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Title: SETTLING VELOCITIES OF PLANKTONIC FORAMINIFERA: DENSITY VARIATIONS AND SHAPE EFFECTS

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Abstract Approved ______________________

Paul D. Komar

Sinking rates of shells of four species of planktonic Foraminifera have been measured in a settling tube. One species (*Orbulina universa*) has a spherical shell which permits comparisons with the well-established relationships for the settling of spheres in a fluid. The other three species are non-spherical and so the analysis of their settling rates must take shape effects into account. All measurements involved tests larger than 0.210 mm in size settling in water, and it was found that these do not settle in the Stokes region, their Reynolds numbers always being greater than 0.5. The various species have different settling rates, due to differences in effective densities and to shape effects. The effective densities of the 109 shells are calculated from their measured settling rates and are found to be similar to values reported by other researchers. The data do indicate that the four species have slightly different average effective densities.

A detailed analysis of *O. universa* demonstrates that its effective density is a function of size, decreasing with increasing shell diameter.

The settling rates of the non-spherical species are shown to depend on their shapes as quantified with the Corey Shape Factor. A simplified method for predicting the settling rates of the four species is presented, an approach which depends on an empirical equation based on glass spheres settling in water, corrected with a factor that depends on the shell density and shape.

SETTLING VELOCITIES OF PLANKTONIC FORAMINIFERA: DENSITY VARIATIONS AND SHAPE EFFECTS

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SETTLING VELOCITIES OF PLANKTONIC FORAMINIFERA: DENSITY VARIATIONS AND SHAPE EFFECTS

INTRODUCTION

Planktonic Foraminifera are ubiquitous and abundant organisms in the open ocean. Due to their ability to secrete calcite tests they are also geologically significant, constantly producing carbonate material which has "rained" down to the sea floor over the past 130 million years (Bé, 1977). This "rain" of planktonic Foraminifera shells in the ocean is particularly demonstrated by the recent experiments deploying particle traps, which are found to catch mainly fecal pellets and Foraminifera tests (Honjo, 1976, 1978; Bishop et al., 1977). Fossil assemblages of their shells in the sediments are used in paleoceanographic and biostratigraphic studies, but the reliability of such applications depends on our ability to determine the degree of transport experienced by the tests while settling through the water column and due to currents while they reside on the bottom (Kontrovitz et al., 1979). Because of their small sizes they can be transported by a variety of geological, biological and physical agents, becoming displaced from their life environments and places of entombment (Jones, 1958).

An important aspect to understanding the vertical flux of Foraminifera shells in the water column and their transport on the sea floor is the ability to evaluate their settling velocities. The purpose of this study is to investigate the settling rates of whole, empty tests of planktonic Foraminifera of various species and to determine the effects of their densities and shapes on their settling rates.

There are relatively few previous measurements and analyses of this type. The earliest are those of Thoulet in 1891, whose results are summarized and tabulated in Kuenen (1950, p. 250). Specimens of various sizes were measured, but whole tests were not distinguished from fragments. Berthois and LeCalvez (1960) determined settling rates of two sizes classes of Foraminifera (0.392 and 0.625 mm) by visually following the fall of single specimens. Berger and Piper (1972) undertook the most detailed study and provide the largest set of measurements. Subsamples containing 100 to 1,000 Foraminifera were settled simultaneosly rather than utilizing single specimens. A good trend of settling rate versus maximum test diameter was found (Berger and Piper, Fig. 1), and it was concluded that the modal settling velocity of the species studied is equivalent to that of a quartz sphere of diameter approximately a factor 2.4 less than the maximum diameter of the foraminifer.

Berger and Piper (1972) indicated that the large scatter in their data probably resulted from the varying test shapes and wall thicknesses (effective densities). The primary purpose of my study is to obtain more detailed measurements of settling rates of individual Foraminifera shells in order to investigate the roles of shells density and shape. For this purpose I have selected four species that are spherical or approximately ellipsoidal in shape, as this allows comparisons with the well-established relationships for the settling of these shapes in a fluid (Graf, 1971; Warg, 1973; Komar and Reimers, 1978; Komar, in press).

METHODOLOGY

The Foraminifera specimens employed in this study were obtained from a sediment sample collected from 510 meters water depth off the coast of Morocco (*Meteor* cruise 8, 1967, sample 21B, coordinates 33° 26.5'N, 09° 8.0'W). This sample was selected due to the well-preserved nature of the planktonic Foraminifera, as established by Thiede (1973). This was further demonstrated by my own observations, the details of surface morphology of the specimens indicating that solution or abrasion effects must have been negligible.

The original sample had been wet sieved and stored in a glass jar. For my experiments the tests were sieved through a screen with a mesh aperture of 0.210 mm so that the measurements are limited to larger sizes, a necessity for making the necessary shape measurements and for visually following their descent through the settling tube.

Four species of planktonic Foraminifera were selected for investigation, the spherical form *Orbulina universa* and the roughly ellipsoidal forms *Globigerinoides ruber*, *Globigerinoides sacculifer* and *Globorotalia hirsuta*. Only intact shells were utilized in the experiments. The specimens were identified under a binocular microscope, picked with an artist's brush, and then measured with an ocular micrometer. For the spherical *O. universa* the shell diameter was measured, whereas for the three non-spherical species three axial diameters were measured at approximately 90° orientation to each other, the test's longest axis, D_l, intermediate axis, D_i, and shortest diameter, D_s.

This corresponds to the measurements made by Komar and Reimers (1978) in their investigations of the settling behavior of such shapes.

The individual specimens of Foraminifera shells were pretreated in basically the same manner as described by Berger and Piper (1972). They were soaked in demineralized water for at least 15 days, enough time for air bubbles to disappear.

The experiments were performed in a 2-meter long, plastic, cylindrical tube, 11.4 cm inside diameter, filled with demineralized water. Times of descent were measured over a one-meter section of the tube, the upper timing line being 50 cm from the top. This initial 50 cm of descent insured that they had reached a constant terminal velocity before measuring their settling rates. The timing was done with a Hewlett-Packard 55 pocket calculator with a digital timer, permitting time measurements accurate to about 0.1 sec (Komar and Reimers, 1978). After filling the tube with water, 48 hours elapsed before conducting the experiments so as to allow time for the water to reach room temperature. A thermometer was hung within the tube to monitor the temperature during the measurements.

Wall effects were minimal due to the large inner diameter of the tube in comparison with the small shell diameters. In a few instances the settling forams spent an appreciable amount of time near the cylinder wall or hit it; these were excluded from the subsequent analyses.

