UNDERSTANDING COASTAL DYNAMICS IN HETEROGENEOUS SEDIMENTARY ENVIRONMENTS

K. Todd Holland,[1] Timothy R. Keen,[2] James M. Kaihatu,[3] and Joseph Calantoni[4]

Abstract: Although recent advances in data collection and numerical modeling have greatly extended our skill in predicting coastal hydrodynamic and morphodynamic processes, the influence of mixed sediments or temporally varying sediment characteristics on coastal dynamics has largely been ignored. We hypothesize that not only is the influence of sediment heterogeneity significant, but that it is also important, in that heterogeneous sedimentary environments comprise approximately 80% of the world's non-rocky coastal regions. A literature review of relevant findings strongly suggests that coastal processes within heterogeneous sedimentary environments, defined as areas with sediments comprised of mixed grain sizes (poorly sorted), spatial regions with diverse sediment properties (patchy), and/or areas where sediment characteristics change rapidly over time (dynamic), can greatly differ from those in more uniform (either sand or mud) environments. We discuss a new five-year research program designed to investigate the influence of sediment heterogeneity on coastal dynamics with an ultimate goal of extending our predictive capability to a more global extent.

INTRODUCTION

Even though field measurements suggest that coastal sediments typically exhibit a wide range of characteristics such as variation in grain size, research findings and numerical models often generalize this diversity in terms of simple descriptive statistics, such as a median value. This reduction in complexity is helpful in categorizing sediments and is often used in the initialization of numerical models describing coastal processes. The problem with this approach, however, is that it assumes the actual dynamics are either similar to those within an environment comprised of uniform sediments or equivalent to the linear summation of results determined for individual grains within an overall distribution. There is little evidence to substantiate this approach, and given the natural complexity of grain mixtures and potential for nonlinearity between forcing and response, we believe that these generalizations will fail in application within environments that display significant heterogeneity in sediment properties.

We define heterogeneous sedimentary environments as coastal areas with substantial variation in sediment properties. An excellent example is shown in Figure 1. The variation magnitude is exhibited with respect to the size of the heterogeneous region relative to the domain over which oceanographic processes (such as waves and currents) or geophysical processes (such as sediment

---

1) Naval Research Laboratory, Marine Geosciences Division, Code 7440.3, Stennis Space Center, MS. 39529, USA. tholland@nrlssc.navy.mil.
2) Naval Research Laboratory, Oceanography Division, Code 7320, Stennis Space Center, MS. 39529, USA. keen@nrlssc.navy.mil
3) Naval Research Laboratory, Oceanography Division, Code 7320, Stennis Space Center, MS. 39529, USA. kaihatu@nrlssc.navy.mil
4) Naval Research Laboratory, Marine Geosciences Division, Code 7440.3, Stennis Space Center, MS. 39529, USA. joec@nrlssc.navy.mil.

transport) would be expected to be mostly homogeneous. There are many similar descriptions that would fall under this definition of heterogeneity, for example, surf zone environments comprised of mixed grain sizes (poorly sorted), large spatial regions with diverse sediment properties (patchy), and/or isolated areas where sediment characteristics change rapidly over time (dynamic). We make no distinction between horizontal, vertical, or temporal gradients nor between mixtures that are poorly sorted or evenly graded. In each of these cases the sediments are clearly non-uniform. In addition to grain size, sources of heterogeneity could also include density, cohesion, or other sedimentological parameters. However, for the purposes of limiting the scope of our research, we do not include coastal environments that are only mildly heterogeneous such as thick veneers of uniform sand within a muddy delta or dynamics that are impacted by heterogeneity at only very small scales (e.g. boundary layer evolution, biogeochemical processes, etc.). Within this description, heterogeneous environments are thought to comprise approximately 80% of the world's non-rocky coastal regions (Hayden and Dolan, 1976). In summary, we have little assurance that advanced models describing hydrodynamic and morphodynamic coastal processes under homogeneous sedimentary conditions are applicable in many of the more heterogeneous regions of the world.

