Journal of Marine Research, 43, 605–614, 1985

Analyses of the settling velocities of fecal pellets from the subtidal polychaete *Amphicteis scaphobranchiata*

by Paul D. Komar[1] and Gary L. Taghon[2]

ABSTRACT

Measured settling velocities of fecal pellets produced by *Amphicteis scaphobranchiata,* a deposit-feeding subtidal polychaete worm, are analyzed to determine the effects of pellet shapes and to arrive at improved formulae for predicting settling rates of fecal pellets in general. Drag coefficients calculated from the measured settling velocities and pellet densities decrease with increasing Reynolds numbers, the trend roughly paralleling the drag-coefficient curve for spheres but having higher values due to the nonspherical shapes of the pellets. No clear dependence could be found on the pellet shapes, however, when the shape is expressed as pellet elongation (length/width). Comparisons are also made between the measured settling velocities and equations for the prediction of settling of spheres, the relationships between the two serving as the basis for improved equations for the evaluation of settling velocities of fecal pellets of diverse origins.

1. Introduction

The ability to quantitatively predict the settling velocities of fecal pellets produced by marine organisms is important to many aspects of oceanic processes including the deposition of sediments, geochemical cycles and nutrient availability. The settling of pellets from the near-surface photic zone to deeper waters generally dominates the vertical flux of materials in the sea, shown by the collections of pellets obtained in particle traps (Wiebe *et al.,* 1976; Honjo, 1978). Fecal pellets also play a role in sediment transport processes operating in the benthic boundary layer, and evaluation of their settling rates is one aspect in the study of sediment mobility on the sea floor (Rhoads and Young, 1970; Rhoads, 1974; Taghon *et al.,* 1984).

Measurements of settling velocities of fecal pellets have been restricted almost totally to those produced by pelagic organisms (Fowler and Small, 1972; Wiebe *et al.,* 1976; Small *et al.,* 1979). Much larger pellets are generated by benthic animals, so that settling-velocity equations deduced for the pelagic pellets are not generally applicable. The recent measurements by Taghon *et al.* (1984) of settling rates of benthic pellets now make possible an extension of the quantitative analyses to pellets of

1. College of Oceanography, Oregon State University, Corvallis, Oregon, 97331, U.S.A.
2. College of Oceanography, Marine Science Center, Oregon State University, Newport, Oregon, 97365, U.S.A.

much larger sizes. Initial comparisons of the measurements to available empirical formulae were presented in Taghon *et al.* (1984). The purpose of the present paper is to provide more detailed analyses which will examine the effects of pellet shapes and arrive at improved formulae for predicting settling velocities of fecal pellets.

2. Measurement methods

Details of the procedures of pellet collection and measurements are presented in Taghon *et al.* (1984). The pellets were obtained from the subtidal polychaete *Amphicteis scaphobranchiata* which produces elongate, gradually tapering pellets, intermediate in shape between a cylinder and a cone. Two sets were obtained, one collection being from animals that had been feeding on a sediment fraction less than 61 microns in grain size, and a second collection from worms feeding on a 61 to 250 micron sediment fraction, a factor which influences the densities and hence the settling rates of the resulting pellets. The data sets are unusual in that direct measurements were made of the pellet densities, determined by a technique of isopycnic banding in a density gradient. The total range of densities so determined is 1.086 to 1.282 g/cm^3. The dimensions of the pellets were measured under a microscope (lengths ranging 3.28 to 9.33 mm), and settling velocities were determined by timing their descent in a settling tube over a 100 cm distance (range 3.03 to 5.94 cm/sec). Tables of the results are provided in Taghon *et al.* (1984).

3. Analyses of the measurements

Due to the large sizes of the pellets and resulting high settling rates, the Reynolds numbers of the settling pellets (50 to 152) are well beyond the Stokes region where viscous forces dominate. Therefore, the measurements are not amenable to comparisons with Stokes-type equations of particle settling as employed by Komar *et al.* (1981) in analyses of settling rates of pellets of pelagic origin. This tends to make their analysis more difficult in that the effects of particle shapes are not completely known at these higher Reynolds numbers, and the equations available even for spherical particles tend to be highly empirical and in some cases with problematical evaluations of drag coefficients.