RESULTS

The resulting 51 measurements on the spherical *O. universa* are given in Table 1 and are plotted in Figure 1 as the settling velocity versus the test diameter. It is apparent that there is a good trend of increasing settling rate with increasing test size. The curve fitted to the data is based on the well-established equation

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

for the settling of spheres in a fluid, where w_s is the settling rate, ρ_s and ρ are respectively the grain (foram) and fluid densities, g is the acceleration of gravity (981 cm/sec^2), and D is the particle diameter. C_d is an empirical drag coefficient which is related to the Reynolds number

$$Re = \frac{w_s D}{\nu} \qquad (2)$$

where ν is the kinematic viscosity of the fluid. Curves of C_d versus Re are given in Rouse (1949), Komar (in press), and in most fluid mechanics textbooks. In a later section equation (1) will be used to calculate the foraminifer shell density, ρ_s , from its known measured settling velocity, w_s. Those calculations give an average density of ρ_s = 1.482 g/cm^3 for *O. universa*, and it is this value that was used in equation (1) to generate the w_s versus D curve shown in Figure 1. It is seen that it fits the trend of the data very well.

The Reynolds numbers for *O. universa* range Re = 7.3-40.0 (Table 1), which is much too high for application of the simpler Stokes settling relationship (Hutchinson, 1967, Eq. 13, p.258) rather than equation (1), the Stokes equation being limited to Re < 0.5 . According to my data and that of Berger and Piper (1972), the diameter of *O. universa* would have to be less than approximately o.1 mm for the Stokes equation to apply.

Also shown in Figure 1 is a curve based on the results of Berger and Piper (1972, Fig. 1). This line was obtained by sketching a curve through their data, centered in the cross-hatched area of their figure. Their measurements were mainly in the size range 0.1-0.5 mm, so their curve legitimately extends only over that range as shown. But it is apparent that the *O. universa* data agree very well with their results, my data and curve based on equation (1) being a natural extension of their results to larger test diameters. Also shown plotted in Figure 1 are the averaged measurements of Thoulet as tabulated in Kuenen (1950, p. 250), and the three data points of Berthois and LeCalvez (1960).

The resulting measurements on the three non-spherical Foraminifera species are given in Table 2, 3 and 4, and are plotted in Figure 2. Following Berger and Piper's (1972) approach, the data are plotted in Figure 2A as the settling velocity versus the maximum diameter, D_1, assumed to correspond to the "maximum test diameter" of Berger and Piper's Figure 1. It is seen that my data for non-spherical Foraminifera depart significantly from the curve of Berger and Piper, contrasting with the agreement in Figure 1 for the settling rate of *O. universa*.

TABLE 1: Measurements for *Orbulina universa*.

D (mm)	w_s (cm/sec)	Re	C_d	ρ_s (g/cm³)
0.44	2.80	12.8	3.69	1.500
0.54	4.30	24.2	2.43	1.633
0.42	2.78	12.2	3.83	1.536
0.44	2.74	12.6	3.74	1.485
0.46	2.57	12.3	3.79	1.414
0.70	3.25	23.7	2.46	1.282
0.40	3.21	13.4	3.58	1.702
0.44	2.27	10.4	4.27	1.380
0.56	3.27	19.1	2.83	1.411
0.42	1.89	8.3	5.03	1.325
0.54	3.46	19.5	2.80	1.472
0.42	3.05	13.3	3.59	1.605
0.42	2.03	8.9	4.77	1.355
0.62	3.97	25.6	2.34	1.452
0.40	3.06	12.8	3.70	1.659
0.42	2.47	10.8	4.14	1.457
0.74	3.16	24.4	2.42	1.248
0.48	2.58	12.9	3.68	1.388
0.52	2.63	14.2	3.44	1.348
0.52	3.29	17.8	2.95	1.467
0.56	2.41	14.1	3.46	1.272
0.50	3.27	17.0	3.05	1.496
0.42	1.98	8.7	4.87	1.345
0.48	3.04	15.2	3.29	1.482
0.62	4.02	26.0	2.33	1.462
0.50	2.86	14.9	3.33	1.414
0.46	3.06	14.7	3.37	1.522
0.40	3.88	16.2	3.16	1.906
0.36	3.01	11.3	4.03	1.772
0.60	3.43	21.4	2.62	1.390
0.68	3.85	27.3	2.26	1.374
0.78	5.00	40.6	1.78	1.434

TABLE 1: Continued

D	w_s	Re	C_d	ρ_s
0.72	3.63	27.2	2.26	1.314
0.52	2.94	15.9	3.18	1.402
0.80	4.25	35.4	1.93	1.331
0.40	3.66	15.2	3.27	1.834
0.72	5.33	40.0	1.80	1.540
0.40	2.48	10.3	4.29	1.502
0.42	3.76	16.4	3.12	1.800
0.64	3.36	22.4	2.55	1.342
0.52	2.59	14.0	3.46	1.339
0.40	2.05	8.5	4.93	1.394
0.42	3.69	16.1	3.16	1.780
0.72	3.84	28.8	2.18	1.339
0.44	3.99	18.3	2.91	1.802
0.44	2.80	12.8	3.68	1.499
0.54	4.30	24.2	2.43	1.633
0.42	2.78	12.2	3.83	1.536
0.46	2.57	12.3	3.79	1.414
0.70	3.25	23.7	2.46	1.282
0.34	2.07	7.3	5.52	1.529

Temp. = 22°C; ν = 0.00963 cm²/sec ;
ρ = 0.998 g/cm³.

