

CHAPTER 345

Risk-Based Analysis of Coastal Projects

Edward F. Thompson¹, Member, ASCE, Michael Wutkowski², Member, ASCE,
and Norman W. Scheffner¹, Member, ASCE

Abstract

Coastal engineering usually embodies large uncertainties about attacking forces and coastal/structure response. The coastal engineer must address these uncertainties with judgement and experience, supplemented with some level of direct probability analysis. The nature and scope of risks related to coastal projects are reviewed. Analysis approaches developed for wider engineering application, where risks are usually better defined (e.g. Ang and Tang 1975, 1984; Harr 1987), may be less effective in coastal engineering. Two accepted general approaches for risk-based analysis of coastal projects are discussed. The approaches are illustrated with an example shore protection project.

Introduction

The approach for analyzing coastal projects is undergoing some fundamental changes, shifting from the traditional deterministic emphasis to a more comprehensive probabilistic, risk-based methodology. The changes strongly impact both planning and engineering phases of project formulation and design.

The changes, which can be expected to be distilled into a new standard for coastal practice by the end of the decade, are driven by several progressive developments. First, our understanding of probabilistic coastal processes continues to advance, particularly due to advances in field measurement, physical modeling, and numerical modeling.

¹ Research Hydraulic Engineer, US Army Engineer Waterways Experiment Station, CEWES-CR, 3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6133, USA.

² Civil Engineer/Programmer, US Army Engineer District, Wilmington, CESAW-EN-C, P.O. Box 1890, Wilmington, NC 28402-1890, USA.

Second, standard computing capabilities are increasing rapidly, facilitating lengthy probabilistic calculations which would have been impractical in the past. Third, engineers, cognizant of limitations in the traditional approach, are often eager to implement better procedures, provided that they are well-founded and clearly improve the analysis. Finally, the public is becoming more aware and concerned about coastal project performance, and they expect realistic project analyses. In the U.S., public involvement in coastal projects is further intensified by legislation which increases the proportion of costs borne by the client (typically state or local government) in Federal projects.

Traditional vs. Risk-Based Analysis

Traditional analysis treats a coastal project in deterministic terms. The forces of nature are often represented as a design significant wave height, period, and direction, a design water level, etc. Coastal response is described as *the* response if no project is implemented, *the* response if one plan is implemented, *the* response if another plan is implemented, etc., without much formal recognition of the wide variation in possible responses.

In contrast to traditional analysis, some significant developments in probabilistic treatment of coastal projects have appeared during the 1990's. Most relate to coastal structure design (CIRIA/CUR 1991, ICCE 1992). Within the U.S. Army Corps of Engineers (CE), water resource planning guidance has moved from a deterministic to a risk-based approach, which incorporates considerations of risk and uncertainty. Similar concepts are now being adapted to CE coastal engineering studies (U.S. Army Corps of Engineers 1996).

Reasons for Risk-Based Analysis

There are a number of reasons why coastal projects in the broader sense, not just structure design, may be effectively analyzed from a risk-based point of view, as follows (Table 1):

1) *Coastal forcing is probabilistic.* Wave characteristics vary greatly both over short term (individual waves) and long term (from one sea state to another). Similar considerations arise with winds, water levels, infragravity waves, and currents.

2) *Coastal engineering embodies major uncertainties.* Knowledge of both the forcing processes and coastal response usually involves major uncertainties.

Table 1. Reasons for Risk-Based Analysis of Coastal Projects

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| <ol style="list-style-type: none"> 1) Forcing is probabilistic 2) Major uncertainties in behavior 3) Damage & functional performance change incrementally 4) Benefits & risks not fully represented in deterministic terms 5) Uncertain effects on adjacent areas |
|--|

Deterministic representations mask the uncertainties and can be misleading.

3) *Damage and functional performance change incrementally.* Coastal projects rarely progress from the design condition to total failure during a single storm event. Damage usually occurs incrementally. For example, damage to a rubble mound breakwater (when it occurs) typically begins during an unusually severe storm and progresses during subsequent severe storms until repairs are done. Similarly, beach fills erode incrementally in response to storms over a period of years. Coastal projects often continue to provide some measure of functional benefit even in a damaged state. A damaged breakwater continues to provide some protection from incident waves; a partially eroded beach fill continues to reduce coastal flooding risks.

