Mathematical Modeling of Beach Behavior Doesn't Work

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ABSTRACT
The use of mathematical modeling to predict the behavior of beaches does not work. Some of the major assumptions behind the models used by coastal engineers in the United States are wrong or are unverified. In addition, the models are deterministic and fail to account for the uncertainty of storms or for the chaotic nature of the nearshore environment. The Dutch and Australians do a better job of predicting beach behavior with an observational approach, predicting how a particular beach might behave in the future by studying its past behavior.

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Introduction

Beach replenishment is now the most common form of shoreline stabilization along the US east coast barrier-island shoreline. Design of replenished beaches, usually by the US Army Corps of Engineers, involves doing an extensive mathematical description of the behavior of beaches. My interest in these mathematical models started when it became apparent from a survey of the national beach-replenishment experience that predictions of artificial-beach life spans were consistently way off the mark. In all but a very few cases, the US Army Corps of Engineers or local consultants underestimated the costs and overestimated the lifespans of the artificial beaches.

The accuracy of beach-replenishment predictions is not necessarily a simple function of the quality of the analytical or numerical models. The beach-design process is deeply mired in the political process, where both Corps of Engineers officials and city and state politicians often seek the lowest possible estimate of replenished beach cost and the best possible estimate of benefits, so taxpayers will not object to paying for the new beach.

To understand the role of the models in engineering beach design, my graduate and advanced-undergraduate students and I have conducted seminars over the last three years in coastal-engineering mathematical modeling. Among other things, we examined the assumptions behind the mathematical equations used in the models, a task that does not require any particular understanding of the models *per se* but does require an understanding of coastal processes. The bibliography section of this article is a list of papers that could be used as the basis for such a seminar. The bulk of the comments made here are the result of "discoveries" made in those classes.

Our investigations have convinced me that mathematical modeling for coastal-engineering purposes is misguided. Modeling can't work in a system where processes are poorly known, and, in fact, can't be measured. For example, we don't know how to meaningfully measure the behavior of waves in the storm-surf zone, and, even if we could measure them, we don't know in detail how waves in a surf zone transport sand. To put it bluntly, we do not have any means of measuring rates of sand transportation in surf zones except in the most indirect way.

Mathematical modeling has become very fashionable today. Perhaps modeling works when materials of known strength and behavior are involved, but it should never be applied to systems where major parameters are unknown. At the very least one should not take answers from such models seriously for engineering purposes. We also believe that modeling in other fields could benefit from the kind of assumption analysis we have undertaken.

The alternative to the modeling of beach behavior is to accept the fact that nearshore-sediment behavior is not understood well enough to be modeled for engineering purposes. Design of beach projects, such as replenishments or jetty construction and so forth, should be based on a combination of experience in the region and a qualitative understanding of shoreline processes. There are, for instance, large regional differences in the lifespans of replenished beaches (Pilkey, 1988). South Florida beaches, for example, last much longer than New Jersey beaches (seven to nine years compared to one to three years). Thus engineering estimates of the replenished-beach durability could be based on experience with similar beaches on neighboring shorelines.

Instead of using mathematical modeling, the Dutch (Verhagen, 1992) and Australians (Smith and Jackson, 1993) conduct careful studies of beach profiles for a number of years before and after beach replenishment and try to understand and imitate the natural system on a particular beach. For example, on the Gold Coast of Australia engineers built an offshore sand bar to the same dimensions observed on the same beach after typhoons had passed by. The artificial storm bar definitely prolonged the life of that particular replenished beach.

I have a coastal-engineering associate with whom I have had a long dialogue about numerical and analytical models. He argues that, "Yes, there are problems with these models but we're getting closer to reality all the time." I believe we are not getting closer to reality, and what troubles me is that coastal-engineering modelers are so sure of their methods that they aren't even going into the field to check the basic assumptions behind the models.

In exasperation, I recently wrote my associate a letter urging him to pretend that he is a man from Mars and to take a fresh look at engineering models. Since this letter nicely summarizes my personal analysis of beach modeling, it is being reprinted here.

A Letter to a Friend

Dear ______:

Do me a favor and pretend you've just arrived from Mars. You know nothing about mathematical models or sand transport or beaches, and you want to educate yourself on the subject. You're fascinated by the fact that the earth has oceans and that people build structures right next to shorelines in spite of the fact that the shoreline is known to be moving in a landward direction. So you talk to some engineers about how they halt shoreline erosion and also some geologists and oceanographers about their view of how shorelines work. You learn that people whose communities are threatened by the sea either build hard engineering structures like seawalls or replenish beaches by pumping in new sand or they move buildings back.