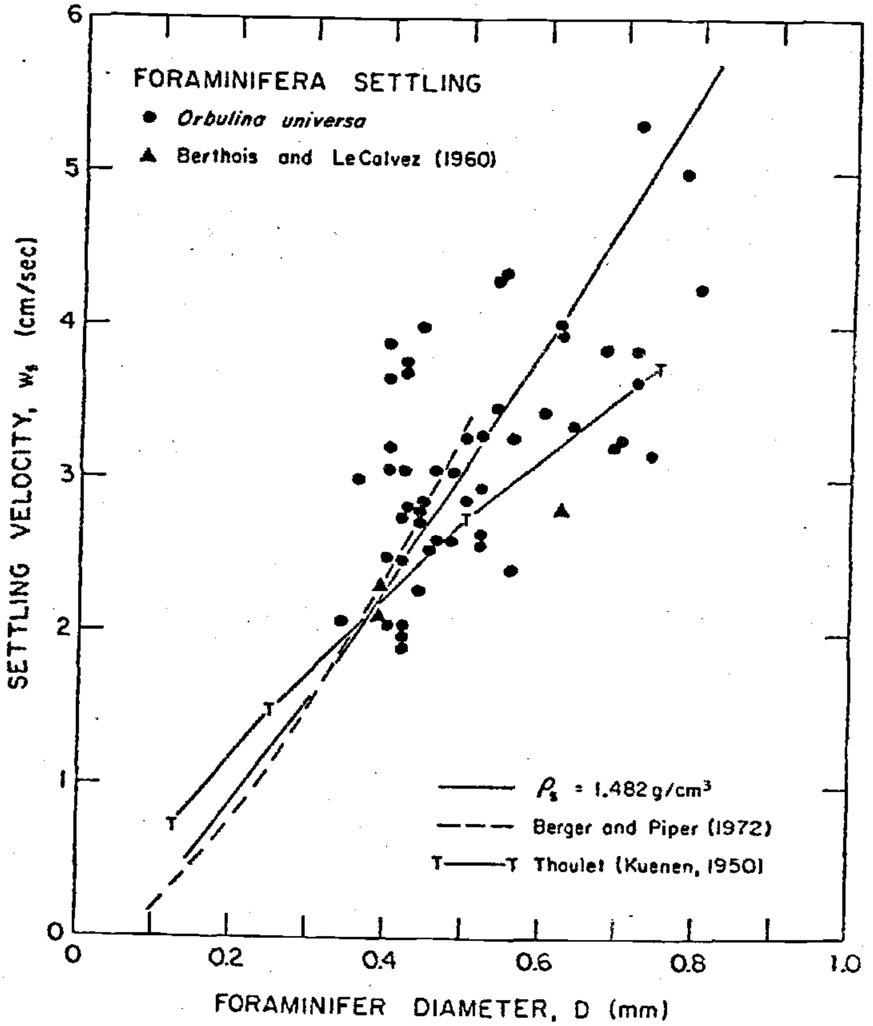

Fig. 1. Measured settling velocities of *Orbulina universa* versus their diameters, with comparisons to the results of previous investigators. The solid curve is based on equation (1) and a mean shell density ρ_s = 1.482 g/cm³.

For investigating the effects of particle shape on settling rates, it is preferable to plot the "size" of the foraminifer as its nominal diameter, the diameter of a sphere having the same weight and volume (Wadell, 1932, 1933). For an ellipsoid the nominal diameter, D_n , is given by

$$D_n = (D_s D_i D_l)^{1/3} \qquad (3)$$

where D_s , D_i and D_l are the three measured axial diameters. When $D_s = D_i = D_l$ and the ellipsoid becomes a sphere, D_n becomes the sphere diameter as it should. The calculated values of D_n are given in Tables 2, 3 and 4. Some systematic error may be introduced in that the three Foraminifera species are not perfect ellipsoids.

Figure 2B plots the measured settling velocities versus D_n for the three non-spherical species. Using D_n, the data now can be compared with the curve of Figure 1 for the spherical *O. universa*. Although the data trend is very good, the settling velocity increasing with the nominal diameter, it is seen that the data plot well below the curve for the spherical *O. universa*. This was to be expected as it is well-established that a non-spherical particle always settles more slowly than does a sphere with the same weight, the more non-spherical the particle the greater the departure (McNown and Malaika, 1950; Komar and Reimers, 1978). A question that will be examined later in this study is whether the departure of the data from the curve in Figure 2B is due entirely to shape effects or because the three non-spherical species have lower effective densities than the 1.482 g/cm³ value for *O. universa* which served as the basis for the curve.

TABLE 2: Measurements for *Globorotalia hirsuta*.

D_l (mm)	D_i (mm)	D_s (mm)	D_n (mm)	CSF	w_s (cm/sec)	Re	C_d	ρ_s (g/cm³)
0.72	0.54	0.34	0.51	0.54	1.78	10.9	4.75	1.22
0.58	0.48	0.30	0.44	0.57	1.33	6.0	7.30	1.22
0.64	0.58	0.32	0.62	0.52	2.46	15.8	3.95	1.29
0.52	0.42	0.34	0.42	0.73	1.67	7.3	5.70	1.28
0.62	0.50	0.26	0.43	0.47	1.77	7.9	6.50	1.35
0.62	0.54	0.32	0.47	0.55	1.67	8.2	5.60	1.25
0.52	0.46	0.26	0.40	0.53	2.05	8.4	5.90	1.47
0.62	0.58	0.32	0.48	0.53	1.85	9.3	5.50	1.29
0.58	0.52	0.34	0.47	0.62	1.70	8.2	5.40	1.25
0.60	0.52	0.38	0.49	0.68	1.98	10.1	4.50	1.27
0.62	0.54	0.34	0.48	0.59	2.25	11.2	4.90	1.39
0.80	0.66	0.42	0.60	0.58	2.33	14.6	4.10	1.28
0.64	0.52	0.34	0.48	0.59	2.16	10.8	4.70	1.34
0.62	0.58	0.30	0.48	0.50	2.05	10.1	5.40	1.36
0.64	0.54	0.32	0.48	0.54	2.01	10.0	5.10	1.32
0.60	0.52	0.30	0.45	0.54	1.57	7.4	6.30	1.26
0.42	0.36	0.20	0.31	0.51	0.83	2.7	15.0	1.25
0.44	0.42	0.40	0.42	0.93	1.44	6.2	6.10	1.23
0.64	0.52	0.34	0.48	0.59	1.69	8.5	6.20	1.28
0.62	0.48	0.30	0.44	0.55	1.65	7.6	6.30	1.29

Temp. = 22°C; ν = 0.00963 cm²/sec; ρ = 0.998 g/cm³.

TABLE 3: Measurements of *Globigerinoides ruber*.

D_l (mm)	D_i (mm)	D_s (mm)	D_n (mm)	CSF	w_s (cm/sec)	Re	C_d	ρ_s (g/cm³)
0.42	0.40	0.34	0.38	0.83	1.78	7.3	5.50	1.34
0.52	0.36	0.32	0.39	0.74	1.03	4.3	8.60	1.17
0.54	0.50	0.36	0.46	0.69	1.52	7.4	5.70	1.21
0.48	0.46	0.30	0.40	0.64	1.39	6.0	6.50	1.23
0.56	0.54	0.42	0.50	0.76	1.67	8.9	4.95	1.21
0.42	0.34	0.34	0.36	0.90	1.14	4.4	8.10	1.22
0.30	0.26	0.20	0.25	0.72	0.40	1.0	28.0	1.13
0.40	0.36	0.24	0.32	0.63	0.42	1.4	21.0	1.08
0.40	0.30	0.22	0.28	0.64	0.20	0.6	48.0	1.05
0.44	0.40	0.30	0.37	0.72	1.25	5.0	7.70	1.24
0.34	0.30	0.24	0.28	0.75	0.44	1.3	22.0	1.11
0.44	0.36	0.32	0.36	0.80	0.87	3.3	10.5	1.16
0.54	0.54	0.40	0.48	0.74	1.26	6.4	6.05	1.15
0.50	0.44	0.34	0.42	0.72	1.26	5.6	7.00	1.20
0.38	0.30	0.30	0.32	0.89	0.20	0.67	42.0	1.04
0.50	0.46	0.32	0.42	0.67	1.28	5.7	7.40	1.22
0.36	0.32	0.24	0.30	0.71	0.40	1.3	22.0	1.08
0.42	0.34	0.32	0.36	0.85	0.94	3.6	10.0	1.18

Temp. = 22°C; ν = 0.00963 cm²/sec; ρ = 0.998 g/cm³.

