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TECHNICAL COMMUNICATIONS

The Relationship between Beach Grain Size and Intertidal Beach Face Slope

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ABSTRACT

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The relationship between beach grain size and beach face slope is investigated with data from 181 sand beaches around the world. The analysis confirms previously identified trends of increasing beach face slope with increasing sediment grain size and decreasing beach exposure to wave energy. The present work extends previous studies by using a repeatable method to classify the beach exposure to wave energy and derives equations for the beach face slope based on sediment grain size and beach exposure. The derived equations match the measured beach face slope with r^2 correlation coefficients of 0.87, 0.88, and 0.87 for protected, moderately protected, and exposed beaches, respectively. The derived equations allow for a rapid estimate of the beach face slope based on the sediment grain size for a range of beach exposures.

ADDITIONAL INDEX WORDS: *Beaches, beach slope, morphodynamics*.

INTRODUCTION

The relationships among beach sediment grain size, beach face slope, and beach exposure have been studied by numerous researchers over the years. The beach face slope generally increases with sediment grain size and protection from wave energy. This relationship was first described with field data by the Beach Erosion Board (1933) and Bascom (1951). The beach face slope was measured at the midtide elevation, referring to a level approximately halfway between the previous high tide and the succeeding low tide. Curved lines for the average beach face slope for exposed, moderately protected, and protected beaches were established and modified as more data became available (Bascom, 1952; Wiegel, 1964).

Although there have been numerous studies on the grain size and beach face slope, the intuitive format of the beach face slope versus grain size figure in Wiegel (1964) has resonated with researchers and practitioners alike. This can be seen by the numerous citations of Wiegel's figure. Unfortunately, no equations are provided that describe the curved lines in the Wiegel (1964) figure, only beaches along the United States coastline were used, and no criteria for classifying the beach exposure are given. Bascom (1952) noted that the beach exposure classification was chosen arbitrarily based on the relative conditions that existed during sampling.

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The present study expands on the work in the Wiegel (1964) figure by including more data from sand beaches around the world, using repeatable and quantifiable criteria for beach exposure classification, and providing equations for curves to estimate the beach face slope based on the sediment grain size and the beach exposure.

Other researchers have derived equations for the beach face slope (King, 1972; Leadon, 2015; Reis and Gamma, 2010; Sunamura, 1975, 1984), but these equations are complicated and require thorough knowledge of the wave characteristics at a site (*e.g.*, offshore wave height, breaking wave height, and wave period) or the sediment characteristics at a site (*e.g.*, grain size, average grain sphericity, sediment sorting, and porosity), or they do not include the beach exposure in the analysis.

King (1972) conducted a multivariable correlation analysis on data from 27 beaches in widely varying conditions. The variables investigated were beach face slope, grain size, sand sorting, tidal range, and wave energy. This analysis found that there was significant correlation among beach face slope, sediment size, and wave energy. No significant correlation could be found between beach face slope and sorting or tidal range. An equation was derived for the beach face slope based on the sediment grain size and wave energy. The wave energy used in the equation derivation was adjusted according to the fetch distance and beach orientation relative to the dominant wave directions, making the application of this equation a complicated endeavor.

The findings of the correlation results from King (1972), which emphasize the importance of sediment grain size and beach exposure to beach face slope, match the results of several other researchers. Beach slope was found to increase with increased sediment grain size (Bascom, 1951, 1952; Beach Erosion Board, 1933; Leadon, 2015; McLean and Kirk, 1969; Shepard, 1963; Sunamura, 1975, 1984; and Wiegel, 1964, among others), and beach slope decreased with beach exposure to waves (Bascom, 1952; Inman, Gayman, and Cox, 1963; Sunamura, 1975, 1984; Wiegel, 1964).

