Design Strategy in a Coastal Environment

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Potential Improvements in Civil Engineering Design Techniques for Coastal Zone Planning ■ ■ ■ November, 1972; DEL-SG-7-72

Sea Grant No. GH-107; College of Marine Studies
University of Delaware, Newark, DE. 19711

DESIGN STRATEGY IN A COASTAL ENVIRONMENT

Potential Improvements in Civil Engineering Design Techniques for Coastal Zone Projects

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DEL-SG-7-72

This is a final report of research sponsored
by NOAA Office of Sea Grant, Department of
Commerce, under Grant No. GH-109

College of Marine Studies Publication No. 2EN-100

November 1972

PREFACE

The authors wish to express their appreciation to all those who supplied the data and background information necessary to prepare this report, much of which comes from unpublished documents, letters and conversation. Such documentation is by nature unpolished, incomplete, and subject to wide interpretation. From it the authors have derived conjecture and opinion and they trust that it is recognized with tolerance as such, without the need for further qualifying statements interspersed throughout the text.

In particular, the authors wish to thank:

Mr. J. Clyde Morris, Executive Director, and Mr. Leon R. Johnson, Chief Engineer of the Chesapeake Bay Bridge and Tunnel District who, with great courtesy and frankness, not only provided a superb tour of their fine bridge, but also a candid resume of their experiences over the last ten years of operation.

Mr. C. M. Metcalf, Partner, Sverdrup and Parcel, for sending preliminary engineering reports on the Chesapeake Bay Bridge and Tunnel.

Mr. John C. Volk, Jr., Chief Engineer of the Delaware River and Bay Authority, who let us borrow private reports on the Lewes-Cape May Ferry and possible bridge crossings.

Mr. Gordon S. Bjorkman, Instructor, Department of Civil Engineering for his active participation throughout the preparation of the report; and, later, the direction of the typing, layout, and reproduction.

Professor David P. Billington who not only supplied information and commentary on the Oosterschelde Bridge but, with Professor Robert Mark, also organized the first Princeton Conference on "Civil Engineering - History, Heritage, and the Humanities" which, in large measure, inspired this study.

The National Science Foundation, the National Oceanic and Atmospheric Administration, and other Federal or State agencies are free to use the contents in any way which serves the public interest, but are requested to respect the intention of the authors to publish material from this report at a later date.

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1. INTRODUCTION

1.1 Difficulties of Construction in the Coastal Zone

The coastal zone - the region where sea and land interact with each other - attracts development and industry for many reasons. It is attractive recreationally, so it is in demand for private homes, hotels, parks and so on. It is attractive to industry as the sea represents easy access to raw materials, a source of cooling water and a sink for the disposal of wastes. Ports are necessary transportation interfaces which must be built in the coastal zone.

Engineering in a coastal environment is, however, technically demanding. Waves, currents, high winds, variable soils, corrosion and tidal fluctuations combine to create a highly dynamic system in a geologic sense and one, at any instant, held in precarious balance susceptible to dramatic, even catastrophic change with only slight external provocation. Often, in fact, other non-mechanical factors such as the vegetation, marine life and water chemistry are necessary to maintain the overall equilibrium.

It is not surprising that engineers, given such a sensitive milieu, have most often adopted either of two extreme strategies for development work on the coast:

1. Avoiding practically entirely the littoral zone by building inland on dry land or off-shore on platforms with channel, conveyor, road or pipeline transportation.

2. Creating a new "stable" condition by extensive filling and/or dredging with breakwaters or other protective structures thereby removing poor soil, plant and animal life, and ameliorating the mechanical problems of tides, currents, waves, etc.

Engineers have usually been conscious that facilities constructed on the shoreline often affect the nature of the coast in a severe and unpredictable way. Hartley(1), reporting on the effects of large structures on the shore of Lake Erie, notes that they "...have caused build-up of beaches on their updrift sides and accelerated erosion downdrift. The effects are not balancing, in that the length of eroding shore is ordinarily five or more times the length of the shore which is protected by build-up."

1.2 Need for a Broader View

It is becoming clear that engineers in charge of the planning and design of coastal structures are beginning to take a broader view of the problems involved and to expand the scope of the factors considered in design beyond the traditional range of technical questions. This broadening of scope is necessary for various reasons. It must come about:

1. because Environmental Impact Statements are required by law, for structures above a certain size;
2. because society expects consideration of environmental consequences. Dee(2) has classified these into four categories: aesthetics, cultural, ecological and quality, and all four must be considered. Currently, the last two categories receive most stress, but the first two are also important;

3. because in the coastal zone, any ecological disturbance usually propagates to some distance from its source;
4. because short-term solutions to a coastal zone problem often have undesirable long-term consequences.

There is, however, no established precedent or methodology by which engineers can look at broader problems. There is no academic discipline which has dealt with overall considerations until very recently. Although environmental impact statements are required by law, there is no universally accepted way of obtaining them.

The broadening of design issues that is taking place must lead engineers to seek innovative solutions which take into account the increased constraints applied to coastal zone designs. The public, which is the ultimate client, will no longer be satisfied with purely cost-constrained structures.

Some of the difficulties produced by a too-narrow planning horizon may be seen in the case study discussed in the next section, which also shows (given the great benefit of hindsight) some ways in which the design might have been improved.

1.3 Aims of the Report

There is evidently a need for some sort of help to be provided for designers of coastal zone structures; this report explores means of providing such help and concludes that further case studies and research ending with the production of a design-aid handbook along the lines of the Corps of Engineers comprehensive Shore Protection Manual(3) is fully justified. Suggestions for such a handbook are derived by considering the process of design as a system, and then by investigating the activities that comprise the system and the information it requires. This analysis shows up areas where classifications, checklists, information sources and other design aids are most needed. Most important perhaps is the development of criteria and techniques for evaluation useful in various degrees of sophistication throughout the design process to control optimization, show up areas of weakness, and finally, judge the project. Case studies provide the illustration, give standards for comparison and opportunity for commentary. A handbook of this nature combining methods, aids, illustration and commentary can be expected to be widely used in practice.

2. VIADUCTS - A CASE STUDY

2.1 Preliminary Remarks

Perhaps the structural form which is most typical and which best exemplifies civil engineering design is a bridge. In a marine setting, bridges are generally multiple span for long crossings in which case they are commonly called viaducts. As shown in Figure 1, viaducts can be roughly classified by span, which in turn reflects their purpose and the economic constraints of building. At one extreme is the magnific and expensive suspension structure with draped cables, which is suitable for particular conditions such as high clearance over a wide channel to accommodate deep-water vessels. At the other is the less spectacular and less expensive trestle of relatively short span used to traverse long distances over shoals or lakes where wide commercial shipping channels are not cut. In the middle ground are the arches, tied bridges with straight suspenders, and modern orthotropic plate girders of intermediate span and expense. Often a variety of types are combined in a long viaduct.

Of all forms of marine bridges, the viaduct remains the most rare and least studied, particularly in the United States. However, as the coastlines and lakeshores of the world are developed and amalgamated into national high-speed transportation systems, the

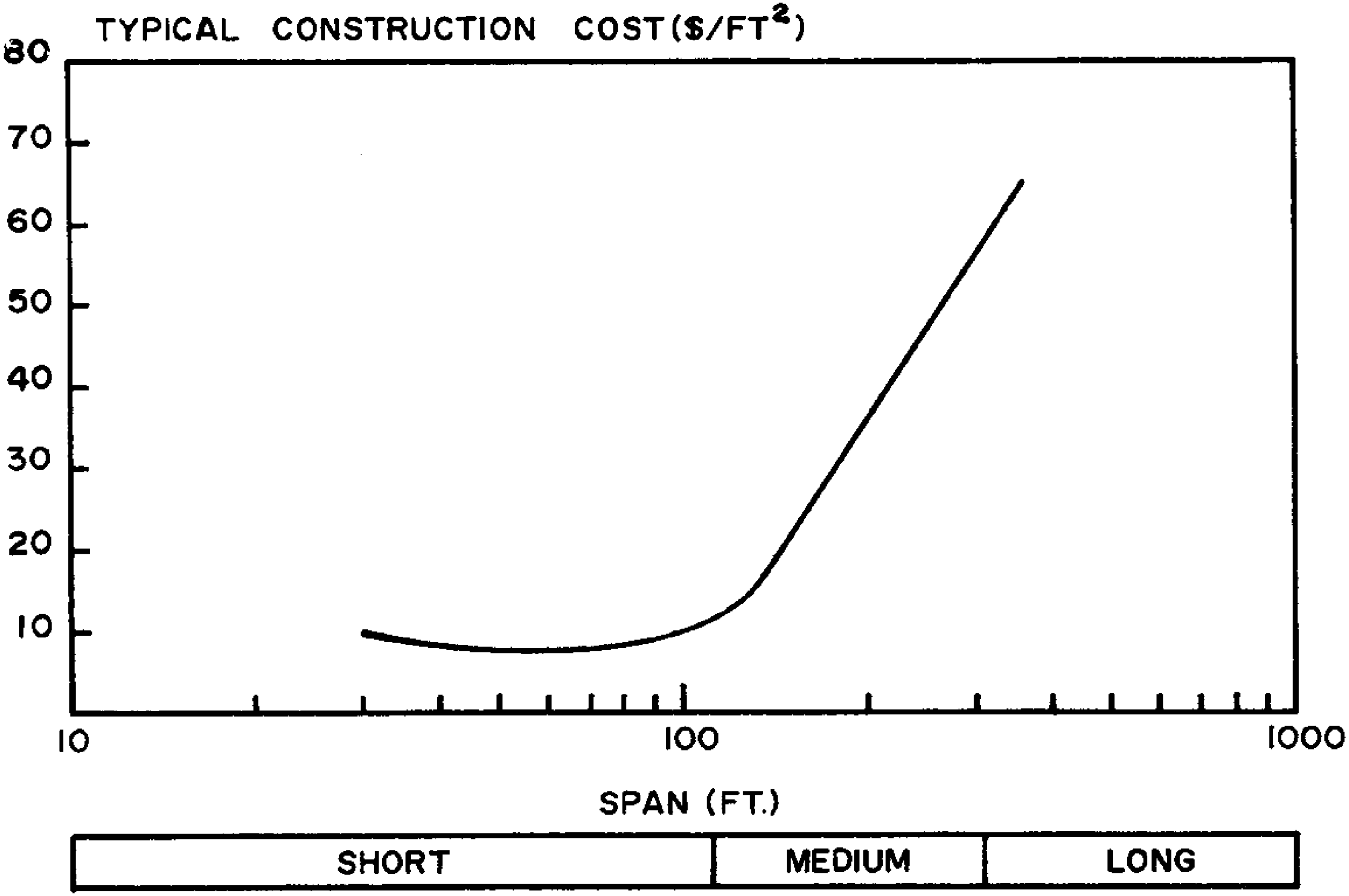


FIGURE I: VIADUCT CLASSIFICATION BY SPAN design and construction of long-distance viaducts across major estuaries, rivers, lakes and even sections of the ocean have become increasingly attractive as alternatives to more circuitous land highways, particularly when forced through urban developments or prime recreational land. The Lake Pontchartrain Bridge and its later counterparts such as the trestle portion of the Chesapeake Bay Bridge and Tunnel, all essentially of the same design, provide the primary example of this form in this country. Additional crossings at sites such as Cook Inlet, Long Island Sound and Delaware Bay are being proposed and appear potentially viable. Thus, it is important that this type of bridge, and more specifically, the Chesapeake Bay Bridge and Tunnel, as representing a standard style and technique, be evaluated both as a case study in itself and as it compares to alternative forms.

In this way, overall strategies for marine viaduct design may be explored, and more general aspects of making decisions on goals, design factors, evaluation procedures and other aspects of engineering development in the marine environment may be clarified. Such discussion should, in turn, highlight the need and help determine the format for a systematic approach to the general design procedure, and classify the many research needs in this developing area.

2.2 The Chesapeake Bay Bridge and Tunnel

2.2.1 Description

- The Chesapeake Bay Bridge and Tunnel is the first and by far the longest viaduct yet built essentially in the exposed ocean. Boyer(4) in his article for the National Geographic gives an excellent general description of the project but no comprehensive technical evaluation has yet been made. The greatest portion is 12.2 miles of low-level trestle or viaduct over relatively shallow water of 20 to 30 feet in depth in areas with no established navigational routes. In addition, to make up the shore-to-shore distance of 17.6 miles, there is 1.6 miles of earth-fill causeway across Fisherman Island and part of Fisherman Inlet, two bridges spanning Fisherman Inlet and the North Channel totaling 4,250 feet, the 5,450 foot Chesapeake Channel Tunnel and the 5,738 foot Thimble Shoal Tunnel. Each tunnel is flanked by five-acre entrance and exit islands. The project received no tax funds and was financed by a $200,000,000 revenue bond issue.

Although somewhat different in detail, the trestle design is essentially that used in the previous crossings of Pensacola Bay and Lake Pontchartrain(5). The trestle consists of 75 foot long spans 30 feet above mean low water made of prestressed concrete girder and deck sections simply supported at each end by three hollow prestressed concrete piles which are filled with sand for additional lateral strength before capping. The completed roadway has 18-inch safety walks on each side and a curb-to-curb width of 28 feet.