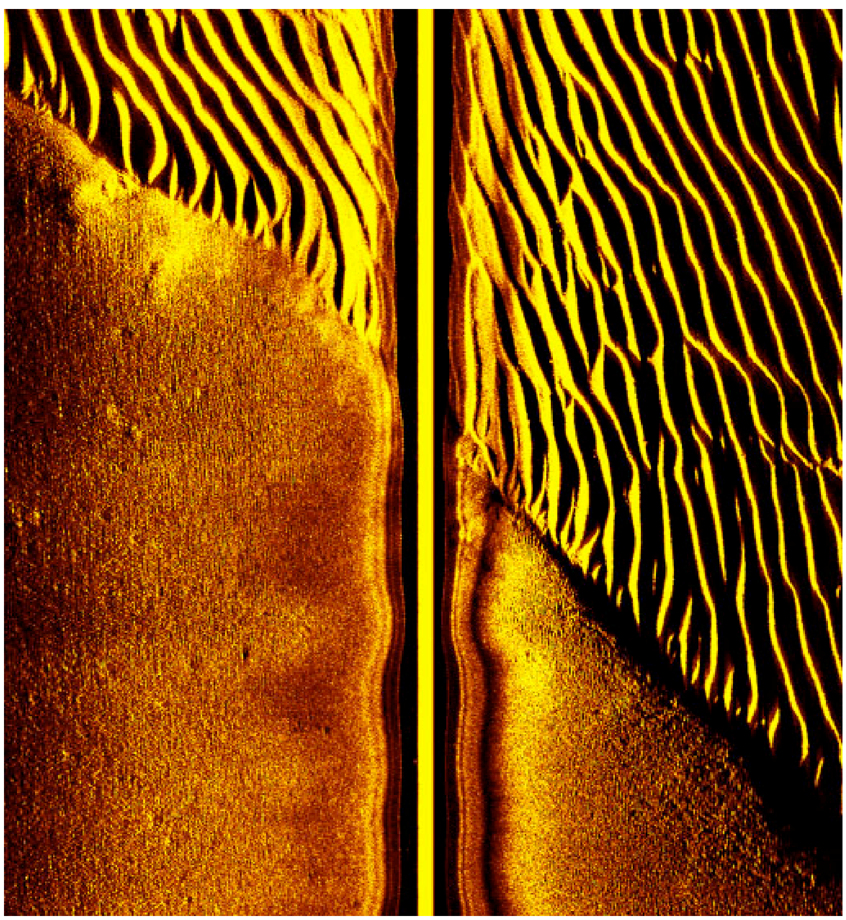

Fig. 1. 900 kHz sonar image showing heterogeneous seafloor sediments off the coast of New Zealand in 23 m depth. Coarse sand and shell hash ripples (~14 cm in length) are sharply delineated from find sand with small-scale bedforms (~100 cm in length). The total swath width is 40 m. (Image courtesy of Don Wright and Art Trembanis, Virginia Institute of Marine Sciences).

This paper describes a new five-year research initiative to improve our understanding of coastal dynamics within heterogeneous sedimentary environments and to extend our predictive capability for estimating nearshore waves, currents, sediment transport, and morphologic evolution to include heterogeneous sites. Since many effects resulting from a broad distribution of sedimentary properties are simply unknown, we seek to answer relevant questions relating to this goal including:

1. How different are coastal dynamics in a heterogeneous sedimentary system specifically with respect to surf zone hydrodynamic processes, beach / bar morphodynamic processes, and turbidity / optical clarity?
2. How do we quantify or classify complex, spatially variant sediment characteristics effectively in mixed grain environments using in-situ measurements and / or remote sensing?
3. How can we parameterize the effects of sediment heterogeneity in hydrodynamic and morphodynamic models and how do we adapt existing numerical models to better predict the dynamics and complexity of heterogeneous sedimentary systems?

Although the program is still under development, we will outline our approach and discuss our expectations in the following sections.