TABLE 4: Measurements of *Globigerinoides sacculifer*.

D_l (mm)	D_i (mm)	D_s (mm)	D_n (mm)	CSF	w_s (cm/sec)	Re	C_d	ρ_s (g/cm³)
0.50	0.40	0.36	0.42	0.80	1.48	6.0	6.80	1.27
0.40	0.40	0.30	0.36	0.75	0.65	2.3	15.0	1.13
0.64	0.50	0.20	0.40	0.35	1.51	5.8	9.60	1.42
0.44	0.40	0.20	0.40	0.48	1.51	5.8	8.40	1.36
0.52	0.44	0.36	0.43	0.75	1.99	8.5	5.30	1.36
0.46	0.30	0.28	0.34	0.75	1.38	4.6	8.50	1.36
0.52	0.38	0.32	0.40	0.72	1.36	5.3	7.30	1.25
0.50	0.40	0.38	0.42	0.85	1.17	4.8	7.50	1.18
0.44	0.36	0.20	0.31	0.50	1.10	3.4	10.1	1.29
0.50	0.48	0.30	0.42	0.61	1.64	6.8	6.50	1.31
0.58	0.50	0.20	0.39	0.37	2.27	8.6	6.80	1.30
0.64	0.60	0.56	0.60	0.90	4.16	24.4	2.50	1.55
0.50	0.44	0.30	0.40	0.64	1.06	4.2	9.20	1.19
0.52	0.42	0.20	0.35	0.43	1.78	6.1	8.00	1.54
0.54	0.50	0.40	0.48	0.77	2.42	11.3	4.50	1.42
0.56	0.40	0.36	0.43	0.76	1.37	4.5	8.50	1.28
0.46	0.40	0.32	0.39	0.75	1.07	4.1	9.50	1.21
0.60	0.48	0.24	0.41	0.45	2.18	8.8	6.10	1.53
0.46	0.36	0.32	0.36	0.79	0.94	3.3	11.0	1.20
0.50	0.36	0.34	0.39	0.80	1.28	5.0	7.50	1.02

Temp. = 22°C; ν = 0.00963 cm²/sec; ρ = 0.998 g/cm³.

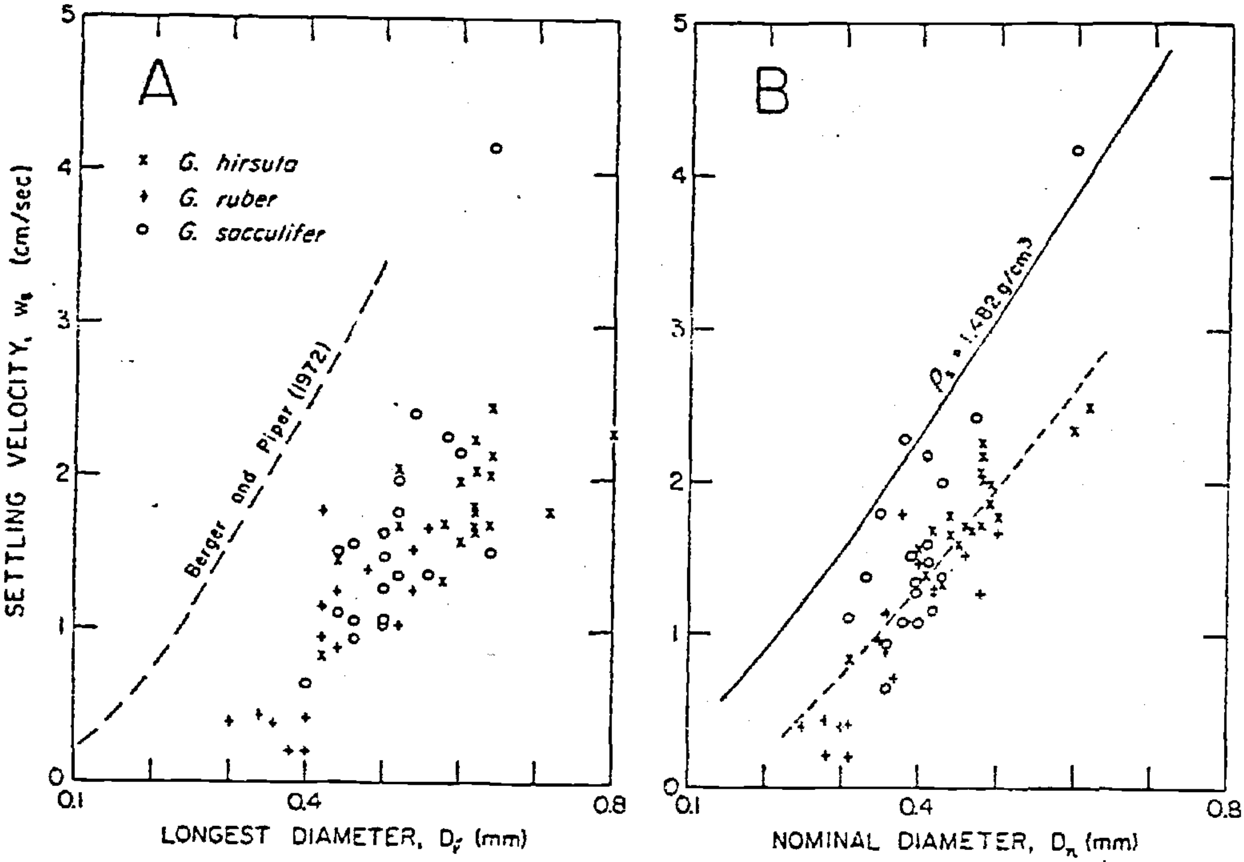

Fig. 2. Settling velocities of the three non-spherical species versus their longest measured diameters (A) and nominal diameters (B) calculated with equation (3). The solid curve in B is the same as that in Figure 1 and the short-dashed curve is based on equations (8) and (11).

