

Office of Naval Research

Tidal Flat Dynamics Departmental Research Initiative Draft Science Plan

1. Introduction

This draft science plan is derived from a more extensive, site-specific plan developed by collaborating researchers from universities, research institutions, private companies and government agencies from the United States, the Republic of Korea, and several other countries. Researchers met collectively on two occasions to develop a detailed plan for tidal flat dynamics studies: an inaugural meeting 26-30 March 2007 in Honolulu, Hawaii and a second meeting 4-8 June 2007 in Incheon, Republic of Korea. The draft science plan presented below is geographically generic and is intended to enable initiation of a series of pilot studies of tidal flat phenomena in different settings. A comprehensive science plan to study tidal flat dynamics in Gyeonggi Bay in the Republic of Korea was developed during the course of the two planning meetings. The Gyeonggi Bay science plan is available as a separate document. Efforts are underway to develop a collaborative administrative plan to undertake the proposed Gyeonggi Bay research in the future.

1.1 Objectives of the Research Plan

The goal of the Tidal Flat Dynamics Departmental Research Initiative (DRI) is to develop an understanding of, and ability to predict, the morphologic and sedimentologic evolution of tidal flats in high-tide-range settings that are dominated by fine-grained sediments. The research plan further seeks to improve and evaluate observational and modeling capabilities through field experiments to be undertaken in collaboration with Korean investigators. Specific objectives are to:

- develop, evaluate and improve coastal and estuarine circulation models, with a focus on the interaction among circulation, sediment and morphology where the role of waves is relatively unimportant;
- determine the relative roles of river- and tidal-induced circulation in forcing sediment transport and the associated morphologic response on tidal flats;
- determine the processes and parameters that govern morphologic stability and change on tidal flats;
- determine the processes and parameters that govern geotechnical stability and change on tidal flats; and to
- determine the linkages between remotely-sensed signatures and sedimentary and geotechnical properties of tidal flats.

Respective time and space scales of interest range, for example, from those associated with high-frequency particle-bed interactions to seasonal (or longer) processes of channel migration; and, from meter-scale surface textural variability to kilometer-scale understanding of tidal flat

evolution. The planning effort that is now underway will be followed by exploratory projects in 2008-09 and by a fully-integrated research program in 2010-11. Exploratory projects (Part I) will include small experiments, equipment evaluation, model implementation, and testing of approaches. Fully-integrated research (Part II) will be designed and implemented on the basis of progress and results from Part I.

A draft Science Plan is presented in the following pages of this document. The Plan has been organized into three sections: tidal flat hydrodynamics, tidal flat morphology, and geotechnical properties/remote sensing. Each section provides background, defines relevant scientific questions, and suggests one or more scientific approaches to meet DRI objectives.

2. Tidal Flat Hydrodynamics

2.1 Introduction

This section provides background on the hydrodynamic processes affecting sediment transport on a great number of the world's tidal flats, with focus on the relative importance of riverine and tidal forcing over time scales ranging from seconds to seasons and length scales ranging from millimeters to tens of kilometers. Scientific background is provided in Section 2.2; capabilities of the investigative teams are described in Section 2.3; and recommendations for the approach to understanding tidal flat hydrodynamics, including modeling, field, and laboratory components are presented in Section 4.

2.2. Scientific Background and Research Questions

2.2.1. Regional Scales

Understanding tidal flats phenomena requires consideration of the boundary conditions and the regional forcing variables affecting the environments adjacent to the flats. The forcing necessary for modeling includes tides, freshwater flow, wind and under some conditions, waves.

Large scale oceanographic dynamics lie outside the scope of this study. Relevant issues include those that significantly influence the circulation, water properties, and sediment transport in tidal flat environments, and those that affect the skill of regional model simulations. Most regional-model skill issues are technical, such as obtaining accurate wind forcing, heat flux, and boundary sea-level and water properties. The issues related to modeling processes in many potential study areas include:

- identification of remote sources of sediment flux;
- coastal currents, which are influenced by freshwater inflow from the rivers, by winds, and by tide-induced pressure gradients and residual currents;
- exchange processes, including tidal, wind-driven, and variations of major currents, including their influence on sediment transport.

2.2.2. Dynamics and Transport Processes on scales up to tens of km

Questions involve the interactions between the large-scale, regional influences, the meso-scale tidal, estuarine, and wind-driven dynamics, and the fine-scale processes associated with the distributary channel mouths, other channel junctions, and the borders between tidal flats and deeper portions of the bay, including:

- what controls the flood-ebb asymmetry in different regions,
- how do tidal-fluvial-estuarine interactions affect the residual flow, and
- what influence do these spatially and temporally varying processes have on the pathways of sediment transport?

An important link between the hydrodynamics and sediment transport is the bottom stress. In addition, to model circulation, the large-scale bottom roughness needs to be parameterized. Bottom stress is influenced by density- and sediment-induced stratification, as well as by waves, particularly in areas of the flat with high winds or large waves from storms.

Sediment transport and trapping are important to the behavior of the tidal flat. Although the complexity of many systems is not conducive to closing mass balances, it is critical to quantify the mechanisms of sediment transport, the influence of particle aggregation, re-suspension, and trapping caused by estuarine and tidal convergences. To understand and model sediment transport in a tidal flat it is important to determine:

- the dominant temporal scales of sediment trapping and remobilization processes (seasonal, fortnightly, or tidal?)
- locations of sediment trapping and remobilization (frontal zones, lateral banks of channels, channel junctions, or the tidal flat proper?)
- the influence of wave re-suspension, and does it impart a large seasonal signal on the patterns of sediment accumulation and erosion?

2.2.3. The River, the Estuary, Tidal Channels, and Flats: Dynamics on the km scale

Important components of many tidal flat systems include the fluvial portions, the estuary, the distributary channels, the open-water tidal channels, and the tidal flats. Although these components need to be considered as a coupled system, both from an observational and from a modeling viewpoint, there are distinct processes in the different components that can be highlighted separately.

Regions landward of the salt intrusion are dominated by fluvial processes that may be influenced strongly by engineering structures. Although details of sediment transport phenomena and interaction with structures, if any, are not critical to understanding and modeling processes on the tidal flat, the fluvial flows and sediment fluxes are important, and thus must be quantified accurately.

To model the behavior of tidal flats it is necessary to understand:

- how external forcing affects the flow, geotechnical properties, and morphology of the tidal flats and adjacent channels,
- how the forcing varies at tidal, spring-neap, and seasonal time scales,
- how bores and other tidal nonlinearities affect the stress distribution and sediment transport on the tidal flats,
- if tidal convergence fronts are critical agents of sediment trapping, and how they are influenced by salinity- or sediment-induced density gradients,
- the wetting and drying processes,

- the influence of smaller-scale channels and other micro-topography on the mud-flat-scale processes,
- how spatial and temporal variations in sediment supply affect the conditions and processes on the tidal flats,
- how bathymetric gradients affect sediment transport,
- the influence of surface waves on bottom stress and sediment erosion, and
- the factors influencing the spatial variability of sediment erodibility.

2.2.4. The Channel-Flat System: Dynamics on the 10-100 m scale:

Models of the larger-scale tidal-flat hydrodynamics and sediment transport require accurate representation of the flows in channels, as well as the fluid and sediment exchange between the channels and the tidal flats.