Figure 2: Layout of the Chesapeake Bay Bridge and Tunnel

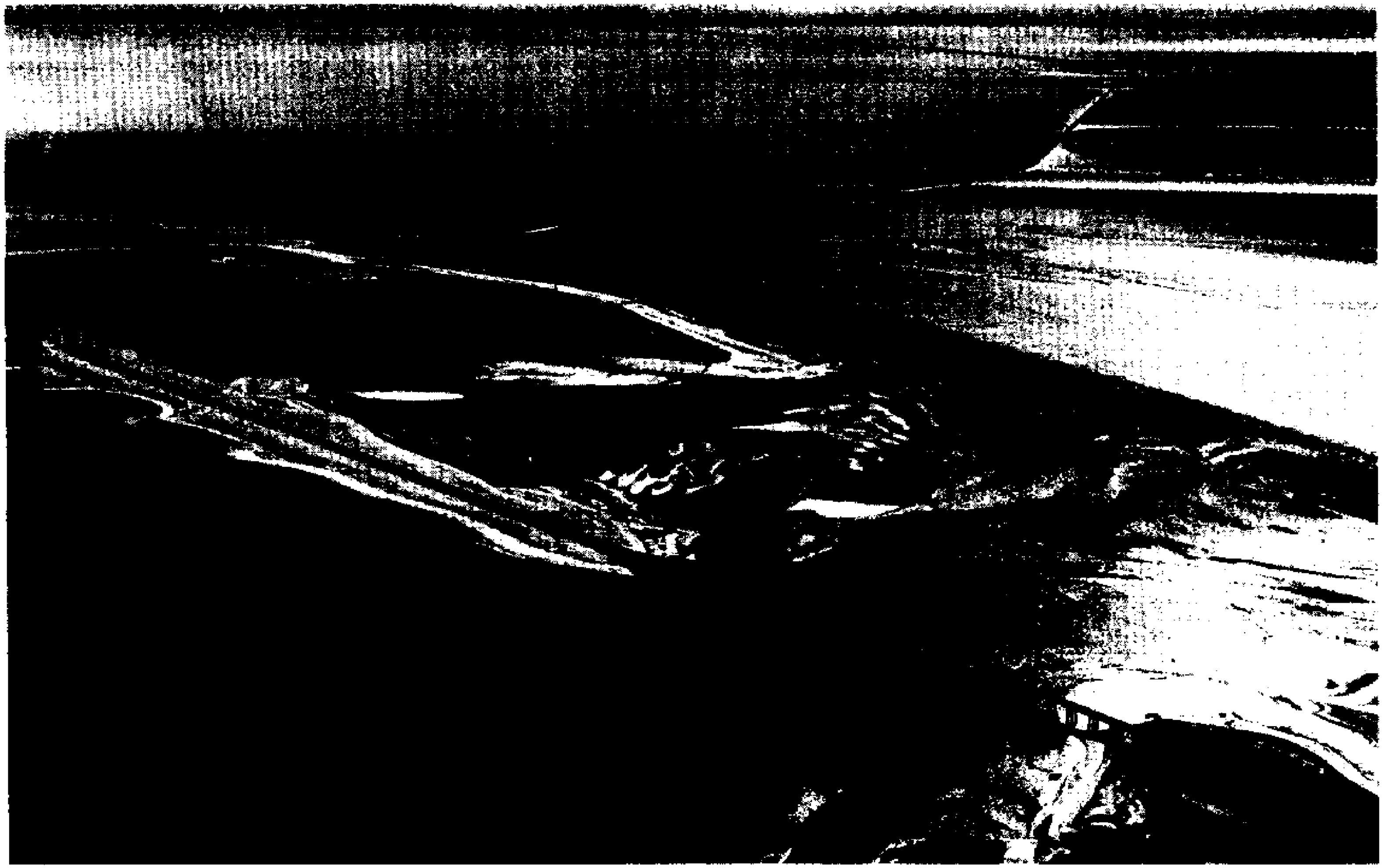


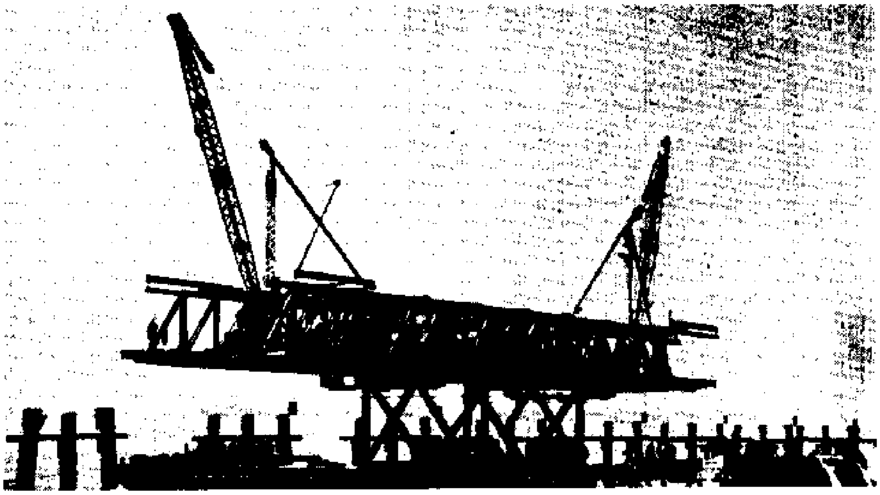
Figure 3: The Chesapeake Bay Bridge-Tunnel as Seen From the Northern Terminus on the Eastern Shore of Virginia

It is axiomatic that, for long viaducts, repeated duplication of a few different types of pieces and design for construction ease and efficiency are of utmost importance. Thus, standardized girder-deck sections, pile caps, and pile lengths were fabricated on an assembly-line basis at a special plant at Cape Charles. The 5-inch thick, 54-inch diameter piles, 60 to 172 feet long weighing 800 to 1,000 lbs/ft were fabricated from sections of various lengths up to 16 feet cast by the patented "Cen-Vi-Ro" process and post-tensioned together. After being barged to the site, they were driven from a special DeLong type "walking" platform. Each group of these piles was cut to the correct elevation whereupon the caps used to tie each group of three piles together into a bent were placed and concreted to the pile from a 175-foot long traveling bridge. Finally, each of the two inner and two outer girder units weighing 75 tons was set on the bent caps by a self-propelled derrick mounted on a steel box girder spanning the completed bents. After transversely post-tensioning the four girders together at the ends and third points, aluminum guard rails, cable trays for utilities, lighting standards and a thin asphalt surfacing completed the viaduct.

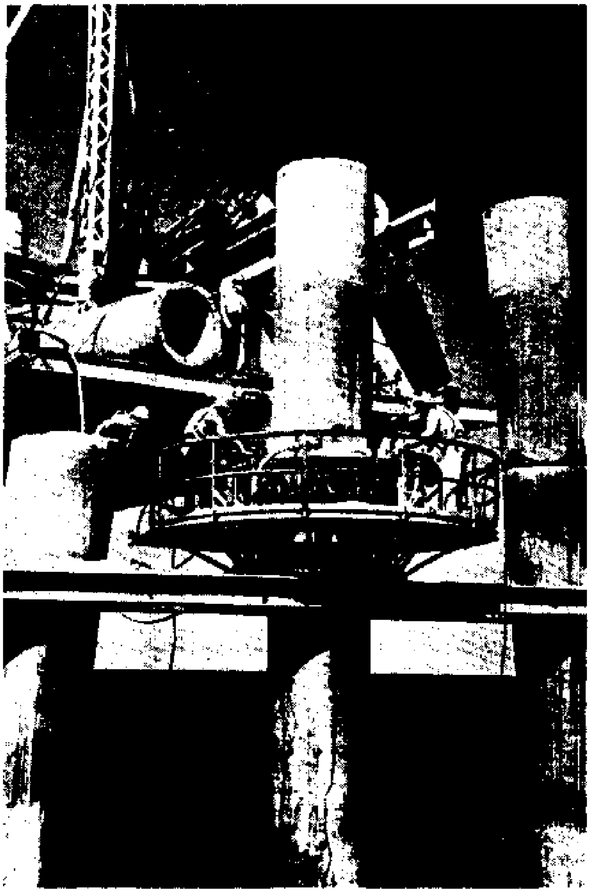
Final total construction cost of the trestle portion of the project was 31 million dollars or $\$17/\text{ft}^2$ where fees for engineering administration, legal services, utilities, tests and miscellaneous items have been prorated. An additional cost arose later when a serious scour problem developed necessitating the

a) Driving Piles

c) Setting Pile Caps



b) Cutting Piles



d) Placing Deck

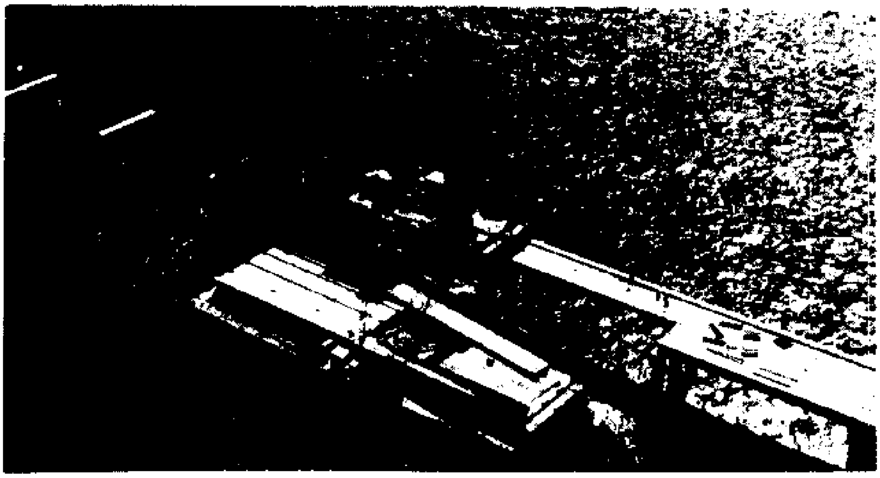


Figure 4: Construction Process

placement of rock dykes or blankets on either side of the trestle. This work is continuing and, in time, will probably be necessary the entire way. This will bring the cost to at least $\$19/\text{ft}^2$.

2.2.2 Design Procedure - Consideration during the preliminary design phase(6)(7), where the crucial decision on the basic type of crossing was made, primarily involved location and the related questions of navigational requirements, soil conditions, current velocities, and anticipated wind and wave loads. Although long-span, high-level bridge sections were rejected in favor of tunnels at the two major channels, alternatives to the basic structural type of viaduct were apparently not suggested. Choice of the Lake Pontchartrain type trestle seems to have been established immediately on the basis of prior art with decisions on slight modifications in span, height, and structural layout made to accommodate more severe construction and service conditions.

Evaluation of decisions by the strictly traditional serviceability, safety, and economic criteria was accepted as sufficient. Environmental impact, recreational possibilities and debate as to aesthetics were not used as decision aids. At a total construction cost of $144,000,000 and an average annual operating and maintenance expense of $815,400 the anticipated revenues from traffic provided sufficient justification to proceed.

2.2.3 Current Status - Traffic across the Chesapeake Bay Bridge and Tunnel is only 60% of the projected average daily volume of

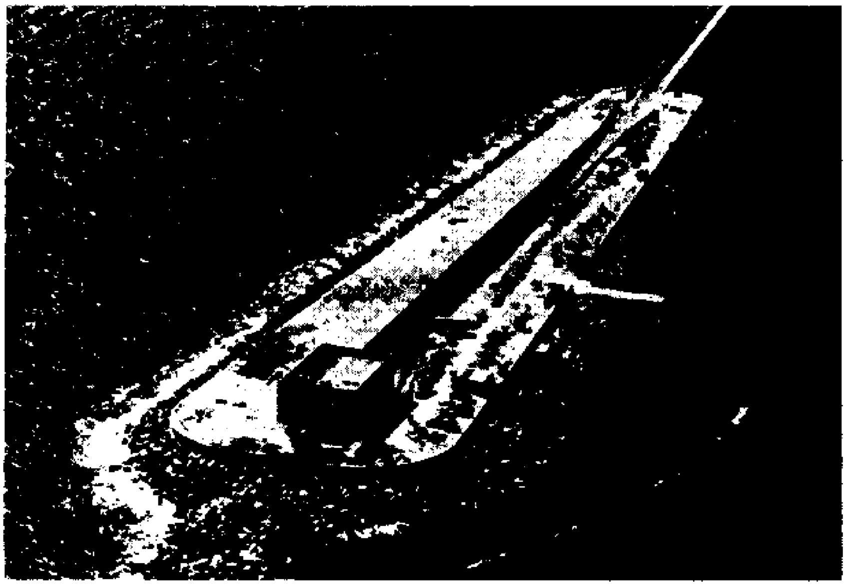
8,000 cars per day by 1972. The "District" as a result has had a default on the interest on the series C bonds. Though currently gaining at a rate of 10% per annum which is twice the rate of increase projected in the preliminary study, it will be some years before the break-even point can be achieved when, in turn, the volume of traffic will approach the capacity of a two-lane highway recommended by AASHO.

A series of collisions with the viaduct has compounded the financial difficulties. The first two of these, involving a Navy LST and an acid barge, broke a few piles but repairs did not require a shutdown. However, the collision of a 400-foot vessel which struck and then bounced along "A" trestle necessitated a two-week closing while the recent ramming by the Navy ship "Yangtse" knocked out several spans and caused a two-month closing. This last accident resulted in a net $9,000,000 loss after the insurance settlement; and, perhaps more severe, the loss of future coverage placing the District in the highly vulnerable position of now being self-insured against ship collision.

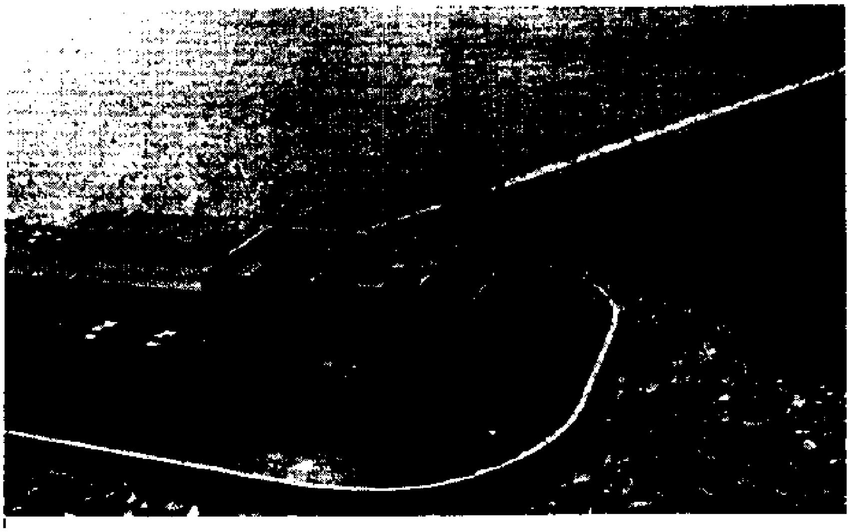
Erosion has been most extensive around the ends of the artificial islands and in the North Channel where the deep channel (which historically has always shifted) has now moved under the trestle beyond the truss span. With a maximum tidal velocity of 6 ft/sec, scour below the bell housing on some piers occurred over a period of only a few weeks as the North Channel shifted requiring intensive efforts in dumping rock around them for protection. The Fisherman Inlet Bridge and north end of the causeway which is protected by a rock blanket have suffered no erosion since the Corps of Engineers maintains a stable channel for the Inland Waterway. However, the installation of a wood groyne was necessary to prevent the eastern bank of the causeway from being eaten away.

