EFFECT OF PARTICLE SHAPE ON GRAIN SIZE, HYDRAULIC, AND TRANSPORT CHARACTERISTICS OF CALCAREOUS SAND

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By

David A. Smith

Dissertation Committee:

Kwok Fai Cheung, Chairperson
Horst G. Brandes
Charles H. Fletcher
Hans-Jürgen Krock
Eugene R. Pawlak
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This study examines the grain size, fall velocity, initiation of motion, and sediment transport rates of calcareous sand collected on Oahu, Hawaii. These characteristics are unique to calcareous sand owing to the irregular shape of the particles and are distinct from those of siliceous sand, which have been studied extensively with well-documented results. Through a series of laboratory experiments and data analyses, this study provides a comprehensive data set of calcareous sand characteristics and quantifies their dependence on particle shape.

Sand samples were selected from the swash zones of Oahu beaches. Sieve and settling techniques separate the samples into groups by sieve size and fall velocity, respectively. Individual grain properties such as shape factor, intermediate dimension, fall velocity, and nominal and equivalent diameters for 998 grains within those groups are presented. Evaluation of the grain size data by sieve and settling groups provides empirical relationships between the median sieve size of the sand samples and the corresponding nominal and equivalent diameters. The fall velocity and drag coefficient expressed respectively as functions of nominal diameter and Reynolds number show strong correlation over a wide range of shape factors. Analysis of the data by flow regime shows that particle shape has stronger influence on the settling characteristics when unstable wakes develop behind the grains.

These findings are used to interpret the initiation of motion of four natural and five sieved calcareous sand samples in unidirectional flow. Flume experiments provide the sediment transport rate as a function of bed shear stress up to bed-form development. Reference-based criteria are supplemented by visual observations to determine the critical shear stress. The results are compared with published data for rounded and irregular particles in terms of the median sieve size and median nominal and equivalent diameters over Reynolds number. The critical shear stresses of the irregular particles, in comparison
with data for rounded particles, are higher in the hydraulically smooth regime and lower in the rough turbulent regime.

Finally, the transport of calcareous sand in unidirectional flow and its prediction through existing sediment transport models are examined. Flume experiments provide 70 sets of sediment transport data and the results are compared with direct predictions from five published sediment transport models developed for siliceous particles. Corrections for the grain size and hydraulic characteristics of calcareous sand developed in this study are applied and the results are compared with the direct calculations. The comparisons show that one of the models gives good results before calcareous sand corrections are considered and another responds well when the corrections are applied. This analysis provides guidelines to the application of existing sediment transport models to calcareous beaches and the gathered data lays a foundation for future model development.
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1. INTRODUCTION

1.1 Calcareous Sand

Tropical island beaches are composed of calcareous sand of marine origin, specifically fragments of such reef-dwelling organisms as coral, coralline algae, foraminifera, and molluscs. The grains of these species have a wide variety of shapes associated with their biological origins in contrast to the rounded, uniform siliceous 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.

Figure 1-1 shows photos of calcareous sand particles from four Oahu beaches. The coarsest two sand samples were obtained from Ehukai Beach and Puuiki Beach, both on Oahu’s North Shore, while the finer two sand samples are from Waimanalo Beach and Kailua Beach on the windward shore of Oahu. The particles in the figure have a variety of shapes, including rounded, rod-shaped, and flat. Smooth and sharp-edged particles are also seen, as well as non-symmetric particles. Moberly (1963) reported on the coastal geology of Hawaiian beaches and found that the distribution of components within the beach sand is site specific.

The various components of calcareous sand produce particle shapes that are significantly different from siliceous sand. Particle shape affects grain size measurements as well as the hydraulic properties. Sieve analysis produces biased size distributions as the particle shape deviates from spherical, causing an error in the measurement of the mass of the particle. The drag on an irregular particle is increased relative to a sphere, as particle shape modifies the boundary layer around the grain, and affects the motion characteristics and transport mechanisms.
The hydraulic properties such as fall velocity, critical shear stress, and transport rates of siliceous sand have been studied extensively, and yet similar information for calcareous sand is limited. Previous studies have suggested the importance of particle shape on the physical and hydraulic properties of sediment, but its impact on the transport rate is not well understood.

1.2 Grain Size and Hydraulic Characteristics

The choice of a characteristic sand size becomes important when the particle shape deviates from spherical. The nominal and equivalent diameters, which are the diameters of a sphere having respectively the same volume and settling velocity as the irregular particle, are commonly used. Sieve analysis, however, becomes biased at determining these properties 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). A consistent description of the grain size characteristics is necessary to compare the results with other data sets. Relationships that can be applied directly to sieve analysis results to infer the nominal and equivalent diameters of calcareous sand are highly desirable.

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.

Particle shape also affects fall velocity. Studies have been undertaken to quantify the fall velocity of non-spherical particles in terms of shape factor. Shultz et al. (1954) investigated the influence of particle shape on the fall velocity of river gravel and the results were re-analyzed by Swamee and Ojha (1991). Alger and Simons (1968) obtained fall velocities and drag coefficients for ten ellipsoidal pebbles settling through eight different fluids. Komar and Reimers (1978) investigated the settling characteristics of 51 smooth, symmetric pebbles in glycerine and presented relationships for the fall velocity and drag coefficient by interpolation with Alger and Simons’ data. Baba and Komar (1981) later examined the settling characteristics of 70 natural quartz grains and obtained lower fall velocities in comparison to those of smooth, symmetric pebbles.

The effect of shape on grain size and settling properties provides insight into the initiation of motion of calcareous sand. Shields (1936) pioneered the study of initiation of motion and his dimensional analysis results in a relationship of dimensionless shear stress in terms of Reynolds number. Many subsequent studies with rounded, uniform particles confirmed Shields’ data and the results were compiled in Miller et al. (1977) and Buffington and Montgomery (1997). There is, however, only scattered data pertaining to irregular particles. Magalhaes and Chau (1983) undertook flume studies on initiation of motion for shale particles, while Prager et al. (1996) and Paphitis et al. (2002) examined calcareous sand and shell fragments, respectively. Each of these studies covers a limited range of Reynolds numbers and produces results noticeably different from Shields’ findings. The discrepancy is primarily due to particle shape, but other factors such as
surface texture and sharp edges may also play a role. Motion initiation characteristics for calcareous sand are necessary for estimating sediment transport rates.

Grain size, fall velocity, and critical shear stress are typical input parameters for sediment transport models. Chang (1988), van Rijn (1993), Yang (1996), and Yang and Huang (2001) provide comprehensive reviews of numerous sediment transport models and discuss their applications in coastal and river environments. The applicability of these equations for use with calcareous sand is unclear. The initiation of motion of irregularly shaped and calcareous particles has been studied (e.g., Mantz, 1977; and Magalhaes and Chau, 1983) and specifically for calcareous particles (e.g., Prager et al., 1996), and Kench and McLean (1996) used settling fractions to interpret calcareous depositions, but there are few published studies on the transport rates of calcareous sand.

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.

The interpretive use of existing transport models depends on accurate input of the grain size characteristics, fall velocity, and motion initiation, which are still not well defined for calcareous sand. Such an approach provides convenient predictions of calcareous sand transport rates, but its validity is unproven. There is a consensus within the coastal engineering communities in Hawaii and other tropical regions that existing sediment transport models need to be re-examined for calcareous sand conditions.
1.3 Objectives and Approach

The present study compiles and evaluates the unique physical and hydraulic characteristics of calcareous sand on Oahu, Hawaii. The specific objectives of the study are to:

1. Examine grain shape and size characteristics;
2. Develop relationships for fall velocity and drag coefficient as a function of grain size and shape;
3. Produce relationships to compare median sand properties found by sieve and settling analyses;
4. Determine the critical shear stress for initiation of motion; and
5. Measure sediment transport rates and compare with published models for calcareous sand collected on Oahu.

This study is directed toward the coastal erosion problem faced by Hawaii and other tropical environments. Though a series of measurements and analyses, a better understanding of the unique physical and hydraulic characteristics of calcareous sand is provided and the interpretive use of existing sediment transport models with the calcareous sand properties as input is investigated.

The applicability of sieve analysis for determining grain size characteristics of calcareous sand is first studied. Relationships amongst sieve size, nominal diameter, intermediate dimension, and shape factor are developed. The settling characteristics of calcareous grains are then investigated to provide a more comprehensive description of the particle shape effect on fall velocity and drag coefficient over the applicable size range. The data is analyzed by flow regime to show the effect of particle shape on the settling characteristics as a function of the wake that develops behind the grains. Empirical relationships between the various grain size definitions and between the sieve and settling results are determined using the calcareous sand samples. These relationships allow
continued use of sieve analysis as the standard method for characterizing sediment and provide correction factors so that data from sieve analysis can be properly interpreted and used in sediment transport models.

A series of flume experiments provides measurements of transport rates at various transport stages. The experiments utilize natural sand samples and sieved fractions to show the effects of classifying non-uniform sediment according to a single characteristic diameter. Initiation of motion of calcareous sand is investigated with special attention to the various particle size characterizations. The study culminates with an independent assessment of five commonly used sediment transport models for calcareous sand conditions. The results are used to provide guidelines for the selection and interpretative use of existing transport models for calcareous sand conditions.
2. PHYSICAL GRAIN SIZE CHARACTERISTICS

2.1 Sand Samples

Oahu beaches are composed mainly of calcareous sand. Samples of beach sand were obtained from the swash zone at numerous Oahu beaches, the locations of which are shown in Figure 2-1. The selected sites provide a balanced representation of the sediment sizes commonly found on tropical island beaches. Most of these sites were selected because of their potential to supply large quantities of good quality samples for the subsequent transport tests.

The north and west shores of Oahu have seasonally high-energy beaches. Swell from North Pacific storms reach these shores in the winter, when surf regularly exceeds 3 m. 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).

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 sand 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.
The mixture of different 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.

2.2 Measurements of Grain Properties

The 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. 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. The median diameter, \( D_{50} \), and sorting parameter, \( \sigma \), of each sample are determined. Sorting is defined as

\[
\sigma = \frac{1}{2} \left( -\log_2 D_{84} + \log_2 D_{16} \right)
\]

where \( D_{16} \) and \( D_{84} \) are the 16th and 84th percentiles of the grain size according to sieve analysis. Twelve grains were chosen at random from each sieve fraction for subsequent analyses to determine their dimensions and fall velocities.

The individual grains obtained from the sieve analysis were analyzed for shape factor, nominal diameter, and intermediate dimension. Grain dimensions 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

\[
F_s = \frac{D_s}{\sqrt{D_i D_l}}
\]
where $D_s, D_i,$ and $D_l$ are the respective short, intermediate, and long mutually orthogonal dimensions of the grain (Dyer, 1986). This shape factor measures the sphericity of the particle and has a maximum value of one for spheres and decreases toward zero as the particle shape deviates from being spherical. The particle shape can be described more precisely by the morphometry index of Sneed and Folk (1958), differentiating spheres, rods, and disks in a triangular diagram (e.g., Verrecchia et al., 1997), or the classification of Zingg (1935) based on the relative thickness, $D_0/D_i,$ and the slenderness, $D_l/D_h,$ of the particle.

