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PREDICTING THE BEHAVIOR OF BEACHES: ALTERNATIVES TO MODELS

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ABSTRACT

In the USA, mathematical models are heavily relied upon in the design of beach replenishment and coastal engineering projects; yet, there is a great discrepancy between the predicted beach behavior produced by the models and the reality of actual beach behavior. Some of the problem is rooted in politics but more important is the unreality of analytical and numerical models used in the design process. The typical assumptions used to simplify the model equations are often highly questionable (e.g.. the existence of closure depth), processes are generalized and incomplete (ignoring seaward flowing bottom currents), models are assumed to apply to all beaches (a shoreface with outcropping rock is treated no differently than a shoreface covered with unconsolidated sand), and adequate real world data (e.g.. wave gauge information) is generally lacking. In addition, the model approach used in USA coastal engineering design is non-probabilistic— in effect, storms are considered to be unpredictable accidents. They are not directly accounted for in most models. The track record of model use is poor and we recommend that models should be shelved for real-world applications while recognizing their potential usefulness in basic coastal science. Taking beach replenishment as an example, there are three design approaches that could be used, avoiding the use of mathematical models: (1) determining beachfill volume requirements by measuring volume loss and shape changes of an eroding shoreline over a period of years, assuming similar behavior of replenished beach in the future (imitating nature), (2), pump sand on the beach without design predictions (the Kamikaze option) and (3), design beaches based on past experience on neighboring or regional beaches (learning from the past).

KEYWORDS

Analytical and numerical models, beach replenishment, sediment transport.

INTRODUCTION

In USA coastal engineering there is an increasing reliance on analytical and numerical models to predict the behavior of replenished beaches and the coastal response to engineering structures. There is, however, no evidence that such models have succeeded in their intended predictive role. A significant part of the problem is that these models are deterministic in nature. They produce resultswith unknown and unquantifiable error. Clearly this approach needs re-examination. Many of the assumptions used in analytical and numerical models are not valid in the context of modern oceanographic and geologic principles (Pilkey,1993). It essential that beach designers understand these model limitations. It is our belief that models should not be relied on as a primary design tool until they have been substantially modified and proven in real world situations. This paper identifies some of the major weaknesses exhibited by all coastal engineering models, presents a list of model limitations for one frequently-applied model (GENESIS), and presents several alternatives for replenished beach design.

MODEL WEAKNESSES

The following are some of the major model weaknesses

1. Engineering models do not consider seaward directed bottom currents. All engineering models used in replenished beach design are based on the assumption that sediment movement beyond the surf zone is a result of the interaction between wave orbitals and the bottom sediment. In this view of the shoreface, closure depth is the point at which wave orbital interaction ceases to be important in sediment transport. The field evidence and the physics of nearshore water movement clearly indicate that bottom currents can be important movers of sediment on the shoreface (e.g. Swift et al., 1986). Even in cases where wave orbitals are primarily responsible for mobilizing the sand, bottom currents frequently determine where the sand will go.

2. The concept of closure depth (a fallout from the no-current assumption) as a sediment fence beyond which there is no seaward transport of nearshore sediment is brought into question by theory and field evidence. Large volumes of nearshore sediment were documented to have been moved well out on the continental shelf as a result of storm driven currents (Hayes, 1967; Morton, 1981; and Snedden et. al., 1988). Pearson and Riggs (1981) document the seaward loss to the continental shelf of a large volume of beachfill sand from Wrightsville Beach, NC. The continental shelf storm sediment sink is not considered by any of the models.

3. The concept of a shoreface profile of equilibrium as described by Bruun (1962) and Dean (1991) has no basis in reality. This concept assumes that grain size is the only variable controlling shoreface shape; thus, any beach with the same grain size must have the same shape.

4. Geologic control of the shoreface shape and its impact on shoreface processes is not considered in engineering models of nearshore sediment transport (Pilkey et al., 1993). Yet outcropping mud and well lithified rock is a common occurrence along many shorefaces in the Gulf of Mexico as well as along the Atlantic Coast. Rock outcrops can control the shape of the profile, can strongly impact on shoreline retreat rates, and may affect the local wave climate by reducing energy absorption and by wave refraction.