The sediment grain size can control the beach face slope by its effect on swash infiltration (Grant, 1948; Quick, 1991) or by its effect on suspended sediment transport (Dean, 1973). The slope of the beach face is governed by the asymmetry in intensity of the wave-swash uprush and the return backwash (Komar, 1988). On beaches consisting of coarser sediment ($d_{50} > 1$ mm, where d_{50} is the median grain size), return backwash is weaker than the swash run-up because of water percolating into the beach and loss of energy due to friction. The dynamic equilibrium of the beach face slope is attained when the onshore force because of the swash uprush is balanced by the offshore gravity component (Masselink and Puleo, 2006). The percolation is governed by sediment grain size, sorting, and skewness (McLean and Kirk, 1969). This conflicts with the observations of King (1972), who found no correlation between beach slope and sediment sorting. The reason for the difference cannot be definitively known, because the range of grain sizes analyzed in King (1972) was not provided, but the analyzed samples may have been finer than the noted coarse sediment criteria. For beaches composed of finer sediment ($d_{50} < 1$ mm), the effect of the grain size on the suspended sediment transport controls the beach face slope. The beach face slope will increase with increased resistance of the sediment to mobilization and increased fall velocity, which are functions of grain size and density (Dean, 1973; Dubois, 1972). The present study focuses on sand beaches with a median sediment grain size of less than 1 mm to avoid the potential influence of sediment sorting and skewness on the relationships among grain size, beach exposure, and beach face slope (McLean and Kirk, 1969).

METHODS

Combining data from field efforts collected at various locations around the world requires a description of the techniques used to collect the data and the methods used in the present analysis. In this section, the original guidance for sampling the beach grain size for comparison to the beach face slope is provided, followed by classification of beach exposure, details of the data used, and a description of the derivation of equations relating grain size, beach face slope, and beach exposure.

Grain Size and Beach Face Slope

Bascom (1951) detailed a standardized sampling and measurement technique to compare grain size and face slope of widely separated beaches. The slope measurement and sediment sample were to be taken at the midtide level, or the level approximately halfway from the previous high tide and the succeeding low tide. He referred to this location as the "reference point" or "reference zone" and noted that this zone may be fairly wide. Slopes should be measured perpendicular to the water, and sediment samples should have the top 1 cm scraped away and be taken from the top 10 cm. In addition, Bascom (1951) noted that the mean or median sediment size is acceptable for well-sorted sands for comparison with the beach face slope. Most successive studies adopted this sampling and measurement technique; also note the similarities to the procedure used by the Beach Erosion Board (1933), which took sediment samples from New Jersey beaches between the high and the low water levels to a depth of 2 inches. Given the similarity in the sampling methods, Wiegel (1964) found it appropriate to combine these data sets.

Classification of Beach Exposure

Beach exposure is a critical characteristic that is required to understand the relationship between beach slope and sediment grain size. A technique detailed in the *Shoreline Management Guidelines* (Mangor *et al.*, 2017) was used to classify beach exposure. The method uses the offshore significant wave height exceeded 12 h/y, or $H_{s,\mathrm{12h/y}}$, to classify the beach exposure as follows:

Protected: $H_{s,\mathrm{12h/y}} < 1$ m
Moderately Exposed: 1 m $< H_{s,\mathrm{12h/y}} <$ 3 m
Exposed: $H_{s,\mathrm{12h/y}} > 3$ m

These criteria are appropriate for open coastlines facing the dominant wave direction and not protected by coastal structures or natural features like capes or headlands. The guidelines also note that morphological features should be accounted for in the classification. In the case where a beach is protected by a feature such as a breakwater, spit, cove, or barrier island, the offshore exceedance wave height is not appropriate for beach exposure classification. The beach exposure should be classified based on the amount of protection provided by the feature. Beaches adjacent to jetties or protected by barrier islands, offshore breakwaters, or spits are generally categorized as protected. Beaches partially protected by coastal cliffs or in coves are generally categorized as moderately exposed. The exposure criteria based on morphological features are detailed more extensively in the *Shoreline Management Guidelines* (Mangor *et al.*, 2017).

A global wave hindcast model was used to determine the offshore significant wave height in the study. The geospatial location (latitude and longitude) was assigned for each sampling location. In some cases the latitude and longitude were recorded with the sediment sample and survey location, but in other cases the position had to be estimated. When only the beach name was provided, the geospatial location was assigned as the center of the beach.

