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# Empirical Relationships for Grain Size Parameters of Calcareous Sand on Oahu, Hawaii

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**ABSTRACT**

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This paper provides quantitative comparisons and relationships for the grain size parameters obtained from 11 medium to very coarse calcareous sand samples collected on Oahu, Hawaii. Sieve and settling techniques separate each sample into groups by sieve size and fall velocity, respectively. Individual grain properties such as shape, fall velocity, intermediate dimension, nominal diameter, and equivalent diameter are presented. The distributions of the nominal and equivalent diameters within the sieve and settling groups are analyzed to provide the respective median diameters for the samples. The wide range of particle shapes in the sand explains the scatter of size parameters within each group obtained from sieve analysis. Settling technique, which separates grains by their hydraulic characteristics, precisely defines the median equivalent diameter for calcareous sand. Correlation of the results provides empirical relationships between the nominal and equivalent diameters of the individual grains as well as the median sieve size of the sand samples and the corresponding nominal and equivalent diameters. The proposed empirical relationships allow the more representative grain size parameters of calcareous sand to be determined directly from the commonly used sieve analysis.

**ADDITIONAL INDEX WORDS:** *Bioclastic sediments, equivalent diameter, calcareous sand, nominal diameter, shape factor, settling analysis, sieve analysis, sieve size.*

## INTRODUCTION

Tropical island beach sand is composed of numerous bioclastic fractions derived from the calcium carbonate skeletons of reef dwelling creatures and has distinct physical and engineering properties compared to silicate sand. MOBERLY and CHAMBERLAIN (1964) and ZAPKA (1984) reported the physical properties related to the chemical composition, hardness, density, and shape of calcareous sand. DAI (1997) showed that the particle shape plays an important role in the engineering properties of calcareous sand, modifying the transport mechanisms and beach profile characteristics. Calcareous sand grains are mostly platy in shape compared to the more spherical silicate sand. Their size characteristics are most appropriately described in terms of the equivalent and nominal diameters based respectively on the fall velocities and the volumes of the particles.

MAIKLEM (1968) and BRAITHWAITE (1973) were among the first to determine the size distributions of calcareous sand in terms of equivalent diameter by settling analysis. This approach sorts sediment hydraulically in a settling tube and the results encompass the effects of size, shape, and density of the particles. SANFORD and SWIFT (1971), KOMAR and CUI (1984) and LUND-HANSEN and OEHMIG (1992) showed that sieve and settling techniques yield similar grain size distributions for silicate sand with uniform density and shape. However, KENCH and MCLEAN (1996, 1997) compared sieve and settling techniques for calcareous sediment and showed that the grain size distribution in terms of equivalent diameter obtained from settling analysis is significantly different from the size distribution found directly by sieve analysis. DE LANGE *et al.* (1997) showed that sieve and settling analyses do not produce the same textural parameters for sand samples composed of mixtures of quartz, feldspar, and volcanic glass. The discrepancy of the two techniques is expected because sieve size and equivalent diameter deviate from each other as particle shape deviates from spherical.

Based on the premise that the grain size distribution and properties determined from settling analysis correctly reflect the hydraulic characteristics of the sand sample, KENCH and MCLEAN (1997) examined the interpretative use of the results for sediment transport models developed for silicate sand. While the equivalent diameter determined from settling analysis better represents calcareous sediment in suspension, motion initiation and bed load transport are more appropriately described by the nominal diameter, which relates to the weight of the particles only. DAI (1997) and MILLER (1998) examined the use of these sediment size parameters to predict the response of tropical island beaches to waves and currents. Pending more comprehensive studies on motion initiation and transport of calcareous sand, these *ad hoc* approaches, with a better description of the grain size characteristics, provide a more rational representation of the transport processes. Such a grain size classification scheme

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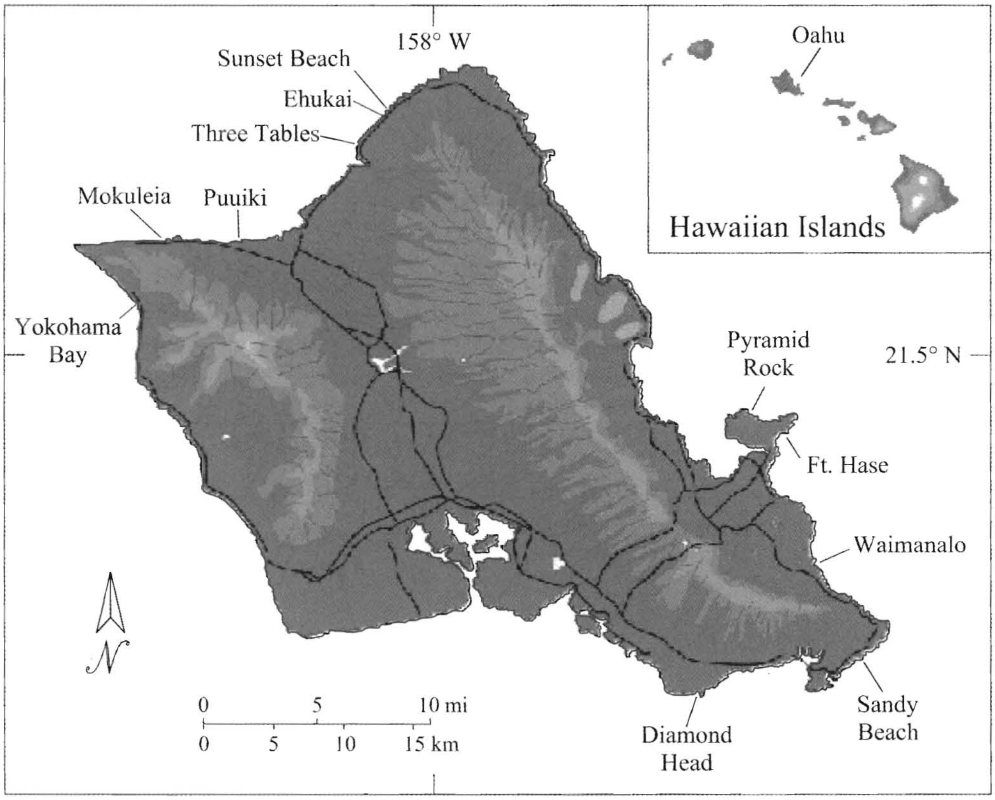


Figure 1. Location map of sand sampling.

is also necessary for any future transport models for calcareous sand.

Sieve analysis becomes biased at determining properties such as nominal and equivalent diameter as particle shape deviates from spherical. Despite this limitation, sieve analysis remains the most common technique to determine grain size properties for calcareous sand (*e.g.,* FRITH, 1983; SAGGA, 1992; LIPP, 1995; and HARNEY *et al.,* 2000). Relationships that can be applied directly to sieve analysis results to infer the nominal and equivalent diameters of the sediment are highly desirable. The present study addresses this by investigating and comparing the grain size properties obtained from sieve and settling techniques based on consistent grain size definitions. Empirical relationships between various grain size definitions and between the sieve and settling results are determined using calcareous sand samples collected on Oahu, Hawaii. These relationships allow continued use of sieve analysis as the standard method for characterizing sediment, but provide correction factors so that data from sieve analysis can be properly interpreted and used in sediment transport models.

## METHODOLOGY

### Sand Samples

Oahu beaches are composed mainly of calcareous sand. Samples of beach sand were obtained from the swash zone at 11 Oahu beaches. Figure 1 shows the locations of these beaches. The north and west shores of Oahu are seasonally high-energy beaches. Swell from North Pacific storms reach these shores in the winter, when surf regularly exceeds 3 meters. These beaches can experience rapid sediment loss during periods of high surf, but recover during the gentler summer season, when the waves are longer and less steep. The east and south shore beaches are generally low to medium energy beaches exposed to the trade-wind waves, with some reaction to north or south swell. High energy beach sediment tends to be coarser and the beach slope steeper than lower energy beaches (GERRITSEN, 1978). The selected sites provide a balanced representation of the sediment sizes commonly found on tropical island beaches.