DENSITY VARIATIONS

Since the settling velocities of the individual Foraminifera have been measured, the only unknown in equation (1) is the density ρ_s of the shell. Rearrangement of equation (1) yields

$$\rho_s = \frac{3}{4} \rho C_d \left(\frac{w_s^2}{gD} \right) + \rho \qquad (4)$$

which permits calculations of test densities from the measured w_s values. This was first done for the spherical *O. universa* because the values of C_d can be obtained with confidence from the C_d versus Re curve as described earlier. Table 1 contains the values of Re, C_d and calculated densities. These densities will of course be the effective densities of the tests, dependent upon the proportions of solid calcite walls and water-filled voids. The 51 density values so obtained for *O. universa* form a reasonably Gaussian distribution, skewed somewhat towards the larger density values, with an average of 1.482 g/cm³ and a standard deviation of 0.158 g/cm³.

The individual density values from Table 1 are plotted against the foraminifer diameter in Figure 3. Although the data are scattered, there is a clear trend of decreasing effective density with increasing test size. The relationship can be linearized with logarithmic transformations, yielding two possible regression equations:

$$\rho_s = 1.228 D^{-0.265} \qquad [R^2 = 0.3219] \qquad (5)$$

$$\rho_s = 1.883 e^{-0.474 D} \qquad [R^2 = 0.3045] \qquad (6)$$

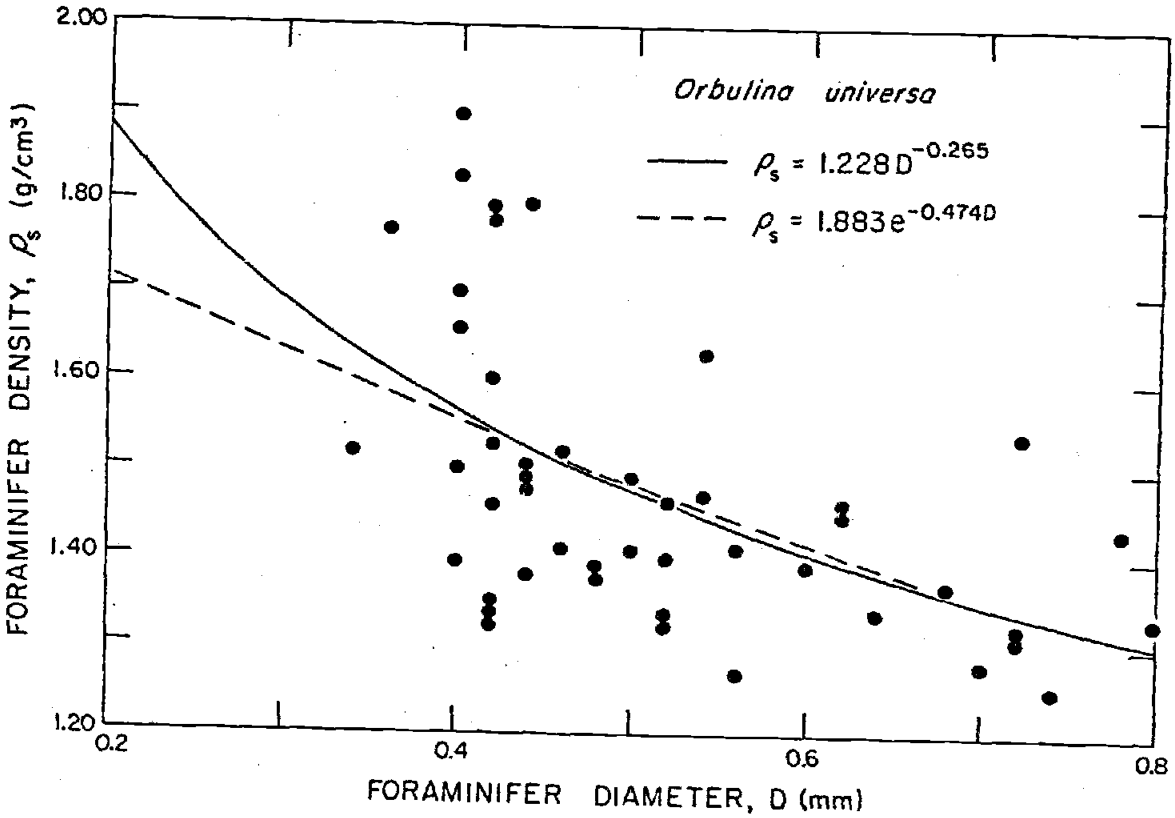

Fig. 3. Effective densities of *O. universa* calculated with equation (4) from their measured settling velocities.

where D is in millimeters and ρ_s is in g/cm³. Both equations explain about the same amount of variability which is small (30-32%), however, due to the large data scatter. Both relationships are plotted in Figure 3 and it is seen that they closely correspond over the range of my data, only differing significantly when extrapolated to smaller test diameters. In the lack of any theoretical knowledge on the relationship between density and size for foraminifera, either equation can be used to approximately describe the density variations within the size range of my data.

Bé et al. (1973) studied in detail the growth of *O. universa* demonstrating that the relationship between its density and size must be complex. This species is unique amongst the planktonic Foraminifera in that its life cycle consists of two distinct stages of test growth, a multichambered trochospiral stage followed by the single-chambered spherical stage. And the spherical stage is a terminal feature; that is, once formed, the test is fixed in overall diameter and no further growth occurs except for some wall thickening. The size of this terminal, spherical chamber is probably controlled by its genetics, nutrition, rate of reproductive maturity, and response to environmental conditions. Bé et al. (1973) also report that wall thickness of *O. universa* shows an inverse relationship with diameter. Their measurements show that individuals with test sizes less than 0.450 mm have thicker walls (25-30 microns) while tests larger than 0.600 mm have thinner walls (about 20 microns). It is apparent that the trend of the data in Figure 3 is in agreement with these growth patterns, the smaller specimens having higher effective densities due to their thicker walls and smaller over-all sizes (ie., having more mass per total volume).

In principle the densities of the non-spherical species can be calculated in the same manner with equation (4), using the nominal diameter D_n for D. But here the evaluation of the drag coefficient C_d is much more uncertain than for the spherical *O. universa*. For non-spherical particles C_d is not only a function of the Reynolds number, Re, but also of the shape itself. Schultz et al. (1954) and Komar and Reimers (1978) provide sets of curves of C_d versus Re, one curve for each shape defined by the Corey Shape Factor, CSF, given by the dimensionless ratio

$$CSF = \frac{D_s}{(D_i D_l)^{1/2}} \tag{7}$$

For a spherical shape CSF = 1.0, and the C_d versus Re curve is the same as that previously employed in the analysis of *O. universa*. At a fixed Reynolds number, the lower the value for CSF and hence the more non-spherical the particle, the larger the resulting C_d and the lower the resulting settling velocity according to equation (1).