In Taghon *et al.* (1984) the measurements were compared with the empirical formulae developed by Rubey (1933), Janke (1966) and Gibbs *et al.* (1971). Best agreement was with the equation from Rubey (1933), a case of serendipity in that Rubey's formula was based on the settling of crushed quartz, very different in shapes from the cylindrical pellets. Although the agreement was reasonable ($R^2 = 0.64$), it is apparent that this approach provides little advance in our understanding of the basic processes of fecal pellet settling, not including examinations of the influence of pellet shapes on their settling rates nor a systematic examination of the departure of those rates from the well-established settling of spheres.

The general relationship for the settling of spheres is

$$w_s = \left[\frac{4}{3}\frac{1}{C_d}\frac{\rho_s - \rho}{\rho}gD\right]^{1/2} \tag{1}$$

where w_s is the settling velocity, ρ_s and ρ are the particle and fluid densities respectively, g is the acceleration of gravity, C_d is an empirical drag coefficient, and D is the sphere diameter. This relationship is based on the balance between the immersed weight of the particle which causes it to settle and the drag of the surrounding fluid which resists its motion. The formulation of the drag was originally based on a model developed by Isaac Newton wherein the resistance is caused by the impact of the fluid molecules on the projected area of the particle transverse to its direction of motion, the drag being the transfer of momentum. This model is now recognized to be conceptually incorrect, even though the resulting mathematical expression for the drag, and hence Eq. (1), is satisfactory (Graf and Acaroglu, 1966). One result of Newton's model, however, is that Eq. (1) is sometimes referred to as the "impact law," and for convenience we will do so here.

A major difficulty in application of Eq. (1) comes from the necessity of evaluating the empirical drag coefficient, C_d, which is a function of the Reynolds number which in turn depends on the settling velocity to be evaluated. The curve of C_d versus the Reynolds number for spheres is given in most fluid mechanics textbooks.

Since the pellet measurements from Taghon *et al.* (1984) include the size, density and settling velocity of the pellet, the drag coefficient itself can be calculated. Such an analysis immediately raises the question as to the replacement of the sphere diameter D in Eq. (1) when we apply the relationship to cylindrical pellets; should it be the pellet length L, width W, or some combination? The traditional approach, going back to the model of Newton, would indicate that in the derivation of a comparable relationship to Eq. (1), but for cylinders, one would balance the cylinder weight against the drag and take the projected area as LW since the pellets settle with their lengths transverse to the settling direction (the projected area being a rectangle with sides L and W). If we take this approach, D in Eq. (1) is replaced by the pellet width W (since weight $\propto LW^2$ so that the ratio with the projected area causes L to drop out, leaving only W; the 4/3 factor also changes to $\pi/2$). The pellet-settling measurements were analyzed by this approach but with very poor results; the calculated drag coefficients for the pellets showed a considerable scatter with little dependence on either the Reynolds number or pellet elongation (L/W).

An alternative approach is to employ the pellet's nominal diameter, D_n, the diameter of the equivalent sphere having the same volume and weight as the original nonspherical pellet. This facilitates direct comparisons with the well-established settling of spheres and thereby permits examinations of pellet-shape effects on the settling rate. In utilizing the nominal diameter, one is conceptually remolding the pellet into a spherical shape while retaining its mass and volume, and then comparing the settling