Flows in distributary channels may be the most energetic components of tidal flat systems and likely play a prominent role in the evolution of tidal flat morphology and sedimentology. The cross-channel structure of flows in channels significantly affects channel discharge, the residual circulation, and sediment pathways. Furthermore, the cross-channel structure of flows is important to channel morphological evolution. For instance, depth variations across channels may cause shear in the along-channel velocity, which can enhance dispersion. The vertical structure of flows and of sediment concentration affects the bed stresses and sediment fluxes that are important to the overall hydrodynamics and morphological evolution of the channels.

Flows and sediment concentrations may be significantly different in channels than on the adjacent tidal flat. Channels often have stronger tidal flows, and bed stresses in the channels may be less affected by waves than stresses on the flat. Channels may enable export of sediments during calm conditions (Wells *et al.*, 1990).

Flow patterns, suspended sediment concentrations, and tidal flat morphology are affected by tidal fluctuations, spring-neap variations in tidal forcing, and seasonal variations in river flow. For example, the vertical structure of flows and suspended sediments, and thus the bed stresses and sediment transport, change from flood to ebb, and from spring to neap tide. During the wet season, relatively high river flow and sediment discharge may increase vertical stratification and the corresponding stratification effects on channel-flat exchange. Seasonal variations in sediment supply, storm energy, and biological armoring result in seasonal variations of channel morphology (e.g., Choi *et al.*, 2004; Ralston and Stacey, 2007).

Thus, to model the tidal-flat hydrodynamics, it is necessary to understand tidal, spring-neap, and seasonal variations in the three-dimensional structure of flows and sediments in channels, and the exchange of fluid and sediment between the channels and the tidal flats. In particular, it is important to determine:

- what controls the cross-shore and vertical flow structure and suspended sediment concentration variations in the channels and on the flats from ebb to flood, spring to neap tides, and wet to dry seasons,
- does flow convergence at frontal zones lead to fluid mud formation on the tidal flats,
- how do the channels affect the flows and sediment transport, and what is the residual circulation (over several tidal cycles) across a channel and neighboring flat,

- how does the flow and sediment discharge scale with the channel geometry, and
- how does the channel-flat exchange vary on tidal, spring-neap, and seasonal time scales, and with channel spacing and morphology?

2.2.5. Vertical Structure of Flows and Sediments: Dynamics on mm-m scales

Accurate modeling of the tidal-flat hydrodynamics requires accurate estimates of the vertical structure of the temperature, salinity, and sediment concentration, and of bottom boundary layer processes, including bottom drag, fluid density, and turbulence, which are affected by sediment conditions near and within the bed (Geyer *et al.*, 2000; Valle-Levinson *et al.*, 2003). High concentrations of fine sediments and low turbulence levels result in rapid flocculation (Hill and Nowell, 1995; Winterwerp, 2002). Flocculation increases the settling velocity of fine silts and clays, thereby reducing dispersal, and leading to rapid settling of particles and development of fluid mud. Density stratification owing to high near-bed mud concentrations (e.g., fluid mud) may damp near-bed turbulence, reducing bottom stress. However, it also is known that muddy bottoms can increase the dissipation of surface wind-waves (e.g., Maa and Mehta, 1990; Sheremet and Stone 2003), possibly owing to rheological properties of unconsolidated sediments that may lead to increased instabilities on the lutocline.

Near-bed sediment and flow conditions affect deposition and erosion rates, which affect the morphological change on the tidal flats, which in turn affects the inundation frequency and duration (Friedrichs and Perry, 2001). The amount of deposition and re-suspension of sediment is determined by conditions near and within the bed. For example, water captured within the fluid mud matrix can hinder settling and cause the bed to remain easily penetrable (Richardson and Zaki, 1954). If consolidation occurs, the bed becomes stiffer and erosion is hindered.

Near-bed processes can be modulated by biological activity, affecting erodibility and flocculation rates (e.g., Dade *et al.*, 2001; Hill and Milligan). Additionally, flow through the bed and water content within the bed can have significant impacts on bed stabilization or de-stabilization. Bacterial and algal mats and drying during periods of exposure can stabilize the bed, whereas rainfall and water runoff can reduce the critical shear stress required to mobilize sediment (e.g., Amos, 1988; Christie *et al.*, 1999).

Near-bed processes typically are parameterized in large-scale models as “bed stress” or “bed roughness.” However, the large temporal and spatial variations in the near-bed processes are not understood, and thus are difficult to parameterize. Improved understanding of the underlying processes is needed to develop better parameterizations.

Thus, to understand the tidal flat hydrodynamics, it is necessary to understand flocculation (which is critical to fluid mud development, and can affect re-suspension), the generation and deposition of fluid mud, and sediment-bed interactions, including biological activity (which affects the stability of the bed). Sediment concentrations and grain sizes likely change on a seasonal cycle, and possibly on spring-neap periods. Additionally, biological activity has a strong seasonal cycle. Thus, studies should be conducted over several spring-neap cycles during different seasons. Collaborations with geotechnical studies may be useful to determine locations of fluid mud, and to determine the linkage between rheology and flow dissipation.

To model tidal flat processes, it is necessary to determine:

- the vertical structure of temperature, salinity, and sediment concentration, and the effects of vertical structure on the flows and sediment transport.

- the effects of winds, tides, river discharge, and morphology on the vertical structure.
- what controls floc size and structure in the water column and the bed,
- if and when fluid muds exist on the tidal flats and in the channels,
- the tidal and riverine processes leading to flocculation, fluid mud formation, and the resulting density-driven flows,
- the critical stresses and sediment concentrations for re-suspension of fluid and consolidated muds, and how biological activity affects the critical stress,
- how the feedback between fluid mud formation and morphological change (e.g., filling of bathymetric depressions) affects the tidal flat,
- the relationship between rheology, mud concentration, stratification, turbulence, and flow dissipation,
- if instabilities on the lutocline lead to increased bottom stress,
- the processes that lead to consolidation of the bed,
- if fines are eroded preferentially, and if so, how the bed roughness changes with time,
- how bottom drag and bed roughness can be parameterized to account for the temporal and spatial variations in the important near-bed processes, and
- how dewatering and rainfall affect tidal flat evolution.

2.3. Capabilities

2.3.1. Modeling

Several models are available (e.g., Kim *et al.*, 1999; Lee *et al.*, 2002; Warner *et al.* 2007) for simulating flows on the tidal flats, but modifications and improvements are needed. For example, DELFT3D and the Community Sediment Transport Model (CSTM), which is based on the Regional Ocean Modeling System (ROMS), are free-surface, hydrostatic models that include several vertical mixing and advection schemes, surface and bottom boundary layer algorithms, biological modules, and wetting and drying formulations. Information can be input to describe the bed, including sediment size, settling velocities, critical shear stresses, bed roughness, and bed thickness. The models allow curvilinear grids, vertical stretching for terrain-following coordinates, and a wide range of options for boundary conditions and forcing. Furthermore, numerous process-based smaller-scale models exist that may be able to simulate some aspects of the tidal-flat hydrodynamics. Testing of these larger- and smaller-scale models will help to determine the processes that are important to the tidal flats, the model sensitivities, and the process formulations that must be improved.

Ongoing work includes developing improved algorithms for non-cohesive boundary layers with suspended load and bedload, for cohesive sediments with erosion, deposition, and consolidation, for optical attributes of the tidal flats system including turbidity, for wave-current interactions, and for shoreline boundary conditions. Additional work in the CSTM is focused on including options to allow users to choose different suites of models to describe different processes, such as SWAN-ADCIRC for waves and circulation, HYCOM-CICE for ice effects,

ADCIRC-WASH123D or FVCOM for circulation with watershed and riverine components, and COAMPS-NCOM for atmosphere-ocean coupling. Future work will involve evaluating the performance of models in mixed-bed systems, improving the algorithms for cohesive sediments, including flocculation processes, and improving the wetting and drying formulations.

