we could not re-

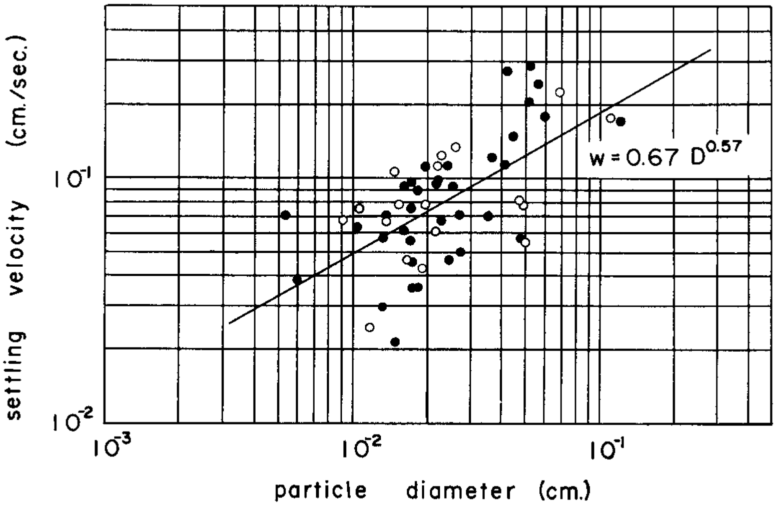

Fig. 4. Relationship between the settling velocity and the particle diameter which is defined as that of a sphere with the same volume (white circles denote a single spherical body or an ellipsoid, and solid circles denote other shapes).

cognize the particles of extreme shape, such as thin plates or long cylinders. Thus, we ignore the shape correction and treat the particle as a sphere.

According to Stokes' law, the settling velocity increases in proportion to the square of the particle diameter; the result of our experiment as shown in Eq. (1) does not satisfy Stokes' law in regard to the relation between the settling velocity and the particle diameter. If we take the shape correction mentioned above into account, the settling velocity will be expected to decrease more with the particle diameter, and thus the difference between the theory and the experimental result will be larger. Accordingly, in order to explain this disagreement, one can only consider density variation with particle diameter.

Provided the porosity of particle is $P(\%)$ and the density of particle (other than a water in the porous media) is ρ_s, we obtain the following equation for the density of particle defined in Eq. (2),

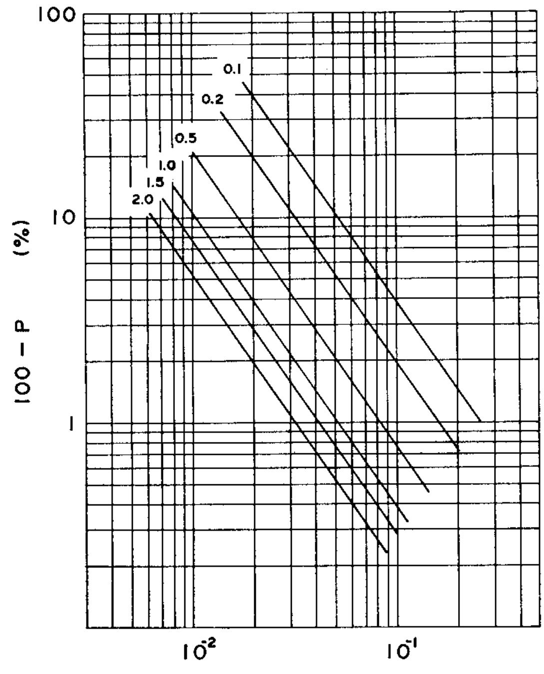

Fig. 5. Relationship between 100-P and the particle diameter, calculated from Eq. (5) (adjacent values are $\rho_s-\rho$).

$$\bar{\rho}=\rho_s-(\rho_s-\rho)\cdot\frac{P}{100} \qquad (3)$$

On substituting this into Eq. (2), Stokes' law for the porous particle is drived as follows,

$$W=\frac{g}{18\mu}(\rho_s-\rho)\left(1-\frac{P}{100}\right)\cdot D^2 \qquad (4)$$

From Eqs. (1) and (4), an expression for the porosity as a function of the particle diameter is found,

$$P=100\left(1-\frac{0.67\times 18\mu}{g(\rho_s-\rho)}\cdot D^{-1.43}\right) \qquad (5)$$

The result calculated from Eq. (5) is represented in Figure 5 taking 100-P as the ordinate, where ajacent values are the density difference, $\rho_s-\rho$. In this calculation, the viscosity is taken as 1.192×10^{-2}, which is the value of water used in this experiment (MIYAKE *et at.*, 1948). If we assume that the materials having ρ_s are fragments of diatoms and clay minerals, the density difference $\rho_s-\rho$ may be considered as 1.0−1.5 (SMAYDA, 1970). Consequently, the porosity of large "*marine snow*" remaked in the sea may be greater than 90 %.

Acknowledgements

The author wishes to express his thanks to Professor Naoichi INOUE for his suggestion and encouragement and to Mr. Hitoshi TAKEDA, technician of "KUROSHIO-II" for his cooperation.

References

HUTCHINSON, G. E. (1970): A treatise on limnology. John Wiley & Sons. Inc., Vol. 2. 260 pp.

INOUE, N., S. NISHIZAWA and M. FUKUDA (1955): The perfection of a turbidity meter and the photographic study of suspended matter and plankton in the sea using an undersea observation chamber. Proc. Unesco Symposium on Physical Oceanogr. 53-58.

MIYAKE, Y. and M. KOIZUMI (1948): The measurement of the viscosity coefficient of sea water. J. Marine Res., **7**, 63-66.

NISHIZAWA, S., M. FUKUDA and N. INOUE (1954): Photographic study of suspended matter and plankton in the sea. Bull. Fac. Fish. Hokkaido Univ., **5**, 34-40.

SMAYDA, T. R. (1970): The suspention and sinking of phytoplankton in the sea. In: Oceanography and Marine Biology. George Allen and Unwin Ltd., Vol. 8, 355 pp.

大きな懸濁粒子の沈降速度と空隙率

梶原昌弘

要旨: 高濁度の海水を放置して得られた凝集粒子を用い，実験室で沈降速度を測定した．そしてこの沈降速度と，粒子を同体積の球に換算したときの直径との関係を求めた．実験式は Reynolds 数が満足されているにもかかわらず，直径に関して Stokes の沈降式を満足していない．これは粒径によって見掛けの密度が変化しているためと考えられる．粒子が porous なときの Stokes の式を導き，その直径と実験的に求められた直径との比較から空隙率を求めた．この結果から，大きな懸濁粒子つまり“*marine snow*”の空隙率は 90% 以上であろうと推定された．