Acting like a reef, the bridge provides food and protection for marine life and fishing has improved dramatically. The bottom fish drawn to the piles and rock islands in turn attract the sport fish. Similarly, demand for a restaurant has developed far beyond the capacity of the small snack bar on South Island near the fishing pier. Moreover, the parking space is scarcely adequate and the turn-off to it is cramped and dangerous. Although a branch of the Inland Waterway goes between Fisherman Island and the Cape, no provision to service or turn this resource into an integral benefit of the project has been made. The low profile and short span of the trestle do not allow passage of any but the smallest classes of sail boats. There are no picnic facilities, docking provisions, or camping areas on Fisherman Island.

Functionally, the bridge works well with no undue hazards to the driver or excessive maintenance. The ride is poor due to the alternating rise over the cambered girders and fall to the discontinuity at the joints all in a 75-foot interval. Wind-blown

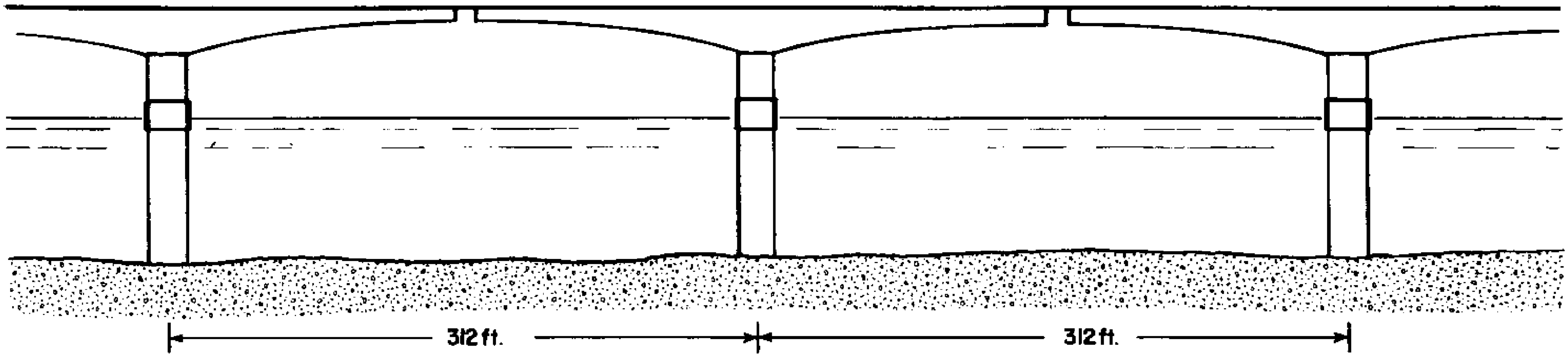


a) Under Construction

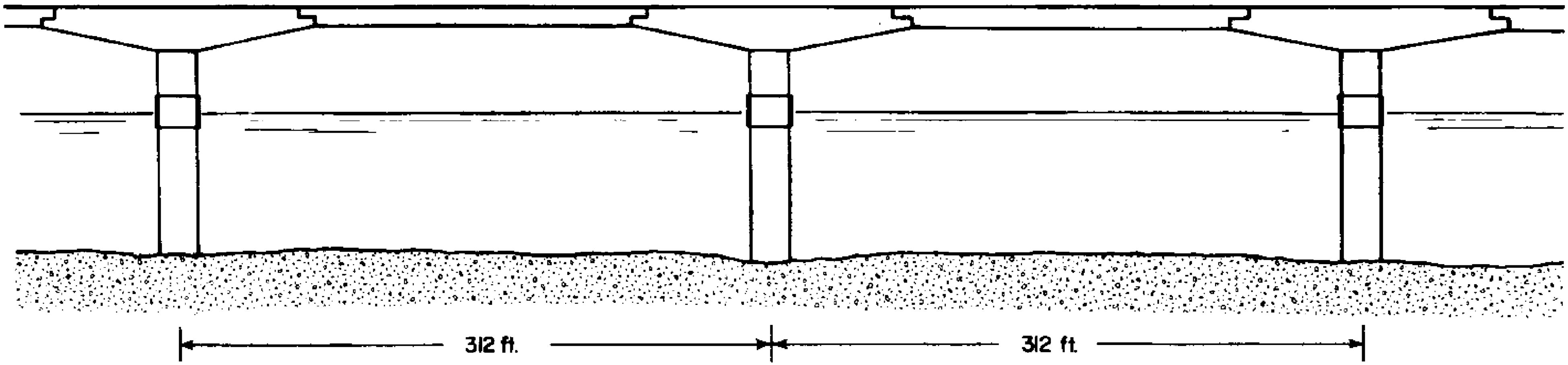


b) With Snack Bar and Fishing Pier

Figure 5: South Island



BRIDGE AS CONSTRUCTED



ALTERNATIVE DESIGN

Figure 6: Alternates for the Oosterschelde Bridge

sand from Fisherman Island can occasionally be distracting. Movement of the islands due to relative settlements has caused some cracking of the sea wall around them and required road repairs and releveling at entrances to the tunnels. With an unusually able staff, engineering department, and administration, the CBBT District apparently has little trouble with upkeep, and the major difficulties from scour and ship collision have been met with dispatch and efficiency.

2.3 Alternative Types

2.3.1 The Oosterschelde Bridge(8)

As part of the Delta Plan for the Netherlands, an investigation in 1962 showed that existing ferry facilities for crossing the Oosterschelde would shortly be inadequate, and it indicated a permanent viaduct financed by toll revenues to be the best solution. The result, completed in 1966, was, until this year, Europe's longest bridge and is a suitable example of a number of such bridges built by the cantilever method in Europe in the last decade using standardized precast segments post-tensioned together.

The total length of the bridge is 16,500 feet or slightly over 3 miles with a width of 39 feet. The clearance of 49 feet allows free navigation to sailboats and practically all other shipping using the waterway. In addition, a bascule bridge was provided. The long span length of 312 feet was chosen to minimize scour and the lateral loads from ice flows as well as from other economic considerations. Due to a water depth of over 100 feet in some places and the necessity of long embedment lengths as well, a foundation system consisting of three piles per pier was chosen. The choice of using precast segmental construction was made to minimize construction time and to allow prefabrication under sheltered conditions rather than on the site which was virtually in the open sea. The size of the piles which were nearly 14 feet in diameter and 200 feet long in some cases, along with savings in erection time, made the choice of very-large prefabricated units attractive.

The final design reached was a series of T-units cantilevered from the piles with a special shear connector/lateral shock adsorber/expansion joint at the center of each span. This alternative effected about a 50 percent saving in quantity of concrete used for the superstructure as compared to a preliminary cantilever design shown in Figure 6. A box section with a deck slab cantilevered on either side was chosen for the superstructure. The depth of the box girder varying from 6.22 feet to nearly 18 feet over the piers followed the dead-weight moment diagram. Sections were prestressed together in three directions in an intricate schedule dictated by the construction procedure.

A total of seven different types of section, shown in Figure 7, were cast in the yard and barged to the site. The foundation piles fabricated to the required lengths from 20-foot

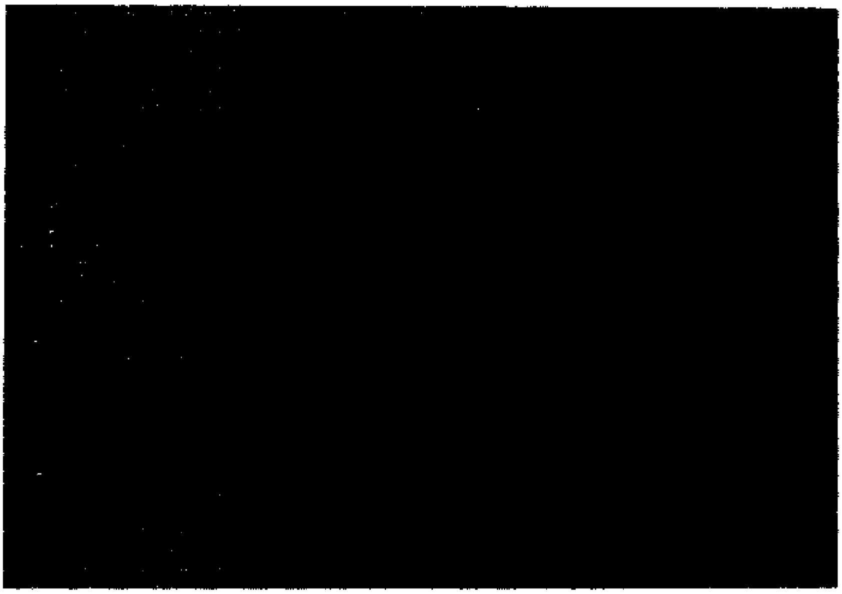


Figure 7: Precast Units

Figure 8: Traveling Overhead Erection Beam

sections were positioned with the help of a 600-ton floating crane and sunk to the desired depth by excavation using a cutter and soil pumping equipment lowered into the shaft. The pile cap was installed using the same crane and grouted in place. Pier units and the hammer section were placed from a vessel especially equipped to suspend them in position (with jacks for fine adjustment) and allow the falling tide to lower them in place. The remaining girder sections were then hoisted into place from a traveling beam as shown in Figure 8.

The contract was let on May 29, 1962 at about 64 million florins or 17.8 million dollars, based on 3.6 florins to the dollar. However, as the project was built under the European system of joint design and construction responsibility (the turnkey approach), this figure includes costs for promotion and financing in addition to design and construction. Moreover, the precasting facilities reputedly amounted to over a third of the total cost ($6 million). Thus, it is difficult to arrive at a design-construction figure for comparison purposes. With these fabrication facilities, the total figure is $\$28/ft^2$, and without them, $\$18.40/ft^2$. If, for direct comparison with the Chesapeake Bay Bridge and Tunnel, they are prorated on an area basis, the price would be $\$22/ft^2$. Finally, estimating promotion and financing at 20% rather than the 27% necessary for the Chesapeake Bay Bridge and Tunnel, the cost of the Oosterschelde Bridge for comparison purposes can be approximated as $\$18/ft^2$.

2.3.2 Other Examples; Classification - Construction technique is the most differentiable aspect of the various types of prestressed viaducts built in Europe over the last two decades. In contrast to precast segmental bridges such as those already discussed are those pioneered by Finsterwalder(9) using cast-in-place segments. Free-cantilever construction is generally used for girder bridges with large spans, while for shorter spans, an overhead traveling beam supported by the piers carries the adjustable formwork. Cantilever construction has also been used for a variety of steel truss bridges, particularly in Russia, and for prestressed concrete suspension shapes with diagonal cables, such as the Lake Maracaibo and Polcevera Creek viaducts. The "stress ribbon" suspension bridge proposed for the Bosporus and the related Rio Colorado Bridge just built in Costa Rica employ precast post-tensioned segments slid along the suspension cables into position and grouted together.

Thus, a great many shapes of different materials built by various methods have been devised for viaducts. In Europe, spans of 200 to 300 feet are the rule and ones twice that are not uncommon. In the United States, spans are generally limited to less than 100 feet with little variety in construction technique. Classification of type by any one criterion is not possible since structural shape, material, and construction procedure are interwoven in an unusually intricate fashion throughout an economic design. Decisions that may not be optimum from a purely structural standpoint as, for example, the choice of simple span rather than continuous girders, may be preferable, nevertheless, due to simplicity in construction. However, such evaluation requires a full consideration of the alternatives organized by some classification scheme such as that shown in Table 2.1. More elaboration with further subheadings is clearly possible. While floating bridges are included in Table 2.1, they are often not true viaducts but more like causeways in that they are supported on continuous pontoons completely obstructing passage.

2.4 Evaluation

Methods for evaluation of facilities built in the coastal zone are discussed in detail later in this report where comparisons under economic, performance, and environmental categories are suggested. It is assumed that for evaluation during design, alternates exist that either were generated internally for the project or are available externally from similar facilities built previously. Therefore, it should be remembered that while it is now easy to find other viaducts for comparison to help in the evaluation of the Chesapeake Bay Bridge and Tunnel, the actual designer was not as fortunate. Moreover, many of the more subjective criteria recognized as highly significant today were not of such concern a decade ago to either the public or their agency commissioning the design. Evaluation of the Chesapeake Bay Bridge and Tunnel by these criteria is no less valuable twelve years

STRUCTURAL TYPE	MATERIAL	ERECTION METHOD
1. Floating	1. Steel a) Welded b) Bolted	1. Cranes a) Floating b) Overhead
2. Girder a) Simple Span b) Continuous c) Cantilever-Suspended Span	2. Prestressed Concrete a) Cast-in Place b) Precast	2. Jacking or Counterweighting
3. Truss	3. Reinforced Concrete a) Cast-in Place b) Precast	3. Free Cantilever
4. Arch	4. Combined a) Composite b) Noncomposite	4. Overhead Traveling Beams a) Launching Gantry b) Pier Supported
5. Suspension a) Draped Cable b) Inclined Cable c) "Stress Ribbon"		5. Falsework
		6. Cable Erection
		7. Temporary Bridge
		8. Float to Site