PREVIOUS STUDIES

There are several prior research findings that relate to heterogeneous sedimentary environments, although only a few are specific to coastal regions. Most are field studies that have observed sediment heterogeneity while monitoring coastal morphodynamics. In other words, differences in observed, local beach profiles with the same offshore wave climate have been correlated with observed variations in local sediment characteristics. For example, Calliari (1994) found variations in grain-size along a stretch of coastline within the North Carolina Outer Banks were the main cause of observed differences in the morphodynamic character of adjacent beaches. Similarly, there is growing evidence that the subsurface geologic framework of a region (e.g. a thin veneer of sand overlying mud) can dominate sand bar migration and short-term shoreline behavior (Mason and Coates, 2001). Smaller scale morphologic features are also impacted by heterogeneity. Ripples formed under unidirectional oscillatory flow with a bimodal distribution of coarse sand were observed to have longer wavelengths than ripples formed with uniform sand having the same mean diameter (Foti and Blondeaux, 1995). In addition to differences in morphologic characterization, previous studies also indicate that morphodynamic processes within heterogeneous environments strongly differ from those in more uniform environments. Moutzouris (1991) observes that heterogeneity of grain-size in the cross-shore is important to the morphodynamic character of a beach (specifically the profile) despite numerous researchers (and their models) ignoring this heterogeneity. In a summary article, Anthony (1998) concludes that the ability of existing sediment-wave parameters (i.e. Dean's ; dimensionless fall velocity; Iribarren number; surf scaling parameter) to characterize beaches is greatly diminished in the presence of mixed sediment types. Also, analysis of field observations from Terschelling, the Netherlands, by Hoekstra and Houwman (1997) indicate that representing a cross-shore profile consisting of heterogeneous sediments with a single size fraction (i.e. - in sediment transport formulae) is inadequate.

There are also documented indications of sediment heterogeneity affecting coastal hydrodynamics. For example, along the approximately 800 km Nigerian coastline heterogeneous sediment variations (from medium grained sand to silt and clay) not only dominated the observed differences in morphology with coarser beaches being steeper than finer beaches, but showed that the same offshore wave heights generated local nearshore wave heights that varied by as much as a factor of four depending on sediment characteristics (Sexton and Murday, 1994). Other researchers have observations that the inclusion of fluid muds can significantly attenuate incident wave energy (Shermet, Kineke, pers. comm. 2002). Although not explicitly tied to sediment measurements, Ardhuin et al (2001) showed that knowledge of the moveable bed bottom roughness, a quasi-sedimentologic parameter, is necessary to predict the evolution of ocean swell across the continental shelf.

Lastly, it is obvious that sediment heterogeneity will strongly impact coastal sediment transport and there are several good studies that we can build upon. One interesting example is from Mitchener and Torfs (1996) who showed that addition of a small amount of mud to an otherwise sandy sediment increases the erosion resistance such that erosion rates are reduced when the critical shear stress is exceeded. Other pertinent studies describing relevant observations in fluvial environments show effects of heterogeneous sediment variations on the initiation of motion and the resulting sediment transport (Bridge and Bennett, 1992; Kuhnle, 1993; van Niekerk et al., 1992; Whiting et al., 1988; Wiberg and Smith, 1987; Wilcock, 1988; Wilcock and Southard, 1988; Wilcock and Southard, 1989). For example, it has been shown analytically that for a fluvial environment with heterogeneous sediments, the threshold for entrainment of individual grain size fractions varies as a function of the ratio of the grain size to bed roughness (Wiberg and Smith, 1987).

METHODS AND RESEARCH PLANS

This review of previous publications relating to the influence of sediment properties on coastal dynamics indicates that present observational and modeling capabilities (that exclude sediment heterogeneity) will be insufficient for many environments. Given that these previous works are restricted in scope and therefore difficult to use for the design of new approaches, we instead have initiated a multi-year study designed to specifically quantify the effects of heterogeneous sedimentary properties on nearshore waves and surf zone flows and to understand the development and evolution of nearshore morphology (via sediment transport) in wave-forced heterogeneous environments. Essentially, the effort involves three separate aspects including: a) the development of theoretical understanding and enhanced models for describing coastal dynamics in heterogeneous environments, b) the design of new approaches for sampling sediment heterogeneity, and c) conducting field experiments to obtain observations that can be used in the development and validation of new predictive capabilities. The description below also outlines the required extensions of prior research to allow application in new domains in addition to the expected sensitivities of various processes to heterogeneity based on existing theory.

Theoretical advances and model development

Although the physics governing fluid-bottom interactions is reasonably well understood, further extensions to include heterogeneous sediments are required. Processes such as selective entrainment, armoring / shadowing, variable sorting and discrete zonation need to be better understood. In addition, the relationships between sediment properties and hydrodynamics are not well known. We propose to investigate some of these issues through the use of numerical simulations including discrete particle modeling of bedload sediment transport.