The Institut Français de Recherche Pour l'Exploitation de la Mer (IFREMER) global wave hindcasts, using the WAVEWATCH III wave model from the Integrated Ocean Waves for Geophysical and Other Applications (IOWAGA) project (Rascle and Ardhuin, 2013) with hindcast data from 1990 to 2012, were used to determine wave conditions. The nearest model save point to the sample location was determined, and the significant wave height exceeded 12 h/y was calculated. The wave hindcast save point was then verified to be in the deepwater wave regime. If the save point was not in the

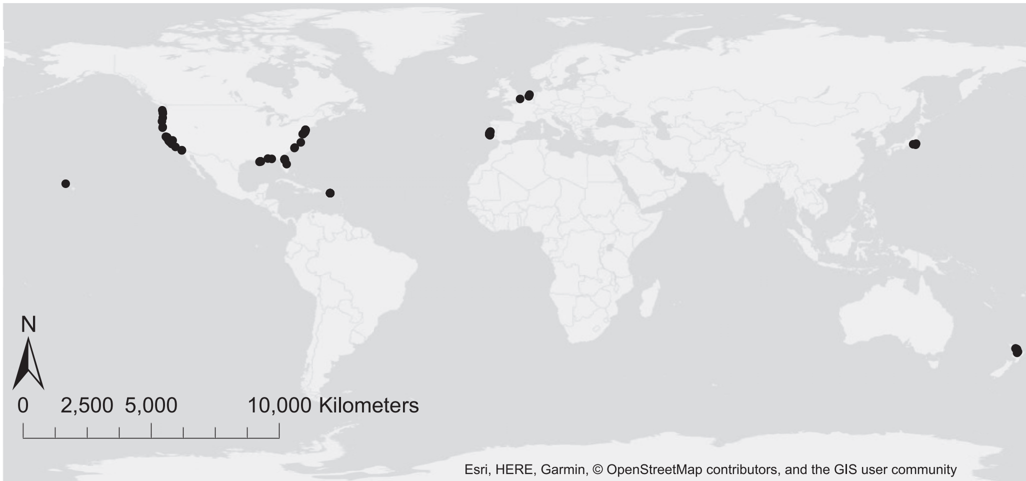

Figure 1. Location of the sand beaches included in the analysis.

deepwater wave regime for the significant wave exceeded 12 h/y, the wave was transformed offshore using the conservation of energy flux, assuming shore parallel contours, to meet the deepwater criteria.

Data Used

Sediment grain size and beach face slope data were collected from beaches around the world. Figure 1 shows the locations of the 181 beaches included in the analysis. Table 1 shows the range of sediment grain sizes and beach face slopes for the data sources used in the analysis. A summary of each data source follows.

United States: Atlantic, Gulf of Mexico, and Pacific Coasts—Wiegel (1964)

To highlight the relationship between sediment grain size and intertidal beach slope, Wiegel (1964) combined field measurements from beaches predominately on the Pacific Coast of the United States but also included some from the Atlantic Coast and the Gulf of Mexico. Data were combined from several sources, including Bascom (1951, 1952) and the Beach Erosion Board (1933). Data collected for the Beach Erosion Board (1933) predates the sampling instructions derived by Bascom (1951), but similar sampling methods were used for the 30 samples taken from New Jersey beaches. The Department of Conservation and Development, State of North Carolina, provided seven samples from beaches in North Carolina to the Beach Erosion Board for inclusion in its report, but the beach profiles were not taken on the same day the samples were taken or in the same position. Even with these small discrepancies, the data from the Beach Erosion Board (1933) were included in the Wiegel (1964) analysis. All data indicated that more exposed beaches had gentler slopes, but the beach exposure was not quantitatively expressed. For the present analysis, locations of each of the beach samples were identified and the wave hindcasts were used to estimate the beach exposure.

Japan—Sunamura (1975)

Sunamura (1975) compared laboratory and field data to improve understanding of the relationships among beach slope, sediment grain size, and wave characteristics using the measured field data from Kujukuri, Katsuura, and Sagami Bay, each along the Pacific Coast of Japan. Sampling techniques for the field data were not discussed, but the work of Bascom (1951) was directly cited and discussed, indicating that the field sampling techniques described by Bascom (1951) would have been familiar to the author and likely would have been used. In addition, the sediment grain size was not identified as the mean or median. Because Sunamura (1975) cites Bascom (1951) in the description of the sand grain size variable, the grain size is presumed to be the median.