Table 2.1: Viaduct Classification

DATE	NAME/LOCATION	RIVER/WATERWAY	TYPE (from Table 2.1)	SPAN shortest/longest (ft)	TOTAL LENGTH (miles)	HEIGHT viaduct/main (ft)	WIDTH (ft)	COST* ($\$/ft^2$)
1948-51	San Marcos/El Salvador	Lempa River	5a, 1b, 6	250/669	.42	86	29	31^{**} tc
1955-56	1st Lake Pontchartrain/USA	Lake Pontchartrain	2a, 2b, 1a	56	23.8	16	28	7.9
1957-58	James River/USA	James River	2a, 3a, 1b	88/260	$.79^{x}$	80^{+}	90	21^{**} tc
1958-59	Fox River/USA	Fox River	4, 2a, 5	73/178	.25	40^{+}	59	28^{**} tc
1958-60	Hood Canal/USA	Puget Sound	1, 3b, 8	-	1.2	-	32	++
1958-62	Lake Maracaibo/Venezuela	Maracaibo Lake					57	48^{**}
	a) Suspended Spans		5b & 2c, 2a & b, 1b & 5	525/771	.93	148		
	b) Trestle Spans		2c, 2a & b, 1b & 5	153/279	3.6	84		
1960-62	Champlain Bridge/Canada	St. Lawrence River	1a, 2b, 4a	128/707	4.25	$40^{+}/120^{+}$	90^{+}	17
1960-64	Chesapeake Bay Bridge and Tunnel Trestle/USA	Atlantic Ocean	2a, 2b, 4b	75	12.2	28	28	17
1961-64	Calcasieu Ship Channel/USA	Calcasieu River	2b, 1a, 1b	46/450	1.6^{x}	$15^{+}/135$	65	21
1962-67	Astoria-Point Ellice/USA	Colombia River					++	++
	a) Main Channel		3, 1, ++	591/1232	.46	205		
	b) Secondary Channel		3, 1, ++	354	.60	70		
	c) Trestle		2a, 2b, ++	60	2.0	25		
1962-65	Tay Road Bridge/England	Firth of Tay	2a, 4a, 1a & 7	180/250	1.4	80	58	++
1962-66	Oosterschelde/Holland	Oosterschelde	2b, 2b, 4b	312	3.1	49	39	18
1962-65	Choisy-Le-Roi/France	Seine	2b, 2b, 1a	123/180	.08	25^{+}	93	16^{**}

DATE	NAME/LOCATION	RIVER/WATERWAY	TYPE (from Table 2.1)	SPAN shortest/longest (ft)	TOTAL LENGTH (miles)	HEIGHT viaduct/main (ft)	WIDTH (ft)	COST ($/ft^2)
1962-67	San Mateo-Haywood/USA	San Francisco Bay						
	a) Orthotropic Main Spans		2c, 1a, 1a	375/750	.28	135	80	78
	b) Orthotropic Approach Spans		2c, 1a, 1a	292	.78	-	80	53
	c) Combined Approach Spans		2c, 4a, 1a	208	.79	-	80	50
	d) Trestle Portion		2a, 3b, 1a	30	4.5	20+	60	10
1964-66	Oleron/France	Atlantic Ocean	2b, 2b, 4a	130/295	1.8	80^{+}	35	19^{**}
1964-66	Lower Volta/Ghana	Volta River	2a, 2b, 4a	125	.41	27	38	67tc
1965-68	Polcevera/Italy	Polcevera Creek	5b, 2b, 3	230/689	0.68^{x}	118	60	40^{**}
1966-69	San Diego-Coronado/USA	San Diego Bay	2c, 4a, 1a	144/660	2.0	50^{+}/197	60	52^{**}
1967-69	Chillon/Switzerland	Lake Geneva	2b, 2b, 4a	++/320	1.33	++	86	11^{**}
1967-69	2nd Lake Pontchartrain/USA	Lake Pontchartrain	2a, 2b, 1a	84	24	16	28	8.5
1969-72	Oland/Sweden	Baltic Sea	2b, 2a, 3	115/426	3.8	50^{+}/118	43	15

* Cost is for design and construction at the time built, including superstructure and substructure

** Viaducts where it was not possible to separate costs of short and long spans

tc Figure is based on the total cost at the time built

x Significant portion of viaduct not over water

\+ Dimension is estimated from photographs

++ Information not received at time of publication

Table 2.2: Viaduct Comparison

after the fact but the perspective of historical context must also be appreciated.

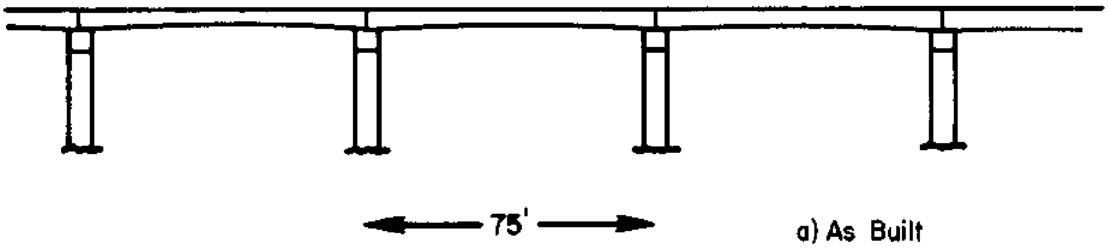
2.4.1 Economic Comparison - Traditionally, economic advantage has been the primary criterion for judging design alternatives. For long viaducts, span length, while remaining one important parameter influencing costs, is certainly not definitive since repetition magnifies rewards from imaginative design and construction procedures. Advantages from careful weighing of alternatives to achieve harmony of structural shape, material, and erection technique all meshed to be mutually reinforcing in a unified system are of major significance. Involved scheduling, special equipment, small design modifications, intricate connections, unusual combination of materials and other details of building usually associated with mass production are all eminently worthwhile if the viaduct is long enough.

A comparison of the Chesapeake Bay Bridge and Tunnel with various bridges also listed in Table 2.2 illustrates the extraordinary extent to which design sophistication can compensate for the inherent expense of long spans and high piers. More specifically, the Oosterschelde Bridge, built under similarly difficult physical conditions in deeper water with four times the span and half-again the height, cost essentially the same per square foot. Moreover, while both employed precast, post-tensioned sections barged to the site for erection by crane and overhead traveling beam, the segments for the Oosterschelde Bridge were eight times the weight and had to be post-tensioned together in intricate progression in the field.

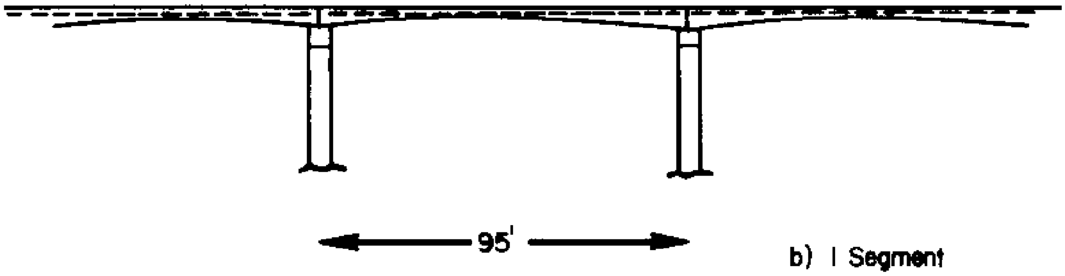
It is difficult to fully account for this cost discrepancy in detail. However, in addition to relative labor costs which bias the figures somewhat, it is possible, with the benefit of hindsight, to conjecture that the following factors seem reasonable at least as a partial explanation:

1. fundamental engineering choices
2. design of details
3. legal system of building in the United States

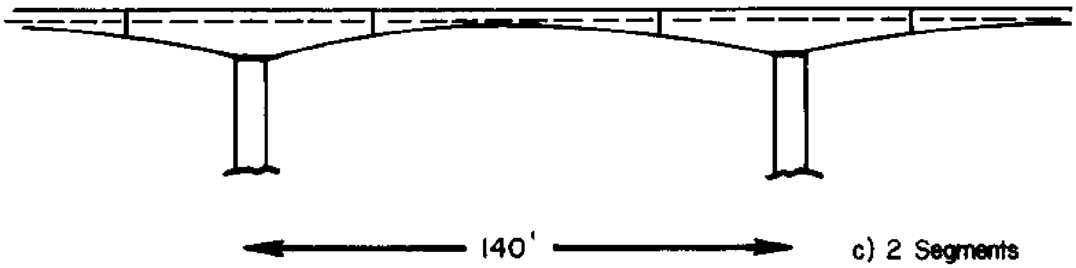
The basic structural system for the trestle is certainly open to question. Simple spans may in some respects be easier to construct, but are far less economic from the standpoint of materials. A saving in material in turn reduces the weight and, consequently, the dead load on the piers. If, for example, the deck of the Chesapeake Bay Bridge and Tunnel were continuous, the 3,600 girders could be reduced in weight by at least a third, allowing an increase in span for the same weight of girder section with great saving in the number of piles and setups for driving them. Thus, using full-span girders weighing 75 tons but post-tensioned for continuity, the span might have been increased to perhaps 95 feet. Using multiple sections, longer spans would be possible as indicated in Figure 9. In all cases there would be complications in the construction due to provisions for expansion joints and field



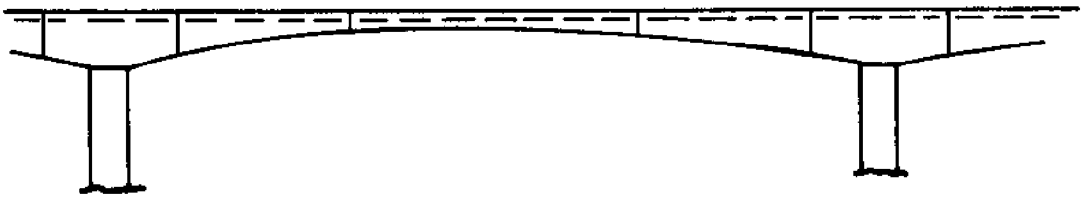
a) As Built



b) I Segment



c) 2 Segments



d) 3 Segments

Figure 9: Conjectured Continuous Alternates (75-Ton Segments)

post-tensioning. However, savings in materials and/or construction costs by adding continuity are large and, from experience with later bridges, can certainly dominate with a careful unified design. Moreover, the added structural integrity may be of value in resisting unusual concentrated surface loads, collision and, in particular, earthquakes. There are other strong arguments for longer, continuous spans from performance and environmental considerations as well.

A second hypothesis is that insufficient design of details contributes to some extent to increased costs. Certainly, in many bridge projects where each part is one of a kind, great attention to detail is not rewarding. For a long viaduct, however, using thousands of identical pieces, the civil engineer is given the rare exercise in mass production usually reserved for the designer of consumer items or standardized plant and machinery. Detailed analysis leading to refinement in the structural shape of each component and the materials employed pays handsome dividends in immediate costs and subsequently in erection expense. As discussed later, the aesthetic benefits from attention to detail should also not be disregarded. For example, the rectangular capping beams, which are not susceptible to simple linear analysis, seem a particularly brutal component of the Chesapeake Bay Bridge and Tunnel. Analysis of this shape by finite elements or photoelasticity would almost certainly have indicated a rounding off at the ends and between piles to be warranted.

Finally, there is the ever-present question of how much the legal way of constructing bridges in this country contributed to excessive costs for the project. In large measure, the previous criticism and conjecture is a consequence of the required separation of duties between design engineer and builder. Moreover, the fee structure based on cost does not promote innovation in design for economy, but instead, penalizes it. Finally, the engineer, particularly when dealing with an unusual structure, on considering who, out of a limited group, can build what he specifies, is constrained toward standard shapes and proven methods so as hopefully to have some competition in bidding and reasonable costs. Thus, neither the overall design concept chosen for the viaduct portion of the Chesapeake Bay Bridge and Tunnel, nor its execution in detail should be surprising, given these constraints to imagination and incentive. To quote the concluding remarks from a paper by T. Y. Lin and Ben C. Gerwick, Jr.:

> The great pioneering steel bridges of the United States were built by an open or covert alliance between designers and constructors. The turnkey approach of designer-constructor has developed and built our chemical plants, refineries, steel plants, and nuclear power plants. It is time to ask, seriously, whether we may not have adopted a restrictive approach by divorcing engineering and construction in the field of bridge construction.
>
> If a contractor-engineer, by some stroke of genius, were to present to design engineers today a wonderful new scheme for long-span prestressed concrete bridges that made them far cheaper, he would have to make these ideas available to all other contractors, even limiting or watering them down so as to "get a group of truly competitive bidders." The engineer would have to make sure that he found other contractors to bid against the ingenious innovator.

> If an engineer should, by a similar stroke of genius, hit on such a unique and brilliant scheme, he would have to worry, wondering if the low bidder would be one who had any concept of what he was trying to accomplish or was in any way qualified for high-class technical work.
>
> Bridge engineers in the United States are constrained to work within the pattern of separation of designer and builder. Can a pattern be evolved which will open the doors for large-scale use of long-span prestressed concrete bridges in the U.S.A.? It is a challenge which we have a professional responsibility to meet.

For long viaducts where benefits from unification of all phases of building are accentuated, this challenge is most appropriate.

2.4.2 Performance Considerations - While designing for economy, performance criteria on safety and serviceability must be met. Factors of safety against collapse incorporate the uncertainties of extreme load conditions, materials, assumptions of analysis, foundation conditions, workmanship, and so forth; and, without detailed knowledge of the various assumptions made, test results, and calculations, it is not possible to evaluate this aspect. From appearance, the design of the Chesapeake Bay Bridge and Tunnel viaduct seems, if anything, conservative except in the unlikely case of earthquake when, from lack of continuity, a total collapse of the roadway might be expected. Also from the standpoint of height above water, a re-evaluation of resistance to extreme hurricane conditions or perhaps a tsunami, say from the Agadir area, piling up on the shoals might be interesting. Analysis of performance, on the other hand, has revealed a major problem with scour and the irritation of a bumpy ride. Interestingly enough, both would likely have been largely eliminated through the choice of longer, continuous spans since fewer expansion joints with smooth transitions and fewer piers to choke off the area of flow would result.

2.4.3 Environmental Effects

A great many factors not easily evaluated can be used to discuss the environmental effects from an engineering development in the coastal zone. In broad context they can be thought of as either "cultural" or "ecological" where the latter term includes physical and chemical changes in addition to those on flora and fauna.

Little change in the ecological balance seems to have been wrought by the Chesapeake Bay Bridge and Tunnel. This would be the general rule for marine viaducts which are "clean" in that they produce no pollution except perhaps during construction. While the physical landscape has been altered somewhat near the ends from shifting sand, this effect is minimal. The islands and trestle serve to generate food and provide refuge for fish, and thereby, on balance, the ecological effect of the structure is perhaps positive.

Environmental effects from "cultural" factors seem significant in the overall assessment of the project. While there is, as yet, no evidence of wide-spread sociological change in terms of new residential patterns, job opportunities, or industry, the increased traffic through the lower Delmarva Peninsula and quick access from the Norfolk area have undoubtedly been felt at a local level. As would be expected, there is no consideration of health involved as there is no pollution connected with the project other than might be associated with increased travel.