In our approach, an existing discrete particle model (Drake and Calantoni, 2001) will be modified to study the effect of heterogeneous sediment variations on nearshore morphodynamics through a multiscale, multi-physics modeling approach that attempts to bridge the gap between the motion of individual sediment particles and the overall morphology of a beach. The modifications will proceed along two fronts; the fluid modeling will be expanded to two (and three) dimensions with an embedded, fully coupled particle model that treats mixtures of sediment sizes from fine to coarse (0.2 mm to 2.0 mm). Discrete particle modeling will also be used to explore the effects of bimodal and polymodal distributions of sediment size, shape and density on phenomena of bedload transport. For heterogeneous sediment distributions, discrete particle model predictions of bedload transport rates, the mode of bedload motion, dispersion of bedload particles, and particle segregation by size, shape and density, made at the smallest length and time scales will be parameterized for use in equations governing fluid and sediment flow at a larger set of relevant length and time scales suitable for morphological modeling. New laboratory experiments (described below) will be necessary to validate and refine model predictions, particularly under combined wave and current flows.

An example of the usefulness of this approach is shown in Figure 2. For 3 different wave shapes (velocity time series for one wave period shown in the inset) having a maximum velocity amplitude of 1 m/s, a series of simulations were performed, each having a homogeneous grain size distribution corresponding to a grain diameter equal to D10, D20… D100 as derived from the distribution used by King (1991), where for D_{xx}, xx is the percent by weight of the particles with diameter smaller than D_{xx}. Flux calculations were also computed for the heterogeneous distribution. In the figure, for each wave shape, the ratio of flux for each of the homogeneous runs to the flux of the heterogeneous run is plotted against the grain size. Note that the estimated flux for homogeneous sediments is between 5 and 17% greater than the heterogeneous flux for the median diameter D_{50}, which suggests that the findings relative to heterogeneous flux cannot be accurately quantified using a single representative statistic. Also note that the results for the three wave conditions are not identical but show varying dependence on the sediment characteristics.

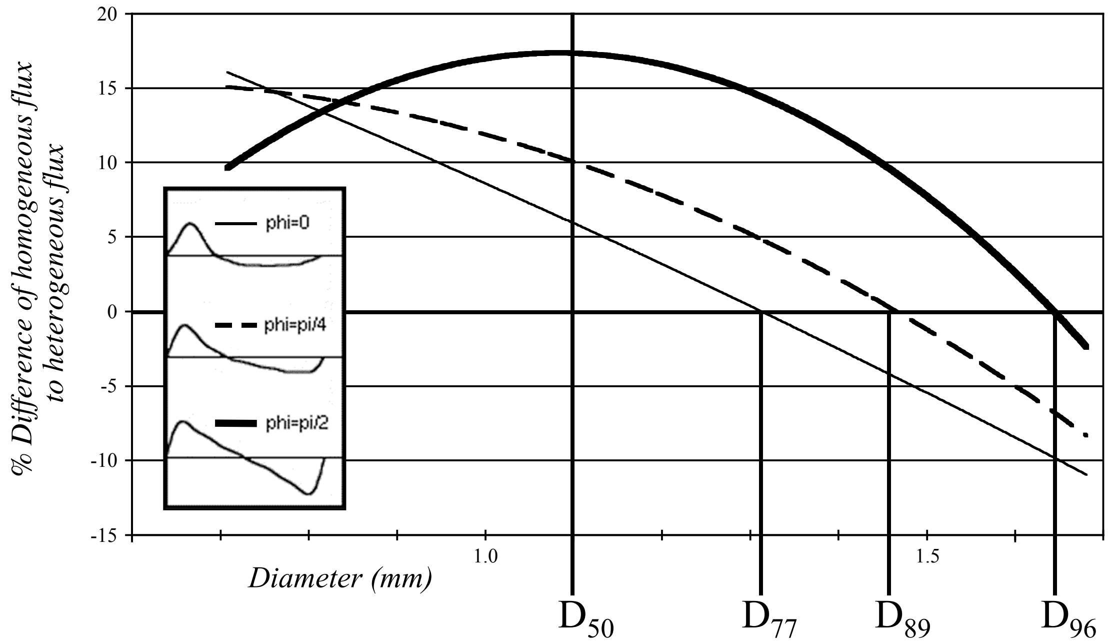

Fig. 2. Example of discrete particle simulation results for homogeneous and heterogeneous grains using data from Thaxton et al. (2001).