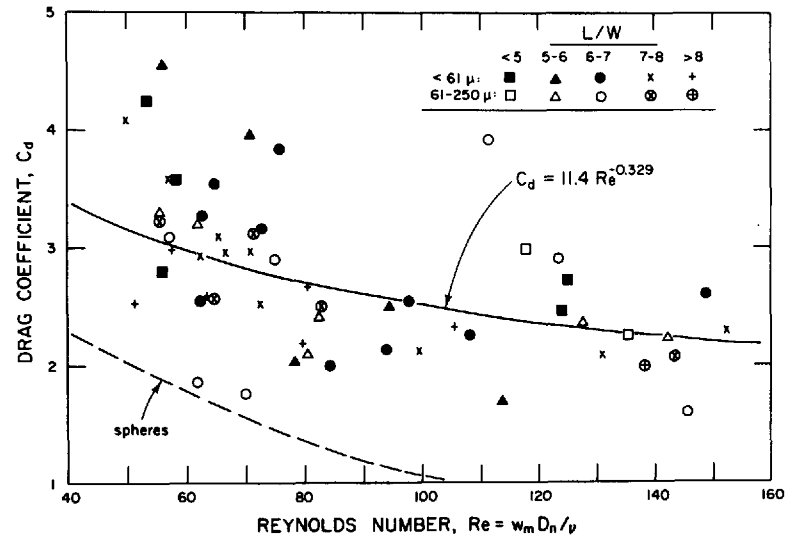

Figure 1. Drag coefficients calculated with Eq. 2 for the fecal pellet measurements obtained by Taghon *et al.* (1984), showing their dependence on the Reynolds number. The different symbols represent the range of pellet elongation (L/W = length/width).

rate it would have as a sphere with its actual measured settling velocity. In calculating the pellet's nominal diameter from its measured length and width, we assumed a cylindrical shape ($D_n = \sqrt[3]{3W^2L/2}$), as did Taghon *et al.* (1984).

For calculations of C_d, Eq. (1) is rearranged to

$$C_d = \frac{4}{3}\frac{\rho_s - \rho}{\rho}\frac{gD_n}{w_m^2} \tag{2}$$

where D has been replaced by D_n, and the calculation is based on the measured settling velocity w_m and pellet density ρ_s. The resulting C_d values are shown in Figure 1, compared with the Reynolds' number $Re = w_mD_n/\nu$ where ν is the viscosity of water. The results are seen to be scattered but with an apparent trend of decreasing C_d with increasing Re. Such a trend is also found for spheres, a small portion of that curve being reproduced in Figure 1. Power regression of the data yields

$$C_d = 11.4\, Re^{-0.329} \tag{3}$$

which further establishes the inverse relationship between C_d and Re.

The data symbols shown in Figure 1 depend on the pellet's elongation, L/W. One might have anticipated that the value of C_d would depend on pellet shape, but no significant pattern is discernible. However, the nonspherical shapes of the pellets are certainly the cause of the higher values of the drag coefficients than those for spheres,

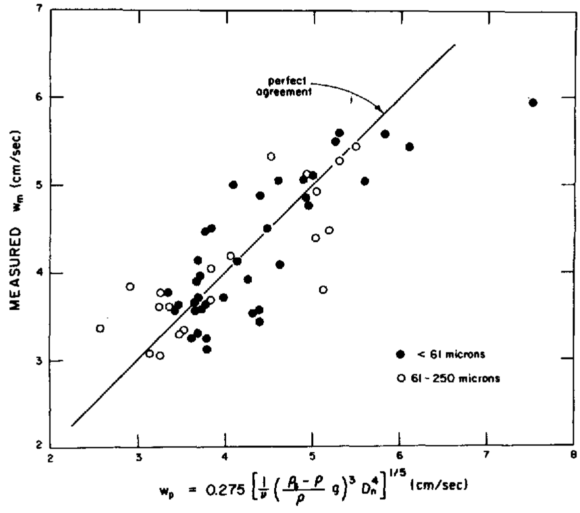

Figure 2. The measured pellet settling velocities versus the value predicted by Eq. (4).

all past studies finding that nonsphericity produces an increase in the drag coefficient and thus a reduction in settling velocity from that of equivalent spheres.

If the C_d relationship of Eq. (3) is substituted into Eq. (2) and the resulting relationship solved for the settling velocity, one obtains

$$w_p = 0.275\left[\frac{1}{\nu}\left(\frac{\rho_s - \rho}{\rho} g\right)^3 D_n^4\right]^{1/5} \tag{4}$$

having approximated the exponent in Eq. (3) as $0.329 = 1/3$. This now gives us a dimensionally-correct analytical equation which relates the pellet's settling velocity to its density (ρ_s) and size (D_n), and to the density and viscosity of water. This semi-empirical equation is compared in Figure 2 with the measured settling velocities, the results being reasonable except perhaps for the largest pellet settling at the highest velocity which departs from the trend.