The beach of Kujukuri is several kilometers long with a breakwater and harbor facility. The sediment grain size is a constant 0.2 mm, but the beach slope ranges from 1:27 to 1:91

Table 1. *Data sources and range of parameters used.*

Data Source	Location	Grain Size (mm)	Beach Face Slope (vertical:horizontal)
Wiegel (1964)	United States	0.15–0.85	1:4–1:90
Sunamura (1975)	Japan	0.2–1.0	1:6–1:91
Hijma and Lodder (2002)	New Zealand	0.15–0.35	1:7–1:140
Dornbusch (2005)	United Kingdom	0.15–0.2	1:25–1:30
Rijkwaterstaat	The Netherlands	0.2–0.25	1:30–1:36
Leadon (2015)	United States	0.1–0.55	1:9–1:40
Silveira (2017)	Portugal	0.25–0.75	1:5–1:50
NAVFAC (2018)	Puerto Rico	0.15–1.0	1:5–1:25

(Sunamura, 1975). The range of beach slope is likely because of the differing levels of shoreline protection along the beach, with steeper slopes near the breakwater and shallower slopes along the exposed coastline. The breaking wave heights at the sample locations were provided by Sunamura (1975). Through simple wave transformation to the offshore, all samples at the Kujukuri beach were categorized as moderately protected.

The beach at Katsuura is in a small protected cove that currently has attached and detached breakwaters, as well as a small harbor facility. The amount of coastal protection present during the Sunamura (1975) study could not be determined, but all measurements at this beach are considered protected because of the beach being sheltered in a small cove and the high likelihood of coastal structures at the time of the measurements. Sagami Bay is a large bay that is estimated to be moderately protected by the Boso Peninsula.

New Zealand—Hijma and Lodder (2002)

Hijma and Lodder (2002) investigated the relationship between beach slope and grain size at 19 beaches on the Coromandel Peninsula in New Zealand. Sediment samples to measure the mean sediment grain size were taken from the top 3 to 5 cm at the midtide level to match the sampling technique described by Bascom (1951). The beach face slope was measured using the method described by Emery (1961), with two vertical rods held 5 m apart. The beach face slope was measured during low tide to measure the slope at the midtide level.

United Kingdom—Dornbusch (2005)

Dornbusch (2005) studied the sediment characteristics of predominately pebble beaches in the United Kingdom to assess regional variations in the sediment with depth and the relative size fractions of beach material. Two of the sites investigated were near the beaches of the Princess Golf Club in Sandwich Bay. Both of these sites consisted of 93% sand and had a median grain size of 0.18 to 0.19 mm. The beach slope was measured and sediment sample was taken approximately halfway between mean high tide and mean low tide levels. At sediment sampling locations, the top 10 cm was removed, and the sediment samples were taken with a coring device to a depth of greater than 20 cm, which is deeper than any other sediment sample used in the present study. The remaining sites studied by Dornbusch (2005) were not included in the present study because of the high gravel content.

The Netherlands

Schagen, Katwijk, and Noordwijk beaches were chosen from the Netherlands for analysis. Grain size and beach slope data for each site were from historical survey data collected by the Rijkwaterstaat and accessed with the MorphAn software (Lodder and van Geer, 2012). Grain size information is from sediment samples from the dune toe, and the beach face slope was measured as the average slope in the intertidal region. The beach at Schagen has evenly spaced, shore perpendicular groins to protect the shoreline. The beach at Katwijk is popular and nourished regularly. To avoid the influence of nourishments, the beach face slope measurement was taken from the 1984 beach survey. The beach at Noordwijk is also popular and nourished regularly. The beach face slope measurement was taken from the 2009 beach survey, allowing the beach 1 year to reach a dynamic equilibrated state after nourishment.

United States: Atlantic and Gulf of Mexico Coasts—Leadon (2015)

Leadon (2015) used prestorm profiles at three study sites in the United States to investigate the use of beach slope and sediment grain size trends for numerical model input parameters. Poststorm profiles were used for numerical model calibration. The study sites were St. Johns County, Florida; Panama City Beach, Florida; and the barrier islands within Barataria Basin, Louisiana. St. Johns County is on the Atlantic Coast of Florida, and Panama City Beach and the Barataria Basin are in the Gulf of Mexico. The beach face slope was measured as average slope from 0 to 1.5, 0 to 2.4, and 0 to 3 m using the North American Vertical Datum of 1988, which is relatively close to the mean sea level (MSL). The beach face slope was compared with the mean sediment grain size, and some data points from California and Oregon (Wiegel, 1964) were included in the analysis of Leadon (2015). Only the beach face slope and grain size information from the three study sites are included in the present study.