Assuming our understanding of the basic theory can be enhanced, significant model alteration will also be required to describe the simultaneous interaction between waves, currents, bathymetry and sediments. This is because present models either exclude sediment variations by parameterizing their influence in terms of a derived quantity (like bottom friction) or require high resolution, localized measurements of specific sediment parameters that are typically not available for model application (e.g. time series of concentration). Many present models assume an infinite supply of uniform, non-cohesive sand is available for transport or that sediment is isolated into either purely mud or purely sand. For example, all presently available wave models will typically overpredict the heights of waves over a muddy coast. In contrast, we will need to extend these models to allow for a mixture of sediments. We will also use models to determine parameter sensitivities (Figure 3). The specific modeling efforts that will be involved within the initiative include:

i. Develop a framework for integrating heterogeneous sediments into nearshore hydrodynamic models. We need models with multiple classes of sediments concurrently evolving and responding to variable waves and currents. A new formulation for spatially variant bottom friction is required.
ii. Derive a physics-based assimilation scheme for measured sedimentary properties and apply it to numerical sedimentation models. Feedback mechanisms involving the resuspension and transport of sand must be allowed to appropriately predict sedimentation and sandbar development/migration.
iii. Couple the prediction of turbidity resulting from the underlying physical processes to optical signatures (including hyperspectral). This kind of relationship between bed conservation and water column optics has only been partially validated for non-cohesive sediments, much less mixed sediments.

iv. Compare and extend existing morphodynamic models to include the range of morphologies associated with different grain size classes and their physical behaviors. For example, mixed sediment regimes often have interesting multi-barred morphology that responds at different temporal and spatial scales from their sand counterparts.

Ultimately at the conclusion of this project we hope to leverage development in related modeling efforts, such as the nearshore NOPP project (http://chinacat.coastal.udel.edu/~kirby/NOPP/), to produce a three dimensional, state-of-the-art modeling technology that will be applicable to heterogeneous sedimentary environments.

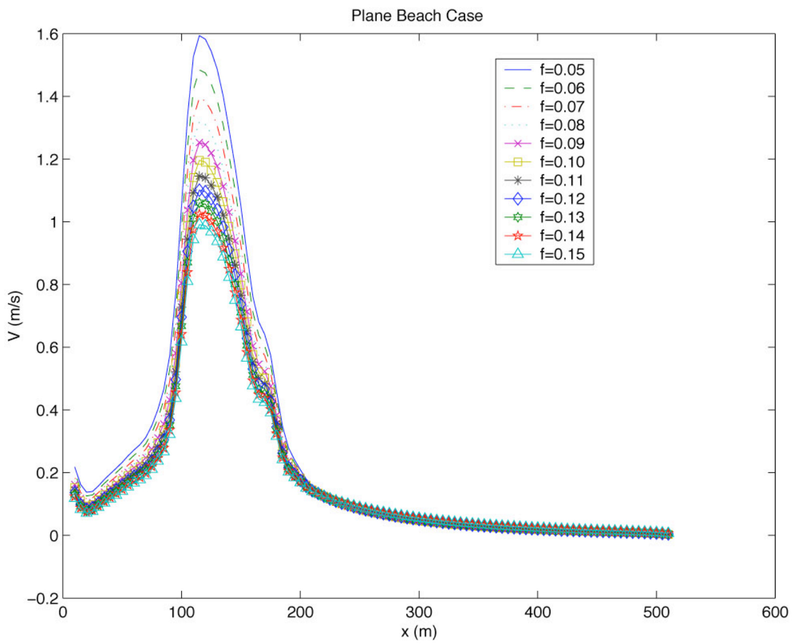

Fig. 3. Synthetic example of the effect of apparent bed friction (resulting from roughness induced by grain size variation) on longshore current speed. Realistic choices of this single parameter consistent with present nearshore models indicate a greater than 50% variation in current magnitude. Spatial variability in sediment will further complicate the model.

Application of new sampling approaches

Under the assumption that the modeling aspects of this project will be successful, the improved models will have requirements for sampling heterogeneous sedimentary environments that greatly exceed our present capabilities. The question of how we quantify or classify complex, spatially variant sediment characteristics effectively in mixed grain environments is a difficult one. Rather than pursuing the development of new sampling equipment or approaches we intend to investigate the modification of existing in-situ and remote sensing data collection technologies for quantifying the spatial and temporal patterns of variability in sediment characteristics. These methods include the use of both in-situ and remote sensing instrumentation in conjunction with more traditional sampling methods.