While the exact composition of the sand is site specific, the main constituents of beach sand around Oahu are foraminifera, coralline algae, and mollusc shells, with lesser amounts of coral, echinoids, and *Halimeda* (MOBERLY, 1963). A limited amount of volcanic rock fragments is also found in the sand. The species that constitute the sediment have unique particle shapes. Foraminifera are the most spherical, while sand grains derived from coralline algae have a variety of shapes. Fragments of mollusc shells are generally blade and disk-shaped. The spines of echinoids tend to be rod-shaped and *Halimeda* are disk-shaped. KENCH and MCLEAN (1997) reported that sand grains of the coral genus *Pocillopora* are also rod-shaped. Mixture of these species in natural beach sand gives rise to a wide range of particle shapes. Classification of calcareous sand by biological composition can provide a qualitative description of the particle shape, but falls short of providing quantitative data that can characterize the sediment as a whole.

## Sieve and Settling Techniques

The 11 sand samples were carefully cleansed and prepared prior to the analyses. Each sample was rinsed with fresh water, dried in a 95°C oven, and divided into sub-samples for sieve and settling analyses. Dry sieve analysis was performed using a series of 15 eight-inch sieves ranging in mesh size from 0.063 mm to 4.76 mm. Each sample of approximately 600 to 1000 grams was shaken for 15 minutes and each sieve fraction was weighed and saved in a separate bag. Grain size distributions by weight were determined graphically and distribution statistics, including median, mean, and sorting, were found graphically or by the method of moments. Twelve grains were chosen at random from each sieve fraction for subsequent analyses to determine their dimensions and fall velocities.

Figure 2 shows a schematic of the experimental setup for a long settling tube, which includes a 12.2 m (40 ft) long tube sealed at the bottom with a clear acrylic cylinder. The long settling tube was designed to separate the sediment in each sample according to fall velocity. The length of the tube was maximized, under the constraints of the laboratory facility, to provide the most differentiation of the grains during settling. During the experiment, the system was filled with fresh water and temperature readings at the top and bottom were noted prior to the tests. The sediment poured into the tube was differentiated by fall velocity and collected in the acrylic cylinder. The acrylic cylinder was disconnected at the end of the test and plugged to preserve the sediment column. Holes were drilled at pre-specified levels along the cylinder and 12 grains of sediment were randomly collected at each level for subsequent analyses to determine their dimensions and fall velocities.

Initial tests using the long settling tube were performed with approximately 375 grams of sediment. Subsequent analysis of the fall velocities of individual grains from the same level showed a remarkably high standard deviation. Since the experiment sorted the sediment by fall velocity, a small standard deviation was expected. A large enough volume of sediment was necessary for vertical resolution in the sediment column, but too much sediment in the initial tests caused significant turbulence and grain-to-grain interactions throughout the water column. The standard deviation decreased as the amount of sediment was decreased to 200 grams, and then a satisfactory combination of standard deviation and vertical resolution was found for a sample size of 125 grams. Subsequent tests were performed using a sample size of 125 grams.

## Measurements of Grain Properties

The individual grains obtained from the sieve analysis and the long settling tube were analyzed for shape factor, nominal diameter, fall velocity, and equivalent diameter. Grain di-

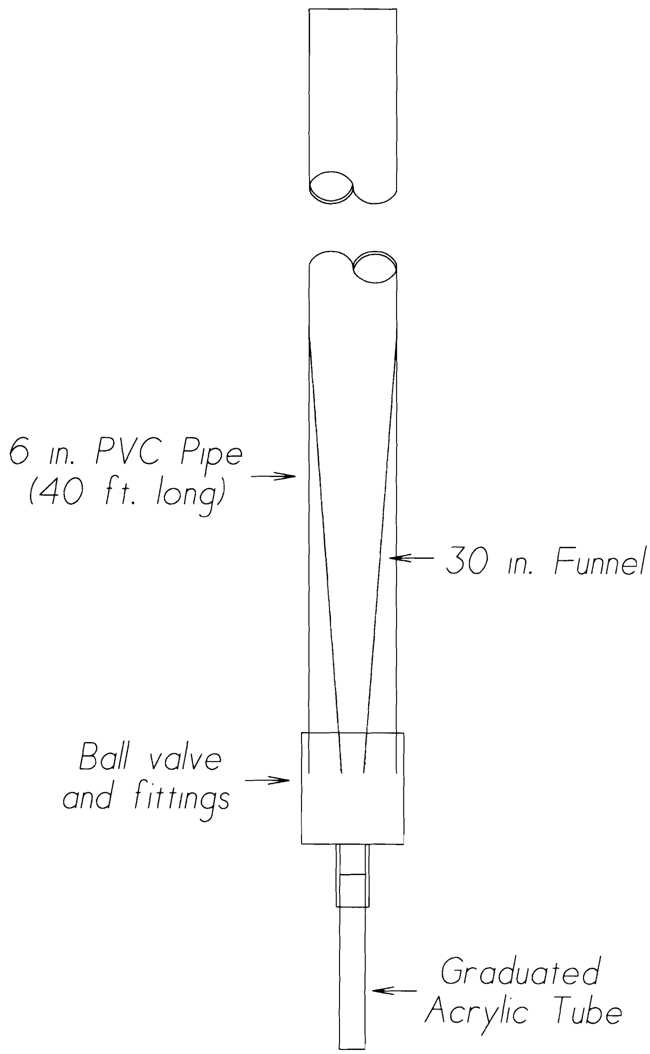


Figure 2. Schematic of long settling tube experiment.

mensions in the three principal orthogonal directions were measured using a dissecting microscope with 10.4 to 72 times magnification and readability of 0.017 mm. The range of dimensions measurable is 0.017 mm to 13.3 mm, which covers the particle sizes considered in this study. The particle shape is described using the Corey shape factor defined as

$$F_S = \frac{D_s}{\sqrt{D_i D_l}} \tag{1}$$

where $D_s$, $D_i$, and $D_l$ are the respective short, intermediate, and long mutually orthogonal dimensions of the grain. The volume of the particle is calculated as the volume of an ellipsoid as suggested by WADELL (1932, 1933) and later adopted by KOMAR and REIMERS (1978) as

$$V = \frac{\pi D_s D_i D_l}{6} \tag{2}$$

Table 1. *Results from Fall Velocity Repeatability Test.*

| Grain | $D_s$ (mm) | $D_i$ (mm) | $D_l$ (mm) | $F_s$ | $V$ (mm$^3$) | $D_n$ (mm) | $\bar{w}$ (m/s) | $\sigma_w$ (m/s) | $D_e$ (mm) | $Re$ ($\bar{w}\ D_n/\nu$) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.43 | 0.64 | 0.76 | 0.62 | 0.11 | 0.59 | 0.073 | 0.000 | 0.51 | 43 |
| 2 | 0.60 | 0.69 | 1.22 | 0.66 | 0.26 | 0.80 | 0.102 | 0.001 | 0.68 | 82 |
| 3 | 0.71 | 1.12 | 1.31 | 0.58 | 0.54 | 1.01 | 0.114 | 0.001 | 0.76 | 116 |
| 4 | 0.97 | 1.46 | 1.49 | 0.65 | 1.10 | 1.28 | 0.164 | 0.002 | 1.10 | 211 |
| 5 | 1.07 | 1.46 | 1.64 | 0.69 | 1.35 | 1.37 | 0.162 | 0.003 | 1.08 | 222 |
| 6 | 1.16 | 1.64 | 1.72 | 0.69 | 1.71 | 1.48 | 0.168 | 0.004 | 1.13 | 249 |
| 7 | 0.88 | 1.05 | 3.53 | 0.46 | 1.71 | 1.48 | 0.142 | 0.003 | 0.95 | 211 |
| 8 | 1.01 | 1.94 | 3.08 | 0.41 | 3.15 | 1.82 | 0.156 | 0.008 | 1.04 | 284 |
| 9 | 1.44 | 1.84 | 2.65 | 0.65 | 3.68 | 1.92 | 0.213 | 0.011 | 1.49 | 407 |
| 10 | 1.27 | 2.01 | 3.02 | 0.52 | 4.04 | 1.98 | 0.169 | 0.003 | 1.13 | 333 |
| 11 | 1.41 | 1.74 | 3.35 | 0.58 | 4.30 | 2.02 | 0.202 | 0.003 | 1.40 | 407 |
| 12 | 1.34 | 2.38 | 2.58 | 0.54 | 4.30 | 2.02 | 0.214 | 0.004 | 1.50 | 431 |
| 13 | 1.81 | 2.31 | 3.65 | 0.62 | 7.98 | 2.48 | 0.207 | 0.002 | 1.44 | 513 |
| 14 | 1.47 | 2.73 | 3.86 | 0.45 | 8.12 | 2.49 | 0.215 | 0.003 | 1.51 | 535 |

The nominal diameter of each grain is calculated from its volume as

$$D_n = \left(\frac{6V}{\pi}\right)^{1/3} \tag{3}$$

and is the diameter of a sphere having the same material and volume as the measured grain.