Tables 2, 3 and 4 contain the calculated CSF values, the Reynolds numbers from equation (2) using D_n , and the C_d values obtained from Komar and Reimers (1978, Fig. 5). Also given are the calculated effective densities obtained from equation (4).
Due to the uncertainties in the estimated C_d values, the calculated densities are given to only three significant figures, and this may be too many.

Attempts were made at relating the densities of these non-spherical species to their sizes, much as done in Figure 3 for *O. universa.* No comparable trend could be found, in part due to the large uncertainties in the density calculations, but also due to the smaller ranges in sizes of the non-spherical species in the data sets.

The averages of the density values for *G. hirsuta, G. ruber* and *G. sacculifer* are respectively 1.29, 1.16 and 1.30 g/cm^3 . All of these values are lower than the 1.482 g/cm^3 average determined for *O. universa,* which fits in with the generally more fragile structures of these non-spherical forms. These differences in densities indicate that the departure seen in Figure 2B of the data for the non-spherical species from the curve based on *O. universa* is due both to the lower densities of these species and to their shapes reducing their settling rates.

There are very few published measurements of effective densities with which to compare our results. Based on their measurements of settling velocities, Berger and Piper (1972) calculated an effective density much as I have done, but employing the Stokes equation rather than equation (1). They obtained a value of 1.50 g/cm^3 which corresponds closely to my average for *O. universa.* On the basis of one unpublished density determination by Malgre and a similar use of the Stokes equation to calculate the effective density, Berthois and LeCalvez (1960) give a value of 1.162 g/cm^3 for *O. universa* and *Globigerina bulloides.* In connection with their study of threshold of Foraminifera tests in a current, Kontrovitz et al. (1979) determined effective densities for fifteen different species by directly weighing a number (10 to 32) of tests whose volumes were estimated from microscopic measurements. The values they give (Kontrovitz, et al., Table 1) are the effective densities in air, that is, where the pore spaces are filled with air. The measurements of Bé et al. (1973) for *O. universa* indicate a total shell porosity of about 90%. Using this to change the effective density values as given in Kontrovitz et al. to effective densities in water, I obtain the following values for the species of interest to this study: 1.62 g/cm^3 for *O. universa*, 1.72 g/cm^3 for *G. sacculifer* and 1.52 g/cm^3 for *G. ruber*. *G. hirsuta* was not included in their study. Their value for *O. universa* agrees reasonably well with my result, but their values for the non-spherical species are higher than mine. It is uncertain how reliable their results are in that some of their values are too high to be possible; for example, their effective density of *Globorotalia tumida* in water would be 5.35 g/cm^3, and 2.41 g/cm^3 for *G. truncatulinoides*. The measurements of wall thicknesses and test diameters of *O. universa* by Bé et al. (1973) also permit approximate calculations of effective densities. Using a test diameter of 0.60 mm and a wall thickness of 20 microns containing 7.5% pore spaces, the calculated effective density is 1.15 g/cm^3, lower than my value and that of Berger and Piper (1973), but close to that of Berthois and LeCalvez (1960). This calculated value may be somewhat low in that I assumed the shell to be completely hollow, with no internal structures. However, Bé et al. (1973) have shown that the multichambered trochospiral shell of the infant stage may be contained within the adult spherical form.

But they also indicate that it is extremely fragile and seems to be reabsorbed with time, so if present it probably contributes very little to the mass of the shell and would not appreciably affect the calculated density value.

It is apparent from this comparison of the various studies using different techniques of evaluating densities of Foraminifera shells that although there is approximate agreement, a significant uncertainty remains. Further investigations are certainly warranted.

PREDICTIONS OF SETTLING VELOCITIES

Baba and Komar (1981) have presented approaches to the simplified calculation of settling velocities of natural sand grains. A similar approach can be used for the settling of Foraminifera shells. It relies on the empirical equation of Gibbs et al. (1971) for the settling of spheres,

$$w_g = \frac{-3\mu + [9\mu^2 + gr^2\rho(\rho_s - \rho)(0.015476 + 0.19841r)]^{1/2}}{\rho(0.011607 + 0.14881r)} \quad (8)$$

where μ (poise) is the dynamic viscosity of water, r (cm) is the sphere radius, w_g (cm/sec) is the settling velocity, and the remaining terms are as defined previously. This relationship is empirically based on measurements of settling rates of glass spheres in water, but Komar (in press) has shown that it yields good results for a wide range of particle densities including Foraminifera if a density-dependent correction factor is employed to reduce systematic errors.

The measured settling velocities of *O. universa* are plotted in Figure 4A against w_g calculated with equation (8) using $r = D/2$ and the effective densities given in Table 1. As expected from the examination by Komar (in press) of the applicability of equation (8) to Foraminifera settling, there is not exact agreement between w_s and w_g, but there is a linear proportionality. The straight line fit shown to the data yields

$$w_s = 0.915\, w_g \quad (9)$$

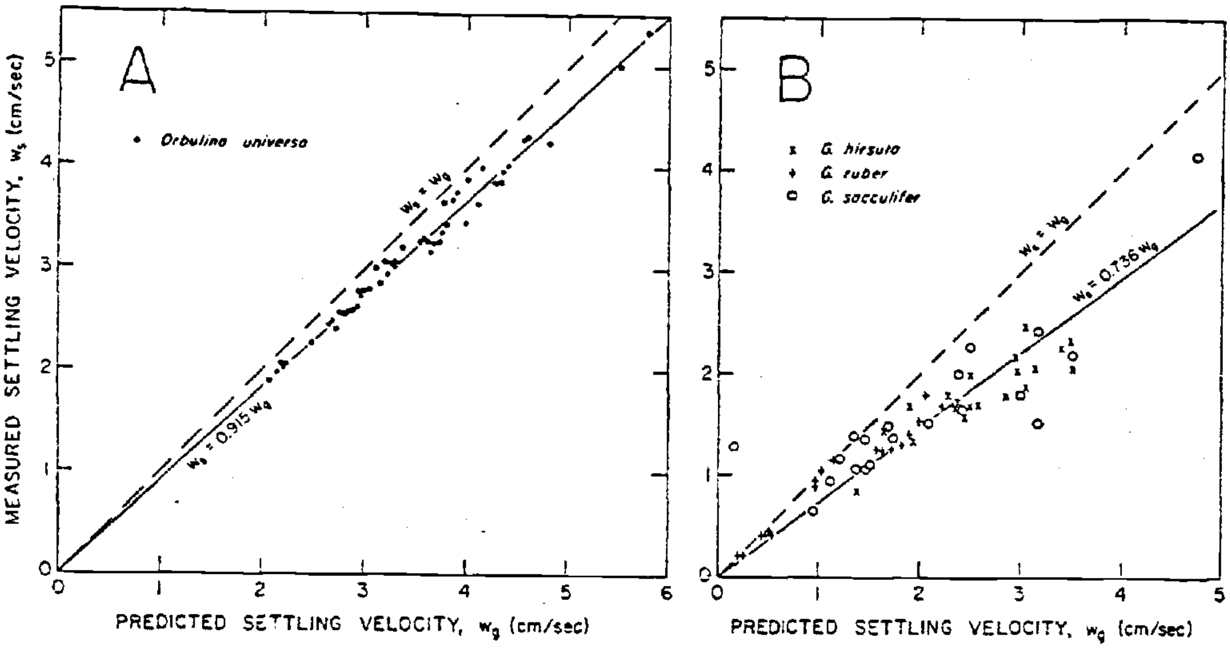

Fig. 4. Measured settling velocities versus those predicted with the Gibbs et al. (1971) relationship of equation (8).