Two major environmental criteria remain to be judged however - aesthetics and recreation. The second has been discussed in some detail already in the description of the project when it was noted that not only has sport fishing in the area been improved dramatically, but many opportunities for further recreational and leisure time activities seem possible. The demand for a larger restaurant with more parking on the South Island is most obvious. Utilization of Fisherman Island bordering the Inland Waterway through facilities for various activities might have even a greater impact. Neither of these potential additions are negated by the design, but a consideration of them before construction would most likely have introduced minor alignment changes, differences in the layout and shape of one or more of the artificial islands, and other small provisions that would have made these modifications easier and better at a later date. Certainly they should now be considered, if for no other reason, as sources of revenue.

Of all environmental criteria, aesthetics is hardest to evaluate. Not only is the question subjective and therefore difficult to quantify on an absolute basis, but it is also emotional and therefore difficult to weigh. Certainly for bridges and for long marine viaducts, aesthetic evaluation is extremely important as they are highly visible, very large, and not often dismantled. Moreover, there is perhaps no expression of civil engineering to compare with bridges. As architects revere the cathedral as the most startling expression of their art, so the structural designer looks at the Britannia, Firth of Forth, Brooklyn, or Sydney Harbour Bridges as expressing theirs. Each exemplifies the technical achievement and spirit of its time while still imparting, undiminished today, the emotional impact on viewing, the exhilaration and the wonder which are the prerequisites of a great structure.

No such "marine bridge" has yet been built or at least yet accorded general acclaim by the profession and the public. Certainly, the Chesapeake Bay Bridge Tunnel will not be revered for its beauty. Being the first and by far the longest viaduct in the exposed ocean, it is a technical achievement of historical significance. It is unique and noteworthy, but it is not elegant, graceful, bold or exhilarating, at least in the context of comparison with other viaducts or what might have been accomplished with such an exciting opportunity. The setting is magnificant, the requirements exciting, but the actuality is an anticlimax to the viewer.

There is no question that, in large part, this deficiency is a direct consequence of the basic structural design choices and of the lack of subsequent attention to detail. Short spans of low height supported on columns at various angles seem an imposition on the strong horizon line and give an impression of confusion rather than a graceful expression of structural behavior. Lack of continuity is accentuated by the individual segments which do not flow together expressing their purpose in the transfer of load, but rather appear, as they are, like nothing more than building blocks placed on top of each other. No feel of unified purpose, interaction, or cohesion is achieved in the pieces. The creation was incomplete and the final bridge expresses this conclusion if nothing else.

Comparison with the Oosterschelde Bridge in Figure 10 emphasizes the discrepancy. Both are designed on similar functional criteria, but clearly with no similarity in philosophy. Words such as elegant, graceful, bold, or exhilarating can be translated to more objective phrases such as "expressing function," "sculptural flowing form," "clean geometric lines," "artistic insight and awakening" or, conversely, even more subjective ones like harmony and beauty.

A theory of structural beauty giving criteria and method to criticism should be an essential ingredient of design. In a recent talk, D. P. Billington(11) has more succinctly outlined this mandate:

> ....Beauty will not unconsciously arise out of a search for economy alone. Rather there are personal choices for the engineer and he is to be judged on them.

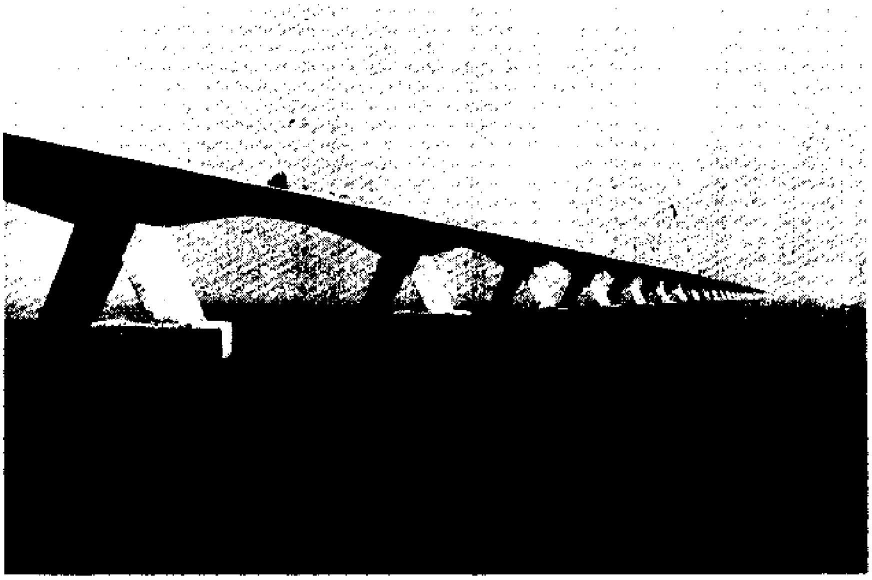


Figure 10: Visual Comparison

> Furthermore, the design ought to exhibit harmony - as the Renaissance designers emphasized - but that harmony need not be strictly mathematical, rather the structure should harmonize with its outer environment and show as well some inner harmony of its elements.
>
> Also design must not violate structure. Although it need not be the very cheapest, it should be competitive. ....Finally, in combining use and beauty, the designing engineer need not avoid some sculpting of the form, but that departure from strict structure needs always to be controlled by construction expense. It is relatively easy to propose novel forms where cost is no object. In a democratic society, where costs for public works should be justified to the public, the search for a unity of use and beauty is difficult and demands dedication.
>
> When easy sculptural fancy pushes up costs, it needs to be publicly criticized; where thoughtless monotony dulls the environment, it needs to be publicly criticized; and conversely, where fine design embellishes without waste, it needs to be praised. But most important, for the usual design - neither really good nor willfully bad - criticism is badly needed to point a way to give to design higher goals and to the general public greater expectations.
>
> So much of past criticism was based upon buildings for church, villa, and the private patron. Now, as the Dutch have for so long recognized, attention must be centered on works for the common good, commissioned and paid for by the public. For these structures to serve fully, there is need for a new criticism, the main burden for which falls inevitably upon those civil engineers who care about the profession and the public it serves.

Evaluation of alternatives in preliminary design can be by a formal grading system of criteria with, perhaps, weighting factors to highlight strong points or deficiencies. When, as for the new San Diego Bridge(12), aesthetics are made the primary focus*, a review board or selection committee may be employed to further judge contesting designs.

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*It was not until after choosing that the selection board learned that their choice would be 4% less expensive than that recommended.

No matter how involved the evaluation process is made, however, one man's vision, the engineer's, will remain as the determining factor. One can only judge alternatives presented. Roebling, Maillart, Eifel, Telford, and Eads built great bridges in spite of controversy and criticism, or perhaps because of it.

2.5 Conclusion - A Possible Delaware Bay Crossing

Speculation as to specifications for a possible Delaware Bay Crossing from Cape Henlopen to Cape May is interesting in itself and can serve as a summary of our case study discussion of marine viaducts. Any engineer proposing a bridge across the Delaware Bay must seriously study the Chesapeake Crossing since they are neighbors and remarkably similar in:

1. distance (about 17 miles),
2. shoreline type,
3. cross section (topography, water depth, sediments)
4. shipping demand,
5. weather, current and tidal conditions.

Moreover, they would complement each other by sharing traffic and jointly attracting it. New Jersey's Garden State Parkway which now runs along the coast to Cape May and then ends would become a through-road providing an alternate highway south around Washington. In fact, a uniform route designation with congressional approval as a named scenic highway could be adopted. Certainly traffic projections must justify any proposal, but support, even financial help, should be sought by Delaware from New Jersey, Maryland, Virginia, and the Federal Government since they would all benefit. Prior studies for the Lewes-Cape May Ferry(13)(14)(15)(16) and a crossing further up the Bay(17)(18) give a good reference base as to traffic, but give little physical data.

Without data for analysis, it is not possible to suggest detailed specifications for a Delaware Bay Bridge or even what types of viaducts might be most appropriate. Suggestions as to what information should be sought from this preliminary survey and how such reconnaissance might be carried out are discussed in later sections. While we might postulate that from Table 2.2 certain options seem unlikely, without data to justify these guesses there is a risk of summarily eliminating precisely that innovative solution, the search for which must be encouraged.

Nevertheless, it is possible from our case study to derive broad guidelines by which ideas can be judged such as, for example, a cost standard for viaducts of perhaps $15 per square foot. Moreover, for consideration of a girder-type viaduct, more detailed suggestions such as those given in Table 2.3 can be suggested.

More important than guidelines or suggestions for design is the selection procedure that should be employed. Criteria for the engineer's internal evaluation of alternates at various stages of design are discussed in succeeding sections. However, the same or a similar evaluation procedure must also be employed by the owner, both on final alternates submitted by one or perhaps more

SUGGESTIONS	ADVANTAGES		
	COST	PERFORMANCE	ENVIRONMENTAL
1. Continuity and spans greater than 125 feet	a. Fewer piers and possibly less material b. More complicated construction but fewer setups c. Savings from less scour d. Less maintenance	a. Smoother ride b. Less scour c. Stronger	a. Better aesthetics b. Better navigation c. Less erosion
2. Height of at least 50 feet above MLW	a. Slightly more material but decreased longitudinal stiffness	a. Added safety	a. Better aesthetics b. Better navigation
3. Careful attention to design of segments	a. Less material b. Lighter piers	a. Perhaps stronger	a. Better aesthetics
4. Provision for immediate or eventual recreation uses	a. Long-run savings b. Possible additional revenues	a. Less congestion with safer traffic flow	a. Better facilities b. Broader public appeal c. Better aesthetics

Table 2.3: Suggestions for Girder-Type Viaduct Design

designers in competition, and in comparison with existing viaducts having similar functional requirements. Moreover, the evaluation procedure should be such that portions of it can be also given to officials, interest groups or members of the public for outside opinion as to the most satisfactory alternative from a particular point of view.

The civil engineer dominates in this process as creator. By being forced to defend his creation on the broad field of environmental impact and in particular aesthetics, he must consider the total quality of his work. In this manner, he will be forced to deal with and satisfy his real clients who actually pay for and use the product.

3. PLANNING, DESIGN AND DESIGN-AID REQUIREMENTS

3.1 Establishment of Design Requirements

By considering the specific case of estuarine bridges, the previous chapter has shown how there is a need for helping the engineer tackle the complex design problems involved in coastal engineering, particularly when wider issues than a purely technical solution are involved and environmental factors must be considered. Before we can suggest ways in which the engineer can be helped in his task, it is necessary to establish what are the needs of the design process in terms of information required and also of activity aids and suggestions on methodology. This chapter of the report aims to show what these needs are by examining the design process.

Section 3.2 begins by examining the design process as a system. At this stage, the concern is not with details of activities, but rather in looking at the overall information requirements of the system. However, in order to be able to list design needs more specifically, analysis of the design process needs to be expanded in more detail; this is done in Section 3.3. Finally, Section 3.4 summarizes the findings in a list of design-aid requirements.

3.2 The Design Process as a System

Let us follow a methodology used elsewhere (19) and first consider the design process as a total system in which various actors - civil engineers, structural engineers, cost estimators and so on - are carrying out a set of activities. Figure 11 depicts the design process as a set of activities (the central box in the diagram) with various overall categories of information flowing into and out of it. The whole can be thought of as a decision process in which a series of potential solutions is first generated. These are modified in order to fit within the bounds set by a series of solution constraints, and they are further modified according to various preference criteria in order to improve them - to change them in the direction of a potential optimum. During the course of this process, from time to time it becomes clearly unprofitable to pursue some of the solutions further and they are dropped. From this point of view, design is a creating, winnowing, improving, and choosing process.

It should be noted that in this section only the stages of design leading up to a firm and detailed concept are considered. The detail design stages where nuts, bolts, connections and reinforcing bars are designed are not included in the system as they contribute far less to the overall nature of the design and to its impact on the environment than do the earlier stages at which the overall concept is formed.

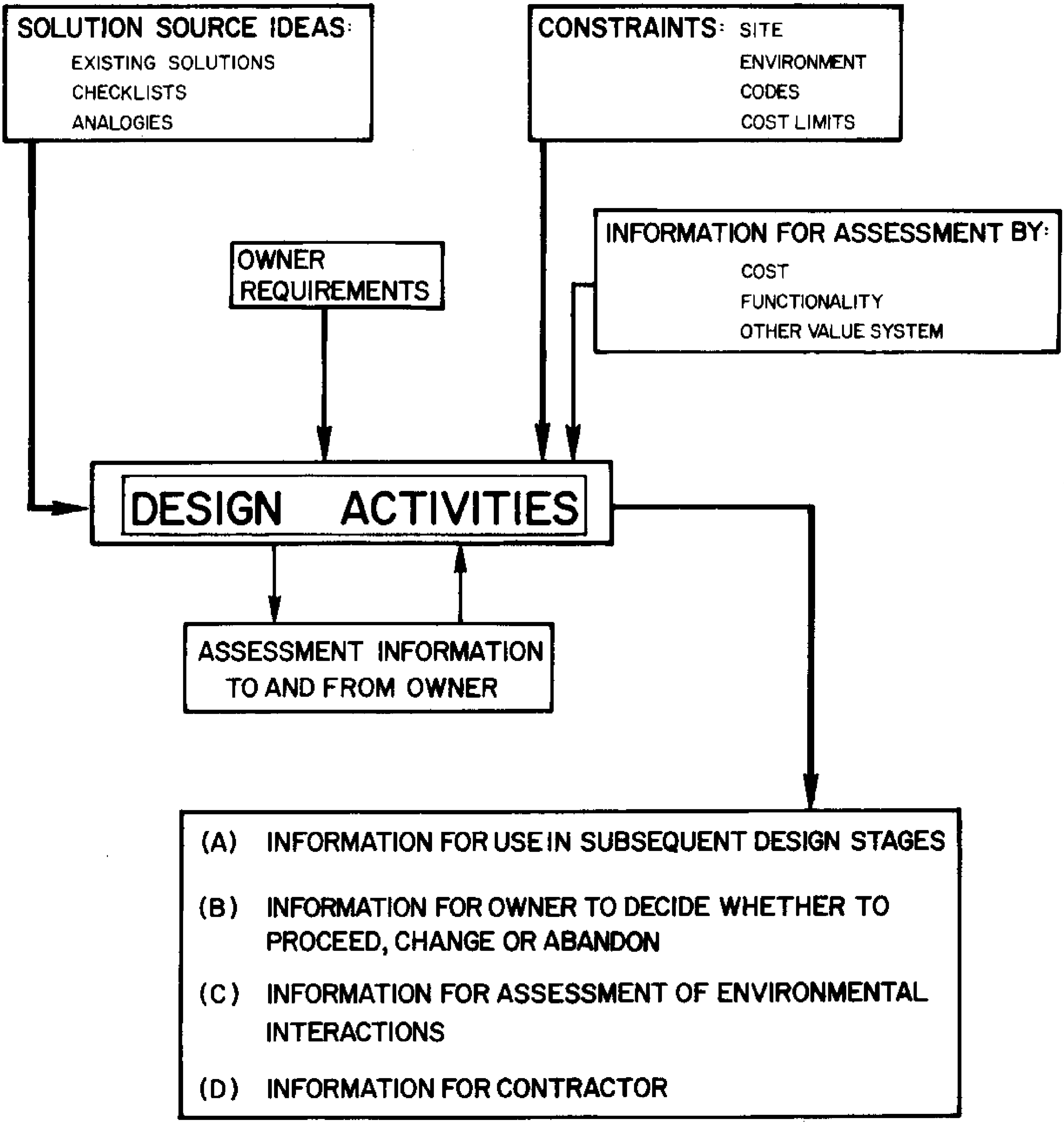

Figure 11: Overall Information Flow for Design System

Basically, the information flowing into the system is placed at the top of the diagram. A source of ideas for solutions to the design problem is first needed so that the actors in the system can generate preliminary solutions. These preliminary solutions are constrained in various ways by the owner's requirements and by the constraints imposed by the site, the environment, local bodies in the form of codes, cost limits, and so on. A design solution fitting all constraints is not necessarily the best solution, however, and to be able to improve it or to choose between alternatives, information by which the solution may be assessed must be available. Assessment may be according to various criteria such as cost, functionality or other value systems.