The fall velocity for each grain was measured in a 182.9 cm (6 ft) long, 8.9 cm (3.5 in) diameter clear acrylic tube containing 20°C fresh water. The grain was released slightly below the surface and allowed to fall for 10 cm to achieve terminal velocity before timing began. Times were recorded over a settling distance of 162.6 cm (64 inches) for the calculation of the fall velocity. The equivalent diameter $D_e$, which is defined as the diameter of a sphere having the same fall velocity, can be determined from an established relationship between the fall velocity and diameter of spheres. The fall velocity curve for $F_s = 1$ as reported by KOMAR and REIMERS (1978) provides such a relationship to determine the equivalent diameter from the measured fall velocity. An accurate estimate of the particle density is needed in the calculation of the equivalent diameter. The weights of some particles were determined to compute the particle density. An electronic balance with a range of 0 to 100 grams and readability of 0.1 mg was used to weigh the individual grains. The particle density is calculated based on the volume of an ellipsoidal grain as computed from Eq. 2 and compared with those reported in the literature.

## RESULTS AND DISCUSSION

### Data Preparation

The sieve and settling analyses provide 75 groups of 12 grains each from the 11 sample sites. Each group contains sand particles that are sorted by either sieve size or fall velocity and are assumed to share some common characteristics. The measurement procedures described in §2.3 yield the three principal orthogonal dimensions and the fall velocity for each grain in the 75 groups. Some of the grains were lost during the procedures, leaving a total of 880 grains measured for the complete set of parameters. The Corey shape factor for each grain is computed directly from the measured grain dimensions. Observations of the particles under the microscope confirm that natural sand particles can be roughly described as tri-axial ellipsoids. Although this is not valid for all the grains, the assumption of an ellipsoidal shape produces a better measure of volume, and therefore nominal diameter, than assuming a box-shaped particle.

Because of the non-spherical shape, each grain might possess a number of possible settling modes and that might result in different fall velocities depending on the Reynolds number (KOMAR and REIMERS, 1978). The fall velocities of 14 specially selected grains, covering the range of grain sizes considered in this study, were tested extensively to examine the accuracy and repeatability of the measurement. Each grain from this special group was settled 10 times. The mean and standard deviation of the fall velocities, denoted by $\bar{w}$ and $\sigma_w$ respectively, along with the grain size characteristics, can be seen in Table 1. The results are arranged in ascending order of nominal diameter. Kinematic viscosity of water $\nu = 10^{-6}$ m$^2$/s at 20°C is used to calculate the Reynolds number *Re*. The range of Reynolds number corresponds to the transition between the laminar and turbulent flow regimes. The particles orient themselves with their largest projected area normal to the settling direction, regardless of the orientation when they are released. Thus, there are two possible stable settling orientations, 180° different. Due to grain asymmetry, one orientation usually dominates the settling. Nearly all of the grains settle in a spiral with diameter varying from grain to grain. In some cases, a grain would settle in two modes with, for example, a large spiral for one run and a small spiral for the next, but produce very close fall velocities. The standard deviations in the fall velocities are very small for all the grains and do not seem to have any correlation with the shape factor or Reynolds number. It was deemed sufficient to settle each grain from the 75 12-grain groups twice and average the fall velocities, which show minimal difference for all the grains analyzed.

A large range for the calcareous sand density has been reported in the literature. HARDISTY (1990) suggested an upper limit of 2.72 g/cm$^3$ corresponding to the material density of calcite. Natural calcareous sand density depends on the biological and chemical compositions and is usually lower due to tiny voids inside the particles. KENCH and MCLEAN (1997) used a particle density of 1.85 g/cm$^3$ for sand samples collected from an Indian Ocean atoll. That is the mid-range value of the densities for bioclastic sediment reported in JELL *et al.*, (1965) and SCOFFIN (1987). DAI (1997) determined the particle density for Oahu and Kauai beach sand by measuring the dry weight of a sand sample and the amount of water the sand displaces. He analyzed 11 natural and 13 sorted sand samples and provided density ranges of 2.22 to 2.56 g/cm$^3$ and 2.35 to 2.50 g/cm$^3$, respectively. In the present study, the weights of the individual grains for 12 groups were also measured for the calculation of particle density. The computed particle densities have a range of 2.18 to 2.97 g/cm$^3$ with an average of 2.55 g/cm$^3$. The densities correspond to the individual grains and because of shape approximation, have a larger range, but nevertheless agree reasonably well with DAI's estimation. Comparison of the present results with DAI's estimates suggests an average particle density of 2.4 g/cm$^3$, which is used in the calculation of the equivalent diameter from the measured fall velocity.

The analysis herein yields the three orthogonal dimensions, shape factors, nominal diameters, fall velocities, and equivalent diameters of the 880 calcareous sand grains from the 75 sieve size and fall velocity groups. This provides a large volume of data to produce reliable relationships between the various size parameters of the individual grains as well as the sand samples.

## Grain Properties

The three orthogonal dimensions of a sand grain completely define its size and shape characteristics. ZINGG (1935) proposed to use $D_i/D_l$ and $D_s/D_i$ to measure respectively the relative slenderness and thickness of a particle. MILAN *et al.* (1999) recently used this approach to classify the shape of coarse-grained particles from an upland stream. Figure 3 shows the plot of $D_i/D_l$ versus $D_s/D_i$ for all the grains analyzed. According to Zingg's definition, 42% of the particles are disk-shaped and 35% are close to equidimensional. The sand also contains minor quantities of rods and blades at 14% and 9% respectively. Platy particles, which include disk and blade shapes, account for one half of the grains. The results reflect the main constituents of beach sand around Oahu as reported by MOBERLY (1963). Although a wide range of particle shape is found in the samples, most of the particles are either in or clustered around the equant sector, showing that they have fairly compact shapes.

SENGUPTA and VEENSTRA (1968) and KOMAR and CUI (1984) suggested that the intermediate dimension is the characteristic size of a sand grain controlling its passage through a sieve opening. Figure 4a illustrates the relationship between intermediate dimension and sieve size for calcareous sand. The figure shows the intermediate dimensions of up to 24 particles selected randomly from each of the sieves between 0.25 to 4.76 mm. Only 8 particles are available on the 4.76 mm sieve; they are shown in the figure but are not used in the analysis. As sieving technique sorts particles by intermediate dimension, all of the particles analyzed have intermediate dimensions greater than the retaining sieve size. The data, however, shows a wide range of particle sizes retained on each sieve. Only 38% of the particles, mostly equidimensional and disk-shaped, have intermediate dimensions bounded by the retaining and next larger sieve size. The effective sieve spacing increases for the platy particles as they might pass through the openings diagonally. The upper bound of the intermediate dimensions of the particles on a given sieve is approximately 1.4 times, or the diagonal of, the next larger sieve size. The majority of the intermediate dimensions, about 76%, lies between 1.2 times the retaining sieve size and 1.2 times the next larger sieve size, indicating a bias in the sieve analysis results. Because of the diverse mix of particle shapes in calcareous sand, sieve analysis tends to produce more scattered data and underestimate the particle size in terms of intermediate dimension.