Portugal—Silveira (2017)

Silveira (2017) conducted beach profile measurements and associated sediment samples for 14 beaches along the central west coast of Portugal every 3 months from March 2011 to June 2013 to study the seasonal trends. The beach face slope was measured between the MSL and the mean high water level (1.05 m MSL), and the mean sediment diameter was measured. The beach face slope and mean sediment grain size at each survey location were temporally averaged for the present analysis. Additional details of the beach profiles are given by Diogo *et al*. (2013) and Silveira *et al*. (2013). Silveira (2017) detailed the survey and sample locations, making the identification of the closest global hindcast save point to each site more accurate for the beach exposure analysis.

Puerto Rico—NAVFAC (2018)

Five dynamic beaches and eight stable beaches were studied on the island of Vieques in Puerto Rico (NAVFAC, 2018). The stable beaches were mostly in protected coves. The beaches were surveyed four times from April 2015 to February 2016, and sediment samples were taken in the intertidal zone. The beach face slope was measured from –1 to 1 MSL. The median grain size and beach slope from each beach were averaged over time for the analysis. Two of the beaches sheltered by an offshore reef had very large sediment grain sizes (2–4 mm) by the criteria of Komar (1998). These two beaches were not included in the present study, because the median grain size exceeded the grain size criterion ($d_{50} < 1$ mm).

Derivation of Predictive Equations

Beach grain size, slope, and exposure data were compiled and analyzed using a range of equation formats (*e.g.*, logarithmic and power). Coefficients for the equations were derived using a nonlinear least-squares solving technique with a fixed form. Only the sediment size and exposure variables were considered in the equation derivation for the beach face slope. These variables were chosen because previous studies have noted the importance of these variables on the beach face slope (Bascom,

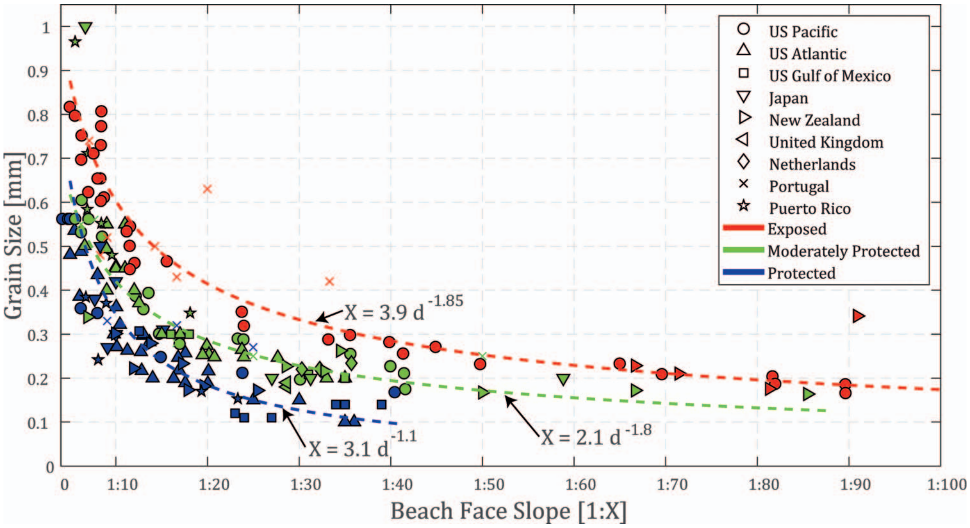

Figure 2. Relationship between sediment grain size and beach face slope. Predictive equations for the beach face slope are shown with dashed lines.

1952; Inman, Gayman, and Cox, 1963; King, 1972; Masselink and Puleo, 2006; Sunamura, 1975, 1984; Wiegel, 1964). A power curve shape best fit the data and matched the shape identified by Wiegel (1964).