4) *Benefits and risks not fully represented in deterministic terms.* Because of the above factors, positive impacts and risks of coastal projects cannot be fully represented in deterministic terms. Some projects provide benefits beyond the design configuration, which are generally ignored in traditional practice. For example, a nearshore berm which is over-built to allow for progressive deterioration provides increased coastal protection during its early life. Another example is an over-dredged entrance channel giving increased vessel access depths until it shoals to the design depth.

5) *Uncertain effects on adjacent areas.* In addition to the uncertainties associated directly with coastal projects, the projects can introduce significant possibilities for changing adjacent areas. While projects are designed with the intent of minimizing adverse impacts on adjacent areas, it is important to recognize that uncertainties and risks can increase beyond the without-project condition. In effect, a project can transfer risk from one area or party to another. When the risks of *all* major aspects of a project are represented as best they can be determined, better-informed final decisions can be made.

Experienced coastal engineers are well-aware of the concerns in Table 1. Even with deterministic methods, they can be expected to produce project plans which include a large measure of professional judgement to insure a technically successful project. However, the ultimate fate of a project can depend upon higher level decision-makers who must weigh technical concerns against economic, environmental, aesthetic, social, and political concerns. By quantifying risks, the coastal engineer can better pass his or her experience and judgement on to other decision-makers, who may not have coastal expertise.

Considerations for Including Risk-Based Analysis in Project Design

Objectives. The main objectives of adopting a risk-based analysis approach rather than a traditional approach are to explicitly identify uncertainties, provide improved information for assessing tradeoffs between risks and cost, and improve decision-making

for project optimization (Table 2).

Key Variables. Although a large number of variables affect any coastal project, a small subset can usually be identified as *key variables*, that is variables which strongly relate to project performance. The key variables will embody the

main forcing mechanisms, project sizing, and project response. For example, some of the key variables for a beach nourishment project might be significant wave height (forcing), beach fill width (project size), and erosion width (response).

Professional Judgement. Coastal engineering requires an unusually large measure of professional judgement because of the number and complexity of processes and responses involved. Analytical and modeling tools help to represent the variability affecting coastal projects, but the judgement of an experienced engineer is a vital ingredient in risk assessment and project optimization.

Resistance and Functional Performance Vary with Time. Both the resistance to damage and functional performance often vary significantly over a coastal project's design life. For example, the resistance (or structural strength) of a rubble mound breakwater may decrease in time due to deterioration of stone such as loss of angular corners, cracking, and breaking. Resistance may also decrease due to displacement of stone and exposure of underlayers to wave attack, which would also decrease protection provided by the breakwater (functional performance). For a beach nourishment project, loss of material to storms decreases the resistance of the beach to future storms. The effectiveness of the beach as a deterrent to coastal flooding is also decreased (functional performance). In some cases, resistance *increases* with time, as in the progressive growth of protective vegetation on coastal dunes and natural cementation of beach sediments rich in calcium carbonate.

Construction Season and Mobilization Concerns. Often maintenance of coastal projects requires major mobilization efforts and is confined to a *construction season* dictated by climate and environmental factors. Therefore the risk during the *interval between construction seasons* rather than during a single storm becomes a key concern. During an unusually stormy winter (such as the winter of 1987-88 in southern California), this risk can be significantly greater than that for individual storms.

Environmental, Aesthetic, Social, and Political Concerns. The role of environmental, aesthetic, social, and political factors in the ultimate planning and design of a coastal project is often at least as important as the technical engineering factors. An optimized final design includes appropriate consideration of these factors and their

Table 2. Objectives of Risk-Based Analysis

- Explicitly identify uncertainties
- Provide improved information for assessing risk vs. cost tradeoffs
- Improve decision-making for project optimization

associated risks and uncertainty.