Observations of the particles under the microscope confirm that natural sand particles can be roughly described as tri-axial ellipsoids. The particle volume is approximated as an ellipsoid as suggested by Wadell (1932, 1933) and later adopted by Komar and Reimers (1978),

$$V = \frac{\pi D_s D_i D_l}{6} \quad (2-3)$$

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

$$D_n = \left(\frac{6V}{\pi}\right)^{\frac{1}{3}} \quad (2-4)$$

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

2.3 Sand Density

A large range for calcareous sand density has been reported in the literature. Hardisty (1990) suggested an upper limit of 2.72 g/cm$^3$ for calcareous sand density 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).

An accurate estimate of the particle density is needed to calculate the equivalent diameter. 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 137 individual grains collected from Ehukai Beach were measured for the calculation of 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 Equation (2-3). After removing the high and low 10% of the calculated particle densities, the results show a range of 2.04 to 3.03 g/cm\(^3\) with an average of 2.53 g/cm\(^3\). The densities correspond to the individual grains and because of shape approximation, have a larger range.

A more precise estimate of the particle density is obtained by measuring the volumetric displacement of a known mass of sand. The density of 10 natural and 14 sorted sand samples is measured from the volumetric displacement of 75.0 g of dry sand in a graduated cylinder containing 50 ml of water at 20° C for each sample. The measured densities are shown Tables 2-1 and 2-2 to have a range of 2.59 to 2.78 g/cm\(^3\) and correspond to the material density if all the tiny voids inside the particles are saturated during the test. There is no apparent relationship between size and density as shown in Figure 2-2. Because of the water content in the particles, a lower-bound estimate of 2.6 g/cm\(^3\) is adopted for the particle density. The choice of this density is supported by the findings of Dai (1997) and the measured densities of the individual particles.
2.4 Particle Shape and Characteristic Dimensions

Milan et al. (1999) recently used the approach of Zingg (1935) to classify the shape of coarse-grained particles from an upland stream and obtained good results. Figure 2-3 shows the plot of $D_i/D_I$ versus $D_i/D_I$ for all the grains analyzed in this study. According to Zingg's definition, 43% of the particles are disk-shaped and 34% are close to equidimensional (equant). 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 more than 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 shapes 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 2-4a illustrates the relationship between intermediate dimension and sieve size for the calcareous sand from Ehukai Beach. The figure shows the intermediate dimensions of 24 particles selected randomly from each of the sieves between 0.25 to 2.00 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, almost 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 size 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%, is
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.

The nominal diameter is a characteristic size representing the volume of a particle. Figure 2-4b 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 2-3 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, which are more likely to be sorted by the long dimension (Kench and McLean, 1997).

Figure 2-5a 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 0.07 to 0.94. 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 2-5b shows that the shape factor follows a normal distribution with a mean around 0.56. Silicate sand, on the other hand, has a shape factor of 0.7 or 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.
3. HYDRAULIC GRAIN CHARACTERISTICS

3.1 Settling Tube Analysis

The fall velocity of an individual grain is measured in a six-foot long (1.83 m), 3.25-inch (8.26 cm) diameter, clear acrylic cylinder containing 20°C fresh water. The grain is released slightly below the water surface and allowed to fall for 10 cm to achieve terminal velocity. Settling times are recorded over a distance of 1.63 m for the calculation of the fall velocity. The Reynolds number is given by

\[ Re = \frac{wD_n}{v} \]  

(3-1)

where \( w \) is the fall velocity of the particle and \( v \) is the kinematic viscosity of water equal to \( 10^{-6} \ \text{m}^2/\text{s} \) at 20°C. At terminal velocity, the drag force on the particle is equal to the particle’s submerged weight, giving rise to the expression for the drag coefficient

\[ C_D = \frac{4(\rho_s - \rho)gD_n}{3\rho w^2} \]  

(3-2)

where \( g \) is gravitational acceleration, \( \rho \) is water density at 20°C, and \( \rho_s \) is particle density.

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.

3.2 Settling Mode and Sensitivity

Calcereous grains have a variety of shapes that can be described as rod, blade, disk, and equant according to the classification of Zingg (1935). The Corey shape factor provides a quantitative measure of the deviation of these primary shapes from
being spherical. Observations under the microscope reveal that most of the calcareous particles are not symmetric about their principal axes and the large particles tend to have rough surface textures and irregular edges. These secondary shape characteristics affect the settling motion and give rise to multiple settling modes. Prior to the production runs, 22 grains covering the size range considered in this study were settled 10 times each to examine the effects of settling mode on fall velocity.

As observed by McNown and Malaika (1950), Komar and Reimers (1978), and Song and Yang (1982), the particles settle with their largest projected areas normal to the settling direction, regardless of the orientation when they are released. Thus, there are two possible stable settling orientations, 180° different. Since the calcareous grains are rarely symmetric, one orientation usually dominates the settling motion. Very few grains settle directly to the bottom without some degree of horizontal motion. Mehta et al. (1980), Baba and Komar (1981), and Göğüş et al. (2001) also observed non-vertical settling motions that vary based on the particle shape and Reynolds number. Nearly all of the grains settle in a spiral with diameter and frequency 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. Grains settling with high Reynolds numbers exhibit a tendency to tumble, flutter, or settle erratically. The settling mode, however, does not cause significant variation of the fall velocity between successive tests of the same grain.

Table 3-1 provides the mean and standard deviation of the measured fall velocities, denoted by $\bar{w}$ and $\sigma_w$ respectively. The results are arranged in ascending order of nominal diameter with Reynolds numbers between the laminar and turbulent flow regimes. The standard deviations in the fall velocities are very small for all 22 grains and do not show distinct correlation with the shape factor. The more erratic settling mode of the larger particles results in slightly higher standard deviations in the turbulent regime,
but does not significantly affect the quality of the measured fall velocities. It was deemed sufficient to settle each of the remaining grains in this study twice and average the fall velocities, which show minimal differences in all cases and provide a quality control of the data.

3.3 Fall Velocity and Equivalent Diameter

The dependence of fall velocity on shape can be attributed to the drag force on the settling particle. The Corey shape factor, however, does not fully describe particle shape. For example, particles with shape factor 0.5 may be classified according to Zingg (1935) as belonging to the blade, rod, or disk category and, in principle, will be subject to different drag forces. Janke (1966) and Alger and Simons (1968) argued that the Corey shape factor is inadequate and suggested that a relationship based on particle surface area better describes the shape. Komar and Reimers (1978) regressed particle surface area and projected area against the fall velocity, but found that the Corey shape factor accounts for most of the shape effect on fall velocity. In the early part of this study, the particle fall velocity was examined based on the two-parameter Zingg classification. No improvement on the correlation was found and, therefore, the Corey shape factor is used in the present paper to describe particle shape.

Figure 3-1 shows the measured and regressed fall velocities for the calcareous sand grains. The fall velocity curves for spheres from Komar and Reimers (1978) and quartz sand particles from Baba and Komar (1981) are also shown in the figure to provide a reference for comparison. The scatter of the data is considerable and might be attributed to the density of the individual grains and the approximation of the grain volume based on an ellipsoid. For a given nominal diameter, the fall velocity approaches that of a sphere as the shape factor increases toward unity and decreases as the shape factor decreases. The data in the four shape factor ranges is used in the regression of the fall
velocity curves. Due to limited data, the fall velocity curves for $D_n < 0.3$ mm are based on the results of Komar and Reimers. The small calcareous particles have smoother textures and the measured fall velocities are comparable to those of the smooth, symmetric pebbles of Komar and Reimers. The quartz grains examined by Baba and Komar span the shape factor range of 0.5 to 0.9 with an average value of 0.69. The corresponding fall velocity curve agrees well with the curve for $F_s = 0.7$, thereby validating the present relationships.

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 3-2 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 in Figure 3-1 are also shown 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 particle is spherical. 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 2-4b, 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 suggest that possible relationships exist between characteristic size parameters derived from sieve and settling analyses.

3.4 Drag Coefficient

The measured fall velocities and regressed curves are converted to drag coefficients to provide insight to the hydraulic characteristics of the settling motion. Figure 3-3 shows the drag coefficient as a function of the Reynolds number and shape factor. The flow
regime in $10 < Re^* < 1000$ is most relevant to sediment transport studies, as it represents natural sand grains settling through water. The drag coefficient data shows strong correlation with the shape factor. The curves are tightly grouped at low Reynolds numbers and generally follow the equation for drag in the laminar region, $C_D = B/Re^*$. Cheng (1997) suggested values of $B$ between 24 and 32 based on particle shape.

As the Reynolds number approaches 100, the wake moves from the stable regime into the transitional regime. The particle shape increasingly influences the development of the wake and the spacing between the curves widens. The shift from the stable regime to the transitional regime is indicated by the departure from the equation $C_D = B/Re^*$ and is shown by the first dashed line in Figure 3-3. The transition for particles with smaller shape factors occurs at lower Reynolds numbers as the wake becomes less stable behind a non-spherical particle settling broadside up. Komar and Reimers’ (1978) results for smooth particles do not show the significant influence of particle shape at the onset of the transitional regime that is evident in the present relationships. Swamee and Ojha (1991) showed some dependence of the transition on shape factor, but it occurs at lower Reynolds numbers.

Komar and Reimers (1978) and Swamee and Ojha (1991) showed that the drag coefficients at various shape factors approach constant values at high Reynolds numbers, indicating fully developed unstable wakes behind the grains. The present drag coefficients continue to increase over the same Reynolds number range and do not seem to attain the fully developed unstable wake. Baba and Komar’s (1981) curve for natural quartz grains, reproduced in the figure based on the reported fall velocity curve, agrees with the present data for $F_s = 0.7$, but does not extend to high enough Reynolds numbers to show this effect. The secondary shape features such as non-symmetry and irregular edges give rise to settling modes with significant rotation and spiral motions. These settling motions apparently impede the formation of fully developed unstable wakes and extend the
transitional regime into higher Reynolds numbers. This also explains the increasing deviation between the fall velocities of calcareous sand particles and spheres at large nominal diameters.

3.5 Shape Effect versus Flow Regime

The results of the fall velocity and drag coefficient show that the effect of particle shape varies with wake development. The data is roughly divided into stable, transitional, and unstable by the dashed lines as shown in Figure 3-3 and each group is re-analyzed in terms of the shape factor following the approach of Baba and Komar (1981).