GENESIS

The Generalized Model for Simulating Shoreline Change (GENESIS) is a widely-heralded numerical model used in USA Coastal Engineering (Hanson and Kraus, 1988). It is used to simulate the long term shoreline changes at coastal engineering sites resulting from spatial and temporal differences in longshore sediment transport. In practical terms GENESIS is used by coastal engineers to predict the impact of engineering structures and or beach replenishment that may alter longshore transport. Hanson and Kraus (1989) list a number of model limitations that must be considered before applying GENESIS. These limitations from Hanson and Kraus (1989) are fundamental in nature and are basically fatal to the model's application.

1. "It is rare to have adequate wave gage data for a modeling effort." (p.35)

2. "Empirically, the location of profile closure cannot be identified with confidence..." (p.57)

3. "Some types of data are difficult to quantify such as permeability factors for groins and transmission factors for detached breakwaters..." (p.39)

4. "Typically...boundary conditions are ill defined." (p.41)

5. "In practice, data sets sufficiently complete to perform a rigorous calibration and verification procedure are usually lacking." (p.44)

6. "GENESIS is not applicable to calculating...beach change...produced by storm-induced beach erosion in which cross-shore sediment transport processes are dominant..." (p.19)

7. "It should be remembered that obliquely incident waves are not responsible for all longshore sand transport and shoreline change. Potential errors also enter the hindcast of the incident waves, in representing an irregular wave field by monochromatic waves and, sometimes through undocumented human activities and extreme wave events that have modified the beach." (p,46)

8. "...the assumptions are idealizations of complex processes and therefore have limitations. In a strict sense, the assumption that the beach profile moves parallel to itself along the entire model reach is violated in the vicinity of structures." (p.49)

9. "In light of the profound variability of coastal processes, it is clear that a single answer obtained with a deterministic simulation model must be viewed as a representative result that has smoothed over a large number of unknown and highly variable conditions." (p.42)

In addition to these problems and limitations, the calibration and verification process used in numerical models such as GENESIS has been criticized. McAnally (1989) notes that in a complex natural system, the two step process of model adjustment is insufficient to demonstrate the models validity. Oreskes et al., (1994) state that "verification and validation of numerical models in natural systems is impossible."

Table 1 is a summary of geologic and oceanographic principles related to sediment transport and indicates whether or not each factor is considered in the GENESIS model (yes (Y) or no (N) in the left hand column of the table). It is apparent from this list that a large number of very important processes and principles are either omitted or ignored by the model.

Geologic Considerations	
Are different coastal types recognized? (e.g., rocky, sandy, etc.)	N
Is an equilibrium shoreface profile applied in the model?	Y
Is a closure depth assumed?	Y
Is smooth shoreface bathymetry (e.g., straight/parallel bottom contours) assumed?	Y
Is shoreface and/or subsurface/surficial geology considered?	N
Are areal and temporal variations in sediment supply and grain size considered?	N
Is longshore loss/gain of sediment considered?	Y
Is offshore loss/gain of sediment considered?	N
Is overwash loss of sediment considered?	N
Is aeolian loss/gain of sediment considered?	?
Are other sedimentary attributes (e.g., shell lags, cohesion, slime, etc.) considered?	N
Are water temperature/viscosity effects considered?	N
Are the effects of bedforms and offshore bars on sediment transport considered?	N
Is the effect of beach state (e.g., antecedent, modal, seasonal, etc.) on erosion potential considered?	N
Are the effects of engineering structures on the beach/shoreface considered?	Y
Are variations in dune characteristics (e.g., degree of vegetation, slope, width, overwash gaps, etc.) considered?	N
Is longshore sediment transport assumed to be uniform across the surf zone?	Y
Is sediment transport seaward of the surf zone considered?	N
Are the effects of the water table and/or pore pressure in beach/dune sediment erodibility considered?	N
Is liquefaction of surf zone sediments by breaking waves considered?	N
Oceanographic Considerations	
Are storm events considered?	N
Are multiple randomly occurring storm events considered?	N
Is sediment transport assumed to be caused only by wave orbital/sediment interactions?	Y
Are wave refraction/diffraction effects considered?	Y
Is frictional dissipation of wave energy across the shoreface considered?	N
Are the effects of bottom type on wave energy considered?	N
Does the model require monochromatic, unidirectional waves?	N
Are the effects of offshore bars on wave energy considered?	?
Are seasonal variations in wave climate considered?	Y
Are local wind effects on wave shape/breaker type considered?	N
Are landward boundary conditions (e.g., wave reflection off a seawall or steep beach) considered?	N
Is linear wave theory used in wave transformations?	?
Are infragravity waves considered?	N
Is the benthic boundary layer's effect on water column velocity profiles considered?	N
Are turbidity currents considered?	N
Are rip currents considered?	N
Are storm surge ebb currents considered?	N
Are the effects of gravity-driven currents considered?	N
Are wind-induced up/downwelling currents considered?	N
Are wind-induced longshore currents considered?	N
Are wave setup/down-induced curents considered?	N
Are the effects of forced long waves and/or groupy waves on currents considered?	N
Are wave-current interactions considered?	N
Are tidal currents considered?	N
Is the tidal range considered?	N