The engineers tell you the basic assumption behind virtually all their predictive shoreline-behavior models is that there is a shoreface profile of equilibrium. The shoreface is the nearshore zone on the inner shelf that extends seaward from the beach to a change of slope (usually at around 10 m water depth on the North American Gulf and Atlantic coastlines). This profile anywhere in the world is described by the equation (Bruun, 1954; Dean, 1991):

$$Y = AX^n,$$

where Y = distance offshore,
X = water depth, and
A and n are constants.

Naturally, you are curious about how the equation was derived. It turns out that least-squares-regression fits of this equation on 500 cross-shore profiles were used to obtain A and n. The value of n ranged from 0.03 to 1.4 for the real-world profiles with an average of 0.66. Coastal engineers decided to use n = 0.66 for all profiles. This bothers you a bit because many profiles will not be accurately described by that particular value of n. Is this a good place to use averages?

You are told that A is related to grain size and are shown the original master's thesis (Moore, 1982), where this idea was developed. You replot, to arithmetic scale, the log-log plot from the thesis and find that no conceivable relationship exists between grain size and A in the sand-size range. Now you're really puzzled. How can engineers say that the shape of every sandy shoreface in the world can be described based on grain size if the relationship connecting grain size to the equation is nonexistent?

Well, even if the mathematic concept doesn't work, maybe the physical concept of the shoreface profile of equilibrium is a good one. You are told that the shoreface is assumed to be covered by a more or less uniform cover of unconsolidated sand-size sediment that is distributed by the interaction of wave orbitals with the sea floor. As the water gets deeper, there is less and less interaction with the sea floor until a point known as closure depth is reached. This is a depth beyond which no significant amount of seaward transport of sand occurs. In recent beach replenishment projects, closure depth has been defined to range between 4 m in Florida, 6 m off Maryland, and 9 m off North Carolina.

Being a man from Mars with lots of skepticism and curiosity, you talk to some geologists and oceanographers about these assumptions. They tell you that grain size on the shoreface off the US east coast and Gulf of Mexico coast barrier islands is quite irregular. There are even outcropping rocks and mud layers on the shoreface, which must affect the profile of the shoreface and shoreline-retreat rates. During storms, a great deal of sediment is probably moved by bottom currents that pick up grains suspended by breaking waves and move them long distances. Closure depth on even a short time scale clearly does not exist. Sediment from natural beaches as well as from replenished beaches has been found far beyond the supposed closure depth and well out on the continental shelf. More important, strong currents moving in a seaward direction across shorefaces are well documented and were first suggested by oceanographers (for example, Ekman) at the turn of the century. Scour channels, some mapped immediately after storms and some not, have been seen extending across the shoreface. It is almost certain that these channels form by cross-shoreface transport.

So, the shoreface profile-of-equilibrium equation doesn't work, and the concept of the profile is based on nonexistent oceanographic and geologic principles (Pilkey and others, 1993). It's hard for you to believe that a shoreface profile of equilibrium as defined and used by engineers even exists!

Next, you examine the other assumptions behind some numerical and analytical models used to predict the behavior of beaches. Among these are the GENESIS model of Hanson and Kraus (1989), the SBEACH model of Larson and Kraus (1989), the "longshore transport equation" and "beach length equation," of Dean (1983), and something called the "overfill ratio" of James (1975). First you note that these all depend in one way or another on the profile-of-equilibrium concept with its accompanying invalid assumptions of closure depth and sand transport by waves only and its presumed general applicability. All these models are used to predict the behavior of beaches for engineering purposes, but none of them takes storms into account. By now you have learned that the margin between the earth's sea and land areas undergoes major disturbances called "storms" and that their frequency, intensity, direction, and duration cannot be predicted. Thus it makes sense to you that predictions of beach behavior, environmental impacts, replenished-beach lifespans, costs and benefit/cost ratios should reflect some of these uncertainties. You are surprised that the models are not probabilistic, and you are told that this is so because the body (Congress) that hands out money for projects doesn't want to deal in uncertainties. You ask what kind of legislative body would accept such meaningless estimates, and what kind of scientific/engineering agency would give the legislative body numbers they know are wrong.