Figure 3-4 shows the ratio of the measured fall velocity to that for a sphere having the same nominal diameter as the natural grain. Logarithmic trendlines are fit to the three data groups. The one passing through the stable data lies above the transitional trendline and shows that the effect of shape is less significant at low Reynolds numbers. The trendline for the unstable data falls below the others, illustrating the increased effect of particle shape in the turbulent flow regime. The linear trendline obtained by Baba and Komar (1981) for quartz grains is close to the trendline for the transitional flow regime. None of the trendlines, however, passes through the upper right-hand corner of the diagram where the fall velocity ratio is equal to one for spherical particles. This indicates a dramatic decrease in the fall velocity as particle shape deviates slightly from being spherical and highlights the effect of the secondary shape features, which modify the development of the wake.

A similar comparison is made using the drag coefficients, divided into the same three groups as in the fall velocity comparison. Figure 3-5 shows the ratio of the measured drag coefficient to the drag coefficient for a sphere of the same nominal diameter. Logarithmic trendlines are fit to the data and show that the measured drag coefficient deviates from that of a sphere as the shape factor decreases from unity. As in Figure 3-4, none of the trendlines passes through the point where the ratio equals one for a sphere, although the
trendlines for the stable and the transitional data approach this point. The greatest effect of shape on the drag coefficient is seen in the unstable regime and the effect is magnified at low shape factors where the secondary shape features become more important. Such an increase in drag coefficient has significant implications on the motion initiation and transport of calcareous particles in flowing water.
4. MEDIAN GRAIN SIZE

4.1 Settling Techniques

Settling techniques can be used as an alternative to sieving in obtaining median or characteristic grain sizes (e.g., Kench and McLean, 1997; and De Lange et al. 1997). Figure 4-1 shows a schematic of the experimental setup for a long settling tube, which includes a 12.2-m (40-ft) long, 15-cm (6-in) diameter tube sealed at the bottom with a clear 3.8-cm (6-in) diameter 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 sand. 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 sand was necessary for vertical resolution in the sediment column, but too much sand in the initial tests caused significant turbulence and grain-to-grain interactions throughout the water column that affected the settling characteristics of the particles. The standard deviation decreased as the amount of sand 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 for the results presented in this dissertation were performed using a sample size of 125 grams.

4.2 Sieving versus Settling Techniques

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 sand can be classified as very coarse sand. Figure 4-2 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 4-2 are based on sieve size, which might not truly represent the intermediate dimension when the shape factor is small and the nominal and equivalent diameters deviate from the sieve size.

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 more consistent based on the nominal and 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 is interpolated 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 4-3 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 4-3a 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 4-3b.

Figure 4-4 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, 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 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 appropriate
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.

4.3 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 4-2, 4-3, and 4-4 provide these median size parameters for the Ehukai Beach sample. Table 4-1 gives a summary of the grain sizes estimated from sieve and settling analyses for all 11 samples using the different size definitions. Based on the results in Table 4-1, relationships between the various median size parameters are examined in this section.

Figure 4-5 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 2-4b 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 2-4a 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 4-5 are consistent with those of the individual grains.

Figure 4-6 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 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
The results in Figures 4-5 and 4-6 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 4-7 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 4-7a 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. 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 4-7b is on average 12% 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 3-3. Furthermore, larger particles tend to have lower shape factors, which in turn lower the fall velocities.
5. INITIATION OF MOTION

5.1 Sand Samples

The results presented so far confirm that the choice of a characteristic sand size becomes important when the particle shape deviates from spherical. Most studies use the median sieve diameter to characterize the particle size, while the nominal and equivalent diameters are more appropriate for non-spherical particles. The present chapter thus investigates the initiation of motion of calcareous sand with special attention to the various particle size characterizations.

Sand samples from the four Oahu beaches shown in Figure 1-1 were further examined for initiation of motion. These sites were chosen to represent the size range of calcareous beach sand based on the findings in Chapter 4. The coarsest two sand samples were obtained from Ehukai Beach and Puuiki Beach, both on Oahu's North Shore, while the finer two sand samples are from Waimanalo Beach and Kailua Beach on the windward shore of Oahu. Moberly (1963) showed that the nearly spherical foraminifera and blocky coralline algae dominate Oahu's North Shore beaches. Lesser amounts of rod, blade, and plate shaped corals and mollusc fragments are also present. Kailua Beach is dominated by the platy *Halimeda* and the blade and plate-shaped mollusc shell fragments, with a reduced amount of foraminifera relative to the North Shore beaches. Waimanalo Beach has a more uniform distribution of components.

Additional sand obtained from Ehukai and Waimanalo beaches was sieved to provide five size fractions representing the natural size range. A large-volume sieving system was constructed using a 3600 v.p.m. vibrating motor and a series of sieves consisting of 5-gallon buckets and steel mesh. The sand was vibrated for 15 minutes and collected in separate containers. Ehukai Beach sand was passed through meshes with openings 1.30, 0.99, 0.71, and 0.51 mm and the sand particles retained on the 0.99, 0.71, and 0.51 mm
sieves produce three of the sieved samples. Waimanalo Beach sand was passed through meshes with openings 0.51, 0.36, and 0.20 mm and the sand on the 0.36 and 0.20 mm sieves produce the finer two sieve fractions. The median diameters and sorting parameters of the sieved fractions are determined based on a logarithmic distribution of sand diameters between the adjacent sieves.

Twenty-five gallons each of the natural and sieved samples were collected for the flume experiments. The grain size characteristics of the sand samples are compiled in Table 5-1. The median sieve diameters range from 0.20 to 1.13 mm and cover the fine to very coarse sand range under the Wentworth classification. The natural sand samples have sorting parameters ranging from 0.43 to 0.90, which correspond to moderately sorted to well sorted, according to the classification of Folk and Ward (1957). The sieved samples have sorting between 0.13 and 0.27 and are considered to be uniform.

5.2 Test Setup and Preparation

A flume study was performed at the R.L. Albrook Hydraulic Laboratory at Washington State University. The tilting flume is 21 m long, 0.9 m wide, and 0.6 m deep and the test setup is shown in Figure 5-1. A 0.038-m thick gravel bed was laid along the first 17.7 m of the flume to assist in development of the turbulent boundary layer for the test section downstream. The gravel at the upstream end of the flume was the coarsest and poorest sorted, with particle size becoming smaller and more uniform downstream to approach the roughness of the test section. The gravel bed was manually leveled and packed to assure uniform bed thickness.

Each sample was placed in a 3 m long by 0.6 m wide by 0.038 m thick test bed at the downstream end of the flume. The sidewall effects on the sediment transport were reduced by a 0.15-m buffer of fine gravel between the test bed and the adjacent flume walls. A 0.3-m end section spanning the width of the flume was constructed at the same
height as the test bed to provide a downstream boundary for the sand. This section was constructed from 0.64-cm PVC sheet, layered with artificial roughness, and mounted on four legs. Gravel was packed under the sheet so that the flow of water through the sand would not be disrupted at the end section. The sand bed was separated from the gravel by perforated aluminum sheet lined with nylon mesh.

Preparation of the sand bed is critical to producing reliable and repeatable results. Defects in the bed can cause premature bed-form development, disturbing the desired uniform plane-bed transport. The sand was placed in the bed, soaked with water, and smoothed with a cement trowel to achieve plane-bed conditions. Uniform, gentle, and consistent pressure was used in leveling the sand. Additional tests were performed for one sand sample with the bed surface scuffed and with a packed bed. The scuffed bed was prepared with the trowel held perpendicular to the bed and lightly dragged across the surface. The packed bed was achieved by tamping the bed to the required thickness with 27.3 kg (60 lbs) of lead in a 20 cm × 30 cm pan. Seams left by the pan were manually smoothed.

The flow rate in the flume is up to 0.057 m$^3$/s (2 ft$^3$/s), measured using a manometer and Venturi meter. The tilting flume is set for all tests with a slope of 0.00155, measured using a theodolite. Small rod-shaped baffles are inserted horizontally at the downstream end of the flume to counteract the drawdown effect as the water spills into the tail tank and are adjusted to maintain a uniform water depth over the test section. Water depth was monitored at four locations along the test section. Fine nylon mesh bags were constructed to fit into the tail tank of the flume to trap the transported sediment.

5.3 Test Procedure

Following the approach of Shields (1936), initiation of motion is determined from measured pairs of shear stresses and transport rates at a range of flows that produces
measurable transport. Each sample was prepared as outlined in the previous section and a trial run was performed to find the approximate range of motion up to bed-form development. Four to seven runs spanning this range were performed for each sand sample.

For each run, the pump was started at a very low flow rate to minimize the effects of the initial surge. When the predetermined bed shear stress was achieved and the flow stabilized, the collection bag was connected and timing began. Water depth and manometer readings were recorded and monitored throughout the test. Following each run, the water temperature was measured and the sediment in the bag was collected and dried in an oven for the calculation of the bed-load transport rate $q_b$. The corresponding bed shear stress is determined from

$$\tau_b = \gamma d S_e$$

(5-1)

where $\gamma$ is the unit weight of water, $d$ is water depth, and $S_e$ is the slope of the energy grade line or the flume slope that produces constant water depth over the test section.

Test runs had durations of up to 13 hours, limited by the development of bed forms, which produced non-uniform sediment transport, or when a sufficient amount of sediment had accumulated in the collection bag. Selective sorting of the sediment was a concern, so the upper layer of sand was cleared away and replaced with fresh, wet sand prior to each run. Upon completion of a full set of tests for a given sample, the sand was removed from the flume and the test section was prepared for the next sand sample. A total of 56 runs were performed with the nine sand samples. Suspended transport was not observed in any of the runs.

5.4 Characteristic Grain Diameters

The median sieve diameter $D_{50}$ deviates from the corresponding nominal diameter $D_n$ and equivalent diameter $D_e$ as particle shape departs from spherical. Median sample
results found in Chapter 4 for calcareous sand on Oahu show that
\( D_{n,50} = 1.18D_{50} \) \hspace{1cm} (5-2)
\( D_{e,50} = 0.88D_{50} \) \hspace{1cm} (5-3)

The nominal diameter of calcareous sand is greater than the sieve diameter, because plate-shaped particles pass through the sieve openings diagonally. The equivalent diameter is lower because of the increased drag on non-spherical particles of the same weight. Relationships (5-2) and (5-3) are valid for the calcareous sand found on Oahu with an average shape factor of 0.56.

The empirical relations (5-2) and (5-3) convert the median sieve diameters of the sand samples in Table 5-1 to nominal and equivalent diameters to include effects of particle shape in the characterization of initiation of motion. The same relations also convert the median sieve diameters reported by Prager et al. (1996), whose sand samples collected in the Caribbean contain similar biological components as Oahu sand. Such conversions are necessary for consistent comparisons between the data sets. Paphitis et al. (2002) provided threshold data of shell fragments in terms of both the median sieve and equivalent diameters. The large difference between the two reported sets of diameters indicates much lower shape factors of the particles than those considered in Chapter 2. No attempt is therefore made to express Paphitis et al.’s data in terms of nominal diameter.