Frequency-Based vs. Life Cycle Approach

Risk-based analysis of coastal projects can be done by either of two fundamentally different approaches. The *frequency-based approach* deals with frequency-of-occurrence relationships among the key variables. By combining key forcing variables with various occurrence frequencies, information about the frequency-of-occurrence of key project responses can be developed. For example, a traditional stage (water level) vs. frequency curve and a stage-damage curve can be combined to generate a damage vs. frequency curve. This approach can be applied as an add-on to traditional planning and design procedures.

The *life cycle approach* deals with multiple realizations of possible evolution of the project with *time* during the span of its design life. The suite of life cycle realizations is constructed with consideration of the probabilities of key variables. For example, the realistic time variation of key forcing and response variables during a 50-yr life cycle can be generated for 1000 different possible life cycles. Uncertainty in the data and models relating natural forcing to coastal response can be represented as another source of variability. Probabilities and risks associated with the project are then compiled by analyzing project performance over the 1000 life cycles.

An example shore protection project helps to illustrate the life cycle approach in comparison to a more traditional frequency-based approach. The project area is a relatively uniform stretch of beach with several rows of houses along the shore (Fig. 1). The example project is a beach nourishment to widen the existing beach and dune (Fig. 2). The frequency-based approach used for this example is based on a set of six storms representing 5-, 10-, 25-, 50-, 100-, and 500-year events. Expected erosion of the existing or project beach profile and property damages are calculated for each storm. An average annual damage is calculated by integrating over the range of storm probabilities. For each year of the project life span, the shoreline is retreated according to a long term erosion rate and calculations of annual damage are repeated. Total damage over the project life span is the sum of the annual damages. This more traditional approach produces a single result based on a single set of storms and response parameters. There is no indication of confidence level of the answer. The example project shows net benefits of \$980,000 over a 50-year life span and a benefit/cost ratio of 2.4.

The life cycle approach in this example embodies sequences of storms (including provisions for multiple storms of varying intensity during each year of the life cycle), erosion and post-storm recovery during each event, partial and complete property damage during each event (depending on water level, waves, extent of storm erosion, and type of building construction), cumulative property damage due to a succession of storms, optional repair or rebuilding after a suitable time lag (with conformance to any stricter building codes in effect), and periodic renourishment of the beach when needed