2.3.2. Field Observations

Existing sensors include pressure gages to measure sea-surface elevation and waves, current meters and profilers to measure flows and to estimate turbulence and stresses, conductivity sensors to measure salinity, acoustic and optical backscatter sensors and fiber optic sensors to measure sediment concentration, sensors to measure pore pressure, acoustic sensors to measure the lutocline and bed levels, and sensors to measure sediment sizes and flocculation rates. Drifters capable of tracking currents in deep and shallow waters are available. It may be possible to mount additional sensors on the drifters. Although development of new instrumentation could provide improved measurements, the existing instrumentation and scientific expertise is sufficient to address the science objectives. However, additional information regarding biological activity may be useful to improve understanding of near-bed processes and sediment transport. Limited numbers of sensors may require balancing competing needs for spatially dense observations with the desire to span a large region.

Infrared imaging, particle image velocimetry, video, and waterline extraction techniques will provide estimates of surface and sub-surface flows, bathymetry, turbulence intensity, and surface and bed shear stresses that will be used to study tidal flat processes, to augment in-situ observations collected to address the process studies, and to test models and provide boundary information. Additional satellite, LIDAR, and radar measurements of winds, surface flows, biological activity, and bathymetry may be useful. Furthermore, sensors can be mounted on UUVs to enable measurements of heat flux, sub-surface flows, water density, optical properties, bathymetry, and bottom roughness. Potential limitations are primarily logistical, and include potential constraints on the elevation of remote sensing equipment, and the legal operating area of UUVs. Additionally, there is a trade-off between spatial and temporal coverage and resolution. Ideally, remote-sensing and UUV studies will be nested to allow spatially and temporally dense observations over small areas to be embedded in larger-scale (but sparser) measurements.

In situ surveys using manned vessels and autonomous vehicles will be necessary for verifying the remote-sensing observations and providing depth-resolution, particularly for suspended sediment. New approaches using light equipment off of small vessels may be required in the very shallow regions of sampling, and AUVs will need to be reconfigured for very shallow water operations.

New equipment may be needed to deploy the sensors on the tidal flats, and to improve access to the muddy tidal flats. For example, to measure the vertical structure of flows and sediments, it may be possible to instrument pilings or to deploy profilers, but it may also be useful to build towers or miniature “jack-up” frames. Large spatial arrays of single-point sensors, remote sensing techniques, UUVs, and instruments mounted on vessels will enable observations of spatial variations in processes, but it may also be useful to develop small, manned or autonomous floating platforms. Although some instrumentation may be deployable from boats, other sensor platforms may require transportation across the tidal flat at low tide. However, few flat-capable vehicles exist. Additionally, new platforms may be needed to enable measurements during high-flow-rate, debris-laden, flood waters and during icy winter months. Trawl-resistant

frames or rapidly moveable systems may be needed to reduce instrument losses owing to fishing. Areas requiring low tidal-flat impact (e.g., locations of small-scale studies on bed and near-bed processes) will need to be delineated and avoided by tidal-flat traffic.

Logistical challenges include developing methods to deploy and maintain instruments on muddy tidal flats, designing equipment to measure the hydrodynamic and sediment processes during winter ice and summer floods, and designing trawler and fishing resistant equipment platforms or determining how to get the required measurements while avoiding fishing areas. Constraints on instrument use, sensor elevation, and airplane flyovers need to be identified.

2.3.3. Laboratory Facilities

Existing facilities include flumes that can be used to study two-dimensional wave, flow, and sediment processes, and basins that can be used to study three-dimensional tidal flows, directionally-spread waves, circulation, and morphological change. For example, the Experiment Center for Ocean Environment Simulation in Korea will contain a new laboratory facility with a 100-m long, 2-m wide, 3-m deep tide-wave flume that will allow tidal flows up to 1.2 m/s and waves with heights up to 1.1 m. The facility also will contain a 40-m long, 30-m wide, 1-m deep, tide basin with a wave generator that can drive up to 128 tidal harmonic constituents. The existing facilities and scientific expertise is sufficient to address the science objectives. However, additional instrumentation and new techniques for studies with cohesive sediments may be useful to extend the results of the laboratory studies. Logistical challenges might include minimizing scale- and seiche effects, and incorporating affects of river inflow (density gradients), ice, fluid muds, and biology to improve parameterizations and to compare measurements with field observations.

2.4. Approach

We recommend an approach to tidal flat studies based on two phases, each of which includes a combination of modeling, laboratory experiments, and field observations. In Phase I (2008-2009) one option is to focus on model evaluation and module development, process-based field and laboratory studies, site characterization, and instrument testing. In Phase II (2010-2011) parameterizations and new physics could be incorporated into the models based on the Phase I field studies, and additional observations could be collected to test model predictions and to examine non-equilibrium conditions, flow and sediment pathways, and interannual variability.

2.4.1. Modeling

The modeling effort will emphasize the multi-scale nature of tidal flat processes, with several nested scales:

- the regional scale [O(100 km)]
- the “system” scale [O(10 km)]
- the “local” scale of the tidal flats and channels [O(1 km)]
- the “feature” scale of sub-channels, banks, and frontal zones [O(10-100 m)], and
- the “process” scale of the bottom boundary layer, sediment-flow interactions, turbulent processes, and fluid mud [O(mm-m)].

One-way nesting and where appropriate, two-way nesting, will provide the transfer of model information between the different scales.

At the regional scale, the modeling will emphasize the processes that are thought to most significantly impact the system scale: principally tidal-, wind-, wave- and buoyancy-driven motions. The driving variables for the outer-scale model will be provided from existing data sources and collaborations with other projects.

The modeling of the “system” scale is typically challenging, owing to the interaction of processes on multiple scales. A priority of the modeling at this scale is to represent the communication of large-scale forcing variables, including tidal energy flux, suspended sediment, fresh water, wave energy flux, to the smaller scales of the individual channels and tidal flats.

The “local” scale modeling of the tidal flats and channels is an important scale to be addressed, because it is the nexus of the large-scale forcing and the small-scale interactions. Multiple model domains could be developed to represent these scales, with typical outer dimensions of 10 to 20 km (to resolve the tidal excursion) and horizontal resolution on the order of 10 m. Several different field sites are worthy of detailed consideration, using idealized as well as realistic geometries. The idealized geometry is needed for process identification and theoretical verification. Realistic geometry is required for comparison with observations and for skill assessment. Different models with varying ability to incorporate hydrodynamic, sedimentologic, and morphodynamic processes should be investigated,

Embedded within the “local” scale models will be finer-scale models to address the influence of intertidal channels and other microtopography, as well as fronts and secondary flows. These models will extend to scales as fine as 1 m, and potentially will include non-hydrostatic effects.

At the mm to m scale, models will be used to examine the vertical structure of the flow and suspended-sediment processes. The sediment-water interface, flow within and across fluid mud layers, sediment aggregation and disaggregation, and the small-scale influence of biology will be addressed by these local, fine-scale models. The results of these models will be fed into the larger-scale models via parameterizations rather than via model nesting.