Magalhaes and Chau (1983) used the median sieve diameter as the characteristic particle size for shale and reported a shape factor of 0.2. The data is beyond the applicable range of (5-2) and (5-3). It was shown in Chapter 2, however, that the effective sieve opening approaches 1.4 times the reported sieve opening as \( D_i \) approaches zero, with a lower bound of 1.2 times for most of the calcareous sand particles. Since \( D_i \) controls the passage of particles across a sieve, an average value of \( D_i = 1.3D_{50} \) is assumed. Based on the reported \( D_i/D_i = 0.68 \) and \( D_i/D_i = 0.26 \), \( D_n = 0.94D_{50} \) is obtained.
for the flat shale particles. The relation is expected because the nominal diameter is much smaller than the intermediate dimension for flat platy particles, even though the sieve size underestimates the intermediate dimension. There is, however, insufficient information to express their data in terms of equivalent diameter.

5.5 Bed-load Transport

Plane-bed transport rates were measured over a range of shear stresses to provide a basis for determining initiation of motion. The bed-load transport rate and bed shear stress are respectively expressed in dimensionless form as

\[
q^* = \frac{q_b}{\rho_s g \sqrt{(s-1)gD^3}} \tag{5-4}
\]

\[
\theta = \frac{\tau_b}{\rho g (s-1)D} \tag{5-5}
\]

where \(\rho_s\) is the density of sand, \(\rho\) is the density of water, \(g\) is gravitational acceleration, \(s\) is the specific gravity of sand, and \(D\) is the characteristic particle diameter. The dimensionless bed shear stress \(\theta\) is also known as the Shields parameter.

Figure 5-2 contains the plots of dimensionless shear stress \(\theta\) versus dimensionless transport rate \(q^*\) for the four natural and five sieved sand samples. For illustration, only the set of results expressed in terms of nominal diameter is presented here. The data points follow power trendlines, which have been shown by Paintal (1971) to be representative of the bed-load transport process. Additional tests were performed for the Ehukai sample with the bed surface scuffed and with the bed packed by weight. The corresponding data, which is also shown in Figure 5-2a, falls along the trendline for the regular tests. With the onset of particle motion, the surface of the bed quickly evolves, regardless of the preparation method. This also corroborates the findings of White (1970), who prepared the sand bed under gently moving water in one set of experiments and with
manual leveling in another set, concluding that the bed preparation method had no effect on the results.

The point of maximum curvature of each trendline is identified in Figure 5-2 by an asterisk. This point represents the greatest rate of change in sediment transport per incremental change in shear stress and can be interpreted as an upper bound for initiation of motion. This occurs at $1.7 \times 10^{-3} < q^* < 4.5 \times 10^{-2}$ for the present data. Paintal (1971) fit power curves to his data and found that $q^*$ is proportional to $\theta^{16}$ at low transport rates and $\theta^{2.5}$ at high transport rates. The two curves intersect at $q^* = 10^{-2}$, which he suggested corresponds to general motion. Re-analysis of his results shows the maximum curvature of the trendline occurring at $q^* = 4.2 \times 10^{-3}$. The intersection of Paintal's curves at $q^* = 10^{-2}$ can thus be interpreted as the onset of general motion.

5.6 Definitions of Initiation of Motion

Initiation of motion has been investigated to a great extent, yet its definition is still ambiguous. A common misconception is that the critical shear stress for initiation of motion occurs at the lowest shear stress that produces sediment transport. Paintal (1971) and Lavelle and Mofjeld (1987), however, suggested from stochastic points of view that, due to the fluctuating nature of the instantaneous velocity, there is no mean shear stress below which there will be zero transport. With this consideration, the critical condition has to be defined as the shear stress that produces a certain minimal amount of transport. Visual and reference techniques are the most common methods of determining initiation of motion (Buffington, 1999).

Kramer (1935) listed visual observation criteria for describing sediment transport and suggested how the threshold might be related, while White (1970) referred to the threshold of motion as the condition where a few grains move over a unit area. The Task Committee on Preparation of Sedimentation Manual (1966) accepts Kramer's definition.
of weak transport as most closely representing initiation of motion. More recent studies use video imaging techniques. Paphitis et al. (2002) performed initiation of motion studies on shell particles and used image analysis techniques to determine the number of particles in motion per unit area. Papanicolaou et al. (2002) used a video imaging technique to develop a stochastic incipient motion criterion for spheres under various bed-packing conditions.

Other researchers employ the reference technique, interpolating or extrapolating the shear stress at a small transport rate for the critical value. Waterways Experiment Station (1935) defined a minimum flux for motion initiation as $4.0 \times 10^{-3}$ N/mls, corresponding to $q^* = 8.2 \times 10^{-4}$ to $1.1 \times 10^{-2}$ for the present range of nominal diameters. Magalhaes and Chau (1983) extrapolated the trendlines of $\tau_b$ versus $q_b$ to near zero transport, defined in their study as $q_b = 10^{-3}$ N/m/s. For the grain sizes in the present study, this gives $q^*$ between $2.0 \times 10^{-4}$ and $2.8 \times 10^{-3}$ for motion initiation. Prager et al. (1996) averaged the measured shear stresses that produced small amounts of sediment transport for the critical shear stress. The corresponding range of $q^*$, re-computed in terms of $D_n$ based on Equation (5-2), is $3.2 \times 10^{-3}$ to $1.4 \times 10^{-2}$.

The results from the previous studies show a wide range of $q^*$ from $2.0 \times 10^{-4}$ to $1.4 \times 10^{-2}$ for the initiation of motion criterion. The present results in Figure 5-2 show an upper bound of $q^*$ on the order of $10^{-3}$ as indicated by the point of maximum curvature. Significant transport, however, was observed for the flume tests well below this value. Observations made during the flume tests suggest the threshold occurs around $q^* = 10^{-4}$. Although the flume tests measured quantifiable transport below this value, this transport can best be described as a small number of grains from the finer part of the distribution moving sporadically at isolated locations on the bed. At $q^*$ slightly above $10^{-4}$, the particle motion is more continuous across the bed and encompasses a greater portion of the sand distribution. This condition is also consistent with Kramer's (1935) definition of
weak transport. Though not stated in his report, it is believed that Shields (1936) also
used a combined visual and reference technique to determine initiation of motion
(Buffington, 1999).

5.7 Initiation of Motion

The critical shear stresses for initiation of motion of the four natural and five sieved
calcareous sand samples are determined from the dimensionless transport trendlines in
Figure 5-2 at $q^* = 10^{-4}$. The data is presented as a function of the grain Reynolds number
(Brownlie, 1981)

$$R_P = \sqrt{(s-1)gD^3/v^2}$$

in terms of sieve, nominal, and equivalent diameters. The quantities $q^*$ and $\theta$ of
Magalhaes and Chau (1983), Prager et al. (1996), and Paphitis et al. (2002) are
recalculated with the appropriate grain size definitions, but the authors' definitions of
motion initiation are not changed. Their intuition and judgment in determining the critical
shear stresses are most important. Since the intent is to compare the initiation of motion
of irregular grains with the widely used Shields curve, no adjustment with regard to size
characterization is made to Shields' (1936) data.

Figures 5-3 and 5-4 present the critical shear stresses from the various studies in
terms of the median equivalent and nominal diameters respectively. The Shields curve in
the form presented by Brownlie (1981) provides a comparison for rounded particles. The
data spans the hydraulically smooth flow regime and extends into the rough turbulent
flow regime in both particle size definitions. The natural calcareous sand data has the
same trend as the sieved sand, but with a slightly lower critical shear stress, due to
selective transport of the finer fractions within the natural samples. A distinct coarsening
of the test bed was observed for the four natural sand samples during the flume
experiments. The data in Table 5-1 shows natural calcareous sand found on Oahu is
already sorted to a certain extent. The small difference in the results between the natural and sieved samples is expected and suggests that the effect of size distribution in these cases is small.

The present data for both particle size definitions exhibits the same relation with the Shields curve. In Figure 5-3, the critical shear stress in the lower transitional regime plots above the Shields curve and is substantiated by the data of Paphitis et al. (2002). Since the critical shear stress is evaluated from the transport rate, the results indicate less transport for irregular grains of the same equivalent diameter under the same flow conditions. The bed-load transport modes of sliding, rolling, and saltation were observed to be less efficient for irregular particles in the hydraulically smooth regime. These particles have more sporadic motions than the rounded particles, which could freely roll across the bed. The present data crosses the Shields curve in the transitional regime and is complemented by the Prager et al. (1996) data. In the rough turbulent regime, the present data extends into the Magalhaes and Chau (1983) data below the Shields curve as shown in Figure 5-4. The transport is greater for irregular particles of the same nominal diameter, because of the significant increase in particle drag and rotation at high Reynolds numbers as shown in Chapter 3.

Figure 5-5 shows the critical shear stress data in terms of the median sieve diameter reported in the various studies. The data from the present study, Prager et al. (1996), and Magalhaes and Chau (1983), shows a minor shift from the other two size definitions, but retains the same general relation with the Shields curve. Paphitis et al.’s (2002) data, however, exhibits a strong dependence on the particle size definition. As concluded in their study, this is due to the inadequacy of sieve analysis in defining the size for shell particles. The present study shows that the continued use of the original Shields diagram for initiation of motion can lead to inaccurate estimates for the transport of calcareous sand. Sediment transport models, which use the critical shear stress as the definitive
boundary between transport and no transport, might produce better estimates of transport rates of calcareous sand by using the present results.
6. TRANSPORT RATES

6.1 Test Setup and Procedure

Additional sediment transport experiments on the four natural sand samples described in Chapter 5 were also performed at the R.L. Albrook Hydraulic Laboratory at Washington State University. The data collected in this set of tests covers the bed-form and suspended transport stages and is supplemented by plane-bed transport data of the sieved and natural sand samples from Chapter 5 for a comparison of published sediment transport models. Approximately one cubic meter of each natural sample was collected for these tests. The grain size properties of the natural and sieved sand samples are compiled in Table 5-1.

This series of tests provides measurements of the bed and suspended-load transport rates of the four natural samples with fully developed bed forms. The tests utilize an 11-m long and 0.1-m thick sand bed in the test section to allow for bed-form propagation and to provide sufficient sand for the higher transport rates. The flume configuration is shown in Figure 6-1. Preparation of the sand bed for the higher transport stages is not as critical as in the plane-bed transport tests, since bed-form development is encouraged. The sand was placed in the bed, wet, raked, and smoothed with a cement trowel to achieve plane-bed conditions. Uniform and consistent pressure was used in leveling the sand. The 0.10-m bed thickness was referenced to elevation marks on the sidewalls. Perforated metal sheet is inserted perpendicular to the flow at the downstream end of the flume to vary the water depth and counteract the drawdown of the water surface as the water spills into the tail tank.