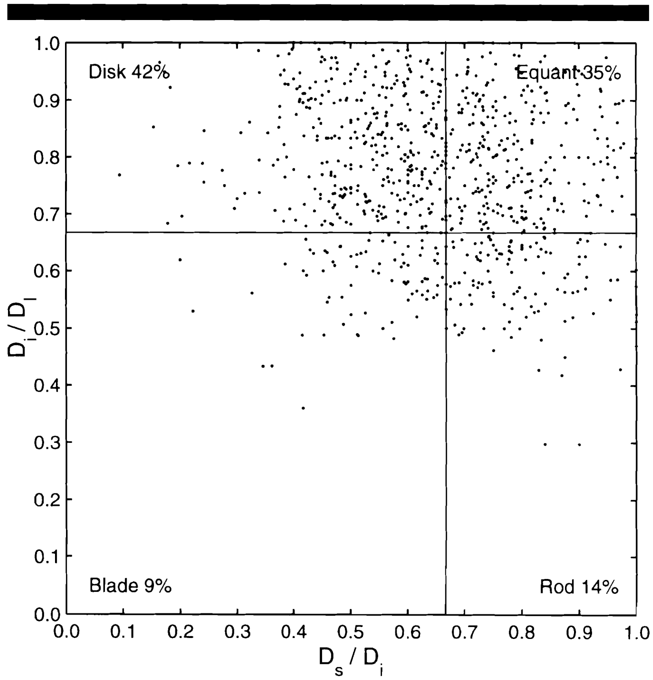


Figure 3. Particle shape classification by $D_i/D_l$ and $D_s/D_i$.

The nominal diameter is a characteristic size representing the volume of a particle. Figure 4b shows its relationship with the intermediate dimension for calcareous sand. The majority of the sand grains analyzed in this study corresponds to medium to very coarse sand according to WENTWORTH (1922). The results show that the nominal diameters are typically smaller than the intermediate dimensions of the measured grains, confirming the results shown in Figure 3 that there are more disk-shaped than rod-shaped particles in the samples. Since both the intermediate dimension and nominal diameter are characteristic sizes of a particle, good correlation between the two parameters is obtained regardless of the shape of the particle. The results suggest that if sieve analysis sorts particles by their intermediate dimensions, it also sorts the sediment by nominal diameter. This is generally valid with the exception of highly slender particles,

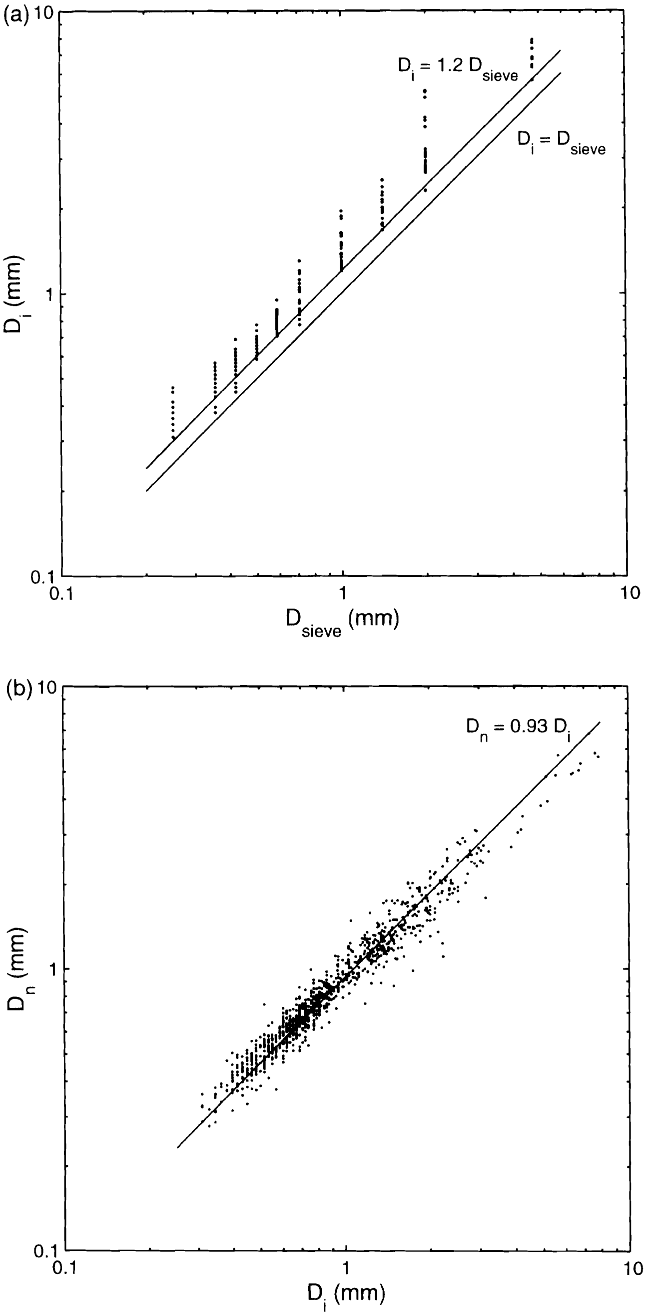


Figure 4. Relationships between characteristic grain sizes. (a) Intermediate dimension and sieve size. ———, linear size relationships. (b) Nominal diameter and intermediate dimension. ———, linear trendline.

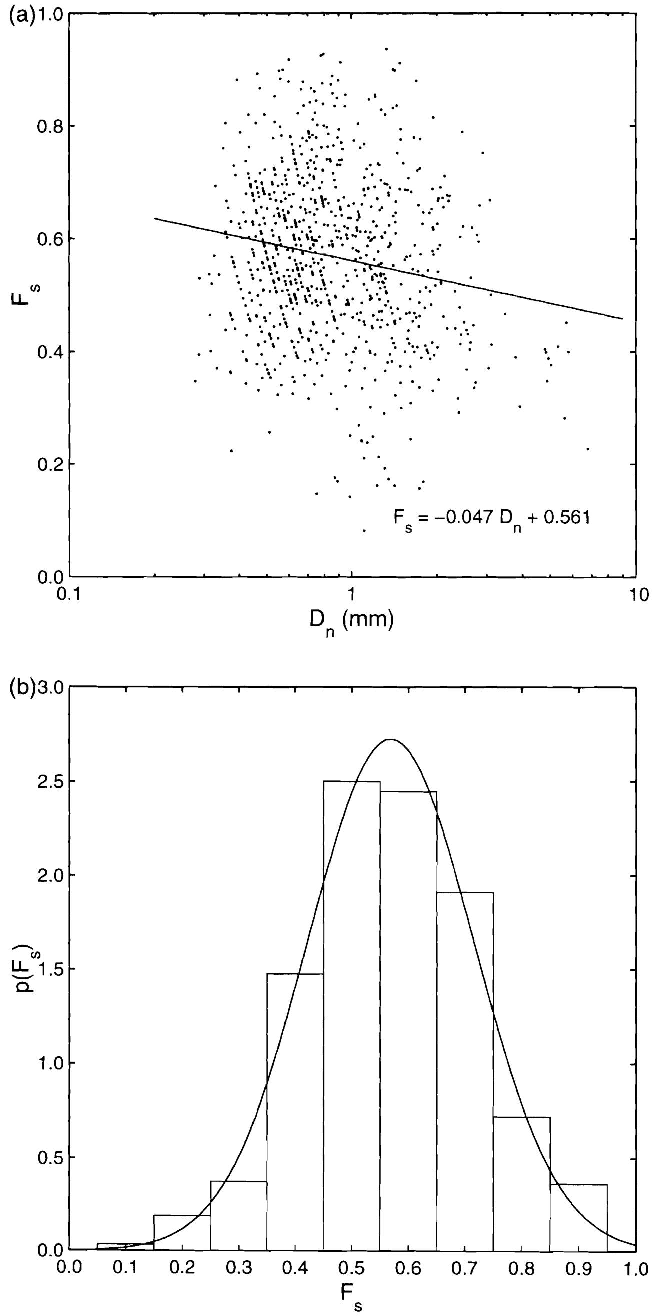


Figure 5. Distributions of shape factor. (a) Shape factor versus nominal diameter. ———, linear trendline. (b) Probability density. ———, normal distribution fitted to data.

which are more likely to be sorted by the long dimension (KENCH and MCLEAN, 1997).