2.4.2. Field observations

Phase I (2008-2009): The goals of the Phase I field studies are to investigate the science questions listed above, to obtain observations to characterize the processes on a large tidal flat, to evaluate and improve existing models, and to determine tidal, spring-neap and seasonal variations in flat processes. In addition, these field efforts will provide an opportunity to test new instrumentation and deployment techniques developed to overcome logistical challenges on the tidal flats. To determine the seasonal variations in processes, one option is to conduct three one-month-long (to cover spring-neap cycles) suites of studies during the winter (Dec 2008-Jan 2009), the windy-dry (Mar-Apr 2009), and wet (Jul-Aug 2009) seasons. Ideally, an array of instrumentation spanning a large portion of the tidal flat (e.g., covering at least 10 sq. km) and including boundary information would be deployed throughout the study period to provide background information, to test large-scale models, and to evaluate the relative importance of riverine and tidal forcing. The experiments would be nested, with smaller-scale studies embedded within larger-scale studies.

Individual scientists and groups of scientists will determine the sensors and array designs needed to test specific hypotheses and to evaluate numerical model predictions. Arrays may include vertical stacks of sensors and profilers to measure vertical structure of flows and sediment (as well as bed properties), and horizontally separated arrays of single-point sensors to measure two-dimensional wave, flow, and sediment patterns (see the Capabilities section for more information on sensors and deployment techniques). Additionally, samples may be collected from shipboard or by walking onto the flats to evaluate processes that don't require high frequency, continuous measurements. Observations and model simulations from all studies will be shared to provide a larger data set that can be used to test large-scale models, and to evaluate variability across the tidal flat. Results from small-scale studies will be used to develop parameterizations that can be included in models for the processes on larger-scales. Observations made in the large-scale studies will be used to provide background information for the smaller-scale experiments.

Remote systems (e.g., IR imaging, video, radar) and UUVs may be used to provide estimates of surface and sub-surface flows, water density, turbulence intensity, surface and bed shear stresses, suspended sediment concentrations, bed roughness, and bathymetry that could be used to study tidal flat processes, to augment in-situ observations collected to address the process studies, and to test models and provide boundary information. Ideally, coverage by remote systems would be nested to embed regions with high spatial resolution inside larger regions with sparser measurement.

High-resolution bathymetric surveys will be required before and after each study period, as well as before and after flood and wave events within each study period. The required spatial resolution of the bathymetric surveys will vary as a function of water depth, with higher-density surveys in and near the channels and intertidal regions in the focus areas, and lower-density surveys obtained less frequently elsewhere.

High-resolution hydrographic surveys (water properties, suspended sediment, currents, in situ optical properties) will be required through the course of all of the study periods. Some variables can be measured with AUVs, but high-resolution, manned surveys will be required to document spatial and temporal variability within the study sites.

Sea-surface elevation, winds, heat fluxes, and vertical profiles of flow, temperature, and salinity need to be measured to provide model boundary conditions and to evaluate model predictions. The measurements could be collected with buoys, UUVs, or via remote sensing, and need to be obtained throughout the study periods. Measurements of deposit thickness and composition, critical bed stress and erodibility, vegetation, biological activity, and surface sediment size are required for model validation and process-based studies of sediment transport and near-bed processes.

Phase II (2010-2011): Phase II studies could involve manipulations of the environment to determine the response of the tidal flats when conditions are out of equilibrium, tracer studies to observe flow and sediment pathways, and investigations of the interannual variability of the hydrodynamics and resulting sediment transport.

Coupling and feedback between fluid forcing and morphology can result in large changes in flow and sediment transport patterns. If permitted in the study site, artificial perturbations to the bathymetry may be useful to elucidate this coupling. For example, a channel dug into the tidal flat might result in stronger flows and additional erosion, causing the channel to grow. If flow conditions remain constant, an equilibrium condition could be reached between the channel

width and depth, and the forcing. Alternatively, water flowing off the flats into the man-made channel might deposit sediments, or fluid muds may form in the channel. The time scale of channel evolution likely depends on the flow and sediment conditions, as well as the biological activity, and thus perturbation studies would be conducted in several locations across the tidal flats, and during different seasons.

If, as suggested above, the Phase I studies are focused on process-based measurements using in-situ and remote sensors, tracer studies could be conducted in Phase II to track the riverine sediments and water masses over time, and to enhance the observations made with fixed in-situ sensors. Tracer studies also may be useful to explain the flat-channel exchange, and the flow pathways through the channels and across the flats during flood and ebb tides.

The proposed Phase I studies would help to determine the seasonal fluctuations of processes affecting the tidal flats. However, interannual variability can be large in many tidal flat systems. Longer-term studies should be conducted during Phase II, and ideally spanning between Phase I and Phase II to provide continuous, long-term observations. Seasonal studies should be repeated to understand the interannual variations in the tidal-flat processes.

2.4.3. Laboratory Experiments

The goals of the laboratory studies are to investigate processes affecting the tidal flat circulation and sediment transport, to evaluate numerical model simulations, and to develop parameterizations and empirical formulations for processes that can be incorporated into numerical models.

Individual scientists and groups of scientists will determine the experiment designs needed to test specific hypotheses and to evaluate and improve numerical model predictions. Field scientists will share site information with the laboratory experimentalists so that comparisons of field and laboratory results could be used to evaluate scale effects. Collaborations with small-scale and large-scale numerical modelers will enable model evaluation, and could be used to determine needs for improved parameterizations. In return, laboratory studies could improve understanding of processes that cannot be resolved or parameterized in the field, and thus could assist with interpretation of field observations and numerical predictions.

3. Tidal Flat Morphology: Stability and Change

3.1. Introduction

This section describes proposed investigations of the dominant morphologies characterizing a specific tidal-flat environment, Gyeonggi Bay, Republic of Korea, over diverse temporal and spatial scales. In addition, the proposed investigations will evaluate the most important processes impacting accretion, erosion and the morphodynamic response of the seabed. The following sections discuss background and important questions to address; potential strategies to address those questions and scientific approaches; and suggestions for optimal collaboration strategies to achieve study objectives.

3.2. Scientific Background and Example Questions

Fundamental objectives to be addressed arise from two overarching questions:

- How and why does the morphology of tidal-flat coastlines vary in time and space?

- How can specific forcings and feedbacks associated mainly tides and also by other processes be related to variability of morphology?

3.2.1. Morphological Variations in Time

The temporal variability of tidal ranges in environments of interest typically vary on a variety of time scales, including diurnal inequalities, biweekly spring to neap cycles, and a number of longer time scales. Furthermore, seasonal cycles may occur in winds, waves and river discharge, while interannual forcing is typically associated with major river floods and storms, including typhoons in some areas. Changes at decadal and longer scales are associated with natural migrations of shorelines as well as anthropogenic impacts such as land reclamation and other engineering works.

The strong temporal variability in external forcing appears to be correlated with morphological variability on similarly diverse time-scales in many areas.

Example key questions:

- Can processes occurring over **semi-diurnal/diurnal** time-scales (e.g., erosion, deposition by individual tidal cycles) be scaled-up to better understand longer-term morphological change?
- Are significant morphological changes (e.g., preserved deposition/erosion packets) associated with **fortnightly/lunar-monthly** cycles, and if so, how?
- In general, what is the relationship between short-term **deposition** (e.g., event beds) and long-term **accumulation** (i.e., permanent burial)?
- How are **annual** cycles of morphological change (e.g., erosive/sandy flats in winter/spring versus depositional, muddy flats in summer/autumn) tied to seasonal fluctuations in river discharge and winds/waves?
- Are interannual **episodic** events (e.g., large typhoons, river floods) significant to morphological stability or change?
- What are the main drivers of **decadal** and longer net change (e.g., prograding, retrograding shorelines; channel migration; land reclamation)?