A series of qualitative trial runs were preformed for each natural sample with various combinations of flow rate and water depth to determine the range of sediment transport from bed-form development up to the maximum flow rate of the pumps, from which the
final test conditions were determined. Eight to nine runs covering this range of transport were performed for each sand sample. The pump was started and gradually increased to a predetermined setting. The flume slope was adjusted to maintain uniform flow over the sand bed as bed forms developed. Development was closely monitored and the bed was deemed fully developed when the water depth and bed-form height and length stabilized. This process took up to 2.5 hours and sediment transport measurements were performed only after the bed was fully developed. Non-uniform flow was identified by a change in water depth over the bed, in which case the test was restarted and the bed was allowed to redevelop.

Following each run, the water temperature was measured and the sediment in the collection bag was removed, dried in an oven, and weighed to calculate the transport rate. Crest and trough heights and locations along the flume centerline were measured in the tests where the bed was developed. Upon completion of a full set of tests for a given sample, the sand was removed from the flume and the test area was prepared for the next sand sample. The duration of each test was dependent on the rate at which sand collected in the bag. A high rate of transport or a large amount of collected sediment caused the bag to plug and the flow to back up into the flume, in which case the run was aborted. Test runs with suspended sediment had durations of up to 17 minutes. Tests that showed only bed-load transport with bed forms were run for up to 91 minutes, while plane-bed transport runs were performed for as long as 13 hours.

A total of 29 runs with bed forms were performed with the four natural sand samples. Suspended sediment transport occurred in 17 of those tests and only with the finer 2 sand samples. The data is supplemented by the 60 plane-bed transport tests performed with the four natural and five sorted sand samples, with 41 producing transport above initiation of motion as defined in Chapter 5.
6.2 Transport Models

The sediment transport rates found in the flume studies are compared with predictions from published sediment transport models. The models are evaluated using input parameters as suggested by the respective authors and also with corrections for the calcareous sand properties described in Chapters 2 through 5. Yang and Huang (2001) compared the applicability of 13 sediment transport models with 3,391 sets of measured data and found that the formulas based on energy dissipation rate, such as Engelund and Hansen (1967), Ackers and White (1973), and Yang (1973, 1979), show superior results versus models developed based on other principles. Van Rijn's (1984c) semi-empirical model, although not evaluated by Yang and Huang, makes a distinction between suspended and bed-load transport, while the other energy-based models provide estimates of the total-load transport only. These five sediment transport models are selected for this comparative study and are summarized in the following sections.

6.2.1 Engelund-Hansen (1967)

Engelund and Hansen (1967) used dimensional analysis to formulate their sediment transport model in terms of Bagnold's (1966) stream power, which is defined as the product of the depth-averaged velocity, $\bar{u}$, and the energy slope, $S_e$. The total sediment transport rate in kg/m/s can be stated as either

$$ q_t = \frac{0.05(S_e d)^{3/2} \bar{u}^2 \rho_s}{(s - 1)^2 \sqrt{g D_{50}}} \quad (6-2) $$

or

$$ q_t = \frac{0.05 \bar{u}^5 \rho_s}{(s - 1)^2 \sqrt{g D_{50} C^3}} \quad (6-3) $$

in which $C$ is the Chezy coefficient given by
\[ C = \frac{\bar{u}}{\sqrt{dS_e}} \]  

(6-4)

where \( g \) denotes gravitational acceleration, \( d \) is water depth, and \( s \) and \( \rho_s \) are respectively the specific gravity and density of the sand.

Particle fall velocity is not considered in this model and no specific relationship for critical motion is included. This approach relates the stream power and the resulting transport rate regardless of the sediment hydraulic characteristics. Van Rijn (1984c) suggests this model should be used under flume conditions, for which it was calibrated, and not used for field conditions.

6.2.2 Ackers and White (1973)

Ackers and White (1973) also used Bagnold’s (1966) stream-power concept and dimensional analysis to formulate their sediment transport model. Their formulation makes use of the grain size parameter and shear stress velocity defined respectively as

\[ D_s = D \left( \frac{(s-1)g}{\nu^2} \right)^{1/3} \]  

(6-5)

\[ u_* = \sqrt{\frac{\tau}{\rho}} \]  

(6-6)

where \( D \) is a characteristic grain size, \( \nu \) is the kinematic viscosity equal to \( 10^{-6} \) \( \text{m}^2/\text{s} \), \( \tau \) is bed shear stress, and \( \rho \) is water density. The bed-load and suspended-load transport equations were developed separately through dimensional analysis and combined through a transition parameter that weights the transport based on the grain size from 0.06 mm to 2 mm. Flow depth, flow velocity, energy gradient, and sediment size are the input parameters and the model was calibrated with 925 sets of data.

The general form of the sediment transport function is expressed in terms of empirical coefficients \( F, A, B, \) and \( m \) as
\[ G = B \left( \frac{F}{A} - 1 \right)^m \]  

(6-7)

The sediment mobility \( F \) is given by

\[ F = \frac{u_*^n (\bar{u})^{1-n}}{\sqrt{gD(s-1)[\sqrt{32 \log(10d/D)]^{1-n}}}} \]  

(6-8)

in which \( n \) is the transition parameter given by

\[ n = 1 - 0.56 \log(D_*) \]  

(6-9)

Unlike the stream-power approach of Engelund and Hansen (1967), this model uses the empirical relation \( A \)

\[ A = \frac{0.23}{\sqrt{D_*}} + 0.14 \]  

(6-10)

to account for initiation of motion. Ackers (1990) used additional data to update the expressions for \( m \) and \( B \) respectively as

\[ m = \frac{6.83}{D_*} + 1.67 \]  

(6-11)

\[ \log(B) = -3.46 + 2.79 \log D_* - 0.98(\log D_*)^2 \]  

(6-12)

The sediment transport rate in kg/m/s is given in terms of the sediment transport function \( G \) as

\[ q_t = GDu\bar{s} \left( \frac{\bar{u}}{u_*} \right)^n \]  

(6-13)

The model was developed for uniform particles and the authors state that it can be applied to non-uniform sizes by calculating the transport rate for each size fraction. Dyer (1986) and van Rijn (1993), however, recommend applying the model using \( D_{35} \) as the characteristic grain size, and that approach is followed here.
6.2.3 Yang (1973, 1979)

Yang (1973) developed a sediment transport model based on 463 sets of lab and river data and correlated the total sediment concentration with the stream power. This model is most useful for low concentrations near critical conditions and is best applied to flumes and small rivers (van Rijn, 1993). The total sediment concentration, $C_t$, is found from

$$ \log C_t = 5.435 - 0.286 \log \frac{w D_{50}}{v} - 0.457 \log \frac{u_s}{w} +$$

$$\left(1.799 - 0.409 \log \frac{w D_{50}}{v} - 0.314 \log \frac{u_s}{w}\right) \log \left(\frac{u_S e}{w} - \frac{\bar{u}_{cr} S_e}{w}\right) $$

(6-14)

where $w$ is the fall velocity and the critical depth-averaged velocity $\bar{u}_{cr}$ is given by

$$ \frac{\bar{u}_{cr}}{w} = \frac{2.5}{\log (\frac{u_s D_{50}}{v})} + 0.66 $$

(6-15)

In contrast to Ackers and White (1973), Yang’s model uses both the fall velocity and critical velocity to represent the transport characteristics of the sediment.

Yang (1979) simplified his 1973 equation to remove the dependence of the model on $\bar{u}_{cr}$. The new equation, which is also based on the stream-power concept, was developed using 1093 sets of flume data and 166 sets of field data and is applicable for flow over all types of bed forms. The regressed line shows a 3% difference from the trendline of perfect agreement between the measured and computed results and 90% of the data used to calibrate the model falls within a factor of 2 of the predicted concentration. The total sediment concentration is found by

$$ \log C_t = 5.165 - 0.153 \log \frac{w D_{50}}{v} - 0.297 \log \frac{u_s}{w} +$$

$$\left(1.780 - 0.360 \log \frac{w D_{50}}{v} - 0.480 \log \frac{u_s}{w}\right) \log \frac{u_S e}{w} $$

(6-16)

In both models, the sediment transport rate in kg/m/s is calculated as
\[ q_t = 0.001C_t ud \]  \hspace{1cm} (6-17)

While Yang (1979) cites comparisons between his 1973 and 1979 models as showing no practical differences, he suggests that the 1973 model is better at low concentrations and the 1979 model is generally more useful when the shear stress is substantially greater than critical.

6.2.4 van Rijn (1984c)

Van Rijn (1984a, 1984b, 1984c) developed a set of semi-empirical and empirical transport models that compute bed load and suspended load as functions of flow conditions and grain size characteristics. Unlike the stream-power approach, these models are based on the transport mechanism of the individual particles in the bed-load layer and in suspension. The models were verified with 786 field and 758 flume data sets, where flow depth \( d \) is greater than 0.1 m, the ratio of channel width to depth \( b/d \) is greater than 3, and grain size \( D_{50} \) is between 0.1 and 2.5 mm.

The model of van Rijn (1984c) is simpler and is useful in a predictive sense because few flow parameters are required. The total transport rate \( q_t \) is divided into the bed load and suspended load given respectively by

\[
\frac{q_b}{ud} = 0.005 \left( \frac{u - u_{cr}}{\sqrt{(s-1)gD_{50}}} \right)^{2.4} \left( \frac{D_{50}}{d} \right)^{1.2} \hspace{1cm} (6-18)
\]

\[
\frac{q_s}{ud} = 0.012 \left( \frac{u - u_{cr}}{\sqrt{(s-1)gD_{50}}} \right)^{2.4} \left( \frac{D_{50}}{d} \right)^{1.2} D_{*}^{-0.6} \hspace{1cm} (6-19)
\]

The depth-averaged critical flow velocities are found by

\[
-\frac{u_{cr}}{u} = 0.19(D_{50})^{0.1} \log \left( \frac{12d}{3D_{90}} \right) \hspace{1cm} \text{for } 0.1 < D_{50} < 0.5 \text{ mm} \hspace{1cm} (6-20a)
\]
\[
\bar{u}_c = 8.5(D_{50})^{0.6} \log\left(\frac{12d}{3D_{90}}\right) \quad \text{for } 0.5 < D_{50} < 20 \text{ mm}
\] (6-20b)

where \(D_{90}\) is the 90th percentile of the grain size according to sieve analysis and signifies the roughness of a plane bed.

All five models used a characteristic grain size of the sediment in the formulation, but not all models fully account for the particle hydraulic characteristics in terms of the threshold velocity and fall velocity. Both van Rijn (1984c) and Yang (1973) provide their own definitions of the threshold condition for sediment motion instead of using the Shields diagram, while Ackers and White (1973) use an empirical parameter to represent the transport stage above the critical condition. Yang's (1973, 1979) models use the fall velocity explicitly, but the same parameter is built into the transport equation of van Rijn (1984c) and cannot be modified easily.