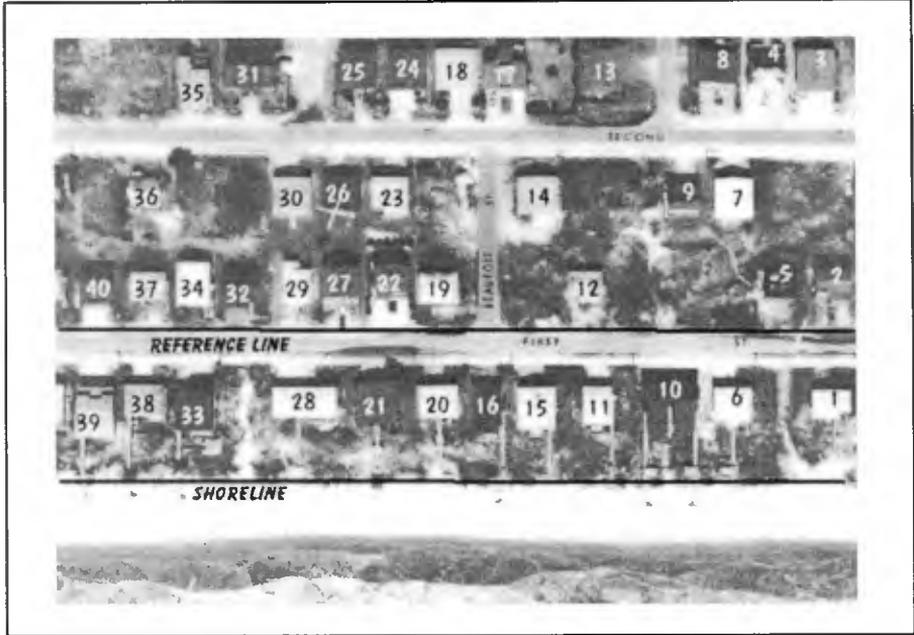


FIG. 1. Sample Section of Coastline

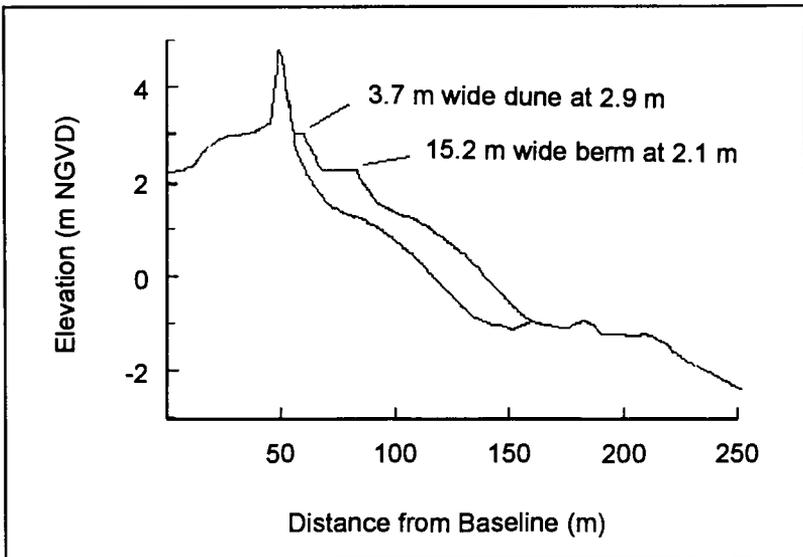


FIG. 2. Example Project Profile

and feasible during the life cycle. A key result from this analysis is the renourishment required during each life cycle, which can be converted to an economic present worth dollar value. The costs and net benefits in this example vary over a wide range, depending on the occurrence of major storms during the life cycle simulation (Fig. 3). The expected cost and economic risks associated with maintaining the beach can be realistically assessed by condensing information from many different life cycle simulations (Figs. 4 and 5). The mode and mean net benefits are \$275,000 and \$814,000, respectively (Table 3). There is a 65% probability that the net benefits will be less than the \$980,000 amount calculated by the more traditional frequency-based approach. There is a 7% probability that the net benefits will be negative (cost of the project exceeds the damages prevented). Negative benefits come from simulations with mild storm climates. While net benefits are used to optimize a project, the benefit/cost ratio is also of interest (Table 3 and Fig. 6).

Statistic	Net Benefits (\$1,000)	Benefit Cost Ratio
Mode	275	1.50
Mean	814	3.09
Standard deviation	649	1.59
Maximum value	3557	8.92
Minimum value	-119	0.67
Number of cases	7000	7000

The life cycle approach appears better suited to most coastal engineering applications. Variation with time is an essential ingredient in most coastal projects, and it is directly incorporated into the life cycle approach. Time variation of resistance and functional performance, constraints imposed by construction season and mobilization, even some economic, environmental, and political factors, can be conveniently and flexibly introduced into the life cycle approach. This approach leads to a unified analysis of technical performance and many economic factors which are critical to project success. As illustrated in the above example, the life cycle approach provides valuable information relative to the objectives of risk-based analysis (Table 2). In addition to its technical and economic strengths, the life cycle approach is more easily understood by nontechnical parties involved with a project. This type of approach is evident in the Empirical Simulation Technique (Scheffner et al. 1996) and CE guidance in preparation (U.S. Army Corps of Engineers 1996).

Typical Project Elements

Risk-based analysis can be integrated into the major planning steps of a coastal engineering project. Typical project elements which are especially well-suited to