RESULTS

Grain size and beach face slope data from 181 locations were analyzed, consisting of 64 protected beaches, 71 moderately protected beaches, and 46 exposed beaches. The parametric equation for the inverse beach face slope can be represented as:

$$X = A\ d^{n} \tag{1}$$

where, X is the inverse beach face slope, d is sediment grain size in millimeters, A is the derived coefficient, and n is the derived exponent. This form of beach slope was chosen to be similar to the intuitive layout of the Wiegel (1964) figure, in which the beach slope is given in the form 1:X (vertical:horizontal). The inverse beach face slope can be easily converted to an angle using the equation $\alpha = \tan^{-1} 1/X$. The equations for the inverse beach face slope for the levels of beach exposure are as follows:

$$\text{Protected}: X = 3.1d^{-1.1} \tag{2}$$

$$\text{Moderately Protected}: X = 2.1d^{-1.8} \tag{3}$$

$$\text{Exposed}: X = 3.9d^{-1.85} \tag{4}$$

with r^2 correlation coefficients for the protected, moderately protected, and exposed beaches of 0.87, 0.88, and 0.87, respectively. More than 95% of the predicted beach face slopes had a percent error of less than 50%, and the mean percent error for all beach face slopes predicted was 21%. The relationship between grain size and beach face slope can be seen in Figure 2, with Equations (2) to (4) shown with dashed lines. The measured versus the predicted beach slope for each of the beach exposure classifications is shown in Figure 3. From Equations (2) to (4), the magnitude of the exponent increases with increasing exposure. This is expected, because exposed beaches generally have a gentler slope than more protected beaches of the same grain size, as observed in Figure 2.

DISCUSSION

The beach profile is a dynamic system that is never in a truly equilibrated state. Thus, some amount of scatter is expected from the measured beach slopes compared with the derived equations. There would be some variation in the beach face slope and grain size even if the same beach was resampled during different seasons because of the seasonal variations in wave conditions (Prodger *et al.*, 2016, 2017). The beach face becomes flatter when eroding and steeper when building up (Wiegel, 1964). The present study attempts to minimize the effects of the variations by fitting an adequately large and diverse data set and averaging whenever more than one survey is available. Differing measurement techniques in the data collection will increase the amount of scatter between predicted and measured beach slopes, as would the presence of beach cusps (Sunamura, 1984). Wiegel (1964) attributed some scatter in his figure to sorting of the beach sediment, similar to the observations of McLean and Kirk (1969). The present study attempts to minimize the effects of sediment sorting by only considering beaches composed of finer sediment ($d_{50} < 1$ mm) where the beach face slope is controlled by the suspended sediment transport (Dean, 1973; Dubois, 1972), but sediment sorting may also contribute to some scatter in Figure 3, particularly for the larger grain sizes included in the present work.

The simple derived equations appear to capture the governing processes of the dynamic beach face slope, as seen by the high correlation coefficients. Intuitively, one might expect more complicated equations to increase accuracy, but simple morphological models often perform better for long-term predictions (Davidson *et al.*, 2017) and are easier to apply with limited data.