### 6.3 Model Implementation

Each of the models examined in the present study employs the depth-averaged velocity, \(\bar{u}\), as the principal determining factor for sediment transport. This velocity is obtained from manometer readings for each test run. Analysis of the readings and comparison amongst plane-bed transport tests show that the readings might be unreliable, likely due to air in the lines. The flume slope was carefully surveyed and the energy slope is considered reliable. The average velocity is thus determined from bed roughness, flow depth, and energy slope as

\[
\bar{u} = C\sqrt{dS_e}
\] (6-21)

where the Chezy coefficient related to the grain roughness of a plane bed is given by

\[
C = 18\log\left(\frac{12d}{3D_{90}}\right)
\] (6-22)

In the subsequent tests of transport with bed forms, the manometer lines were bled
frequently and the velocity readings were verified with Acoustic Doppler Velocimeter (ADV) measurements.

The energy slope, conversely, can be calculated from the flow and bed-form characteristics. Measured bed-form dimensions are used to determine the effective roughness height \( k_s \) through

\[
k_s = 3D_{90} + 1.1\Delta(1 - e^{-25\Delta/\lambda})
\]

where \( \Delta \) and \( \lambda \) are the respective bed-form height and length (van Rijn, 1984c). The Chezy coefficient is then determined from

\[
C = 18\log\left(\frac{12d}{k_s}\right)
\]

The energy slope is simplified to be

\[
S_e = \frac{1}{d} \left( \frac{u}{C} \right)^2
\]

The resulting values of \( S_e \) are used in the models of Yang (1973, 1979) and Engelund and Hansen (1967) when bed forms are present.

The results of each run are first compared with direct application of the five sediment transport models intended for siliceous sediments. The input grain size characteristics \( D_{35}, D_{50}, D_{90} \) are found from sieve analysis. The methods of each model for determining critical average velocity \( \bar{u}_{cr} \) and particle fall velocity \( w \) are used where applicable.

### 6.4 Corrections for Calcareous Sand

The grain size study in Chapter 2 shows that calcareous grains on Oahu have an average Corey shape factor of 0.56, whereas the shape factor of natural quartz grains is typically around 0.70. The lower shape factor causes standard sieve analysis of calcareous particles to produce biased results in the characterization of sand size. The
irregular particles also have distinct settling velocities and critical velocities from those of
the rounded siliceous sediment. This section describes the corrections for these effects in
an attempt to extend the predictive capability of the existing transport models for
calcareous sand.

The most useful of the size measures for irregular grains are the nominal and
equivalent diameters. Nominal diameter, $D_n$, is the diameter of a sphere that has equal
volume as the irregular particle and equivalent diameter, $D_e$, is the diameter of a sphere of
the same density having the same fall velocity as the irregular particle. The median
nominal diameter, $D_{n,50}$, and the median equivalent diameter, $D_{e,50}$, are related to the
median sieve diameter, $D_{50}$, by Equations (5-2) and (5-3), which provide the median
nominal and equivalent diameters for the sand samples as shown in Table 6-1. As seen in
the equations, the median nominal and equivalent diameters are related to the median
sieve diameter and are therefore not independent. Since the effect of the equivalent
diameter is shown in the fall velocity, the median nominal diameter is used in the five
sediment transport models to account for the grain size characteristics of calcareous sand.

The lower shape factor of calcareous sand particles translates into lower fall velocities
than for spheres of the same volume. Chapter 3 has presented relationships for fall
velocity and drag coefficient as functions of nominal diameter and shape factor. The
relationships show increasing particle shape influence with Reynolds number due to
modification in the boundary layer development. Table 6-1 shows the fall velocities of
the sand samples based on the median equivalent diameters determined from Equation (5-3)
and measured from the curve of the sphere presented in Chapter 3. The nominal
diameters fall in the transition between the laminar and turbulent regimes, where the
particle shape begins to show pronounced effect on the fall velocity. Of the five models
considered, only Yang’s (1973, 1979) models can account for the lower fall velocity of
calcareous sand.
Initiation of motion of calcareous sand is compared in Chapter 5 with the Shields diagram, which shows critical shear stress as a function of dimensionless grain size. In comparison to rounded particles, calcareous sand has critical shear stresses that are higher in the hydraulically smooth regime and lower in the rough turbulent regime. The critical depth-averaged velocity, \( \bar{u}_{cr} \), can similarly be derived to describe the threshold condition for motion. The critical depth-averaged velocities of the sand samples are listed in Table 6-1. The results are used in the models of Yang (1973) and van Rijn (1984c) to account for the transport characteristics of calcareous sand.

### 6.5 Comparison of Transport Rates

The measured transport rates are compared with the calculated transport rates from the five models in their original form and with corrections for calcareous sand characteristics. The comparison is made in terms of the dimensionless transport rate

\[
q^* = \frac{q_t}{\rho_s g \sqrt{(s-1)gD^3}} \tag{6-26}
\]

where \( D \) is the median sieve or nominal diameter, depending on the choice of characteristic grain size definition. Initiation of motion is defined in Chapter 5 to occur at a transport rate that produces a small amount of motion, found to be \( q^* = 10^{-4} \) based on the nominal diameter. Although measurable transport exists below this definition, these data points are not considered in this comparative study.

Figures 6-2 through 6-6 show the comparisons between the measured and calculated transport rates from the five models. The data is sorted by transport stage. The figures include lines of perfect agreement, \( q^{* \text{, calculated}} = q^{* \text{, measured}} \), denoted by a solid line, and dotted lines of slope 0.1 and 10 that respectively indicate under-prediction and over-prediction by an order of magnitude. Model applicability is generally judged based on the percentage of calculated transport rates that fall within a factor of 2 of the measured
transport rates (Brownlie, 1981; van Rijn, 1984a, b; and Chang, 1988). In the present case, where the error is measured using the logarithms of the values, the corresponding range of applicability is -0.3 to 0.3 as indicated by the dashed lines. The data shows considerable scatter due to experimental errors as well as the limitation of the models to fully describe the transport of calcareous sand.

Numerous techniques are available to quantify the comparisons. A logarithmic scale is used to avoid bias between under and over-prediction of the measured transport rate. The difference between the measured and computed results is deduced from

$$\text{Error} = \frac{1}{N} \sum (\log_{10} q^*_{\text{calculated}} - \log_{10} q^*_{\text{measured}})$$

where $N$ is the number of data points. The error measures the deviation of the center of mass of the data points from the line of perfect agreement in Figures 6-2 through 6-6. The scatter of the data, which indicates the consistency of model predictions, is also an important indicator. It is similarly given by the standard deviation of the logarithm of the calculated transport rates.

The error and scatter of the data are calculated separately by model and transport stage and the results are summarized in Tables 6-2 and 6-3. In some cases, models predict no sediment transport for conditions that produced measurable transport rates about the critical value of $q^* = 10^{-4}$. These cases were limited to the plane-bed transport tests and are not considered in the error and scatter calculations. Both the error and scatter are generally higher in the plane-bed transport stage because of the varying definition of the critical velocity or the lack of it in the models. The results are better when bed forms develop and suspended transport occurs. The application of the calcareous sand characteristics in the models produces mixed results, although it does move a few outlying points associated with plane-bed transport toward the line of perfect agreement as shown in Figures 6-2 through 6-6.
Of the five models compared, only Yang’s (1973) model considers all three characteristic parameters: grain size definition, initiation of motion, and particle fall velocity. However, the model significantly under-predicts in the plane-bed transport stage before and after the calcareous sand corrections are applied. The predictions are greatly improved in the bed-form transport and suspended transport stages. Even though Yang’s (1979) model lacks a specific critical motion relationship, it shows the best results of all the models. The error is slightly higher in the plane-bed transport stage, but is reduced and becomes comparable to his 1973 model for the higher transport stages, where initiation of motion is less crucial to the results. In each transport stage, both models show greater error after the corrections for calcareous sand are applied, while the scatter remains comparable.

The models of Ackers and White (1973) and van Rijn (1984c), which include critical motion relationships, under-predict the plane-bed transport rate by an order of magnitude with and without the calcareous corrections applied. The results show significant scatter in the plane-bed transport stage. Both models also over-predict the bed-load transport with bed forms, although the error is greatly reduced in Ackers and White when the corrections are applied. While the model of van Rijn produces better results in the higher transport stages, it shows no improvement over the other models. In the suspended transport stage, the model of Ackers and White has satisfactory results, but does not compare with other models. Corrections for calcareous sand amount to the grain size definition only. The model does not consider particle fall velocity, and the critical motion relationship included in the model is empirical, limiting the application of the calcareous sand corrections.

The model of Engelund and Hansen (1967) includes no critical motion criteria and over-predicts the plane-bed transport similar to Yang’s (1979) model, but to a greater degree. The errors are reduced at higher transport stages, but still do not compare with the
other models. The model, however, responds very well to the calcareous corrections in all transport stages and produces good results in the higher transport stages. The correction applied is only in the grain size definition, as the model considers neither initiation of motion nor particle fall velocity. The scatter of the data is the lowest in most of the cases considered.
7. CONCLUSIONS AND RECOMMENDATIONS

Calcareous sand samples collected from 13 Oahu beaches, subject to varying wave exposure, have been analyzed for physical grain size parameters. The grain characteristics of short, intermediate, and long dimension, shape factor, and nominal diameter for 998 grains are presented. Particle densities measured from 137 individual grains confirm the particle densities determined for 24 samples of beach sand.

The samples analyzed in this study correspond to fine 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. Furthermore, 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 diameter and follows a normal distribution over most of the nominal diameter range considered.

Settling characteristics of the 998 calcareous grains have also been examined. The mostly medium to very coarse sand provides new fall velocity and drag coefficient data for non-spherical particles. The results are validated by published data based on natural quartz grains. The Corey shape factor remains the best representative of shape-dependent hydraulic properties among other more intuitive relationships. Particle shape shows an increasing influence on the settling characteristics with Reynolds number. Calcareous sand particles are typically not symmetric and the large particles tend to have rough surface textures and jagged edges. These secondary shape characteristics cause the grains to settle in a spiral and at high Reynolds numbers to tumble and flutter, but do not cause significant variation of the measured fall velocities of the same grain. These settling
motions, however, cause the wake to become unstable at lower Reynolds numbers, extend the transitional regime to higher Reynolds numbers, and primarily account for the new sets of fall velocity and drag coefficient curves presented in this paper.

Eleven sand samples have been analyzed for median 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 distributions of the nominal and equivalent diameters within the sieve and settling groups are analyzed to provide the respective median diameters for the samples. 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 12% 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. 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.