Figure 5a shows the shape factor as a function of the nominal diameter for the sand grains. Consistent with the results of ZAPKA (1984) and DAI (1997), there is a slight decrease in shape factor with increasing nominal diameter. This is primarily due to the presence of large shell and coral fragments in the samples. There is a large spread in the data over most of the nominal diameter range considered, where the shape factor varies from 0.15 to 0.95. This implies that, unlike the intermediate dimension, the short and long dimensions of calcareous sand particles do not have any significant correlation to the nominal diameter. Although the selection of the grains is not entirely random, Figure 5b shows that the shape factor follows a normal distribution with a mean around 0.57. Silicate sand, on the other hand, has a shape factor of 0.7 or

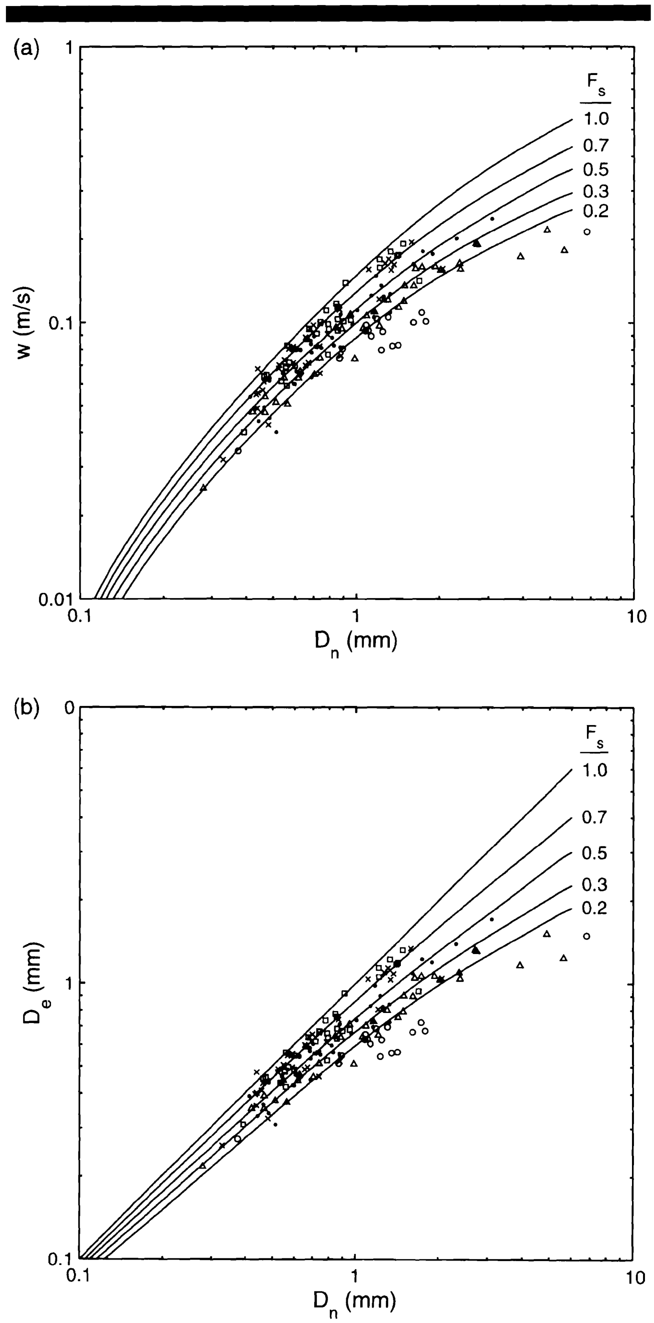


Figure 6. Fall velocity and equivalent diameter versus nominal diameter for different shape factors. (a) Fall velocity. (b) Equivalent diameter. Present study: ○, $F_s$ = 0.15–0.25; +, $F_s$ = 0.25–0.35; ●, $F_s$ = 0.49–0.51; ×, $F_s$ = 0.69–0.71; □, $F_s$ = 0.85–0.95. Komar and Reimers (1978): ———.

higher with less variation between the short and long dimensions (SHORE PROTECTION MANUAL, 1984). The variation in shape factors modifies the engineering properties of the sand as a structure as well as the transport mechanisms of the individual particles.

Fall velocity is one of the key parameters in sediment transport calculations. Figure 6a shows the measured fall velocity as a function of shape factor and nominal diameter. The fall velocity curves of KOMAR and REIMERS (1978), which have been corrected using the density of calcareous sand (2.4 g/cm$^3$), are shown in the figure for comparison. The results show a consistent and expected pattern, in which lower shape factors give rise to lower fall velocities for the same nominal diameter. This is attributed solely to the drag on the particle caused by the shape. As the shape of a particle deviates from spherical, the projected area increases, resulting in a greater drag force and a lower fall velocity. Reasonable agreement is indicated between the present and previous results for nominal diameters between 0.2 mm and 1.0 mm. For larger nominal diameters, KOMAR and REIMERS' curves overestimate the measured fall velocities. Their results are based on interpolation of drag coefficients at low and high Reynolds numbers with few data in the range $Re$ = 10 to 200, which is considered here. Future studies are necessary to revise the drag coefficient and fall velocity in this range of Reynolds number, which is typical for medium to very coarse sand.

Equivalent diameter, which is related to the fall velocity of a particle, is most conveniently used to indicate the size distribution determined from settling analysis. Figure 6b shows the measured equivalent diameter as a function of the nominal diameter for various shape factors. The corresponding relationships computed from the fall velocity curves of KOMAR and REIMERS (1978) are also shown in the figure for comparison. The results indicate that the equivalent diameter is close to the nominal diameter when the shape factor is close to one. In theory, these two size parameters are identical when the shape factor is equal to one. The equivalent diameter significantly deviates from the nominal diameter for small shape factors, indicating the increasing influence of the particle shape on the fall velocity. Because of the good correlation shown in Figure 4b, similar relationships also exist between the equivalent diameter and the intermediate dimension and shape factor. The definitive relationships between the nominal diameter, equivalent diameter, intermediate dimension, and sieve size shown in this section suggest that possible relationships exist between characteristic size parameters derived from sieve and settling analyses.

## Sieve and Settling Analyses

A comparative study of sieve and settling analyses is performed using the sand sample collected from Ehukai Beach Park on the North Shore of Oahu. This is a high energy beach and the sediment can be classified as very coarse sand. Figure 7 shows the cumulative grain size distribution obtained from a standard sieve analysis. The median sieve size and sorting of the sample are found to be 1.05 mm and 0.42 mm respectively. It should be noted that the size parameters obtained from Figure 7 are based on sieve size, which might not truly represent the intermediate dimension when the shape factor is small.

KENCH and MCLEAN (1997) and DE LANGE *et al.* (1997) obtained grain size distributions from settling analysis in terms of equivalent diameter and compared the results with those obtained from sieve analysis in terms of sieve size. In the present study, the comparison between sieve and settling analyses is made consistently based on the nominal and

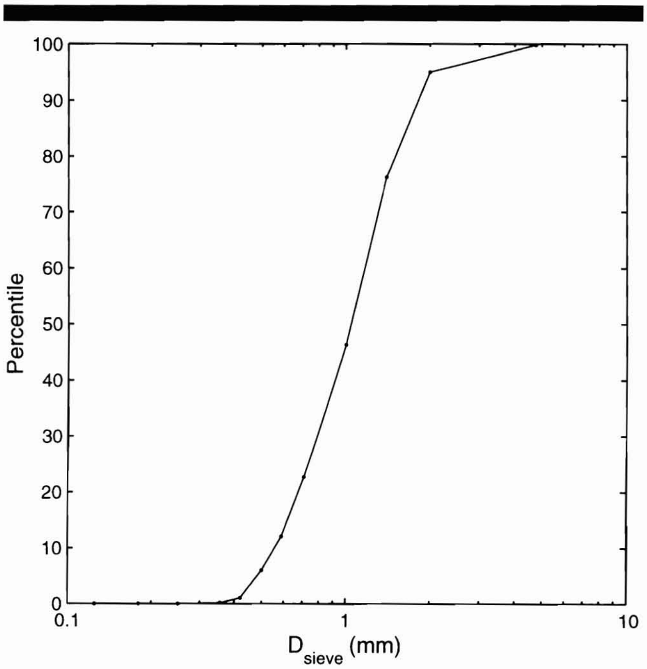


Figure 7. Cumulative grains size distribution for Ehukai Beach in terms of sieve size.

equivalent diameters determined directly from the sorted particles. From the settling analysis, 12 grains were randomly obtained from each of five levels representing the 10, 30, 50, 70, and 90 percentiles measured from the top of the sediment column. After the sieve analysis, 12 grains were chosen randomly from each sieve and the corresponding percentile was averaged between the retaining and the next larger sieve. The median nominal and equivalent diameters by weight are determined for the 12-grain groups, from which the grain size distributions for the whole sediment sample can be determined.