An alternative analysis approach is to directly compare the measured pellet settling velocity, w_m, with the settling velocity w_s of the "equivalent" sphere, that is, the sphere having the pellet's nominal diameter. Here it is best to evaluate the w_s sphere settling with the power series provided by Davies (1945); Warg (1973) presents computer programs to facilitate the computations. Still simpler is to utilize the analytical equation of Gibbs *et al.* (1971), empirically based on the settling of glass spheres, although the relationship does yield systematic errors when applied to low-density particles (Komar, 1981).

The measured settling velocities w_m of the pellets are compared in Figure 3 with the settling rates w_s of the equivalent spheres calculated with the power series of Davies

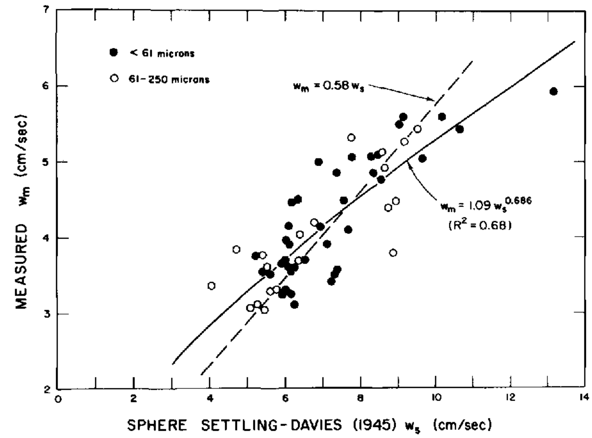

Figure 3. The measured pellet settling velocities versus the settling rate w_s of the equivalent sphere, calculated with the power series of Davies (1945) as described by Warg (1973).

(1945). The overall pattern of the data plot is almost precisely the same as seen in Figure 2 where Eq. (4) was tested. The straight line fitted to the data, but forced to have a zero intercept, is $w_m = 0.58w_s$, a line which is nearly the same as the "perfect agreement" line of Figure 2. Power-curve regression yields

$$w_m = 1.08 w_s^{0.686} \tag{5}$$

which, as seen in Figure 3, provides better agreement with the fastest-settling pellet which was previously an outlier. A similar analysis but with the Gibbs *et al.* (1971) analytical equation yields the regression relationship $w_m = 0.824 w_s^{0.767}$; this equation provides as good predictions as Eq. (5), the different coefficients accounting for the systematic error in the w_s evaluation with the Gibbs *et al.* relationship.

The proportionality factor of the linear relationship $w_m = 0.58w_s$ (Fig. 3) reveals that on average the settling rates of the pellets are about six-tenths that of their equivalent spheres. This is no doubt due to their nonsphericity increasing the drag as seen above in the C_d evaluations, thereby decreasing their settling velocities. The effects of shape are examined in Figure 4 where the ratio w_m/w_s for the individual pellets is plotted as a function of the pellet elongation L/W. Again, no dependence on pellet shape is apparent.

The results of the present analysis are compared in Figure 5 with the Stokes range relationship based on the experiments of Komar (1980) on the settling of glass cylinders and shown by Komar *et al.* (1981) to agree with the measured settling velocities of fecal pellets of pelagic origin. This relationship includes the E shape factor of Janke (1966) as a measure of the particle's nonsphericity; three curves are thereby given, $E = 1$ being for spheres and the $E = 0.25$ curve representing a pellet elongation

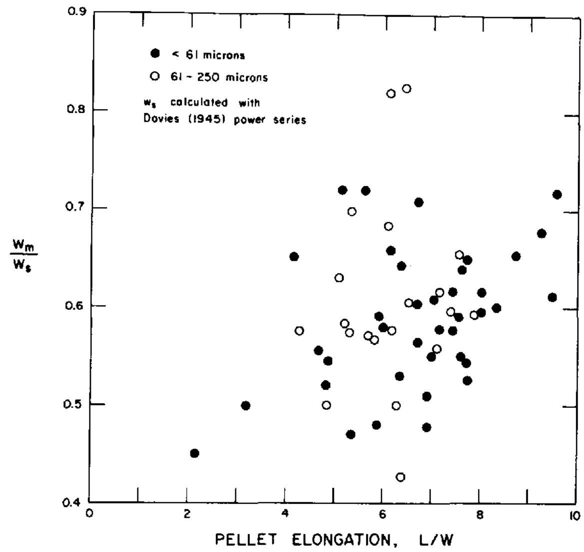

Figure 4. The ratio of the measured settling velocity divided by that for the equivalent sphere versus the pellet elongation, indicating a lack of dependence on the pellet shape.