Four natural and five sieved calcareous sand samples were studied in a unidirectional flume experiment for the effect of particle shape on initiation of motion. The samples span the range of particle sizes for tropical island beach sand. Plane-bed transport rates were measured as a function of bed shear stress up to bed-form development. A total of 56 tests were performed for the nine samples. The effect of bed preparation was examined in one sample and shown to be insignificant. The data for each sample was analyzed to determine the initiation of motion using a combination of visual and reference techniques. The dimensionless quantities of the Shields diagram are evaluated using the median nominal, equivalent, and sieve diameters as the characteristic particle
sizes. The present data is supplemented by calcareous sand and shell data in the hydraulically smooth and transitional regimes, and flat platy shale particle data in the rough turbulent regime. The data follows the general shape of the Shields curve, but the critical shear stresses are higher in the hydraulically smooth regime and lower in the rough turbulent regime. The effects of particle size distribution are noticeable, but are secondary compared to the effects of particle shape and size characterization.

Sediment transport flume studies were performed for the four natural and five sieved samples of calcareous sand. The sand covers the range of sizes from fine to very coarse normally found on tropical beaches. The 70 tests cover the plane-bed, bed-form, and suspended transport stages. The flow conditions and sediment characteristics were input to five published models for total load transport. The models were then tested using physical and hydraulic quantities unique to calcareous sand. These quantities include nominal diameter, fall velocity, and critical depth-averaged velocity. Yang's (1979) model, even though it does not contain a relationship for critical motion, produces the best results for all three transport stages when applied as is. When corrections for calcareous sand are applied, the model of Engelund and Hansen (1967) produces good results for the bed-form and suspended transport stages.

The effect of particle shape on the grain size, hydraulic, and transport characteristics of calcareous sand has been presented. The corrections to grain size, fall velocity, and initiation of motion applied to existing transport models, however, are devised for Oahu beaches and may not be universally applicable. In most of the cases shown, model error increases when corrections for calcareous sand are applied, suggesting that the corrections do not fully account for the physics involved. The models compared are inconsistent in their inclusion of fall velocity and initiation of motion. Further research into the physics of sediment transport, particularly for irregular grains, will give a better understanding of the forces affecting the grains. Models developed for calcareous sand
should consider the effect of shape factor, nominal diameter, fall velocity, and critical shear stress as calibration parameters. A larger database of flume studies will assist in the calibration of the models.
Table 2-1. Sand Densities for Natural Samples.

<table>
<thead>
<tr>
<th>Beach</th>
<th>$D_{50}$ (mm)</th>
<th>$\rho_s$ (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond Head</td>
<td>0.93</td>
<td>2.59</td>
</tr>
<tr>
<td>Ehukai</td>
<td>1.05</td>
<td>2.68</td>
</tr>
<tr>
<td>Fort Hase</td>
<td>0.86</td>
<td>2.63</td>
</tr>
<tr>
<td>Mokuleia</td>
<td>0.49</td>
<td>2.73</td>
</tr>
<tr>
<td>Puuiki</td>
<td>0.59</td>
<td>2.59</td>
</tr>
<tr>
<td>Pyramid Rock</td>
<td>0.33</td>
<td>2.68</td>
</tr>
<tr>
<td>Sandy Beach</td>
<td>0.50</td>
<td>2.78</td>
</tr>
<tr>
<td>Sunset Beach</td>
<td>0.58</td>
<td>2.73</td>
</tr>
<tr>
<td>Waimanalo</td>
<td>0.43</td>
<td>2.59</td>
</tr>
<tr>
<td>Yokohama Bay</td>
<td>0.49</td>
<td>2.78</td>
</tr>
</tbody>
</table>
Table 2-2. Sand Densities for Sieved Samples.

<table>
<thead>
<tr>
<th>Beach</th>
<th>$D_{50}$ (mm)</th>
<th>$\rho_s$ (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ehukai (12*)</td>
<td>1.71</td>
<td>2.68</td>
</tr>
<tr>
<td>Ehukai (14)</td>
<td>1.41</td>
<td>2.68</td>
</tr>
<tr>
<td>Ehukai (18)</td>
<td>1.14</td>
<td>2.68</td>
</tr>
<tr>
<td>Ehukai (24)</td>
<td>0.85</td>
<td>2.68</td>
</tr>
<tr>
<td>Ehukai (30)</td>
<td>0.61</td>
<td>2.73</td>
</tr>
<tr>
<td>Waimanalo (40)</td>
<td>0.43</td>
<td>2.63</td>
</tr>
<tr>
<td>Waimanalo (70)</td>
<td>0.28</td>
<td>2.63</td>
</tr>
<tr>
<td>Waimanalo (120)</td>
<td>0.17</td>
<td>2.68</td>
</tr>
<tr>
<td>Sans Souci</td>
<td>&gt;4.76</td>
<td>2.59</td>
</tr>
<tr>
<td>Sans Souci</td>
<td>3.09</td>
<td>2.63</td>
</tr>
<tr>
<td>Sans Souci</td>
<td>1.67</td>
<td>2.63</td>
</tr>
<tr>
<td>Sans Souci</td>
<td>1.18</td>
<td>2.59</td>
</tr>
<tr>
<td>Sandy Beach</td>
<td>0.54</td>
<td>2.78</td>
</tr>
<tr>
<td>Mokuleia</td>
<td>0.46</td>
<td>2.73</td>
</tr>
</tbody>
</table>

* Retaining sieve number
Table 3-1. Results from Fall Velocity Sensitivity Test.

<table>
<thead>
<tr>
<th>Grain</th>
<th>$D_n$ (mm)</th>
<th>$F_s$ (m/s)</th>
<th>$\bar{w}$ (m/s)</th>
<th>$\sigma_w/\bar{w}$</th>
<th>$Re* (D_n/v)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.42</td>
<td>0.74</td>
<td>0.052</td>
<td>0.010</td>
<td>21</td>
</tr>
<tr>
<td>2</td>
<td>0.48</td>
<td>0.56</td>
<td>0.048</td>
<td>0.011</td>
<td>23</td>
</tr>
<tr>
<td>3</td>
<td>0.51</td>
<td>0.36</td>
<td>0.057</td>
<td>0.012</td>
<td>29</td>
</tr>
<tr>
<td>4</td>
<td>0.59</td>
<td>0.62</td>
<td>0.073</td>
<td>0.005</td>
<td>43</td>
</tr>
<tr>
<td>5</td>
<td>0.70</td>
<td>0.51</td>
<td>0.082</td>
<td>0.008</td>
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</tr>
<tr>
<td>6</td>
<td>0.80</td>
<td>0.66</td>
<td>0.102</td>
<td>0.006</td>
<td>82</td>
</tr>
<tr>
<td>7</td>
<td>1.01</td>
<td>0.58</td>
<td>0.114</td>
<td>0.010</td>
<td>116</td>
</tr>
<tr>
<td>8</td>
<td>1.28</td>
<td>0.65</td>
<td>0.164</td>
<td>0.009</td>
<td>211</td>
</tr>
<tr>
<td>9</td>
<td>1.37</td>
<td>0.69</td>
<td>0.162</td>
<td>0.020</td>
<td>222</td>
</tr>
<tr>
<td>10</td>
<td>1.48</td>
<td>0.69</td>
<td>0.168</td>
<td>0.024</td>
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<tr>
<td>11</td>
<td>1.48</td>
<td>0.46</td>
<td>0.142</td>
<td>0.020</td>
<td>211</td>
</tr>
<tr>
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<td>0.41</td>
<td>0.156</td>
<td>0.054</td>
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<tr>
<td>13</td>
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<td>0.053</td>
<td>407</td>
</tr>
<tr>
<td>14</td>
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<td>0.015</td>
<td>407</td>
</tr>
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<td>0.017</td>
<td>431</td>
</tr>
<tr>
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<td>0.62</td>
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<td>0.010</td>
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</tr>
<tr>
<td>18</td>
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<td>0.016</td>
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<td>0.29</td>
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<td>0.017</td>
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<tr>
<td>20</td>
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<td>0.018</td>
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<tr>
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<td>0.016</td>
<td>1977</td>
</tr>
<tr>
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<td>0.48</td>
<td>0.290</td>
<td>0.017</td>
<td>2004</td>
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</table>
Table 4-1. Median Diameters Determined from Sieve and Settling Analyses.

<table>
<thead>
<tr>
<th>Sample Site</th>
<th>Analysis</th>
<th>$D_{50}$ (mm)</th>
<th>$D_n$ (mm)</th>
<th>$D_e$ (mm)</th>
<th>$F_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ehukai</td>
<td>Sieve</td>
<td>1.05</td>
<td>1.16</td>
<td>0.92</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>Settling</td>
<td></td>
<td>1.21</td>
<td>0.81</td>
<td></td>
</tr>
<tr>
<td>Diamond Head</td>
<td>Sieve</td>
<td>0.93</td>
<td>1.11</td>
<td>0.80</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>Settling</td>
<td></td>
<td>0.97</td>
<td>0.73</td>
<td></td>
</tr>
<tr>
<td>Fort Hase</td>
<td>Sieve</td>
<td>0.86</td>
<td>0.95</td>
<td>0.71</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>Settling</td>
<td></td>
<td>1.10</td>
<td>0.71</td>
<td></td>
</tr>
<tr>
<td>Three Tables</td>
<td>Sieve</td>
<td>0.76</td>
<td>0.91</td>
<td>0.73</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>Settling</td>
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<td>0.94</td>
<td>0.73</td>
<td></td>
</tr>
<tr>
<td>Puuiki</td>
<td>Sieve</td>
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<td>0.68</td>
<td>0.50</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>Settling</td>
<td></td>
<td>0.73</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td>Sunset Beach</td>
<td>Sieve</td>
<td>0.58</td>
<td>0.68</td>
<td>0.55</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>Settling</td>
<td></td>
<td>0.66</td>
<td>0.57</td>
<td></td>
</tr>
<tr>
<td>Sandy Beach</td>
<td>Sieve</td>
<td>0.50</td>
<td>0.61</td>
<td>0.51</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>Settling</td>
<td></td>
<td>0.66</td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td>Mokuleia</td>
<td>Sieve</td>
<td>0.49</td>
<td>0.54</td>
<td>0.49</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>Settling</td>
<td></td>
<td>0.57</td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td>Yokohama Bay</td>
<td>Sieve</td>
<td>0.49</td>
<td>0.62</td>
<td>0.51</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>Settling</td>
<td></td>
<td>0.64</td>
<td>0.53</td>
<td></td>
</tr>
<tr>
<td>Waimanalo</td>
<td>Sieve</td>
<td>0.43</td>
<td>0.54</td>
<td>0.38</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>Settling</td>
<td></td>
<td>0.52</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>Pyramid Rock</td>
<td>Sieve</td>
<td>0.33</td>
<td>0.41</td>
<td>0.32</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>Settling</td>
<td></td>
<td>0.38</td>
<td>0.30</td>
<td></td>
</tr>
</tbody>
</table>
Table 5-1. Grain Size Characteristics of Sand Samples.