There is a lack of data in the literature on the distribution of nominal diameter for calcareous sand. Figure 8 shows the distributions of the nominal diameter at the computed and selected percentiles respectively for the sieved and settled sand samples. A curve fitted to the median of the data at each percentile provides the overall grain size distribution of the sample in terms of the nominal diameter. Although the data shows considerable scatter at each percentile, the sieve and settling analyses are capable of sorting particles by nominal diameter and produce similar grain size distributions. The scatter of data in Figure 8a is due to an increase of the effective sieve size for the platy particles coupled with the large range of particle shapes in the sample. Since settling analysis does not sort particles by nominal diameter or weight alone, the scatter of the data is approximately even throughout the settled sample as shown in Figure 8b.

Figure 9 shows the equivalent diameter distributions of the sand sample based on settling and sieve analyses. Despite the scatter of the sieved data, both approaches produce similar overall distributions of the grain size in terms of equivalent diameter. The scatter of the sieve results is expected,

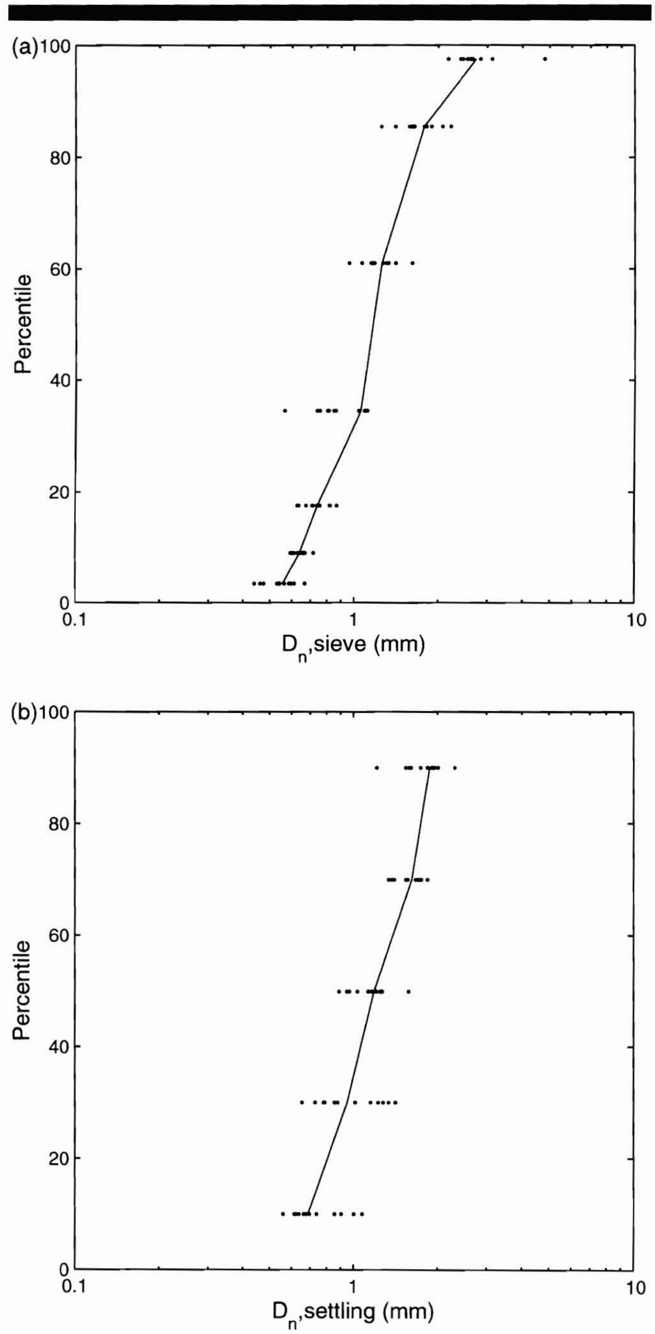


Figure 8. Cumulative grains size distribution for Ehukai Beach in terms of nominal diameter. (a) Sieve analysis. (b) Settling analysis. ———, median curve.

because sieve analysis does not sort particles by shape factor, which has a significant effect on the fall velocity and subsequently the equivalent diameter. The equivalent diameters determined from settling analysis have much less scatter compared to the sieved fractions, because the settling analysis sorts particles by fall velocity. The equivalent diameter determined from settling analysis encompasses both the size and shape of the particles and therefore is the most appro-

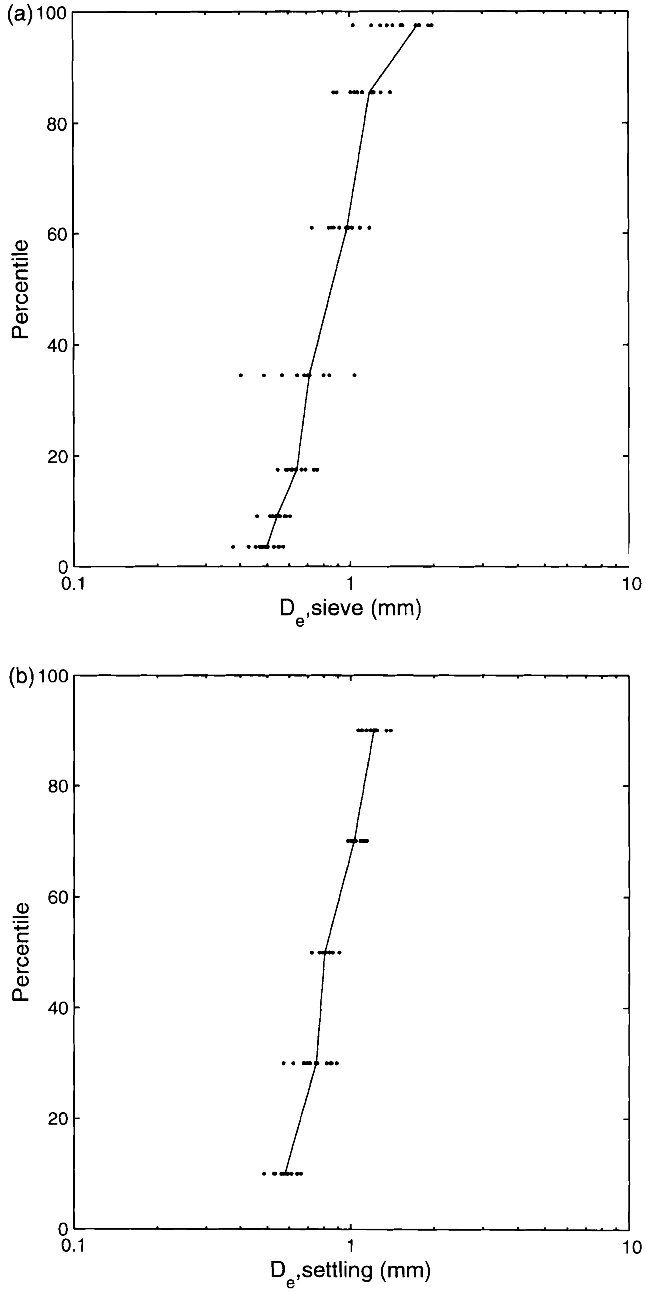


Figure 9. Cumulative grains size distribution for Ehukai Beach in terms of equivalent diameter. (a) Sieve analysis. (b) Settling analysis. ———, median curve.

priate parameter to describe the hydraulic characteristics of calcareous sediment. Settling analysis also provides a continuous distribution of sediment according to fall velocity. The grains that make up the median or any other percentile can be found directly from the sediment column.