In a real design situation, the problem often is how to carry out a design when all the required information is not available. Either explicitly or not, such a situation must be tackled by the use of subjective probability estimates.

3.3 Design Activities and Information

The next stage is to discuss design activities and information categories in more detail in order to obtain a list of activity and information oriented to design-aid needs. A structure for the design process itself is given in Figure 12. This structure (or model) is not presented as a definitive statement of the design process for in practice design is generally carried out in a very ill-defined way with roles that are fuzzy and decisions that are

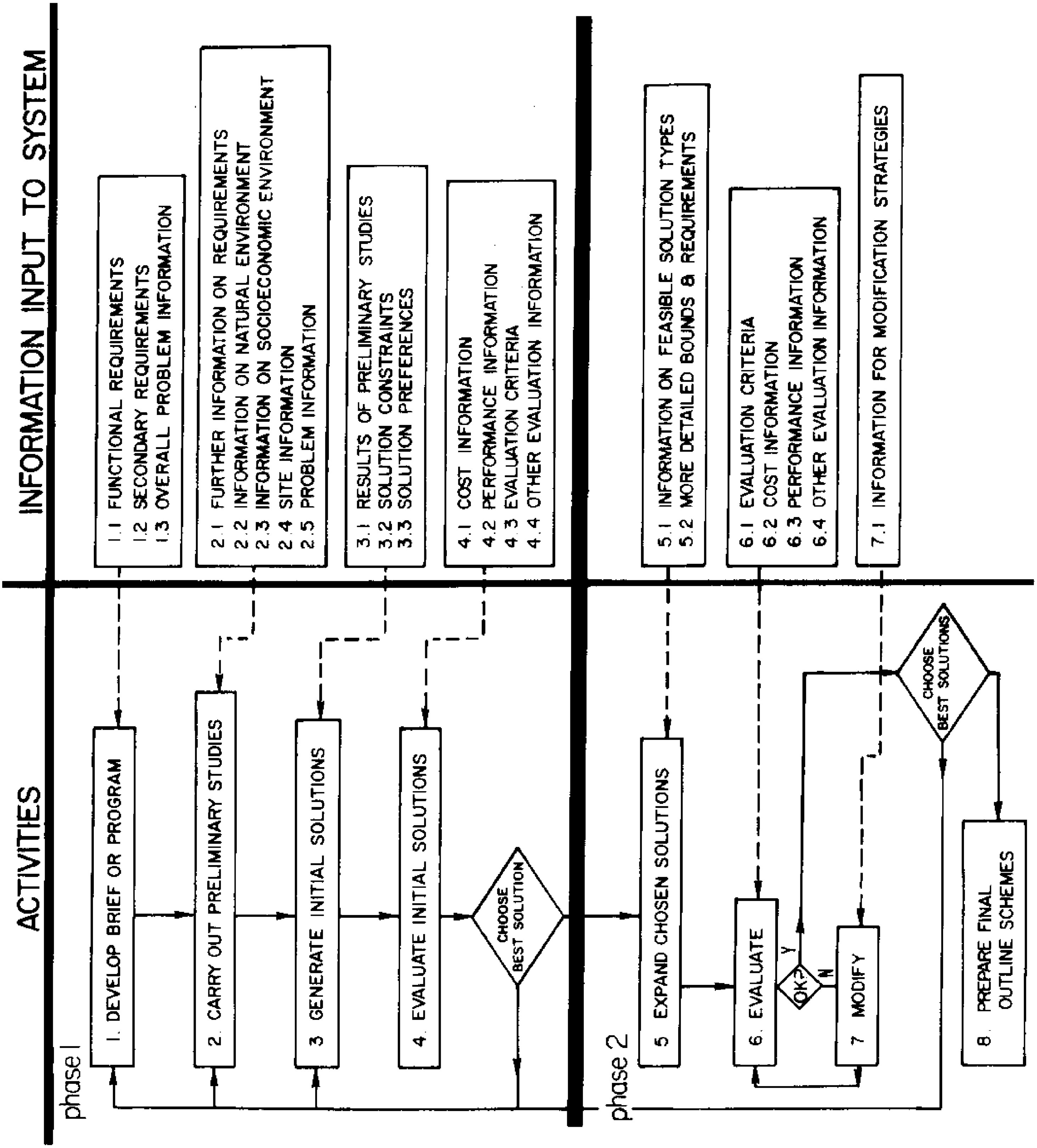

Figure 12: Activities and Information

apt to materialize rather than be made in a logical manner. But by choosing a definite structure such as that shown in Figure 12, we can isolate a series of activities and a set of information requirements as a basis for discussion.

The activities are split up into two phases. The first phase leads to a selected number of broad solution types while the second considers these in more detail and ends up with one or two expanded design solutions developed in sufficient detail for the process of detail design to begin. This, in turn, leads to production of working drawings and specifications. The latter activity is not, of course, discussed here.

3.3.1 - Considering first the activities, the process starts with the development of a program or brief - essentially a specification of what has to be done. This may be carried out by the owner, the engineer, or by both together. At this stage, overall problem information is required, painting a total picture. As particular parts of this, the main functional requirements and secondary requirements need to be known. The first of these specifies the main purpose of the project; for the Chesapeake Bay crossing it was to carry a roadway across the mouth of the Bay (note that no statement is made as to the means of carrying the road across). The secondary requirements for a project are often very important, including such things as environmental impact and recreational facilities; for the Bridge-Tunnel it was important to leave four shipping channels open, and it was felt that it was necessary to provide some minimal recreational facilities which eventually took the form of a snack bar and fishing pier on the South Island.

3.3.2 - Before initial solutions can be developed for the project, or during this development, it is normally necessary to carry out a set of preliminary studies. One study would be concerned with investigating potential environmental impact, another with assessing potential traffic flow patterns, growth-potential utilization, and return on capital. Also, the nature of possible sites - currents, weather, foundation conditions and so on - would have to be determined from tests. In addition, information on previous projects would be helpful. The aim of these studies is twofold - to determine in more detail the requirements of the problem and to identify the constraints that are imposed upon it.

3.3.3 - Once sufficient information is known about project requirements and constraints, trial solutions can be generated. It is at this point that the creative ability and foresight of the designer has most effect on the subsequent success of the project insofar as its effectiveness depends much more on its overall conception than on the details of its construction. Little is known about the process of solution generation except that to produce a great design seems to demand flair and talent displayed by only a few designers. Basically, to come up with good solutions the designer must know virtually all there is to know about the problem; he must know the constraints on it, the results of preliminary studies, secondary preferences and, as a guideline, solutions used previously in similar situations. Moreover, he is faced with a psychological problem of selective vision in that he tends to become attached to a design; the more he works on it, the harder it is for him to come up with totally different alternative solutions.

3.3.4 - Assuming, though, that several different solutions have been retained such as a series of differently sited bridges and tunnels with alternative configurations for crossing an estuary, the next task is to choose those few which are more suitable for further development. It is therefore necessary to evaluate the solutions in some way so that they can be compared. One way of doing this is to compare capital costs but, while this is valid, it is by no means the only criterion for comparison. A more complete cost-benefit analysis, discounting costs and returns to present value, would give another useful evaluation parameter. To do this thoroughly, values would have to be put on various less well-defined benefits and costs such as aesthetics or ecological damage. This, in turn, raises the larger issue of the point of view of the evaluation. A developer, a local authority and an affected resident would all have different points of view on the relative values of a set of project solutions which have to be taken into account in some manner. The designer and owner thus need to have a methodology as well as criteria for carrying out their evaluation of proposed designs if this evaluation tries to take into account (as it should) broader factors than those traditionally used. They also need the appropriate information not only on costs but also on performance of the design and any other assessment information that might be at hand.

3.3.5 - At the end of Phase I, the best solutions are chosen from the contending designs. The solutions are still very broad-based and tentative; for instance, for a high-level crossing of a narrow estuary, it might have been decided that rough designs for a suspension bridge and a stayed girder bridge seemed viable while a tunnel or a cantilever bridge would be uneconomic or unfeasible within the limits of the problem bounds.

3.3.6 - In Phase II, the design process follows much the same steps, but now the designs are treated in greater detail. The solutions still being considered must be expanded into greater detail. If as postulated a suspension bridge has been chosen as a crossing type, then the more exact location of its towers, end piers, anchorages and approach roads must be fixed, and tentative designs for the main bridge and for the approach spans must be produced. By this stage, overall environmental effects will already have been considered, but detailed ways in which the bridge and its construction affect the immediate ecology will still have to be taken into account. More information on site and foundation conditions will have to be determined, and further meteorological data for the area might well be necessary.

3.3.7 - A loop now appears in the design process. Blocks 6 and 7 in Figure 11 represent the modification of the designs as they are improved so as to fulfill the design criteria and to produce as good designs as possible. In order to do this, however, the designer must have access to information which tells him how good each design is. He needs evaluation criteria (more detailed than in Phase I), cost, performance information and any other factors pertinent to the evaluation, and a means of taking into account the points of view of the different people affected. He also needs information which can tell him how best to modify each design so as to improve it; this is included as Block 7.1 in the diagram. If, in the suspension bridge example, the designer wishes to optimize or improve the design of both the main span and the approach spans, he might find the two activities conflict. His main objective must be to optimize the whole project, so he must find some way of handling the interactions between its parts.

3.3.8 - Finally, when further modifications barely improve the efficiency of the designs (or perhaps when the time allocated for the design process has expired) sketch plans and a design report for the owner are produced. In general, the engineer by this time is able to recommend a single design to the owner from perhaps two alternatives that have survived this far. Both, however, might well be presented with arguments pro and con and the reasoning behind the final recommendation by the designer. He may wish to solicit independent designs or request further evaluation by new criteria and comparisons to existing facilities. Finally, however, the owner must decide whether to continue to the production of working drawings and the critical period of planning and design is then complete.

3.4 Design Needs

The major needs identified in the foregoing discussion of the design process fall into four categories:

1. Aids to understanding the overall problem
    a. case studies
    b. literature sources
    c. identifying goals

2. Aids for preliminary studies
    a. functional requirements
    b. secondary requirements
    c. site
    d. natural environment
    e. cultural environment

    and any other pertinent information. All this can be divided into situation constraints and solution preferences.

3. Aids to solution generation (for both Phase I and Phase II)
    a. general aids
    b. previous solutions - case studies

4. Aids to design evaluations (for both Phase I and Phase II)
    a. criteria

b. methods
c. standards
d. examples - case studies

The following chapter makes suggestions as to what form some of these design aids might take and how they might be provided. The help that can be derived throughout the design process from case studies of particular types of facilities was illustrated in the previous one.

4. FULFILLING THE NEEDS

4.1 Handbook Format

This Chapter deals with a number of different design aids ranging from information on the problem to methodological suggestions. Probably the best and most useful way to present these to a practicing engineer would be to produce a reference volume in the form of a handbook, perhaps somewhat along the lines of the shore protection handbook produced by the Corps of Engineers(3). To produce such a handbook in its entirety is far beyond the scope of the present limited project. What is done instead is to present an outline of the design aids that would go in the handbook together with some examples.

The examples given are tentative and should not be taken as either definitive or complete. This very limited research effort was not designed to achieve a satisfactorily detailed understanding of all the specific technical problems involved. The examples are presented only in sufficient detail to show that the production of such a handbook is feasible and would fulfill a very real need in the engineering profession at this time.

4.2 Handbook Outline

Before considering design aids in detail, the proposed contents of the general design-aid position of a possible handbook will be outlined. Case studies and examples of these general aids for specific types of facilities would be included as appendices to the handbook or compiled separately as manuals for each type of civil engineering development.

Sections 4.3 and 4.4 are concerned with a classification of shorelines, together with a discussion of the points of sensitivity of the various shore types. Section 4.3 gives a broad classification while Section 4.4 considers the Delaware coast in more detail.

Section 4.5 presents a hierarchical classification of design situations and possible solutions to them. In the handbook this would be expanded considerably to form not only a source of possible design solutions but also, linked with the shore classification scheme, a checklist of potential trouble areas for design situations.

Sections 4.6 and 4.7 deal with the initial problem of evaluating designs so that their efficiencies may be compared both with each other and also with previously built projects. Section 4.6 first presents a list of evaluation criteria for qualitative use at an early stage of design and Section 4.7 goes on to consider the problem of quantitative evaluation while taking into account not only cost but also other factors such as aesthetics and ecological effects.