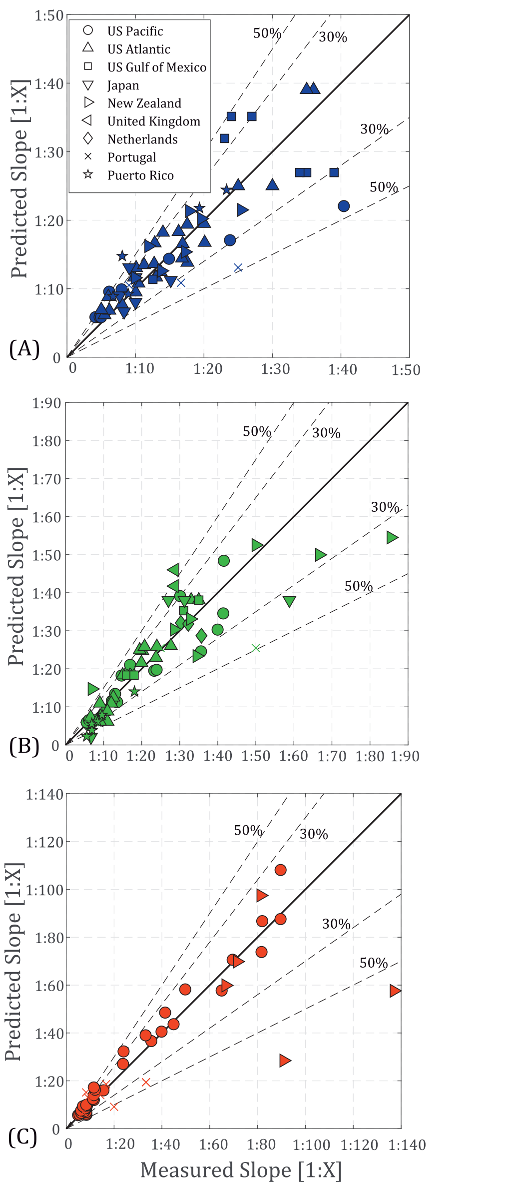

Figure 3. Comparison of the measured and the predicted beach face slope for (A) protected, (B) moderately protected, and (C) exposed beaches. The 30% and 50% error thresholds are shown with dashed lines.

CONCLUSIONS

The present work builds upon previous studies on the relationship between sediment grain size and beach face slope, particularly the work in Wiegel (1964), by analyzing a global data set, using a defined technique to classify beach exposure, and deriving equations for beach face slope. A total of 181 sand beaches from around the world with greatly varying conditions have been analyzed to quantify the relationships among sediment grain size, exposure to wave energy, and beach face slope. A repeatable method to classify beach exposure was performed using global wave hindcasts and the technique described by Mangor *et al*. (2017).

Simple equations were derived for the beach face slope based on beach exposure and sediment grain size. The format of the equations was intentionally chosen for accuracy and ease of use; as the famous quote commonly attributed to Albert Einstein quote says: "Everything should be made as simple as possible, but not simpler." Although the equations have a simple format, the high correlation coefficients indicate that the major governing processes are captured. These simple equations can be used by researchers, practitioners, or even the public to better understand the expected beach face slope for different beach exposures.

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LITERATURE CITED

Bascom, W.N., 1951. The relationship between sand size and beach-face slope. *Eos, Transactions American Geophysical Union,* 32(6), 866–874.

Bascom, W.N., 1952. Beach characteristics. *In:* O'Brien, M.P.; Johnson, J.W., and Wiegel, R.L. (eds.), *Manual of Amphibious Oceanography,* Volume 1. Office of Naval Research Contract No. *N7onr29535*. Berkeley, California: University of California, Berkeley, Section I:I, pp. 58–156.

Beach Erosion Board, 1933. *Interim Report*. Washington, D.C.: Office of the Chief of Engineers, U.S. Army, 96p.

Davidson, M.A.; Turner, I.L.; Splinter, K.D., and Harley, M.D., 2017. Annual prediction of shoreline erosion and subsequent recovery. *Coastal Engineering,* 130, 14–25.

Dean, R.G., 1973. Heuristic models of sand transport in the surf zone. *Proceedings of the First Australian Conference on Coastal Engineering* (Sydney, Australia, AIE), pp. 208–214.

Diogo, Z.S.; Silveira, T.M.; Sousa, H.; Carapuço, A.M.; Silva, A.M.; Lira, C.; Taborda, R., and Andrade, C., 2013. *Estudo de caso da Costa da Caparica—Caracterização da variabilidade morfodinâmica sazonal e pós-temporal das praias da Costa da Caparica*. Entregável *2.2.c*. Lisbon, Portugal: Agência Portuguesa do Ambiente, 119p (in Portuguese).

Dornbusch, U., 2005. *BAR Phase I, February 2003–January 2005, Science Report: Beach material properties*. Rotherham, United Kingdom: Environment Agency and University of Sussex, 25p.

Dubois, R.N., 1972. Inverse relation between foreshore slope and mean grain size as a function of the heavy mineral content. *Geological Society of America Bulletin,* 83(3), 871–876.

Emery, K.O., 1961. A simple method of measuring beach profiles. *Limnology and Oceanography,* 6, 90–93.

Grant, U.S., 1948. Influence of the water table on beach aggradation and degradation. *Journal of Marine Research,* 7, 655–660.