3.2.2. Morphological Variations in Space

Tidal flats commonly display rich and complex morphological variations at a multitude of length scales (Lee, C.B., *et al.*, 1992; Lee, H.J., *et al.*, 1998; Lim *et al.*, 2004; Chun and Kim, 2007; Lee, H.J., 2007). Morphologies are highly dependent on the environments both seaward and landward of the tidal flats. Landward boundaries in particular are often modified by anthropogenic processes.

Example key questions:

- What is the detailed character of **small-scale vertical variability** (order of cm) in the seabed of tidal-flat environments (e.g., bedforms, fecal mounds, event beds) and what controls these features?
- What are the character of and dominant controls on **small to meso-scale horizontal variability** (order of meters to 100s of m) in morphology (e.g., channel formation, channel-bank slumps, channel cross section)?

- What are the character of and dominant forcings determining **large-scale** along- and cross-shore (order km or larger) variability (e.g., changing bed slope, profile shape, drainage networks, gradients in bed texture)?
- How do **regional and geological settings** constrain the morphology of tidal-flat environments (e.g., open coast versus sheltered bay versus tidal river)?

3.2.3. *Dynamic Forcings and Feedbacks Associated Mainly with Tides (and Waves)*

The initial stages of tidal flats studies will investigate the dominant role of tides, modified by a secondary role for waves, in determining tidalflat morphology. As pointed out by Yang *et al.* (2006), a key parameter governing the relative morphodynamic role of tides versus waves is the magnitude of the coast-normal tidal prism. The tidal prism, more than the tidal range, determines the sediment transport capacity of the tidal currents. The coast line shape can strongly affect the local coast-normal tidal prism; and the presence of islands and headlands can further shelters specific areas, allowing significant gradients in tidal dominance to be observed over relatively short distances.

Example key questions:

- Are there characteristic tidalflat morphologies and flux gradients associated with dominance by **tides** (e.g., finer sediment especially near-shore, landward sediment transport, convex up-wards profile) versus **waves** (e.g., coarser sediment especially offshore, seaward transport, concave up-wards profile)? Why (or why not)?
- How important are **non-linear tidal processes** to transporting sediment locally (flood- versus ebb-dominance), advectively (settling lag, scour lag) and/or residually (via tidal rectification)?
- How does **channelized tidal flow** become established, and then adjust and stabilize channel morphology at the scales of individual cross sections, meanders, branches and networks?
- Is bottom stress due to tides and/or waves the dominant cause of **seabed modification** that ultimately leads to morphological change, or are other forms of seabed modification similarly important (e.g., rain, ice, biosuspension, fishing, dredging)?

3.2.4. *Dynamic Forcings and Feedbacks Associated with Other Processes*

Although tides and waves clearly force sediment transport and concomitant morphological response in tidalflat environments, other external forcings and dynamic processes, in particular, riverine ones, play a role in morphological stability and change.

Example key questions:

- What are the dominant morphologies associated with **fluvial processes** (e.g., salinity fronts; estuarine and riverine mean flows) in tidal-flat environments, and how important are they?
- What are the characteristic morphological responses associated with different **sediment budgets** (including textural variability), and how do these responses relate to sediment sources and sinks?

- What are the dominant morphologies associated with net **along-coast sediment transport** (e.g., wind-driven circulation, coastal currents, and/or tidally rectified flows) in tidal-flat environments and what is their significance?
- Are **sediment gravity flows** important contributors to morphologies associated with relatively steep slope (e.g., channel banks) and/or gentler slopes (e.g., flat profiles) along tidal-flat coastlines?
- Does **erodibility** of tidal flats influence evolution of morphology over various temporal and spatial scales? What are the major controls on erodibility patterns affecting morphology (e.g., bioadhesion, bioturbation, consolidation, wetting/drying cycles)?
- How do interactions between sediment and **turbulence** in the water column (e.g., flocculation, sediment-induced stratification) scale up to affect morphology in tidal-flat environments?

3.3. Potential Approaches

3.3.1. Motivation and Strategy

Tidal rivers and intertidal coastal environments are gateways for fluvial-sediment transfer from land to the ocean. Rivers primarily supply mud (i.e., silt and clay), but also discharge some sand. The transfer processes of this sediment vary on time scales associated with the driving forces near the river mouth: tidal fluctuations, river discharge, coastal circulation, and surface-wave intensity. Studies in settings with strong tidal modulation have shown that the superposition of other forcing can create complex time-variable transport mechanisms. Therefore, an understanding of transfer mechanisms for fluvial mud and sand requires **time-series observations** designed to resolve the individual forces and their coupling, without problems from data aliasing.

It can be hypothesized (and tested) that the upper portions of tidal flats near river mouths approach an equilibrium, whereby their upward accumulation is constrained by local sea-level rise. If fluvial sediment discharge is great and new accommodation space associated with sea-level rise is limited, then much sediment must be transferred across the tidal flat. As new sediment is supplied, it is distributed to form a bed morphology controlled by the local forcing processes. Much of the sediment is transferred to the leading fringe of the tidal flat, where progradation dominates. The residence time for sediment transfer (i.e., the time an average particle spends crossing the flat) is likely longer than the time scales for tidal modulation. Therefore, most particles will be deposited and eroded many times during their journey, as shear stresses fall/rise and the water column shrinks/expands. A mechanistic understanding of morphodynamics requires detailed knowledge of **hydrodynamic processes coupled to changes in bed elevation** (deposition, erosion and accumulation).

Tidal flats are spatially heterogeneous, with distinct physical, biological and chemical environments created by differences in vertical position: supratidal, upper-flat, middle-flat, lower-flat, and subtidal settings. In addition, coastal morphology and tidal channels create along-flat variability. Consequently, there are many impacts on the distribution of sediment deposition, erosion and accumulation rates, as well as on the fate of sediment sizes supplied by the river. Flats are locations of intense physical reworking, and fluctuations of shear stresses typically create sedimentary structures with layering of mud and sand (e.g., flaser, wavy and

lenticular bedding), which impacts bulk properties such as porosity and strength. Flats are also locations of intense biological reworking (i.e., bioturbation), which subsequently modifies physical structures and bulk properties of the bed. Knowledge of **bed characteristics** on tidal flats requires investigation of grain-size distribution and its vertical stratification, in conjunction with studies of reworking (e.g., physical, biological) and emplacement of bulk properties (e.g., porosity, strength).

The scientific **goal** of the research described in this section is a thorough understanding of morphodynamics on a tidal flat by:

- undertaking time-series observations with a frequency capable of resolving hydrodynamic and morphodynamic processes associated with several tidal cyclicities (e.g., semidiurnal, fortnightly, lunar monthly), wind-driven currents and local waves, river discharge, and interannual variability;
- documenting changes in bed elevation (deposition, erosion) and texture (surface grain size, bedforms) on these time scales, as well as investigating the record of net accumulation over longer time scales;
- doing this at a range of locations to characterize spatial variability of elevation, as well as compositional properties of the bed (and its vertical stratification).

This work will involve close collaboration between **observational and modeling studies**. The observations are designed to provide validation to the numerical models. The modeling will develop a quantitative formulation for the observations, which will allow the results to be extrapolated to locations with different combinations of forcing processes.

This work will be done in conjunction with **other segments of the program**. Together with studies of coastal and estuarine hydrodynamics, the morphologic studies will develop an understanding that forms a continuum from water surface through the boundary layer and into the seabed. These studies of morphology will provide a larger framework in which to apply the results of geotechnical investigations. In addition, they will provide ground-truth for remote sensing of bed elevation/properties and their evolution.