Section 4.8 gives a checklist as an aid to solution generation. Section 4.9 discusses the possible use of decision gaming as an aid during the initial planning stages of large projects. Section 4.10 is concerned with the system balances which must be checked. Section 4.11 discusses the place of computer simulation models as an early design aid, while Section 4.12 concludes with a few items which should be in a handbook but which it has not been possible to deal with in this report.

4.3 Shoreline Classification

As an aid for early planning of coastal zone engineering projects, this section categorizes shoreline types in general. For use as part of a handbook, however, the section and in particular its ecological statements need to be expanded in far more detail throughout.

A broad classification used elsewhere(20) divides shoreline types into:

1. bluffs and cliffs
2. beaches
3. coastal wetlands

However, a more detailed general classification is presented in Table 4.1. In this table, the characteristics of the various shore types are first described. The next column lists points of sensitivity associated with them, which in turn is followed by a listing of the principal uses to which the coastal types are put. The brief comments of Table 4.1 require some amplification.

Coastal hard rock cliffs characteristically have no beach except in isolated coves and inlets, and fall steeply to the rocks or peneplane at their foot. Due to the lack of a continuous beach, the small cove-beaches have no ready source of sand, so that if the sand is removed for some engineering operation, it will not be replaced by natural means for many years. The uses of such a coastal region are very limited. Selected recreation may take place by hikers and trampers, for the area will have great scenic appeal, but the lack of beaches will keep most people away. Insufficient room and difficulty of access make the region unsuitable for industry, and for the same reasons, major port facilities cannot be constructed in the region though some harbors for small crafts have been successfully constructed as at Dunbar in Scotland.

Beaches do often occur beneath bluffs and cliffs made of softer rock such as chalk (the Møn Cliffs in Denmark are a good example). Provided access is available, such areas are extensively used for recreation and also, above the cliffs, for real estate development. Harbors are sometimes built (as at Dover in

Shore Type	Characteristics	Points of Sensitivity	Principal Uses
1. Coastline			
1.1 Hard rock cliffs	No beaches except in coves.	Fragile vegetation. Lack of sand source means fragile beaches.	Selected recreation Home development
1.2 Soft rock cliffs, bluffs	Sometimes beaches; beaches in inlets.	Cliffs fragile, especially if beaches destroyed.	Selected recreation Home development
1.3 Alluvial deposits	Beaches, lagoons, marshes, dunes, tidal creeks, washover barriers	A dynamic equilibrium situation; change at any point causes an equilibrium shift. Very sensitive ecologically and physically.	Mass recreation Small boat harbors Heavy real estate development Offshore terminals Water-Using industry
2. Inlets			
2.1 Drowned river Valleys-shallow slopes	Alluvial-tidal marshes, washover beaches (e.g., Delaware Bay)	As for 1.3 Pollution is also a problem. Shallow, unstable sea bed.	Recreation Port facilities Small boat harbors Water-Using industry Real estate
2.2 Drowned river Valleys-steep sided	Cliffs and bays beach/marsh in inlets (e.g., Puget Sound)	Stable geologically - sensitive to pollution.	Deep water port facilities Recreation Real estate Water-Using industry

(Cont'd.)

Shore Type	Characteristics	Points of Sensitivity	Principal Uses
2. Inlets (Cont'd.)			
2.3 Drowned glacial valleys	Steep cliffs and shores, beach/marsh inlets (e.g., Fiords)	Vegetation fragile on cliffs Beaches sensitive due to small sand supply.	Selected recreation
2.4 Deep bays	Varied	Varied	Port facilities Recreation Real estate Industry
3. Deltas	Alluvial, unstable, high water table (e.g., Mississippi Delta)	Physically and ecologically unstable.	Port facilities Water-Using industry Real estate

Table 4.1 Shore Classification

England), but access difficulties usually keep industry away. Soft cliffs are readily attacked and eroded by the sea especially if the beach is damaged or removed by storms or by the effect of nearby coastal engineering works as on Martha's Vineyard where the jetties of Oak Bluffs Harbor contribute to the erosion of nearby sandy cliffs.

The shoreline of low-lying land consists of beaches, dunes, tidal lagoons, tidal marshes and washover barriers. Some of these are described in more detail when the Delaware shoreline types are discussed. Such a shore is naturally unstable with a changing topography as it is gradually eroded or built up. Storms may remove or build up beaches and may overtop washover barriers. Tidal marshes may build up with the slow deposition of silt at high tide, while their edges may erode or be transgressed by a washover beach. A gradual raising or lowering of the land level will be reflected in coastline changes. All these effects mean that a shoreline of this type is much more sensitive to human disturbance than any of the previous types. Dunes are a useful protection against sea encroachment during storms so that if they are removed for real estate development, trouble eventually ensues. Dunes can also be affected by destruction of the vegetation that stabilizes them, marram grass can be killed by people trampling a path through to the beach leading to a wind blow-out. Tidal marshes, though they do not appear beautiful to many people, have a very great ecological importance. Quite apart from the abundant bird and other wildlife in a tidal marsh, such a region is a very important source of nutrients and oxygen for coastal waters and, in an inlet or estuary, marshes play a major role in keeping the waters "healthy." Yet tidal marshes are sensitive both physically and ecologically; a turf kicked into a small creek can dam the flow sufficiently for the creek to turn in time into a non-productive salt-pan, or a cut can cause the head of a tidal creek to cut back rapidly(21). Marshes form slowly, so that once a marsh is destroyed by filling, it cannot be re-formed - the process is essentially irreversible.

Low lying shores have many uses and are in great demand. They are very suitable for both water-using industry and mass recreation, though extensive real estate development close to the coast is not always wise; near Cape Henlopen on the Delaware coast, natural erosion takes place at the rate of ten feet a year. Offshore terminal facilities can be constructed (though these will be unprotected) and small harbors can be formed in inlets (Westport Harbor in New Zealand, for example) though their entrances need frequent dredging because of the build-up of sand bars. Attempts to reduce dredging by extending jetties usually interfere with the littoral sand drift causing accelerated erosion on the down-drift side.

Inlets are of great importance. Towns and ports are often situated on them, and because of their scenic attractiveness, they are in demand for both recreation and for real estate development. Industry is generally associated with the presence of a port. But estuaries are also of importance ecologically, for they are rich in nutrients and are the natural breeding grounds of many fish. The classification offered in Table 4.1 divides inlets into drowned river valleys (which are usually but not always river estuaries), drowned glacial valleys and deep bays.

Delaware Bay is an archetypal drowned river valley. Its low-lying shores consist mainly of tidal marshes, washover beaches and mud flats; these are described in more detail below. The estuary is for the most part shallow, with a dredged channel which shipping can follow to Philadelphia. It is the home of an extensive fishing and shell fish industry. The silt and nutrient-bearing river, the tidal marshes, and the shallow waters of the bay all have strong ecological links. There is a disadvantage in using such a bay for port facilities because of the difficulty of maintaining and negotiating the navigable channels. It can be used for recreation though its beaches are smaller than ocean beaches. It can be used for industry, but there is a danger of chemical and thermal pollution, and it can be used for real estate development, though the shore topography is often naturally unstable and the filling of tidal marshes must be strongly discouraged because of their ecological importance. Other major changes may be brought about by bridges (this is discussed elsewhere) or by tidal dams such as that on the Rance, or the proposed Severn Barrage in England. Barrages will, of course, cause major ecological changes.

Steep-sided drowned river valleys such as Puget Sound or the Marlborough Sounds of New Zealand are more stable both topographically and ecologically, though they are equally sensitive to pollution. They make excellent deep-water harbors. Their scenic attractiveness leads to real estate development and extensive recreational use, though road access is sometimes a difficulty.

Drowned glacial valleys such as the steep-sided fiords of Norway, Southern Chile and New Zealand are picturesque but limited in their use of access difficulties and because of the dearth of flat land on which to build. The few beaches have built up their meager sand supply over many years, and there is no ready source from which the sand may be replaced once the beaches are destroyed.

Deep bays are so varied in their nature that it is difficult to discuss them in general terms.

Deltas, of which the Mississippi Delta is an example, are low-lying and alluvial. They are basically unstable both because the river channels are continually building up due to the deposition of silt and because they have little natural defense against storm damage. They are also ecologically unstable. Their flatness makes them attractive for many uses, but extensive protection works must be used which must be planned with care as for the Rhine Delta in the Netherlands.

4.4 The Delaware Coastline

Thinking in terms of the proposed handbook, a more detailed classification of shore types than that given in the previous section would be required. For the Delaware coast as an example, a classification may be derived from a series of typical coast cross-sections given by Kraft(22) and reproduced in Figures 13 through 15. The classification given in this section is still severely limited, however, as it is oriented towards a physical description of the shore types. A detailed discussion of the ecology of the various shore categories together with a description of the short and long-term changes which could result from disturbances should eventually be included.

As a general remark, it should be noted that the Delaware coastline is sinking slightly so that there is a gradual natural transgression of the sea and salt marsh areas in towards the land. This is an overall phenomenon and is distinct from a highly unstable shoreline topography such as found in the Cape Henlopen area.

In Figure 13, the top diagram represents a region well up the bay, above Wilmington, where only a very narrow mud and sand region separates the water from more stable ground. We shall call this

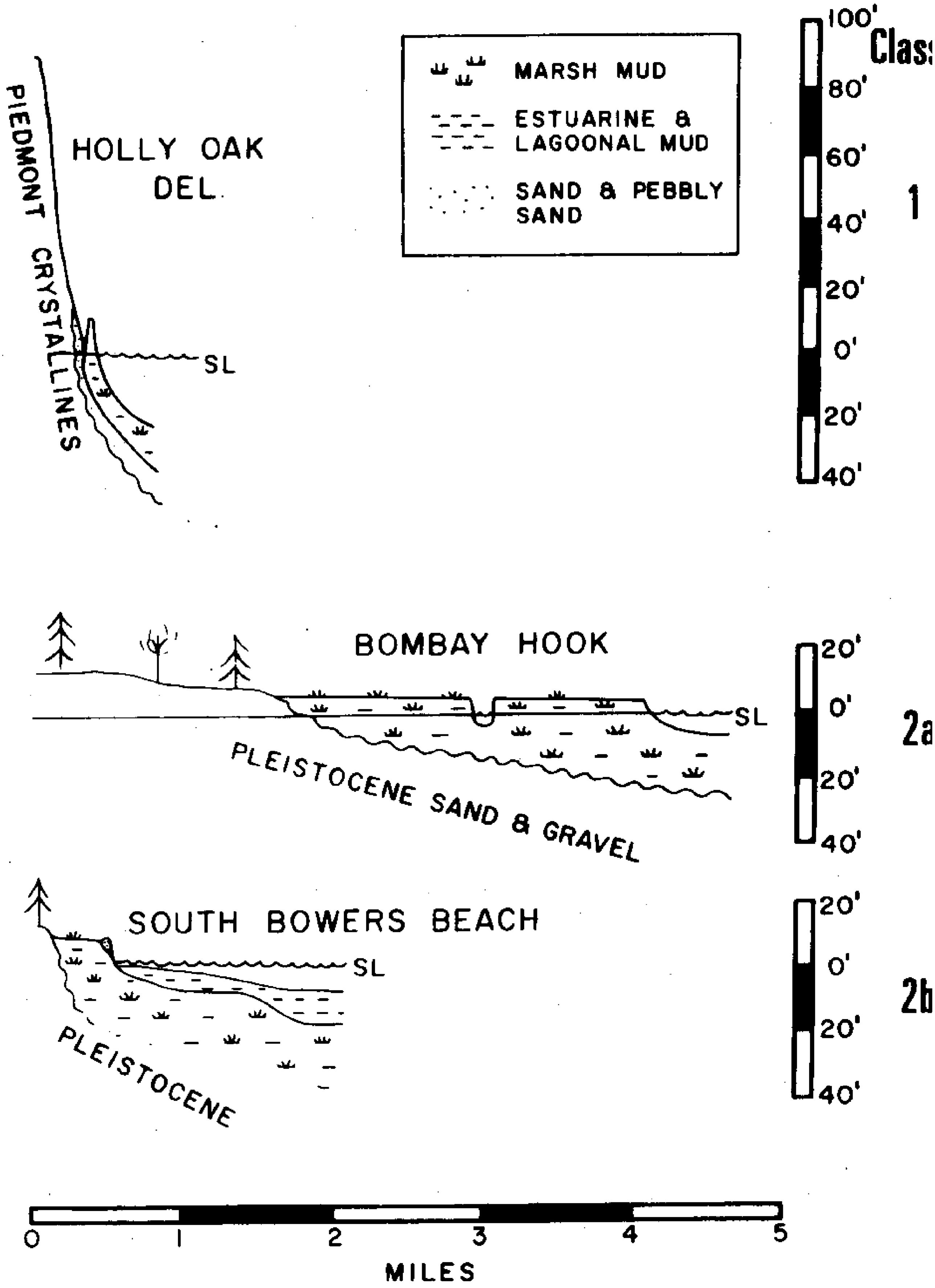

Figure 13: Three Cross-Section Profiles of the Middle-Northern Delaware Bay Shoreline Area

Class 1; it is essentially fluvial rather than estuarine. The next three diagrams (Bombay Hook, Bowers Beach, and the Great Marshes at Lewes) represent estuarine shore types which can be called Classes 2a, 2b, and 2c. All three show an area of salt marsh between the sea and the sand and gravel deposits of the land proper. Bombay Hook has no beach, South Bowers Beach has a small washover beach resting on marsh deposits; while at Lewes a more substantial beach exists between the marsh and the sea. The sand at Bowers Beach has a meager source in various Pleistocene headlands that are being actively eroded, but the supply is small so that if the beach were destroyed, it would take a while to build up again. There is a larger source of sand at Lewes coming probably from Cape Henlopen. Both beaches are washover beaches in that at times of storm, the sea will sometimes overtop them and move them backwards across the marsh.

Whiskey Beach (Class 3) and Rehoboth Beach (Class 4) form part of a transgressive alluvial headland complex. Both are eroding. Whiskey Beach, however, is a washover beach protecting the southern end of the Great Marsh which itself is probably the remains of a coastal lagoon. The beach is similar to the estuarine marsh washover beaches, but in this case is a true ocean beach with a plentiful sand supply. At Rehoboth Beach there is no marsh. The Pleistocene headland is being actively eroded. Note the high dunes and the outlying Hen and Chicken Shoal, a feature associated with Cape Henlopen to the north.