This 0.915 factor is comparable to the R_w correction factor introduced by Komar (in press) for improving the results of equation (8) when applied to Foraminifera, the value given there being 0.9676. This value of Komar (in press) makes corrections only for the particle's density differing from that of the glass spheres upon which equation (8) is based. The slightly lower value obtained here could result from *O. universa* not being precisely spherical, from the presence of surface roughnesses and pores, possibly from a systematic error in the measurements or calculations, or from some unknown factor.

The importance of the relationship of equation (9) is that it permits a simple method for the calculation of settling velocities of *O. universa*. Equation (8) from Gibbs et al. (1971) is first employed to calculate w_g, and that value then is corrected with our equation (9) to yield a result that is in close agreement with the measured settling velocities.

The same procedure can be used for the non-spherical Foraminifera species, even though equation (8) is supposed to be restricted in use to spherical grains. It is most logical to use $r = D_n/2$ in the calculations with equation (8) since the nominal diameter is the diameter of the equivalent sphere. But the evaluation of D_n from equation (3) requires that all three axial diameters of the ellipsoidal Foraminifera test be measured, a rather tedious procedure. Baba and Komar (1981) found in their study of natural sand grains that the intermediate diameter, D_i, of the roughly ellipsoidal grains closely correspond to D_n and so employed D_i in their calculations.

It is apparent from Tables 2,3 and 4 that this is also the case for the non-spherical Foraminifera. This is further demonstrated in Figure 5 where the corresponding values of D_n and D_i are plotted for the three species. Baba and Komar (1981) found almost exact correspondence between D_n and D_i for sand grains. However, for the Foraminifera shells the relationship is

$$D_n = 0.713D_i + 0.087 \quad (10)$$

where both D_i and D_n are in millimeters.

The importance of this close correspondence between D_n and D_i for the non-spherical Foraminifera is that, like Baba and Komar (1981), I can employ measurements of D_i in calculations of settling rates rather than D_n values which require measurements of all three axial diameters. Since the ellipsoidal shells tend to rest with their smallest axial diameters D_s vertical, the required D_i measurement will be the smallest diameter of the elliptical two-dimensional view observed under the microscope.

A plot of measured w_s versus w_g calculated from equation (8) using $r = D_i/2$ for the three non-spherical species is shown in Figure 4B. The result is very similar to that in Figure 4A for *O. universa*, except that the best-fit straight line is now

$$w_s = 0.736w_g \quad (11)$$

for the three species taken together. On an individual basis the three species yield slightly different values for the proportionality coefficient: 0.767 for *G. ruber*, 0.753 for *G. sacculifer*, and 0.687 for *G. hirsuta*.

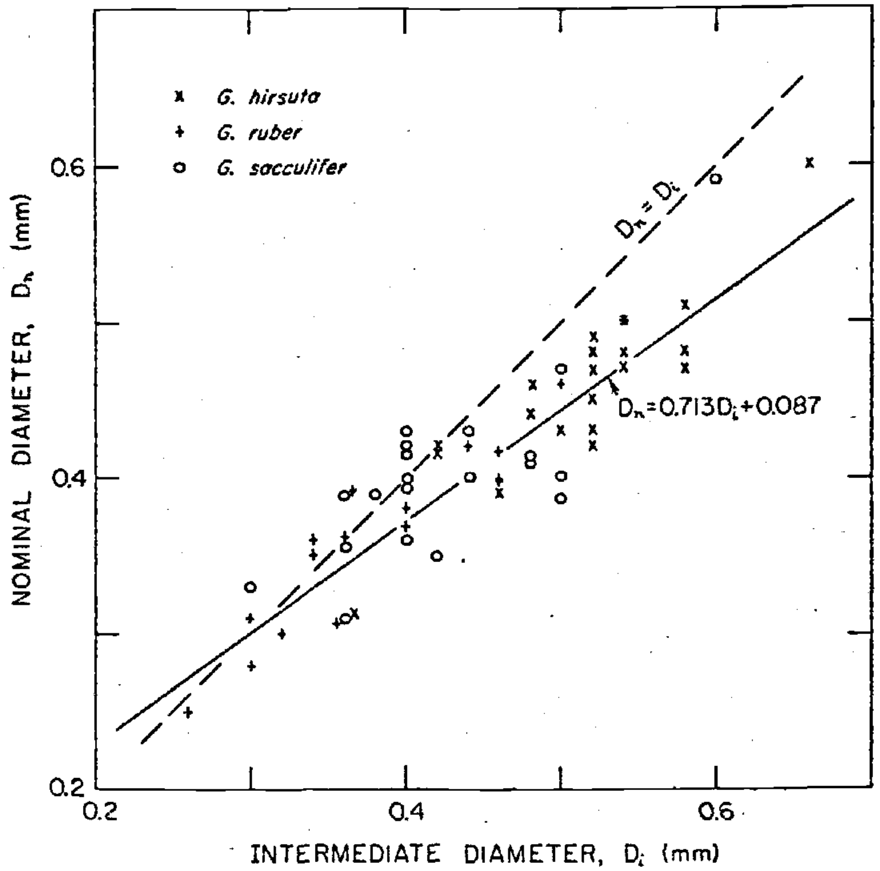

Fig. 5. Nominal diameters of the non-spherical species versus their intermediate diameters.

As with *O. universa*, equation (11) or the individual values of the proportionality factor can be utilized as correction factors with equation (8) for straight-forward calculations of settling velocities from measured D_i values. The curve in Figure 2B through the data for the non-spherical species was obtained in this way, using an average density of 1.25 g/cm³ for the three species and using equation (11) as the average correction of the w_g results obtained with equation (8). Since the plot of Figure 2B involves the nominal diameter, D_n, the D_i values used in the calculations were converted to the corresponding D_n values with equation (10). This was required only for plotting purposes; in general calculations of settling velocities require only the measured D_i values without evaluations of the corresponding D_n values.