You have been fortunate enough to observe a few storms, and you find that the surf zone is quite complex – often consisting of waves coming from several directions at once, all simultaneously affected by local winds and storm surge. The models however assume that waves striking a beach are nice clean monochromatic waves. You also learn that most of the time the assumed waves for a beach are based on wave data from deep water. The waves are "brought into" shallow water using tenuous assumptions. Most startling of all, you find that no one really knows how waves erode, transport, and deposit sand, so another layer of tenuous assumptions is laid down.

Finally you learn from geologists that a whole host of factors that may control sediment transport are not considered in the models. These include the presence or absence of offshore bars, shell lags, bedforms, beach state, and a myriad of other "initial conditions." The vast numbers of uncertainties almost surely mean that beach behavior should be treated as chaotic. Unfortunately, the engineering models continue to treat these complex systems as simple, deterministic systems.

By now you have to be shaking your head in disbelief. Of course, those who use the engineering models for beach behavior must understand that these very fundamental problems exist. Haven't they applied these models and found them to be lacking? Certainly they can't come up with correct answers.

You review the experience the engineers have had in applying their models to actual shoreline situations, and you find they have been very unsuccessful. Although numerous claims of success have been made, you discover that most of the "successes" are part of the "calibration" and "verification" process used in mathematical modeling (McAnally, 1989; Oreskes, 1994). In this procedure, constants are altered and fudge factors are inserted, so the model will successfully predict known past shoreline behavior. Such adjusting of a model based on past beach behavior is a far cry from successful prediction of beach behavior for previously unengineered beaches. What you do discover is that the frequent predictive failures are attributed to unusual or unexpected storms, characterized as bad luck or even tragic "acts of God." Sometimes "politics" are blamed for unsuccessful projects. Can you imagine an engineer who designed a bridge that fell down, claiming that "politics" were responsible for the failure?

When you point out to engineers the fatal flaws in their mathematical models, they argue that "one should not throw out the baby with the bath" and that "although the models may not be perfect, they're the best we have, and they must do until something better comes along." They go on to tell you that your criticism amounts to saying: "If one does not know everything, one should do nothing." They also give you the old, "We've been using asprin for centuries without really understanding how it works" argument. Apparently they have not recognized that the difference between aspirin and mathematical models of beach behavior is that the former works and the latter do not.

It's all very amazing!

With best regards,
ORRIN H. PILKEY
Frustrated Geologist

P.S. Don't miss Sam Smith's startling editorial on this subject in the latest *Journal of Coastal Research* (1994, v. 10, no. 2, p. iii-viii).

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References

Bagnold, R.A., 1963, Beach and nearshore processes, Part I Mechanics of marine sedimentation: *in* Volume III, The Sea, Interscience Publishers, John Wiley, NY, p. 507-528.

Bruun, P., 1954, Coastal erosion and development of beach profiles: U.S. Army Beach Erosion Board Technical Memorandum No 44, U.S. Army Corps of Engineers Waterways Experiment Station, 79 p.

Bruun, P., 1962, Sea level rise as a cause of storm erosion: Proceedings of the American Society of Civil Engineers, Journal of the Waterways and Harbors Division, v. 88 (WWI), p. 117-130.

Dean, R.G., 1977, Equilibrium beach profiles: U.S. Atlantic and Gulf Coasts: Department of Civil Engineering Technical Report No. 12, University of Delaware, Newark, DE.

Dean, R.G., 1983, Principles of beach nourishment, *in* Komar, P.D., editor, Handbook of coastal processes and erosion, CRC Press, Boca Raton, FL, p. 217-231.

Dean, R.G. 1991, Equilibrium beach profile: Characteristics and applications: Journal of Coastal Research, v. 7, no. 1, p. 53-84.

Hallemeier, R.J., 1981, Seaward limit of significant sand transport by waves: An annual zonation for seasonal profiles: U.S. Army Corps of Engineers, Coastal Engineering Research Center, Coastal Engineering Technical Aid No. 81-218 p.

Hanson, H., and Kraus, N.C., 1989, GENESIS: Generalized model for simulating shoreline change: Technical report CERC89-19, U.S. Army Corps of Engineers waterways Experiment Station, Vicksburg, MI, 185 p.