3.3.2. Proposed Designs for Investigations

3.3.2.1. Spatial variability

(i) Small-scale intense-study sites - one possible set of sites for focused investigations include:

- high flat in a muddy area near riverine sediment sources and without dramatic seasonal changes in grain size;
- high flat in a sandier, more exposed area with relatively larger seasonal changes in grain size;
- middle flat adjacent to both muddy and sandy high-flat areas;
- lower flat/subtidal area;
- tidal channel not directly linked to river;
- tidal/river channel.

The above “flat” sites could encompass the local, smaller-scale tidal drainage network. At these sites, high-frequency sampling and time-series observations would be undertaken. These would also be sites for repeated evaluation of small-scale spatial variability (e.g., bed forms, cross-sections of smaller channels, differences between flanks, walls, thalwegs of larger channels).

(ii) Intermediate-scale spatial grid – A logical approach to encompass intermediate-scale variability might be to distribute several dozen sites around and between the sites of intense study. These additional sites could then be reoccupied on a regular but less frequent schedule to sample sediment and measure bed elevation. These observations would provide insights for a broader understanding of tidal-flat sedimentation, through somewhat larger scales of spatial variability.

(iii) Large-scale morphologic variability – To document morphological variability at the scale of entire tidal flats and tidal channel systems, large-scale bathymetric and topographic surveying is recommended. A cost-effective approach might be the use digital aerial photography at various tidal stages along with airborne LIDAR. Bathymetric information for deeper subtidal areas of interest, including larger channels, might require shipboard surveys. Large-scale measurement of bed properties other than elevation is assumed to be addressed in the geotechnical properties/remote sensing section of the white paper.

3.2.2.2. Temporal Variability

(i) semidiurnal/diurnal – In order to fully resolve short-term tidal fluctuations in bed elevation and sediment properties, one approach might be to instrument the intense-study sites with acoustic and optical sensors and surround these with a field of thin measuring sticks secured in the bed. In addition, water-column and bed samples might be collected on an hourly basis for selected periods of ~25 hours. When the bed is exposed, direct observations of elevation could be made.

(ii) Fortnightly and/or lunar monthly – It would be advantageous if the investigations of semidiurnal/diurnal fluctuations at the intense-study sites continued for at least two to four weeks, in order to resolve the impacts of longer-term tidal modulation. It would be logical for the spatial grid to be sampled and bed elevation measured on a regular basis during this time.

(iii) Seasonal – A potential scenario for capturing seasonal variability might be to investigate three periods during distinctly different conditions of river discharge and wind conditions. The former affects sediment supply, and the latter causes fluctuations in coastal circulation, water set-up and surface waves. Logical periods for study might be summer (high discharge), autumn (little discharge and weak winds), and late winter/early spring (strong winds).

(iv) Interannual – In order to better determine information about the variability among years, it is suggested that a two-year period (at least) should be investigated. It is further recommended that existing information on past morphologic conditions (such as past surveys of bed elevation, surface texture, near-surface facies, channel and shoreline position, et cetera) be utilized to assess recent interannual trends in morphologic stability and change.

3.2.2.3. Dynamic Forcings and Feedbacks

To better understand the response of morphology at the above spatial and temporal scales, it is necessary to have additional information available at similar scales concerning variability in tidal, riverine, shelf, estuarine, wind and wave forcing. In addition, data will be needed regarding

spatial patterns of sediment transport and its convergence and divergence in the water column – issues which straddle hydrodynamics and morphology. It is similarly important to have information available on smaller-scale hydrodynamic interactions with sediment and the seabed such as bottom stress, bed erodibility, boundary layer structure, turbulence, and suspended particle properties (including concentration, settling velocity, presence of fluid mud, et cetera). It is anticipated that close interactions with investigators focusing on hydrodynamics, remote sensing and geotechnical studies will provide much of this needed collaborative information exchange.

3.2.2.4. Field Logistics

For completion of the field research described here, two possible types of structures are envisioned for collection of samples/data while preserving the natural integrity of the tidal flat (i.e., minimizing disturbance by people and equipment). These would be community facilities, and their exact design would need to be the result of group discussions during the continued planning phase. In addition, boats and small ships would be needed for observations in subtidal settings.

(i) Mobile platform – In order to transit between the intense-study sites and visit stations on the spatial grid, a mobile platform will be needed. This might be a shallow-draft (<0.3 m), aluminum catamaran (6-m length x 4-m beam). The platform could operate with a small outboard engine for movement in shallow water over short distances, and might be towed in deeper water to locations of deployment. It could have a derrick, generator and winch (with a capacity of several tons), and be used to raise and lower profiling instrumentation and to collect cores and surface samples. The platform might operate with a crew as small as two people or as large as six people.

(ii) Fixed platforms – In order to undertake detailed operations at the intense-study sites, fixed platforms could be constructed. Such platforms should cause minimal impact on tidal-flat hydrodynamics, but provide sites for observations during all stages of the tide. Scientists would need to reach/leave the platforms carefully during mid to high tides. We envision that these platforms might consist of relatively thin aluminum pipes vibrated into the bed, connected by scaffolding, and include a small structure to protect instrumentation and equipment. After the study, the platforms would be removed.

(iii) Boats and small ships – These are needed for work in shallow subtidal settings. They would allow observations of morphologic change (e.g., multibeam surveys) and compositional character (e.g., coring) of the seabed. They could also be used to tow the mobile platform.

3.2.2.5. Morphologic Modeling Studies

(i) Small-scale models – In the context of the proposed investigations, numerical modeling is likely to be an essential tool for helping better understand observed small-scale morphological variability in the immediate vicinity of the sediment-water interface. Conversely, observations from this study can provide the ground-truthing needed to help advance the most appropriate formulations within small-scale models. Example scientific issues of interest include up-scaling of individual cycles of erosion and deposition to form event beds and facies, seabed scour and bedform evolution, temporal variability of seabed erodibility, formation and deposition of fluid muds, and evolution of grain size at the sediment-water interface and within the bed.

Diverse models exist that characterize near-bed sedimentary processes using various degrees of parameterization. Morphologically relevant models closest to “first principles” include particle-tracking models for physical bedform evolution and two-phase and single-phase models for predicting suspended-sediment concentration, including formation of fluid mud. Even for these reasonably well-understood processes, fundamental uncertainties still exist with regard to key aspects, such as controls on seabed erosion and relationships among flocculation, hindered settling, seabed gelling and deposition. Consolidation within the seabed of a uniform clay can be modeled from nearly first principles under idealized abiotic conditions. However, complicating effects in natural environments such as mixed grain sizes, complex layering, bioadhesion and bioturbation require parameterization of mixing and consolidation via ad-hoc approaches such as advection-diffusion coefficients and/or relaxation toward empirical equilibria.

(ii) Field-oriented community model applications – It is anticipated that one or more reasonably robust, widely-used “community” models for sediment transport will be applied in this study to help predict and better understand morphologically relevant processes observed in the field on scales ranging from tens of meters to tens of kilometers. Available models already being used by likely collaborators include DELFT3D, the Regional Ocean Modeling System (ROMS), the Environmental Fluid Dynamics Computer Code (EFDC) and the Community Sediment Transport Model (CSTM). Example scientific issues of interest include: How are seasonal cycles in deposition, erosion and seabed texture tied to fluctuations in river discharge and storms? How are spatial variations in hydrodynamic forcing related to observed gradients in seabed texture? Are episodic events (typhoons, floods) significant to morphological change? How important are tidal non-linearities to net sediment transport and deposition in the region? How do local and regional sediment budgets impact morphology? How do spatial patterns in erodibility affect transport?