Table 1: Characteristics of the GENESIS shoreline change model

ALTERNATIVES TO REPLENISHED BEACH DESIGN BY MODELS

We have identified three approaches to the design of replenished beaches that do not involve the use of physical, analytical or numerical models. These are:

1. Imitate nature: Observe shoreface behavior over some time span and assume similar post-replenishment behavior of the artificial beach.

2, Kamikaze beach: Emplace the beach and see what happens. Take advantage of lessons learned from careful monitoring of the first emplacement to help in the design of succeeding replenishments.

3.Learn from the past: Research the fate of previous replenishment projects (or similar, nearby projects) and assume similar behavior of the new beach.

Imitate Nature: The basis of this approach to replenished beach design is to determine the history of behavior of the natural beach and shoreface system and from this assume the behavior of the replenished beach. Verhagen (1992) describes the Dutch approach which is basically an imitation of nature. Mathematical models are not used to design Dutch beaches because the irregular wave climate makes their predictive value "rather low." Physical models are also not recommended by Verhagen (1992) because of the difficulty of modeling the all-important irregularities in wave conditions.

The initial step in Dutch replenished beach design is to determine how shoreline retreat is occurring. Beach profiles are taken over a period of 10 years, at least one profile per year. The profiles include the subaerial beach and the entire shoreface or zone of active sand movement. From these the behavior of the retreating shoreface is determined.

It is assumed that the replenished beach will behave in the same fashion as the natural beach and that the shoreline retreat rate of the replenished beach will be the same as the pre-existing natural beach. Using these assumptions and knowing the desired beach width of the new beach, the required new shoreface profile can be calculated. The specific steps in the replenishment process outlined by Verhagen (1992) are as follows:

1. Take profile measurements for at least 10 years.

2. Calculate the loss of sand in m^3 per year.

3. Add 40% volume for a loss factor.

4. Multiply this by the desired beach lifespan.

5. Put the sand on the beach between the low water mark (minus 1m) and the foot of the dune.

The Australian beach replenishment approach used in the Gold Coast is discussed by Smith and Jackson (1992). The Gold Coast shoreface system is very sand rich in contrast to the sand poor and often rocky shorefaces of the USA east Coast. More than 20 years of wave observations and profiles exist along this shoreline. Profiling information includes numerous immediate pre-storm and post-storm profiles. The profiles show that very large profile changes may occur during storms (typhoons) and also that post storm recovery is very extensive. The storm response of some Gold Coast beaches involves formation of a large offshore bar which eventually, over a period of years, returns to the lower subaerial beach. During the time of existence of the offshore bar, shoreline retreat in response to smaller but significant storms is subdued relative to beach response to the same storms when no bar is present.

On the basis of this understanding of natural shoreface changes during storms, beach replenishments have been carried out on the Kirra-Billinga shoreline reach by first emplacing an offshore bar imitating the natural storm bar. The artificial bar was emplaced at 9 m depth with a crest depth of about 6 m (Smith and Jackson, 1993). Although long term data are not yet available, the initial impression is that the artificial storm bar has dramatically increased the replenished beach lifespan.

Few beaches in the world are monitored in as much detail as the Australian Gold Coast. On USA beaches some long term data are often available concerning shoreface profile changes from original Geodetic Survey charts which might aid in applying the Dutch approach. The Australian way of imitating nature requires much more data and especially storm documentation.