## Median Grain Size Parameters

For sediment transport calculations, sediment samples are described according to some median parameters, which include the commonly used median sieve size and the median nominal and equivalent diameters. The grain size distribution curves in Figures 7, 8, and 9 provide these median size parameters for the Ehukai Beach sample. Table 2 gives a summary of the grain sizes estimated from sieve and settling analyses for all 11 samples using different size definitions. Based on the results in Table 2, relationships between the various median size parameters are examined in this section.

Figure 10 shows the relationships between the median sieve size and the median nominal diameters determined from sieve and settling analyses. The results indicate highly correlated linear relations among the three size parameters. The data produced by sieve analysis shows less scatter indicating that this approach is more effective than settling analysis in sorting particles by nominal diameter. The median nominal diameter produced by each approach is consistently greater than the median sieve size, which is commonly used for describing a sediment sample. This difference is expected, even though Figure 4b shows that the nominal diameter of most particles is less than the intermediate dimension, which is closely related to the sieve size. The results in Figure 4a indicate that the effective sieve size increases by a factor of up to 1.4 for platy particles and sieve analysis tends to underestimate the intermediate dimension. Considering the percentage of platy particles in the samples and the relationship between the nominal diameter and intermediate dimension, the relationships in Figure 10 appear to be consistent with those of the individual grains.

Figure 11 shows the relationships between the median sieve size and the median equivalent diameters determined from sieve and settling analyses. One might expect that settling analysis is more appropriate in determining the median equivalent diameter, but sieve analysis gives very similar results. The median equivalent diameter based on each analysis is less than the median sieve size, because the platy shape

Table 2. *Median Diameters Determined from Sieve and Settling Analyses.*

| Sample Site | Analysis | $D_{50}$ (mm) | $D_n$ (mm) | $D_e$ (mm) |
|---|---|---|---|---|
| Ehukai | Sieve | 1.05 | 1.16 | 0.92 |
| | Settling | — | 1.19 | 0.81 |
| Diamond Head | Sieve | 0.93 | 1.11 | 0.79 |
| | Settling | — | 0.97 | 0.73 |
| Fort Hase | Sieve | 0.86 | 0.95 | 0.72 |
| | Settling | — | 1.02 | 0.68 |
| Three Tables | Sieve | 0.76 | 0.91 | 0.73 |
| | Settling | — | 0.94 | 0.74 |
| Puuiki | Sieve | 0.60 | 0.68 | 0.49 |
| | Settling | — | 0.64 | 0.48 |
| Sunset Beach | Sieve | 0.58 | 0.68 | 0.52 |
| | Settling | — | 0.64 | 0.56 |
| Sandy Beach | Sieve | 0.50 | 0.61 | 0.52 |
| | Settling | — | 0.66 | 0.49 |
| Mokuleia | Sieve | 0.49 | 0.57 | 0.50 |
| | Settling | — | 0.53 | 0.47 |
| Yokohama Bay | Sieve | 0.49 | 0.62 | 0.51 |
| | Settling | — | 0.63 | 0.53 |
| Waimanalo | Sieve | 0.43 | 0.54 | 0.44 |
| | Settling | — | 0.50 | 0.36 |
| Pyramid Rock | Sieve | 0.33 | 0.41 | 0.33 |
| | Settling | — | 0.38 | 0.31 |

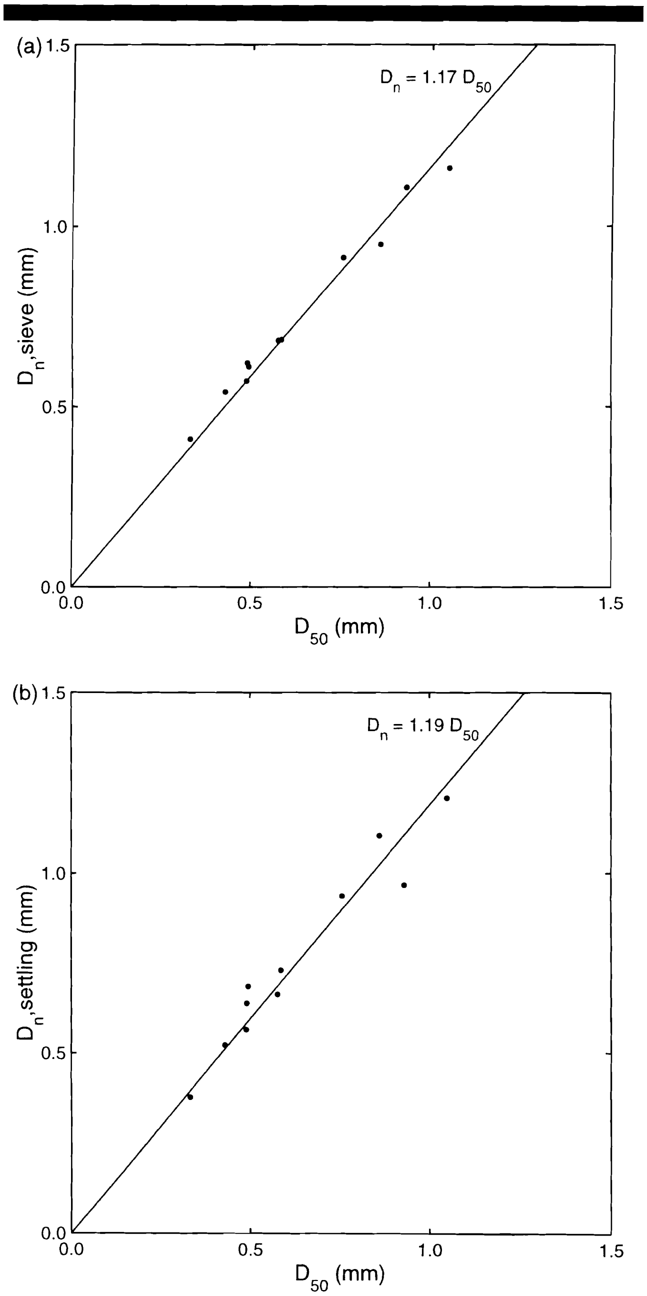


Figure 10. Median nominal diameter versus median sieve size. (a) Sieve analysis. (b) Settling analysis. ———, linear trendline.

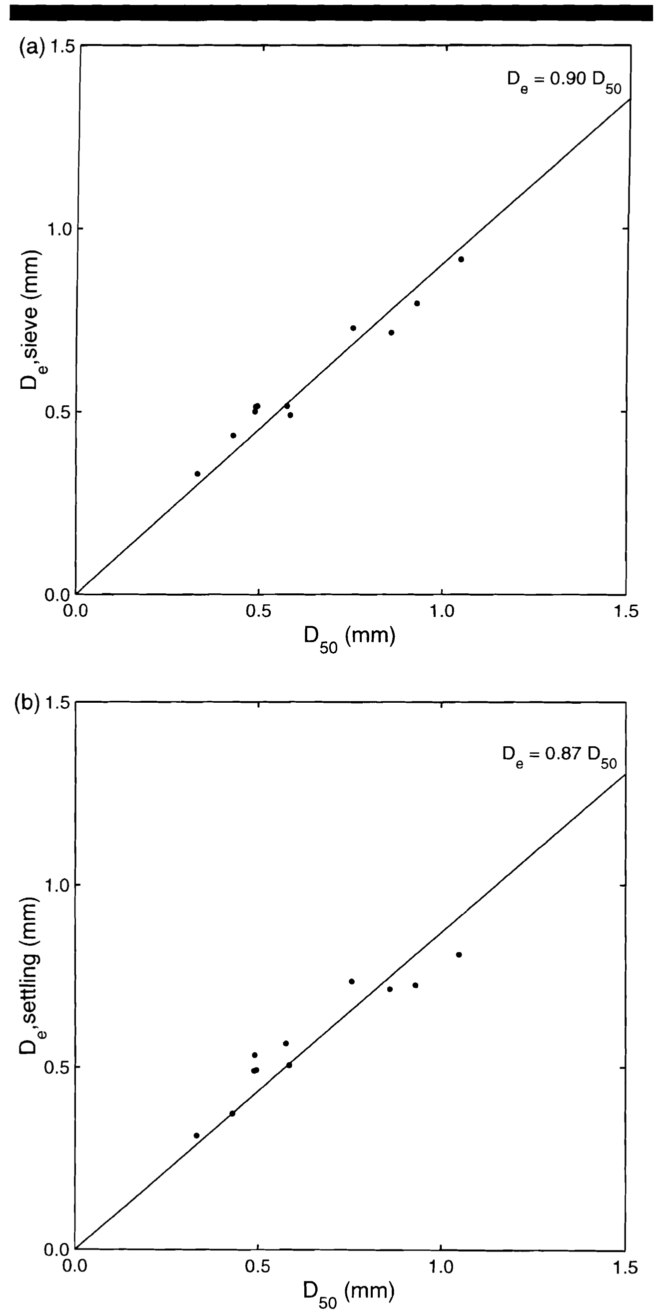


Figure 11. Median equivalent diameter versus median sieve size. (a) Sieve analysis. (b) Settling analysis. ———, linear trendline.

of calcareous sand reduces the fall velocity and subsequently the equivalent diameter of particles of a given volume. The results can be deduced from the relationships between the particle equivalent and nominal diameters in Figure 6b for the mean shape factor of 0.57 and between the median nominal diameter and sieve size presented in Figure 10. The interrelationships between the size parameters of the individual grains and the median size parameters of the sand samples validate the experimental and analytical approaches as well as the results presented in this paper.