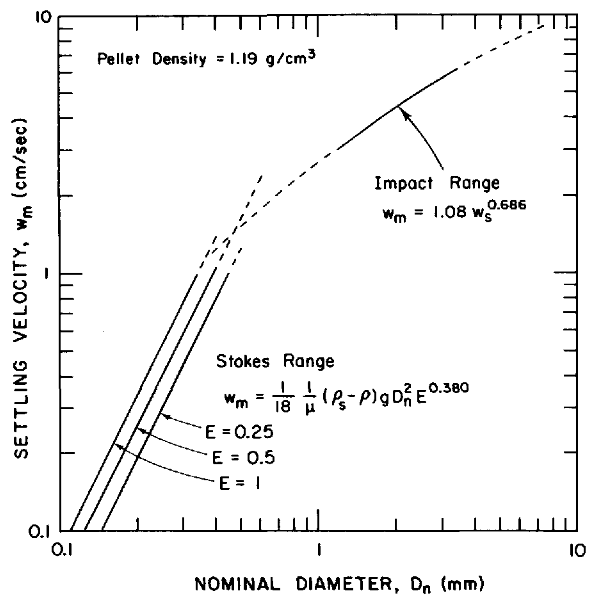

Figure 5. The curve of Eq. (5) for the "Impact Range," obtained in the present analysis, compared with the equation applicable to smaller pellets in the "Stokes Range," deduced by Komar *et al.* (1981).

of approximately $L/W = 6$ to 7, the dominant range of values for the pellets of the present study (Fig. 4). The dashed portions of these curves represent extrapolations beyond the actual ranges of data that served to establish this relationship.

Eq. (5) of the present study is plotted as a simple curve of pellet settling velocity versus its nominal diameter. Such a presentation requires a fixed value for the pellet density, and $\rho_s = 1.19$ g/cm^3 was used here, the average density of the pellets produced by worms feeding on sediments less than 61 microns in size (Taghon *et al.*, 1984) and not much different than the average densities of those feeding on the 61-250 micron fraction (1.14 g/cm^3) or of the pelagic pellets (1.22 g/cm^3). The solid portion of the curve shown in Figure 5 covers the range of pellet sizes and settling velocities represented by the Taghon *et al.* data set, the dashed portions being extrapolations of Eq. (5) beyond the data for purposes of the present comparison.

The resulting comparison in Figure 5 is what one would expect, conforming with the trends of curves for the settling of spheres or natural sand grains [see for example, Baba and Komar (1981, Fig. 3)]. In the Stokes region the relationship predicts that $w_m \propto D_n^2$ so that the slope of the curve on the log-log plot of Figure 5 is 2, and such a trend is confirmed by the measured settling rates of the small pelagic pellets (Komar *et al.*, 1981). As the pellets become too large for Stokes settling, entering the impact range, it would be expected that the slope of the curve would decrease, possibly approaching 1/2 for very large pellets (where $C_d \simeq$ constant). This is seen to be the case for the curve based on the large pellets produced by *Amphicteis scaphobranchiata*. Extrapolation of Eq. (5) to the intermediate pellet sizes and settling rates not presently covered by the available measurements is seen in Figure 5 to form a reasonable bridge whereas extrapolation of the Stokes range equation predicts velocities that are much too high. Until measurements become available within this intermediate pellet-size range, Eq. (5) should be employed for predictions of settling rates for pellets larger than about $D_n = 0.4$ to 0.5 mm and settling velocities greater than about 1 cm/sec. The simpler Eq. (4) provides an acceptable substitute for Eq. (5) over most of this range, up to about $D_n = 3$ mm. However, Eq. (4) would plot as a straight line on Figure 5, not following the curvature of other impact range settling curves, and would likely overpredict the settling rates of large pellets ($D_n > 3$ mm).

4. Discussion

The settling velocities of fecal pellets produced by *Amphicteis scaphobranchiata* are consistent in their hydraulic behavior with the settling of much smaller pellets produced by pelagic animals. Being larger, these benthic pellets conform with the general impact law, Eq. (1), whereas the smaller pelagic pellets follow Stokes-type settling equations. As seen in Figure 5, the curve based on the benthic pellets merges smoothly with the Stokes-range equation at the extremes of their respective applications.