<table>
<thead>
<tr>
<th>Sand Source</th>
<th>Composition</th>
<th>Sieve Analysis</th>
<th>$D_{s0}$ (mm)</th>
<th>$\sigma$ ((\phi) units)</th>
<th>$D_n$ (mm)</th>
<th>$D_e$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kailua</td>
<td>Natural</td>
<td></td>
<td>0.20</td>
<td>0.69</td>
<td>0.23</td>
<td>0.18</td>
</tr>
<tr>
<td>Waimanalo</td>
<td>Natural</td>
<td></td>
<td>0.29</td>
<td>0.68</td>
<td>0.34</td>
<td>0.26</td>
</tr>
<tr>
<td>Puuiki</td>
<td>Natural</td>
<td></td>
<td>0.67</td>
<td>0.43</td>
<td>0.80</td>
<td>0.59</td>
</tr>
<tr>
<td>Ehukai</td>
<td>Natural</td>
<td></td>
<td>0.76</td>
<td>0.90</td>
<td>0.90</td>
<td>0.67</td>
</tr>
<tr>
<td>Waimanalo (70*)</td>
<td>Sieved</td>
<td></td>
<td>0.27</td>
<td>&lt;0.41</td>
<td>0.32</td>
<td>0.24</td>
</tr>
<tr>
<td>Waimanalo (40)</td>
<td>Sieved</td>
<td></td>
<td>0.43</td>
<td>&lt;0.26</td>
<td>0.51</td>
<td>0.38</td>
</tr>
<tr>
<td>Ehukai (30)</td>
<td>Sieved</td>
<td></td>
<td>0.60</td>
<td>&lt;0.24</td>
<td>0.71</td>
<td>0.53</td>
</tr>
<tr>
<td>Ehukai (24)</td>
<td>Sieved</td>
<td></td>
<td>0.84</td>
<td>&lt;0.24</td>
<td>0.99</td>
<td>0.74</td>
</tr>
<tr>
<td>Ehukai (18)</td>
<td>Sieved</td>
<td></td>
<td>1.13</td>
<td>&lt;0.19</td>
<td>1.33</td>
<td>0.99</td>
</tr>
</tbody>
</table>

*Retaining sieve number

Table 6-1. Hydraulic Characteristics of Sand Samples.

<table>
<thead>
<tr>
<th>Sand Source</th>
<th>$D_n$ (mm)</th>
<th>$D_e$ (mm)</th>
<th>$w$ (m/s)</th>
<th>$u_{cr}$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kailua</td>
<td>0.23</td>
<td>0.17</td>
<td>0.019</td>
<td>0.16</td>
</tr>
<tr>
<td>Waimanalo</td>
<td>0.34</td>
<td>0.25</td>
<td>0.032</td>
<td>0.20</td>
</tr>
<tr>
<td>Puuiki</td>
<td>0.80</td>
<td>0.58</td>
<td>0.086</td>
<td>0.22</td>
</tr>
<tr>
<td>Ehukai</td>
<td>0.90</td>
<td>0.66</td>
<td>0.101</td>
<td>0.23</td>
</tr>
<tr>
<td>Waimanalo (70*)</td>
<td>0.32</td>
<td>0.23</td>
<td>0.029</td>
<td>0.24</td>
</tr>
<tr>
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<td>0.37</td>
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</tr>
<tr>
<td>Ehukai (30)</td>
<td>0.71</td>
<td>0.52</td>
<td>0.076</td>
<td>0.25</td>
</tr>
<tr>
<td>Ehukai (24)</td>
<td>0.99</td>
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<td>Ehukai (18)</td>
<td>1.33</td>
<td>0.97</td>
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*Retaining sieve number
Table 6-2. Model Error and Scatter for Uncorrected Results at Various Transport Stages.

<table>
<thead>
<tr>
<th>Model</th>
<th># Points</th>
<th>Error</th>
<th>Scatter</th>
<th>Error</th>
<th>Scatter</th>
<th>Error</th>
<th>Scatter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engelund and Hansen</td>
<td>41</td>
<td>0.43</td>
<td>0.35</td>
<td>0.32</td>
<td>0.24</td>
<td>0.16</td>
<td>0.36</td>
</tr>
<tr>
<td>Ackers and White</td>
<td>15</td>
<td>-1.13</td>
<td>1.35</td>
<td>0.20</td>
<td>0.38</td>
<td>-0.21</td>
<td>0.62</td>
</tr>
<tr>
<td>Yang 1973</td>
<td>20</td>
<td>-0.60</td>
<td>1.10</td>
<td>0.09</td>
<td>0.33</td>
<td>-0.10</td>
<td>0.46</td>
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<td>0.35</td>
<td>0.13</td>
<td>0.28</td>
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<td>0.42</td>
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<tr>
<td>Van Rijn</td>
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Table 6-3. Model Error and Scatter for Corrected Results at Various Transport Stages.

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<th>Suspended</th>
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<td>Scatter</td>
<td>Error</td>
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<td>Van Rijn</td>
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Figure 1-1. Photographs of natural calcareous sand samples. (a) Kailua Beach sand: $D_{50} = 0.20$ mm. (b) Waimanalo Beach sand: $D_{50} = 0.29$ mm. (c) Puuiki Beach sand: $D_{50} = 0.67$ mm. (d) Ehukai Beach sand: $D_{50} = 0.76$ mm.
Figure 2-1. Location map of sand sampling.
Figure 2-2. Calcareous sand density as a function of median nominal diameter. ○: natural sand; ●: sorted sand.
Figure 2-3. Particle shape classification by $D_l/D_i$ and $D_s/D_i$. 
Figure 2-4. Relationships between characteristic grain sizes. (a) Intermediate dimension and sieve size. ——, linear size relationships. (b) Nominal diameter and intermediate dimension. ——, linear trendline.
Figure 2-5. Distributions of shape factor. (a) Shape factor versus nominal diameter. ---, linear trendline. (b) Probability density. ---, normal distribution fitted to data.
Figure 3-1. Fall velocity of calcareous sand as a function of nominal diameter and shape factor. Present data: o, $0.15 < F_s < 0.25$; □, $0.25 < F_s < 0.35$; ⊙, $0.45 < F_s < 0.55$; △, $0.65 < F_s < 0.75$. ---, regressed curves. ——, Baba and Komar (1981).
Figure 3-2. Relationship between nominal diameter and equivalent diameter. Present data: o, $0.15 < F_S < 0.25$; □, $0.25 < F_S < 0.35$; ○, $0.45 < F_S < 0.55$; △, $0.65 < F_S < 0.75$. ——, regressed curves.
Figure 3-3. Drag coefficient of calcareous sand as a function of Reynolds number and shape factor. Present data: ○, 0.15 < $F_s$ < 0.25; □, 0.25 < $F_s$ < 0.35; ◦, 0.45 < $F_s$ < 0.55; △, 0.65 < $F_s$ < 0.75. ——, regressed curves. ——, Baba and Komar (1981).
Figure 3-4. Ratio of measured fall velocity to fall velocity of a sphere as a function of shape factor. ○, stable regime; △, transitional regime; □, unstable regime. ——, regressed curves. ———, Baba and Komar (1981).
Figure 3-5. Ratio of measured drag coefficient to drag coefficient of a sphere as a function of shape factor. o, stable regime; △, transitional regime; □, unstable regime. ——, regressed curves.
Figure 4-1. Schematic of long settling tube experiment.
Figure 4-2. Cumulative grains size distribution for Ehukai Beach in terms of sieve size.
Figure 4-3. Cumulative grains size distribution for Ehukai Beach in terms of nominal diameter. (a) Sieve analysis. (b) Settling analysis. ——, median curve.
Figure 4-4. Cumulative grain size distribution for Ehukai Beach in terms of equivalent diameter. (a) Sieve analysis. (b) Settling analysis. —— median curve.
Figure 4-5. Median nominal diameter versus median sieve size. (a) Sieve analysis. (b) Settling analysis. ——, linear trendline.
Figure 4-6. Median equivalent diameter versus median sieve size. (a) Sieve analysis. (b) Settling analysis. ———, linear trendline.
Figure 4-7. 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.
Figure 5-1. Schematic of flume experiment for initiation of motion tests.
Figure 5-2. Shear stress versus bed-load transport rate of calcareous sand. (a) Natural sand samples. ×, scuffed bed; +, packed bed for $D_n = 0.90$ mm. (b) Sorted sand samples. —, regressed curves; *, point of maximum curvature.
Figure 6-1. Schematic of flume experiment for bed-form and suspended transport tests.
Figure 6-2. Calculated versus measured sediment transport rates using Engelund-Hansen (1967) model. □, ■, plane-bed transport stage; ○, ●, bed-form transport stage; Δ, ▲, suspended transport stage (□, ○, Δ: uncorrected; ■, ●, ▲: corrected). ——, perfect agreement; ———, factor of 2 difference; ·······, factor of 10 difference.
Figure 6-3. Calculated versus measured sediment transport rates using Ackers and White (1973) model. □, ■, plane-bed transport stage; ○, ●, bed-form transport stage; Δ, △, suspended transport stage (□, ○, Δ: uncorrected; ■, ●, △: corrected). ——, perfect agreement; ———, factor of 2 difference; ·····, factor of 10 difference.
Figure 6-4. Calculated versus measured sediment transport rates using Yang (1973) model. □, ■, plane-bed transport stage; ○, ●, bed-form transport stage; △, ▲, suspended transport stage (□, ○, △: uncorrected; ■, ●, ▲: corrected). ——, perfect agreement; ——, factor of 2 difference; - - - - , factor of 10 difference.
Figure 6-5. Calculated versus measured sediment transport rates using Yang (1979) model. □, ■, plane-bed transport stage; ○, ●, bed-form transport stage; △, ▲, suspended transport stage (□, ○, △: uncorrected; ■, ●, ▲: corrected). ——, perfect agreement; ——, factor of 2 difference; ····, factor of 10 difference.
Figure 6-6. Calculated versus measured sediment transport rates using van Rijn (1984c) model. □, ■, plane-bed transport stage; ○, ●, bed-form transport stage; Δ, ▲, suspended transport stage (□, ○, Δ: uncorrected; ■, ●, ▲: corrected). ———, perfect agreement; — — — , factor of 2 difference; ————, factor of 10 difference.
## APPENDIX A. PLANE-BED TRANSPORT DATA

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<th>Sand</th>
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<th>Depth (m)</th>
<th>Slope</th>
<th>Temperature (deg C)</th>
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<th>$D_{90}$ (mm)</th>
<th>$\tau_c$ (m/s)</th>
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# APPENDIX B. BED-LOAD AND SUSPENDED-LOAD TRANSPORT DATA

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LITERATURE CITED