***The Kamikaze option*:** This approach involves beach emplacement on a trial basis without any particular design effort other than planning methods of the spreading sand pumped up on the beach. Pump it up and see what happens! This approach has been used many times on USA beaches (although perhaps not consciously) in conjunction with channel dredging for navigation projects. The navigation category of USA federal government projects involves disposal of sand in the cheapest fashion possible and if the cheapest option happens to be a beach, as opposed to disposal on spoil islands, a nearby beach is replenished. Often these beaches are small but in some instances on the USA East Coast, more than a million cubic yards have been involved. An example of this is Atlantic Beach, NC which has been replenished 4 times in the last 10 years using sand removed from Morehead City, NC harbor. This approach avoids the often heavy design costs common on USA replenished beach projects. Because beach design with mathematical models produces a beach of unknowable durability, the no-design approach may be just as successful.

***Learning from the past*:** Pilkey and Clayton (1989), Dixon and Pilkey (1991), and Clayton (1991) in their studies of the US replenishment experience observed strong regional differences in subaerial replenished beach durability. This was especially true on the USA Atlantic coast. Beaches in South Florida, south of Cape Canaveral, have typical life spans of 7 to 9 years. North of Florida, through North Carolina, life spans range from 3 to 5 years. In New Jersey, life spans of replenished beaches are almost always less than 3 years. It is important to note that replenished beaches disappear at uneven rates along their length, and lifespan is defined as the point at which almost all of the beachform has completely disappeared.

Within a given region, however, there may be a wide range in the durability of replenished beaches (Pilkey and Clayton, 1989). For example, south of Cape Canaveral, FL, beach durabilities range from the experience of Miami Beach which has lasted more than 12 years without major renourishment to that of nearby Jupiter Island which typically needs extensive renourishment every 3 years or so.

The regional differences in beach durability on the USA east coast appear to be very generally related to average wave energy and frequency of storms, both of which generally increase from south to north along this shoreline reach. Higher wave energies and more frequent storms lead to shorter replenished beach life spans. However, other factors are clearly involved. For example, the 1978 replenished beach on Tybee Island Georgia, a shoreline reach tucked within the low wave energy Georgia Bight was largely lost within a year.

Pilkey (1989) suggested a thumbnail method for use in estimating beach durability on the USA east coast. It is based on the largely emperical *regional beach durability* experience from past replenishment projects. Pilkey (1989) suggests using the following relationship to obtain a rough estimate or to make a rough check on the volume of sand required for initial replenishment.:

$$V_l = (X/_n)v \qquad \text{(Eq. 1)}$$

where: V_l is the total volume of sand required to maintain a design beach of a given length (**l**), **n** is the assumed interval of required major restoration (for Florida, n = 9 years, for New Jersey, n = 3 years, and for the remaining East Coast barriers, n = 5 years), **X** is the desired project life or design life, and **v** is the volume of initial fill placed along beach of length (**l**).

The factor **n** in Eq. 1 is based on Table 1 in Pilkey (1989) which is a summary of beach replenishment performance on USA east coast beaches. With increased experience in replenishment of neighboring beaches the factor should be adjusted accordingly.

Eq. 1 integrates the replenishment experience over reaches of hundred of miles. Alternatively, one can use strictly local beach durability experience if such is available. Local could be defined as beaches separated by a few tens of miles. In general this may be more accurate than the regional approach, but local factors such as proximity to an inlet or variations in local sediment supply could result in large differences in replenished beach behavior on adjacent shoreline reaches.

Previous experience on the same beach should provide the most accurate barometer of all for prediction beach response and lifespan. The more nourishments the more useful.

The success in using previous experience as a design guide will depend in large part on the quality and extent of physical monitoring of beaches. Using nourishment intervals as a measure of durability of beaches is generally not valid. Politics and economics rather than beach condition often determine the schedule of beach nourishment.

CONCLUSION

Numerical and analytical models have not yet achieved the degree of sophistication and/or accuracy required to be dependable for engineering application on ocean beaches. This has already been recognized by Dutch and some Australian replenished beach designers. Current predictive, deterministic engineering models are based on faulty and oversimplified assumptions, produce results that are of unknowable accuracy, and give the user a false sense of confidence in beach design. The alternatives to the use of models avoid these pitfalls. While they may seem overly simplistic, they have many benefits: low cost, based on real historic beach behavior or the behavior of nearby beaches, and greater intellectual honesty in that they do not fool the user into false confidence.

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