The results of this comparison, therefore, indicate that the Stokes-range equations given in Komar *et al.* (1981) are limited to pellets having nominal diameters less than about 0.4 to 0.5 mm and having settling velocities less than about 1 cm/sec. The relationships deduced in the present study apply to the larger pellets which settle in the impact range. The analytical Eq. (4) is simplest to employ, but its extrapolation beyond the immediate range of the Taghon *et al.* (1984) data is questionable. Although the empirical Eq. (5) is more difficult to apply, it shows better overall agreement with the Taghon *et al.* data, especially the largest pellets which settle at the fastest rates. The curve of Eq. (5) also conforms more closely in overall shape to other impact-range settling-velocity curves (ie., those for spheres and natural sand grains). If applications are required beyond the immediate range of the Taghon *et al.* data, Eq. (5) therefore can be expected to yield better results than the simpler Eq. (4).

Although the settling rates of the nonspherical pellets are lower than velocities for their equivalent spheres, no relationship could be found with the pellet shape as characterized by its elongation (length/width).

Acknowledgments. We would like to thank L. Small for his comments in reviewing this paper. This research was supported by NSF grant OCE-8214708.

REFERENCES

Baba, J. and P. D. Komar. 1981. Measurements and analysis of settling velocities of natural quartz sand grains. J. Sed. Petrol., *51,* 631–640.

Davies, C. N. 1945. Definitive equations for the fluid resistance of spheres. Proc. Physical Soc., *57,* 259–270.

Fowler, S. W. and L. F. Small. 1972. Sinking rates of euphausiid fecal pellets. Limnol. Oceanogr., *17,* 293–296.

Gibbs, R. J., M. D. Matthews and D. A. Link. 1971. The relationship between sphere size and settling velocity. J. Sed. Petrol., *41,* 7–18.

Graf, W. H. and E. R. Acaroglu. 1966. Settling velocities of natural grains. Bull. Inter. Assoc. Sci. Hydrol., *11,* 27–43.

Honjo, S. 1978. Sedimentation of materials in the Sargasso Sea at 5,367 m deep station. J. Mar. Res., *36,* 469–492.

Janke, N. C. 1966. Effect of shape upon the settling velocity of regular convex geometric particles. J. Sed. Petrology, *36,* 370–376.

Komar, P. D. 1980. Settling velocities of circular cylinders at low Reynolds numbers. J. Geol., *88,* 327–336.

—— 1981. The applicability of the Gibbs equation for grain settling velocities to conditions other than quartz grains in water. J. Sed. Petrol., *51,* 1125–1132.

Komar, P. D., A. P. Morse and L. F. Small. 1981. An analysis of sinking rates of natural copepod and euphausiid fecal pellets. Limnol. Oceanogr., *26,* 172–180.

Rhoads, D. C. 1974. Organism-sediment relations on the muddy sea floor. Oceanogr. Mar. Biol. Annual Rev., *12,* 263–300.

Rhoads, D. C. and D. K. Young. 1970. The influence of deposit-feeding organisms on sediment stability and community trophic structure. J. Mar. Res., *28,* 150–178.

Rubey, W. W. 1933. Settling velocities of gravel, sand and silt particles. Am. J. Sci., *25,* 325–338.

Small, L. F., S. W. Fowler and M. Y. Unlu. 1979. Sinking rates of natural fecal pellets. Mar. Biol., *51,* 233–241.

Taghon, G. L., A. R. M. Nowell and P. A. Jumars. 1984. Transport and breakdown of fecal pellets: Biological and sedimentological consequences. Limnol. Oceanogr., *29,* 64–72.

Warg, J. B. 1973. An analysis of methods for calculating constant terminal settling velocities of spheres in liquids. Mathematical Geol., *5,* 59–72.

Wiebe, P. H., S. H. Boyd and C. Winget. 1976. Particulate matter sinking to the deep-sea floor at 2000 m in the Tongue of the Ocean, Bahamas, with a description of a new sedimentation trap. J. Mar. Res., *34,* 341–354.

Received: *6 August, 1984;* revised: *10 April, 1985.*