Hanson, H., 1989, GENESIS – A generalized shoreline change model: Journal of Coastal Research, v. 5, no. 1, p. 1-27.

James, W.R., 1975, Techniques in evaluating suitability of borrow material for beach nourishment: Technical Memorandum no. 60, U.S. Army Corps of Engineers, Coastal Engineering Research Center, 81 p.

Kraus, N.C., 1988, The effects of seawalls on the beach: An extended literature review, *in* Kraus, N.C. and Pilkey, O.H., editors, The effects of seawalls on the beach: Journal of Coastal Research Special Issue no. 4, p. 1-28.

Kraus, N.C., Larson, M., and Kriebel, D.L., 1991, Evaluation of beach erosion and accretion predictors: American Society of Civil Engineers, Coastal Sediment '91, p. 572-587.

Krumbein, W.C., and James, W.R., 1965, A log normal size distribution model for estimating stability of beach fill material: Technical Memorandum, no. 16, U.S. Army Coastal Engineering Research Center, 17 p.

Larson, M., and Krause, N.C., 1989, SBEACH: Numerical modeling for simulating storm induced beach change: Technical Report CERC 89-9, U.S. Army Corps of Engineers Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, MI, 265-67 p.

McAnally, W.H., 1989, Lessons from ten years experience in 2d sediment modeling, *in* Wang, S.S.Y., editor, Sediment Transport Modeling, American Society of Civil Engineers, New York, p. 350-355.

Moore, B., 1982, Beach profile evolution in response to changes in water level and wave height: M.S. Thesis, University of Delaware, Newark.

Nairn, R.B., 1991, Problems associated with deterministic modeling of extreme beach erosion events: American Society of Civil Engineers, Coastal Sediments '91, p. 588-602.

Oreskes, N., Shrader-Fredrette, K., and Belitz, K., 1994, Verification, validation and confirmation of numerical models in the earth sciences: Science, v. 263, p. 641-646.

Pilkey, O.H., 1988, A "thumbnail method" for beach communities: Estimation of long term beach replenishment requirements: Shore and Beach, July, p. 23-31.

Pilkey, O.H., 1993, Can we predict the behavior of sand: In a time and volume framework of use to humankind (editorial): Journal of Coastal Research, v. 9, p. iii-iv.

Pilkey, O.H., and Wright, H.L., 1988, Seawalls versus beaches, *in* Pilkey, O.H. and Kraus, N.C., editors, The effects of seawalls on beaches, Journal of Coastal Research, Special Issue no. 4, p. 41-66.

Pilkey, O.H., Young, R.S., Riggs, S.R., Smith, A.W. Sam, Wu, Huiyan, and Pilkey, W.D., 1993, The concept of shoreface profile of equilibrium: A critical review: Journal of Coastal Research, V. 9, no. 1, p. 255-278.

Shore Protection Manual, 1984, U.S. Army Corps of Engineers Waterways Experiment Station, Coastal Engineering Research Center, Volumes 1 and 2, see especially v. 1, chapter 5.

Smith, A.W. Sam, 1994, The coastal engineering literature and the field engineer (editorial): Journal of Coastal Research, v. 10, p. iii-viii.

Smith, A.W. Sam, and Jackson, L.A., 1993, A review of Gold Coast nourishment 1972-1992: Report to the Gold Coast City Council #181, 66 p.

Verhagen, H.J., 1992, Method for artificial beach nourishment: Coastal Engineering 1992, Chapter 190, p. 2474-2485.

Weggel, J.R., and Perlin, M., 1988, Statistical description of longshore transport environment: American Society of Civil Engineers, Journal of Waterway, Port, Coastal and Ocean Engineering, v. 114, no. 2, p. 125-145.

Weggel, J.R., Douglass, S.L., and Tunnell, J.E., 1988, Sand bypassing simulation using synthetic longshore transport data: American Society of Civil Engineers, Journal of Waterway, Port, Coastal and Ocean Engineering, v. 114, no. 2, p. 146-161.

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Food for Thought

. . . the belief that folk societies, "primitives" in an earlier, more judgemental parlance, were more harmonious and hence better adapted than larger, more urbanized societies is so ancient and deeply entrenched in Western thought that it has taken on the quality of a myth, a sacred story not to be challenged.

Robert. B. Edgerton, 1992, *Sick Societies – Challenging the Myth of Primitive Harmony*: New York, The Free Press, 278 p. (from p. 202)