Hijma, M. and Lodder, Q., 2002. *On the Correlation between Beach Slope and Sediment Parameters from the Coromandel Peninsula, New Zealand*. Report for the Department of Earth Sciences at University Utrecht, The Netherlands, and University of Waikato, New Zealand, 27p.

Inman, D.L.; Gayman, W.R., and Cox, D.C., 1963. Littoral sedimentary processes on Jauai, a sub-tropical high island. *Pacific Science,* 17, 106–130.

King, C.A., 1972. *Beaches and Coasts*. New York: St. Martin, 570p.

Komar, P.D., 1998. *Beach Processes and Sedimentation,* 2nd edition. Upper Saddle River, New Jersey: Prentice Hall, 544p.

Leadon, M., 2015. Beach slope and sediment-grain-size trends as a basis for input parameters for the SBEACH erosion model. *Journal of Coastal Research,* 31(6), 1375–1388.

Lodder, Q.J. and van Geer, P.F.C., 2012. MorphAn: A new software tool to assess sandy coasts. *In:* Kranenburg, W.; Horstman, E., and Wijnberg, K.M. (eds.), *Jubilee Conference Proceedings, NCK—Days 2012* (Twente, The Netherlands), pp. 161–164.

Mangor, K.; Drnen, N.K.; Kærgaard, K.H., and Kristensen, S.E., 2017. *Shoreline Management Guidelines*. Hrsholm, Denmark: DHI, 462p.

Masselink, G. and Puleo, J.A., 2006. Swash-zone morphodynamics. *Continental Shelf Research,* 26(5), 661–680.

McLean, R.F. and Kirk, R.M., 1969. Relationships between grain size, size-sorting, and foreshore slope on mixed sand-shingle beaches. *New Zealand Journal of Geology and Geophysics,* 12(1), 138–155.

NAVFAC (Naval Facilities Engineering Command), 2018. *Beach Dynamics Investigation Report: Atlantic Fleet Weapons Training Area—Vieques Former Naval Ammunition Support Detachment and Former Vieques Training Range, Vieques, Puerto Rico*. Norfolk, Virginia: U.S. Naval Facilities Engineering Command, 525p.

Prodger, S.; Russell, P., and Davidson, M., 2017. Grain-size distributions on high-energy sandy beaches and their relation to wave dissipation. *Sedimentology,* 64(5), 1289–1302.

Prodger, S.; Russell, P.; Davidson, M.; Miles, J., and Scott, T., 2016. Understanding and predicting the temporal variability of sediment grain size characteristics on high-energy beaches. *Marine Geology,* 376, 109–117.

Quick, M.C., 1991. Onshore–offshore sediment transport on beaches. *Coastal Engineering,* 15(4), 313–332.

Rascle, N. and Ardhuin, F., 2013. A global wave parameter database for geophysical applications. Part 2: Model validation with improved source term parameterization. *Ocean Modelling,* 70, 174–188.

Reis, A.H. and Gama, C., 2010. Sand size versus beachface slope—An explanation based on the constructal law. *Geomorphology,* 114(3), 276–283.

Shepard, F.P., 1963. *Submarine Geology*. New York: Harper & Row, 557p.

Silveira, T.M., 2017. Geomorphological Framework Control on Beach Dynamics. Lisbon, Portugal: Universidad de Lisboa, Ph.D. dissertation, 368p.

Silveira, T.M.; Diogo, Z.S.; Taborda, R.; Andrade, C.; Sousa, H.; Carapuço, A.M., and Silva, A.M., 2013. Estudo do litoral na área de intervenção da APA, I.P./ARH do Tejo—Caracterização da variabilidade morfodinâmica sazonal das praias-piloto representativas do litoral em estudo. Entregável *1.2.3.e*. Lisbon, Portugal: Agência Portuguesa do Ambiente, 146p (in Portuguese).

Sunamura, T., 1975. “Static” relationship among beach slope, sand size, and wave properties. *Geographical Review of Japan,* 48(7), 485–489.

Sunamura, T., 1984. Quantitative predictions of beach-face slopes. *Geological Society of America Bulletin,* 95(2), 242–245.

Wiegel, R.L., 1964. *Oceanographical Engineering*. Englewood Cliffs, New Jersey: Prentice Hall, 532p.