These models include morphologically relevant processes important in tidal-flat environments such as advanced horizontal advection formulations, wetting and drying, multiple grain sizes, and settings for cohesive and non-cohesive sediments. However, other relevant aspects of some of these models are highly parameterized or limited, such as treatment of sediment settling velocities, interaction with wind waves, evolving seabed erosion rates and reference concentrations, and deposition boundary conditions. Through communication with developers of small-scale models, this project also provides an opportunity for continued improvement of community models relevant to tidal coast environments.

(iii) Idealized, parameterized, analytical and statistical models – Idealized or otherwise simplified modeling and statistical approaches to predicting morphological change and stability facilitate isolation of individual external forcing factors as well as the systematic consideration of a large range of forcing conditions. Statistical approaches, for example, can be used to empirically inter-compare extensive data-bases of forcing variables and morphological responses from the field site region and elsewhere. Key forcing variables include: tidal range, tidal prism, riverine sediment discharge, wave height and geological setting. Morphological responses include such variables as: tidal-flat width, elevation, profile shape and accretion/erosion rate; channel width, depth, cross-sectional shape, sinuosity, branching, lateral migration rate and deposition/scour; and seabed median grain-size, grain-size distribution, surface roughness, bulk density, and other geotechnical parameters. Multidimensional statistical relationships can then be compared to theoretical trends derived from other simple theoretical arguments, more qualitative conceptual models or the results of more sophisticated modeling.

Modeling of highly simplified tidal flat and/or channel morphology, whether using relatively sophisticated community models, highly parameterized models or analytical approaches, can allow the isolation of individual forcings, accelerate sensitivity studies, and, depending on the modeling approach, can allow for very long-term simulations. The strengths of applying a community sediment transport model to an idealized geometry could include initial testing of the morphological significance of new features proposed for the model in general, such as sediment induced gravity flows, wave damping by fluid mud, or advanced flocculation/hindered settling algorithms. Highly parameterized numerical models utilizing bulk transport formulations or diffusive transport, for example, allow simulations long enough to investigate ramifications of shoreline and channel migration, channel network evolution, or long-term changes in sediment supply. Analytical modeling, if based on appropriate long-term governing mechanisms, can provide insight into fundamental theoretical relationships between equilibrium morphologies and dominant external forcings.

(iv) Laboratory models – Opportunities exist to utilize experimental facilities in both Korea and the U.S. for morphological studies in conjunction with this project. Advantages of laboratory approaches include enhanced control of forcing variables relative to field conditions, a greater ability to sample over fine spatial and temporal scales, and the ability to develop scenarios optimally suited to test numerical modeling. Important morphology issues that may be particularly amenable to laboratory study include: time-dependent changes in erodibility due to physical consolidation, bioturbation and bioadhesion; effects on sediment disturbance of ice and rainfall; fluid mud and gravity flows; development of bedforms over intertidally exposed sandy and muddy surfaces; and initiation of channels by both erosional and depositional processes.

4. Geotechnical Properties and Remote Sensing

4.1. Introduction

Tides, rivers, currents, and waves force sediment transport within the intertidal zone and produce seabeds with properties that vary in time and space. The seabed variability complicates commercial, recreational, and strategic activities in the intertidal zone. For example, traversing the intertidal zone can be challenging when the underlying sediments cannot adequately support the required load. Similarly, safe emplacement of structures requires detailed understanding of the strength of underlying sediments.

The response of sediments to applied stresses is characterized broadly under the heading of “geotechnical properties.” The many physical and biogeochemical qualities of sediments that interact to determine the geotechnical properties are termed “seabed properties.” Of these, sediment size distribution, porosity, and water content are key physical parameters, while organic matter content, gas content, and grain-scale microbiological interactions are some important biogeochemical properties. In addition, several processes, including the time evolution of applied stresses, can alter the geotechnical properties of the seabed. Self-weight consolidation is a relatively well-understood example of how the time history of stresses affects strength. Less well-understood processes that are likely to be important in the intertidal zone are repeated wetting and drying, erosion and deposition, bioturbation, and gas formation and release. Because these processes and properties vary in space and time, geotechnical properties in the intertidal zone are heterogeneous.

Macrotidal environments are typically expansive and heterogeneous, and can be difficult to operate in. Characterization of the large-scale geotechnical and seabed properties using in situ sampling is simply not practical. Techniques to measure geotechnical properties remotely, over long temporal and large spatial scales, would be a valuable tool, yet the likely techniques, discussed below, are only in the initial stages of development. In particular, existing remote sensing techniques only observe the sediment surface, so techniques to infer the geotechnical properties at depth within the sediment will have to be investigated.

4.2. Goals

Four primary goals fall under the heading of “Geotechnical Properties and Remote Sensing”:

- Identify the seabed properties that control geotechnical properties;
- Improve understanding of how environmental processes generate spatial and temporal variability in the seabed properties that control geotechnical properties;
- Develop and ground-truth remote sensing tools to characterize the seabed properties that control geotechnical properties;
- Develop models or techniques to relate seabed and geotechnical properties at the surface to geotechnical properties at depth.

4.3 Scientific Approach

4.3.1. General Approach

Establishing links among remotely sensed properties, seabed properties, and geotechnical properties requires that measurements be made at the same places and times. The measurement program will be structured to assess variability over a range of space and time scales. Horizontal scales of interest extend from meter-scale variability to variability on the Bay scale. Vertical scales of interest range from the top few millimeters of the seabed to depths of several meters. It is important to resolve temporal changes that occur during a single tidal cycle, during a spring-neap cycle, during seasonal cycles, and on to inter-annual variability. A set of nested measurements will be used to address variability over the wide ranges of space and time. Intensive measurements at several sites will be conducted periodically throughout the year. The measurements will be linked in time by carrying out a reduced set of lower resolution observations. Similarly, properties between sites selected for intensive measurements will be linked by transects on which a reduced set of observations are made. A nested approach will allow detailed investigation of the relationships among history of physical forcing and the various physical, biogeochemical, geotechnical, and remotely sensed properties of the seabed. It also will reveal the nature and magnitude of spatial and temporal variation of those properties.

4.3.2. Characterization of Seabed Properties

Many seabed properties interact to determine geotechnical properties. Grain size distribution, porosity, and water content are fundamental physical properties. The effects of biogeochemical properties are not as well understood, but variables such as organic content and gas content are likely to be important. Biological activities in and on the sediment also impart geotechnical variability. Microphytobenthos can cause sediment adhesion that grazing can subsequently destroy. Benthic organisms build myriad structures that introduce heterogeneity

into the sediment fabric. The seabed measurement program will be designed to characterize these variables, but it is not restricted to them.

4.3.3. Characterization of Geotechnical Properties

There are many different geotechnical properties and many different ways to measure them, such as field shear measurements (vane or cone) and core sampling (for later lab analysis). The appropriate property and technique, or characterization, will depend on the question being asked. A framework based on the broad concept of “sediment strength” as a function of seabed properties, physical and biological processes, and environmental forcing can serve as a guide for choice of methods. In particular, the proposed geotechnical characterization should be achievable at the same space and times scales as the seabed characterization and remote sensing. If the proposed characterization is new, then it should be accompanied by more conventional techniques (for groundtruth). A shared framework is intended to assure the relevancy of the data and to enable integration of the data with direct and remote measurements of seabed properties. A crucial integration topic will be how to preserve in situ properties while trying to measure them or obtain samples (i.e., non-destructive sampling).