We are particularly interested in recent advances in remote sensing technologies that allow extension of the measurement domains encompassing coastal processes with respect to both space and time. For example, new high-resolution measurements using acoustic altimeters and side scan sonars now quantify the 3D character of bedforms at high temporal and spatial resolution. Similarly detailed vertical profiles of suspended sediment concentration and size can now be measured acoustically in the field. Also long-term, video based remote sensing has been extremely effective at monitoring the morphologic response of sediments to wave forcing. However, few similar capabilities have been developed for monitoring the temporally and spatially variant grain size distribution of sediments. Standard methods of establishing grain size distributions utilize a grab samples or vibracores. Both are clearly too time consuming to be optimal for initializing numerical forecasts or testing models, although the need for such (including subsurface) characterizations is strong. Our expectation is that many important geologic characteristics of the nearshore can be inferred with confidence using adapted remote-sensing methods. For example, inversion of high frequency acoustic impedance and shear modulus measurements to yield sediment properties such as grain size has been recently demonstrated (Bentrem et al., 2002). Side scan and multi-spectral imagery of nearshore regions is also helpful in large-scale sediment classification and estimating vertical heterogeneity such as variation in substrate thickness. In the surf zone, more traditional video imagery may be useful to locate regions of non-sand substrate exposure by using low-variance filters to highlight locations with persistently higher turbidity often associated with exposed muddy sediments, or locations with anomalous breaking-wave patterns. Similarly, monitoring the rate of beach drainage remotely may be useful for inferring grain characteristics. In any case, innovation will be required to redirect these technologies to improve our sampling capabilities and greater understanding may be gained from fusing multiple technologies.

Field experiments

Lastly, we are in the process of designing a series of field experiments to quantify both the long-term and small-scale responses of coastal dynamics in heterogeneous environments. Two field deployments are envisioned - a long-term (> 4 year), large-scale study to monitor regional scale behaviors and a shorter term (~2 month), spatially intensive experiment to examine the specifics of the interactions between physical processes that vary with respect to sediment heterogeneity. The proposed site for the long-term study is in the northern Gulf of Mexico as it is a classic heterogonous sedimentary environment and has ongoing field programs and existing instrument arrays. We intend to supplement these capabilities with the addition of a video imaging system to monitor surf zone dynamics, the deployment of sediment data collection arrays, and development of a comprehensive remote and in-situ sampling program to complement the sedimentological database provided as part of the Northern Gulf of Mexico Littoral Initiative completed in 2002. The shorter-term experiment is planned for 2006 with much more detailed investigation of the geophysical processes pertaining to coastal dynamics. For this experiment, no particular experiment location has been selected, although a site with high spatial variability and dynamic fluctuations is desired. Outside participation in both experiments is strongly encouraged to broaden the scope of the study and to extend the datasets that can be used for adapting and validating the numerical models.

DISCUSSION AND CONCLUSIONS

Previous studies and the findings presented here clearly suggest a strong potential for heterogeneous sediment properties to substantially affect coastal hydrodynamics, morphodynamics and sediment transport. We have outlined a planned initiative to conduct research towards obtaining better observations and understanding of how coastal dynamics in heterogeneous sedimentary environments differ from those in more homogeneous regimes. The metric for success at the conclusion of this research will be an improved capability for quantitative prediction of coastal dynamics in heterogeneous sedimentary environments.

Through careful planning and coordination we envision dramatic advances as a result of this planned research initiative. However, the level of achievement will depend on several factors. For example, with respect to expansion of our theoretical understanding, there is a strong potential for critical sensitivities to go undetected due to a limited sampling of the parameter space in the simulations or field observations. While no major issues are envisioned with respect to adapting the hydrodynamic models to more fully account for spatial and temporal variability in important sediment related parameters, it is conceivable that a feedback relationship between forcing and response could confound the model design. Perhaps the most difficult aspect of this project will be the integration of a diverse range of scientific topics and investigations to maintain a unified approach. It is our desire to work with the community to overcome these potential issues and we invite collaboration in an effort to fully attain our objectives.