The values of the proportionality factors in equations (9) and (11) are basically empirical correction factors, and appear to depend on the shape of the particular species of Foraminifera. The value is highest (0.915) for the spherical *O. universa* and lowest (0.687) for *G. hirsuta* which tends to be the flattest of the three non-spherical species, thereby having the lowest values of CSF from equation (7). In Figure 6 values of w_s/w_g for the non-spherical species are plotted against the corresponding CSF values. The ratio w_s/w_g is the ratio of the measured settling velocity w_s to the calculated value w_g from equation (8), the settling rate of an equivalent sphere. As the shell becomes less spherical and the value of CSF decreases, it would be expected that the actual settling velocity, w_s, would decrease in comparison with the w_g value for a sphere and the w_s/w_g ratio would decrease.

Although the data are scattered, it is apparent that there is such a trend in the plot of Figure 6. For a spherical shape such as *O. universa*, CSF = 1.0 and one would expect $w_s/w_g \simeq 1.0$; from equation (9) the *O. universa* data actually plots at an average $w_s/w_g = 0.915$ due to grain-density corrections required in the Gibbs et al. (1971) relationship for calculating w_g (Komar, in press).

The results of Figure 6 demonstrate that the empirical proportionality factor in equation (11) for the non-spherical species is strongly shape dependent, the more non-spherical the individual foraminifer the lower the value of this correction factor. It is apparent that the graph of Figure 6 could be employed in a more refined analysis of the settling rates of the Foraminifera than the method presented earlier which depends only on a measurement of D_i and the utilization of equation (11) for an average correction for the non-spherical species. Knowing the shell's individual CSF value, Figure 6 could be used to determine a w_s/w_g ratio for that particular shape which is then used to correct the calculated w_g value to a w_s value that corresponds with the measured settling rates. However, this approach does require measurements of D_s and D_l as well as D_i, since all three axial diameters are required in the calculations of CSF with equation (7). Although the resulting estimates of settling rates would be improved, the necessary measurements would require much more effort.

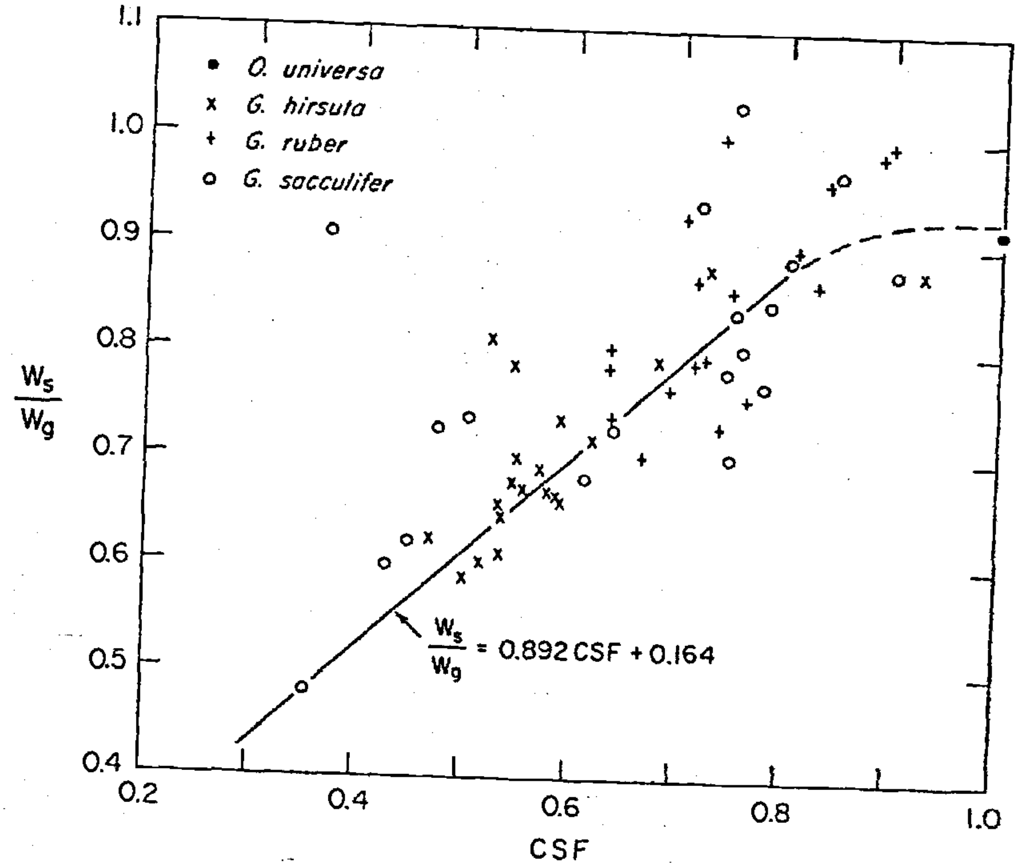

Fig. 6. The measured settling velocity w_s divided by w_g calculated with equation (8), the settling rate of an equivalent sphere, versus the Corey Shape Factor of equation (7), showing that the more non-spherical the shell the greater the reduction in its settling rate. Only the mean value is plotted for the spherical *O. universa*.

CONCLUSIONS

The principal conclusions arrived at in this study of settling rates of planktonic Foraminifera are:

1. The settling velocities of the four species included in the study differ because of their contrasting effective densities and shapes. The higher velocities correspond to the spherical *O. universa* and the lowest are those of *G. ruber*.

2. Effective densities of the shells are calculated from their measured settling rates. The average densities of the four species are shown to be slightly different, the values being in basic agreement with results given in previous studies.

3. A more detailed investigation of *O. universa* revealed that its density is a function of test size, decreasing with increasing shell diameter. This observation is in agreement with the conclusions of Bé et al. (1973) on the growth and morphology changes of this species.

4. Departure from a spherical shape causes the non-spherical species to have settling rates that are lower than those of *O. universa*. It is shown (Figure 6) that their settling velocities depend on the Corey Shape Factor of equation (7), the more non-spherical the test the lower the value of its Corey Shape Factor and the greater the reduction of its settling rate.

5. Equation (8) from Gibbs et al. (1971) can be used for simplified calculations of settling rates of Foraminifera if correction factors are employed.

For the spherical *O. universa* the calculation uses $r = D/2$ where D is its measured diameter, and the calculated w_g value is corrected with equation (9). Calculations for the non-spherical species are based on measurements of their intermediate diameters D_i, and corrected with equation (11). The value of this correction factor is shown to be dependent in part on the effective density of the shell, but mainly on its shape.

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