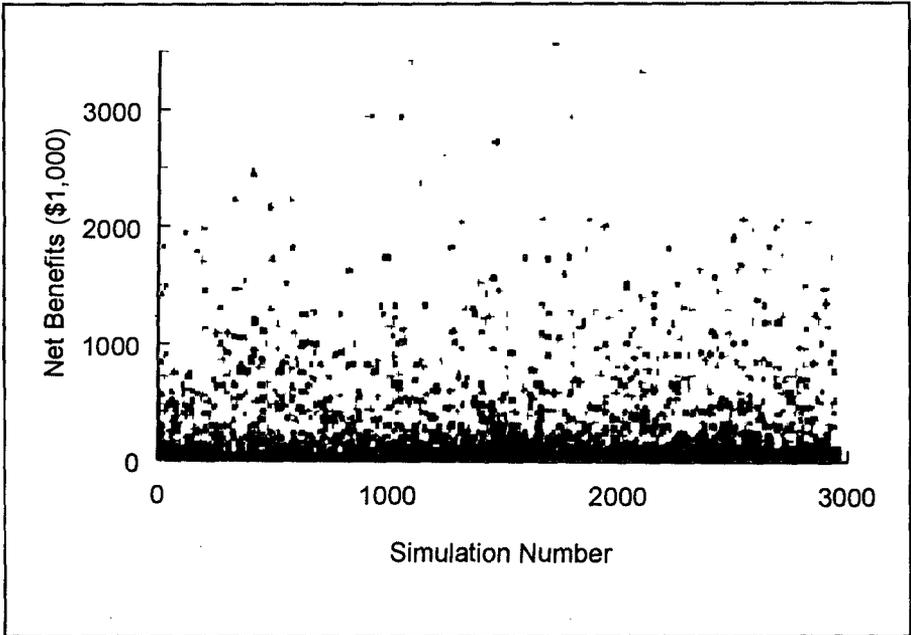


FIG. 3. Unsorted Risk Results

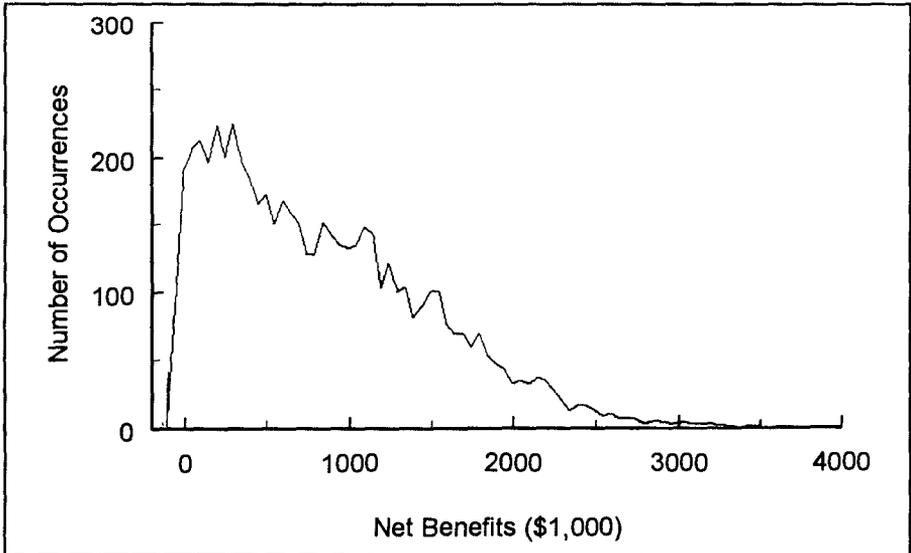


FIG. 4. Net Benefits, Probability Density Distribution

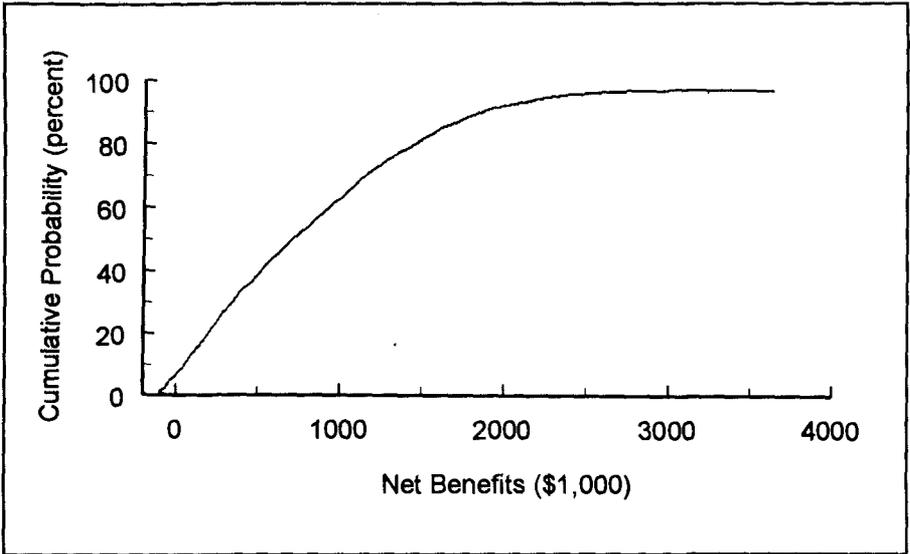


FIG. 5. Net Benefits, Cumulative Probability Distribution

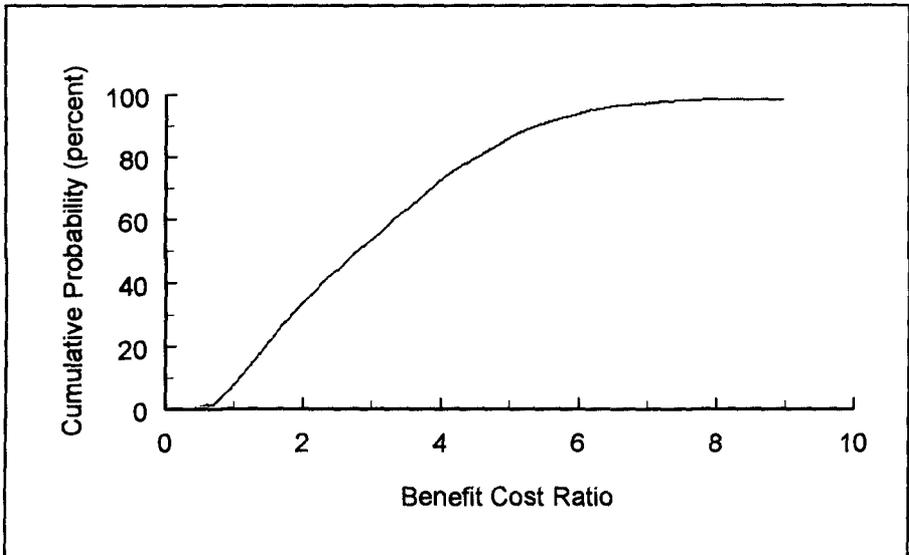


FIG. 6. Benefit Cost Ratio, Cumulative Probability Distribution

risk-based analysis include the following:

Site Characterization. Significant uncertainty can arise in documenting past and present behavior at a site. The uncertainty can be estimated based on data quality and quantity, methodologies used, observed variability, etc.

Without Plan Alternative. Evaluation of what would happen in the future if no project were built involves speculation about the natural processes and human interventions which would affect the site during the proposed project life. The impact of the *without plan* alternative is conveniently described in probabilistic terms.

Formulate, Evaluate, and Compare Alternative Plans. Risk-based analysis can be a powerful tool for formulating and comparing alternative plans. It enables decision-makers to intercompare not only the expected level of performance, but also the probabilities of enhanced or reduced performance levels, which can differ greatly among alternatives. Typically, alternatives involve hard structures (such as walls, revetments, breakwaters, and jetties) and/or soft structures (such as beach nourishment projects, coastal dunes, and nearshore berms). Risk-based analysis of hard structures is increasingly being considered in planning and design (CIRIA/CUR 1991, ICCE 1992). Soft structures involve calculated risks about the movement of sediment through time and the need for future maintenance. Uncertainties arise in forcing processes, sequencing of storms, initial state of nearshore profile when storms occur, and evolution and recovery of storm profiles (especially three-dimensional aspects). The life cycle approach to risk analysis has been shown to be a powerful tool in this type of application.

Conclusions

The following conclusions are reached regarding risk-based analysis of coastal projects:

- Risk-based approaches provide a powerful tool for analyzing coastal projects.
- Risk-based analyses can lead to improved decision-making for project optimization.
- The life cycle approach is especially well-suited to coastal engineering.

Acknowledgements

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