The results in Figures 10 and 11 show that sieve and settling analyses are comparable in providing the median nominal and equivalent diameters for the calcareous sand samples. The median nominal and equivalent diameters also show distinct relationships with the median sieve size. Such a good correlation is possible because most of the particles have rather compact shapes and as a result each approach sorts particles primarily by volume or weight. The shape factor follows a normal distribution with a well-defined mean value and its effect on the sorting appears to be secondary and contributes to the scatter of the data. Sieve and settling analyses, however, respond to particle shape differently and introduce different skewness to the grain size distribution curves. The two analyses are expected to give similar measures of central tendency, but the agreement might deteriorate or the results become more scattered for the higher moments, which are more sensitive to the shape of the distribution curves. Since the beach sand on Oahu is typically well-sorted (GERRITSEN, 1978; and DAI, 1997), the results presented here in terms of the median nominal and equivalent diameters are expected to be applicable to the corresponding mean diameters.

Figure 12 combines the sieve and settling results to provide empirical relationships between the median sieve size and the median nominal and equivalent diameters. The nominal diameter data in Figure 12a follows a linear trendline and is on average 18% greater than the median sieve size. The nominal diameter is more appropriately used in the calculations of the threshold velocity and bed load transport, which are dominated by particle weight. The particle shape certainly plays a role in these near bed mechanisms, but not in the same way it affects the fall velocity. The use of median sieve size to describe calcareous sand underestimates the nominal diameter by 18% and the volume or weight of the sand grains by 39%. The equivalent diameter in Figure 12b is on average 11% smaller than the median sieve size. The results, however, are best described by a power curve, as the effect of particle shape on the equivalent diameter becomes more significant for larger particles as indicated in Figure 6b. Furthermore, larger particles tend to have lower shape factors, which in turn lower the fall velocities. The equivalent diameter is the most appropriate parameter to describe the behavior of sediment in suspension and should be used in the calculation of the transport of suspended sediment. The use of median sieve size would overestimate the fall velocity and such error would increase with particle size.

## CONCLUSIONS

Calcareous sand samples collected from 11 Oahu beaches, subject to varying wave exposure, have been analyzed for grain size parameters. A 12.2 m (40 ft) long settling tube was constructed to separate the samples by fall velocity, while dry sieve analysis was performed to sort particles by sieve size. The sand samples provide 75 sieve size and fall velocity groups, for which the shape factor, fall velocity, nominal diameter, and equivalent diameter for 880 grains are presented. The distributions of the nominal and equivalent diameters within the sieve and settling groups are analyzed to provide the respective median diameters for the samples. An extensive test for 14 specially selected grains, covering the range of grain size considered in this study, assures the accuracy and repeatability of the fall velocity measurement. The measured particle densities for 12 of the 75 groups confirm the particle density determined in an earlier study of Oahu and Kauai beach sand.

The samples analyzed in this study correspond to medium to very coarse sand and are composed primarily of disk-shaped and equidimensional particles with minor quantities of blades and rods. The diverse mix of particle shapes increases the scatter of the sieve analysis results. Sieve analysis tends to underestimate the particle size in terms of intermediate dimension as the large quantity of platy particles passes through the sieve openings diagonally. The nominal diameters of the grains are typically smaller than the corresponding intermediate dimensions, confirming that there are more disk-shaped than rod-shaped particles in the samples. The shape factor slightly decreases with the nominal diam-

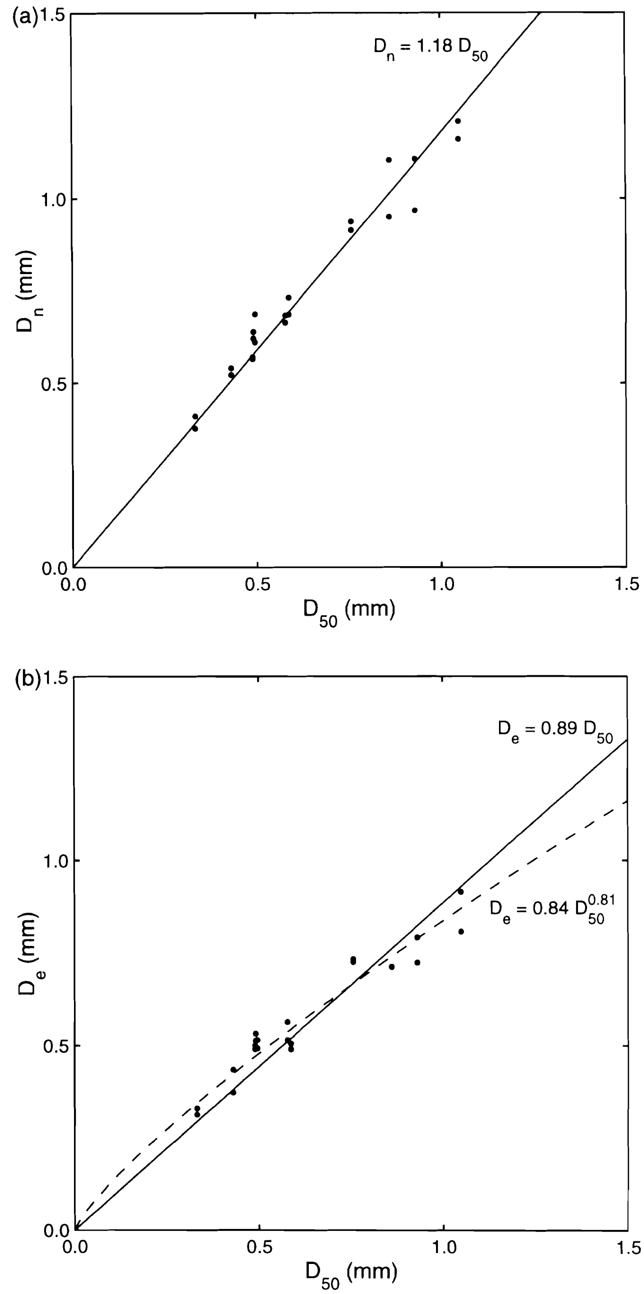


Figure 12. Empirical relationships of median grain sizes. (a) Median nominal diameter and median sieve size. (b) Median equivalent diameter and median sieve size. ———, linear trendline; – – – , power curve.

eter and follows a normal distribution over most of the nominal diameter range considered. The measured fall velocities are checked against previous results before being used in the calculation of the equivalent diameters.

Sieve and settling analyses are comparable in providing the median nominal and equivalent diameters for the calcareous sand samples. The median nominal diameter is 18% greater than the median sieve size and the two show a linear relationship. The median equivalent diameter is on average 11% less than the median sieve size and the relationship between the two size parameters is best described by a power curve. The results are supported by the relationships between the size parameters of the individual particles. The use of the median nominal and equivalent diameters, instead of the median sieve size, will provide significantly different predictions of the threshold velocity and transport of calcareous sediments. Although the determination of the median nominal and equivalent diameters requires lengthy and tedious procedures, the proposed empirical relations provide a useful tool to interpret the characteristic size parameters of calcareous sand from standard sieve analysis.

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