4.3.4. Remote Sensing

The ultimate objective of the remote sensing portion of the Tidal Flats DRI is to develop tools that can estimate sedimentary and geotechnical properties of the tidal flats from existing or soon to exist airborne or satellite remote sensing systems. The anticipated use of these tools would be an operational system for rapidly characterizing tidal mud flats anywhere in the world. Ideally, the tools would be able to characterize both surface properties and properties within the mud layer in order to be able to generate useful estimates of “sediment strength”. Research should focus on the dominant existing remote sensing systems: radar, infrared, or visible. Other remote signals may also be considered, but with an understanding that transition time to an operational system may be substantially longer.

A fundamental challenge is that most remote sensing systems only provide surface characteristics, and often provide observations that come from mixtures of surface properties that make it difficult to separate them. Thus to achieve the ultimate objective, the program will need to develop capabilities that: (1) utilize multiple remote sensing signatures to uniquely characterize the surface properties; (2) incorporate changes in these properties over time and, coupled with physical models, infer characteristics within the mud layer (and possibly beyond); and (3) translates this to an operational system for existing remote sensing sensors, including assimilation of remote sensing signatures into geotechnical models.

4.4. Partnerships and Collaborations

This component of the Tidal Flats DRI is based on collaboration among researchers who study seabed properties, those who study geotechnical properties, and those who use remote sensing to characterize the seabed. The program will be designed to ensure that these groups make measurements on the same time and space scales. Collaboration in analysis and interpretation of these data is expected. Collaborations between researchers deploying in situ instruments and those employing remote sensing techniques are crucial and should be emphasized early in the experiment design.

The research outlined here has clear links to the other components of the program. Erosion and deposition alter seabed properties on a range of time scales, and they are driven by

circulation, waves and riverine inputs in the Bay. Morphodynamic changes also occur because of erosion and deposition, and they respond to variations in geotechnical properties. Remote sensing can be used to monitor circulation, bathymetry, and morphodynamic change. In fact, many relevant research topics do not lie entirely under one research heading by instead link the various subject areas identified in this document.

4.5 Suggested Research Plan

The exploratory research program will require laboratory and field components. First, a database of existing observations and knowledge of the Gyeonggi Bay region is needed to choose appropriate laboratory conditions, as well as field deployments and site selection. Compiling the database is an opportunity to build collaborations between Korean and North American researchers while identifying gaps in the current understanding of tidal flat geotechnical properties. Useful database entries include: bathymetry, sediment type/distribution, and practical information, such as the traffic patterns of local harvesters.

Laboratory experiments to develop new measurement techniques, particularly from remotely sensed signals, are needed to test algorithms and prepare for a successful field program. Testing in a controlled laboratory environment will confirm or refute hypotheses relating remote signals to seabed properties and subsequent inferred geotechnical properties. Testing should include multiple sensing systems and cover many different mud conditions and temporal scales. In addition to algorithm development, multi-investigator laboratory experiments will promote integration of disparate data-types prior to field deployments.

Finally, guidance for the integrated research program requires that the exploratory research provide understanding of both instantaneous surface characterizations and time evolutions that may be related to properties at depth.

4.5.1. Characterizing the Surface Layer of the Seabed

Surface characteristics are the most promising area for application of existing forward models based on remote signals and integration with in situ measurements. Progress requires determining the model combinations that uniquely specify the surface characteristics, such as surface roughness and water content. These combinations could come from multiple wavelengths (both across sensors such as optical, infrared, radar as well as within sensors such as X-band and L-band radars) and/or multiple polarizations (in any E-M wavelength). Some surface remote sensing hypothesizes that should be tested are:

- Radar cross-sections are a function surface roughness and water content, but may be related to rough characteristics uniquely using multiple wavelengths.
- Polarized light may be related to surface roughness characteristics via estimates of Stokes parameters.
- The thermal emissivity of sediments is a function of surface roughness, water content, and incidence angle.
- Hyper- and multi-spectral imaging can provide empirical (ie, look-up tables) classification of sediment type, dominant grain size, and water content.
- Passive microwave sensing can provide direct estimates of water content.

- High-resolution imagery (visible or infrared) can be used to quantify biological activity, including bioturbation.

4.5.2. Linking Surface Properties to Deep Properties

For remote signals, a primary objective is to determine how to utilize what is essentially a surface characterizing system for estimating dynamic properties below the surface, such as shear strength and load capacity. One hypothesis is that changes in time at the surface are communicated to deeper layers according to the properties of those mud layers. Thus, by coupling time-series observations (for example from the drying of the surface from the sun) to full geotechnical models, we may be able to determine uniquely which mud properties generated the observations. Due to the changing local environment it may be quite challenging to derive this information from a single sensor observation over time. More realistically it may require observing differences in time series from multiple sensors. Some specific depth hypotheses that should be tested are:

- The thermal conductivity of sediments can be related to porosity using a one-dimensional heat equation prescribed by a remotely-sensed surface heating rate.
- Short-term (diurnal) changes in radar backscatter and visual polarimetry are dominated by changes in moisture content (wetting, drying, and groundwater flow).
- Changes in hyper- and multi-spectral imaging can provide empirical estimates of erodability, strength, and compaction.

Another hypothesis is that depth-integrated geotechnical properties can be inferred by observing morphologic response to forcing (eg, erosion of less cohesive sediments owing to high flow conditions). This hypothesis overlaps and aligns with investigations of morphology and hydrodynamics, in particular remotely sensed estimates of bathymetric change.

Complementary in situ measurements to characterize geotechnical properties are necessary to evaluate the hypotheses. Some processes and properties that should be observed in situ are:

- Shear strength, Young's modulus
- Desiccation (albedo, relative humidity, temperature, etc)
- Composition: grain size distribution, mineralogy, organic content
- Re-suspension, erosion and redeposition rates
- Energy level (including cyclic loading from waves)
- Freeze/thaw cycles
- Gas formation and release
- Pore fluid: saturation levels, salinity, groundwater flow
- Rheology, thixotropy, plasticity, elasticity
- Bioturbation

4.5.3. Exploratory Field Program

Exploratory field measurements must cover a range of temporal and spatial scales. A nested approach, subject to modification based on laboratory results, would include:

At least two *focus sites*, one muddy and the other sandy/mixed, with:

- tower-based remote sensing at high spatial and temporal resolution,
- intensive seabed sampling during selected single tidal cycles, and
- revisits during spring and neap conditions.
- Transects between sites sampled with a reduced set of in situ measurements.
- Transects sensed remotely from a different platform, perhaps aircraft (short dwell time, large area extent).
- Routine measurements between spring and neap tide intensive sampling.

In addition, the overall set of measurements must be repeated at different times of year, e. g., late winter/early spring when waves are high and biological activity is low, late summer after summer rains have introduced new sediment to the flats, mid- to late fall when biological activity is low and wave energy is increasing.

Owing to the difficulty of operating on the mud flats, collaborations (see above) should seek to share platforms wherever possible. Some platform considerations for remote sensing techniques are given in Table 1.

Table 1. Remote sensing platforms, nominal scales, and costs.

Platform	Dwell Time	Area	Cost
Satellite	None, unless geostationary	100 Km	Low
Aircraft	Hours	10 Km	High
Tower	Years	100 m	Low
Helicopter	Hours	1 Km	High
Tethered Balloon	Days	500 m	Moderate

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The following list includes specific references cited in the science plan as well as a number of general references to the tidal flats literature with particular emphasis on archetypical flats on the western coast of Korea.

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