ACKNOWLEDGEMENTS

This document describes a planned research option starting in October 2003 under base funding from the Office of Naval Research to the Naval Research Laboratory. We appreciate the insight and information received from various researchers including Alex Sheremet, Don Wright, Alex Trembanis, and Chris Thaxton.

REFERENCES

Anthony, E.J., 1998. Sediment-wave parametric characterization of beaches. *Journal of Coastal Research*, 14(1): 347-352.

Ardhuin, F., Herbers, T.H.C. and O'Reilly, W.C., 2001. A hybrid Eulerian-Lagrangian model for spectral wave evolution with application to bottom friction on the continental shelf. *Journal of Physical Oceanography*, 31(6): 1498-1516.

Bentrem, F.W., Sample, J., Kalcic, M.T. and Duncan, M.E., 2002. High-frequency acoustic sediment classification in shallow water, *Oceans 2002*. IEEE, Biloxi, MS, pp. 7-11.

Bridge, J.S. and Bennett, S.J., 1992. A model for the entrainment and transport of sediment grains of mixed sizes, shapes, and densities. *Water Resources Research*, 28(2): 337-363.

Calliari, L.J., 1994. Cross-shore and longshore sediment size distribution on southern Currituck Spit, North Carolina - Implications for beach differentiation. *Journal of Coastal Research*, 10(2): 360-373.

Drake, T.G. and Calantoni, J., 2001. Discrete particle model for sheet flow sediment transport in the nearshore. *Journal of Geophysical Research*, 106(C9): 19859-19868.

Foti, E. and Blondeaux, P., 1995. Sea ripple formation - the heterogeneous sediment case. *Coastal Engineering*, 25(3-4): 237-253.

Hayden, B.P. and Dolan, R., 1976. *Classification of the Coastal Environments of the World*, Office of Naval Research, Arlington, VA.

King, D.B., Jr., 1991. *Studies in Oscillatory Flow Bedload Sediment Transport*. Doctoral Thesis, University of California, San Diego, 184 pp.

Kuhnle, R.A., 1993. Incipient motion of sand-gravel sediment mixtures. *Journal of Hydraulic Engineering*, 119(12): 1400-1415.

Mason, T. and Coates, T.T., 2001. Sediment transport processes on mixed beaches: A review for shoreline management. *Journal of Coastal Research*, 17(3): 645-657.

Mitchener, H. and Torfs, H., 1996. Erosion of mud/sand mixtures. *Coastal Engineering*, 29(1-2): 1-25.

Moutzouris, C.I., 1991. Beach profiles vs. cross-shore distributions of sediment grain sizes. In: N.C. Kraus, K.J. Gingerich and D.L. Kriebel (Editors), *Coastal Sediments '91*. A. S. C. E., Seattle, WA, pp. 860-874.

Sexton, W.J. and Murday, M., 1994. The morphology and sediment character of the coastline of Nigeria - the Niger Delta. *Journal of Coastal Research*, 10(4): 959-977.

Thaxton, C.S., Calantoni, J. and Drake, T.G., 2001. Can a single representative grain size describe bed load transport in the surf zone?, *EOS Transactions - American Geophysical Union*.

van Niekerk, A., Vogel, K.R., Slingerland, R.L. and Bridge, J.S., 1992. Routing of heterogeneous sediments over movable bed - Model development. *Journal of Hydraulic Engineering*, 118(2): 246-262.

Whiting, P.J., Dietrich, W.E., Leopold, L.B., Drake, T.G. and Shreve, R.L., 1988. Bedload sheets in heterogeneous sediment. *Geology*, 16(2): 105-108.

Wiberg, P.L. and Smith, J.D., 1987. Calculations of the critical shear-stress for motion of uniform and heterogeneous sediments. *Water Resources Research*, 23(8): 1471-1480.

Wilcock, P.R., 1988. Methods for estimating the critical shear-stress of individual fractions in mixed-size sediment. *Water Resources Research*, 24(7): 1127-1135.

Wilcock, P.R. and Southard, J.B., 1988. Experimental-study of incipient motion in mixed-size sediment. *Water Resources Research*, 24(7): 1137-1151.

Wilcock, P.R. and Southard, J.B., 1989. Bed-load transport of mixed size sediment - Fractional transport rates, bed forms, and the development of a coarse bed surface-layer. *Water Resources Research*, 25(7): 1629-1641.