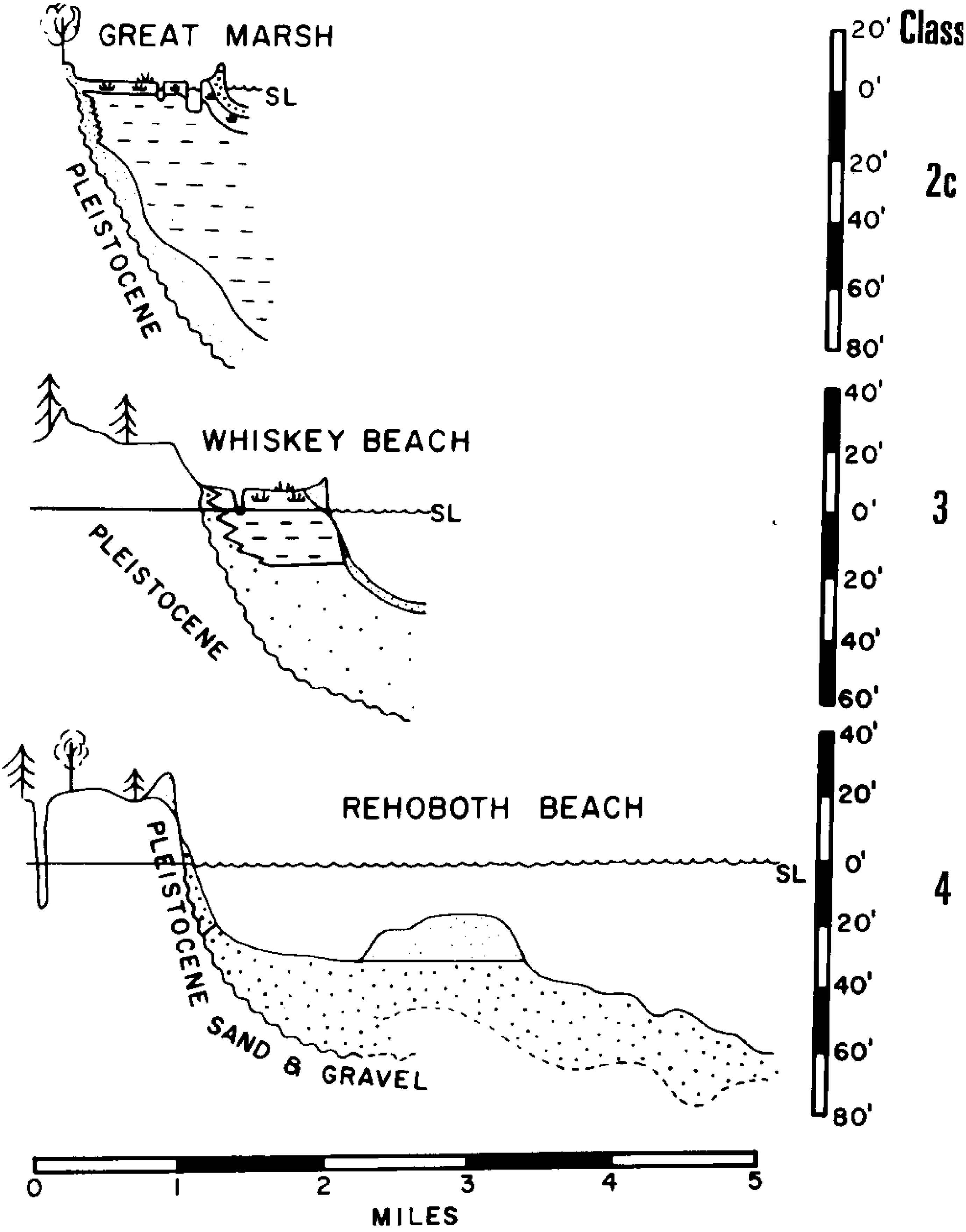

Figure 14: Three Cross-Section Profiles of Southwestern Delaware Bay and Atlantic Coastal Area

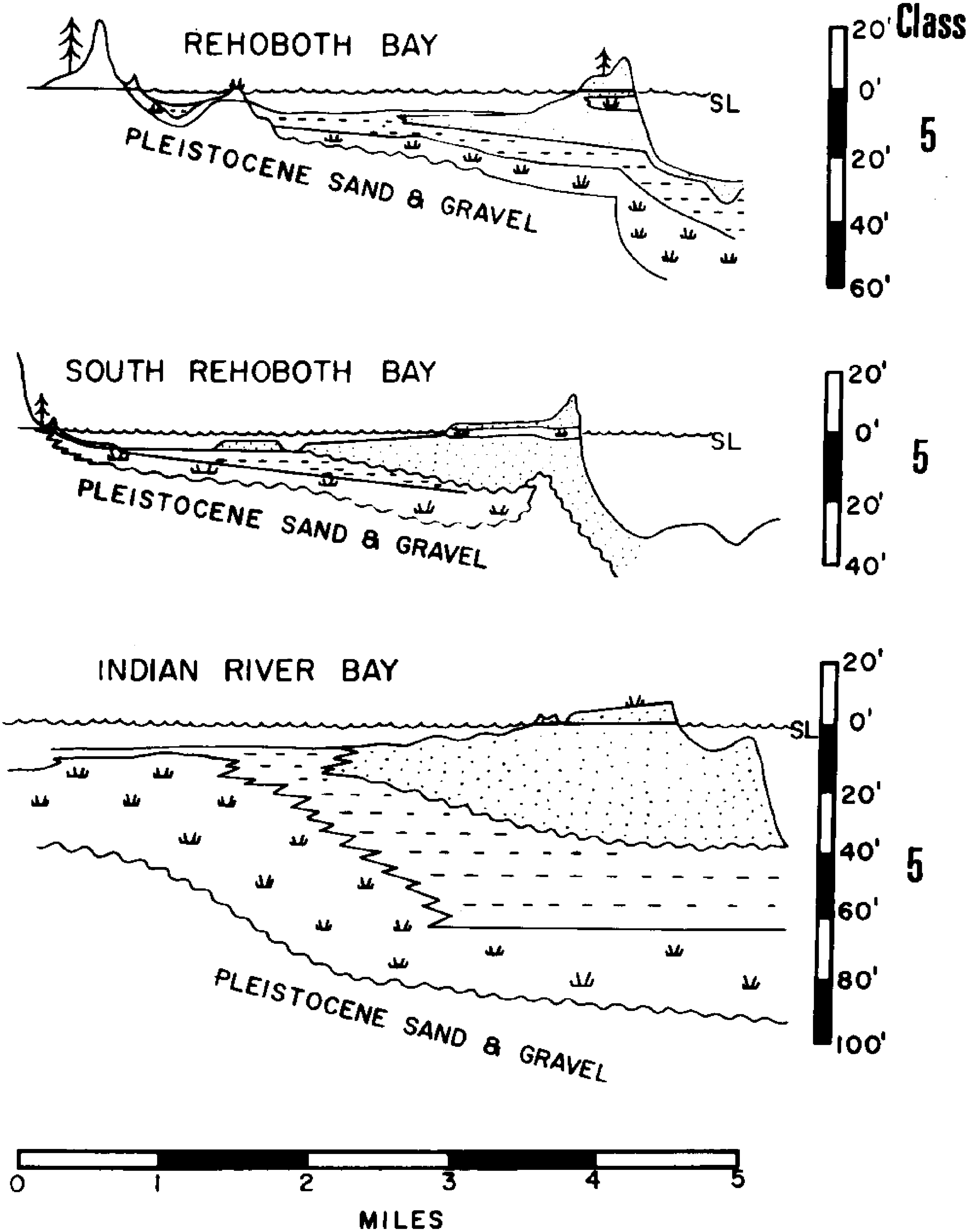

Figure 15: Three Cross-Section Profiles of a Lagoon Barrier Transgressive Coast in the Rehoboth Bay-Indian River Bay Area of Coastal Delaware

The marsh of Class 3 is also sensitive ecologically. Both areas are very suitable for recreation.

Finally, the coastline of Class 5 is sensitive ecologically as a whole. The barrier beaches are suitable for recreation though not construction, however, and care must be taken to avoid the destruction of dunes by excessive pedestrian traffic. The lagoon areas have limited recreational possibilities, and their shores are not suited for most industry because of pollution problems.

4.5 Classification of Design Requirements

Table 4.2 is presented as an initial approximation of a checklist-type design aid whose purpose is to help the engineer at a very early stage by giving him a list of alternative ideas in the planning process for formulating the overall concept of the project. The three columns of the table give activities, alternative means of fulfilling these activities and a set of requirements for each alternative. These three categories form a hierarchy. In the proposed handbook, this table would be extended and a fourth column would be added containing another stage in the hierarchy - solution types. Under 1.1.1 shore protection, for example, we could add groynes, breakwaters, bulkheads, dune stabilization and so on. (The classification of "breakwaters" could itself be expanded to; rock mound, concrete block, tetrapod, pneumatic, floating, etc.). However, in this report the only category to be expanded into the fourth level in detail is 3.1.1 viaducts,which has been done in Chapter 2.

ACTIVITY	ALTERNATIVES	REQUIREMENTS
1. Live by Shore	1.1 by waterfront	1.1.1 shore protection 1.1.2 sea access 1.1.3 car access 1.1.4 parking facilities
	1.2 back from waterfront	1.2.1 sea access 1.2.2 car access 1.2.3 parking facilities
2. Day Visit to Shore	2.1 beach activities	2.1.1 beach 2.1.2 beach access 2.1.3 car access 2.1.4 parking 2.1.5 beach protection
	2.2 view scenery	2.2.1 car access 2.2.2 car parking 2.2.3 foot access
	2.3 use boat	2.3.1 road access 2.3.2 parking facilities 2.3.3 boat ramp 2.3.4 sea access 2.3.5 wave protection
3. Cross Estuary by Car	3.1 bridge	3.1.1 viaduct 3.1.2 road access 3.1.3 ship clearance 3.1.4 sea protection 3.1.5 other requirements
	3.2 ferry	3.2.1 ferry terminals 3.2.2 road access 3.2.3 parking facilities 3.2.4 sea protection
	3.3 causeway	3.3.1 causeway 3.3.2 road access 3.3.3 sea protection

(cont'd)

ACTIVITY	ALTERNATIVES	REQUIREMENTS
4. Moor Small Boat	4.1 boat harbor	4.1.1 mooring facilities 4.1.2 sea access 4.1.3 sea protection 4.1.4 car access 4.1.5 parking facilities
5. Load/Unload Ship	5.1 offshore terminal	5.1.1 buoys 5.1.2 loading facilities 5.1.3 storage facilities 5.1.4 transport access 5.1.5 ship access 5.1.6 parking facilities
	5.2 onshore terminal	5.2.1 sea access 5.2.2 sea protection 5.2.3 wharf or pier 5.2.4 loading facilities 5.2.5 storage facilities 5.2.6 land transport access
6. Build Water-Using Plant	6.1 offshore	6.1.1 piled structure 6.1.2 transport access from shore 6.1.3 plant facilities 6.1.4 water supply and sink
	6.2 onshore	6.2.1 sea protection 6.2.2 transport access 6.2.3 parking facilities 6.2.4 water supply and sink 6.2.5 plant facilities
	6.3 back from shore	6.3.1 transport access 6.3.2 parking facilities 6.3.3 water supply and sink 6.3.4 plant facilities

Table 4.2: Classification of Functional Requirements

4.6 Evaluation Criteria

The evaluation of a project is a very essential part of the design process. Without the ability to evaluate, alternative solutions could not be compared; neither could any one solution be systematically improved. This section considers factors by which a project should be evaluated. The question of weighting the different factors according to the point of view of the person making the evaluation will be considered in the next section. At the early planning stages, it is sufficient merely to present a reasonably exhaustive (though not detailed) checklist such as given in Table 4.3.

1. Cost:
    - 1.1 capital cost and financing
    - 1.2 running, maintenance and depreciation costs
    - 1.3 hidden costs

2. Performance:
    - 2.1 safety
    - 2.2 serviceability
    - 2.3 functional efficiency

3. Environmental Impact:
    - 3.1 culture
        - 3.1.1 aesthetics
        - 3.1.2 recreation
        - 3.1.3 health
        - 3.1.4 sociological factors
        - 3.1.5 historical/scientific interest
    - 3.2 ecology
        - 3.2.1 biological means
        - 3.2.2 physical means
        - 3.2.3 chemical means

Table 4.3: Evaluation Criteria

The three diagrams of Figure 15 (Class 5) are cross sections of the coastal lagoon to the south of Rehoboth Beach. The lagoon generally has a mud bottom. Its landward side is fringed with a salt marsh, and there are occasional eroding islands (top diagram). The washover barriers have a characteristic outline; the beach itself is backed by a dune line, and behind this is a flat barrier back sometimes covered with marsh and forest. During severe storms, the sea occasionally breaks through the dunes and washes over the barrier back, carrying sand into the lagoon and extending the overall washover area shorewards.

Of the five classes we have defined, the first is not particularly sensitive ecologically and could be used for almost anything, except that water pollution should be avoided. The second class, comprising most of the estuarine shore, is ecologically sensitive and is physically unstable as well. The marshland is important for the ecological health of the bay. Development must be carefully controlled and industrial pollution guarded against. The building of homes on an eroding beach front (as at Bowers Beach) must be discouraged and excessive marsh filling cannot be allowed. There is room for limited development for recreational and industrial purposes, however.

Classes 3 and 4 cannot be recommended for the construction of any permanent facilities because of their topographic instability.

The first two cost factors are fairly well known. The hidden costs of a project, however, are not always so obvious. This is a vague heading which can be used for any economic cost arising to any party due to the construction of a project which, all too often, have to be met by the community or by someone other than the owner. A groyne, for example, installed to protect one beach, can lead to the destruction of another; houses built too near an eroding coastline need to be protected if they are not to be lost (this is often paid for by the community), and widespread commercial or real estate development of a scenic and recreational area means it is lost to the community as a whole necessitating construction of alternate facilities. Generally, as in these examples, "hidden cost" factors have an even more pronounced environmental impact than direct economic consequence. Thus, the not-easily quantifiable "costs" of these factors must be considered by those criteria as well. Knetsch has noted (23), "Destruction or alteration of estuarine resources involved economic costs far above those the individual himself pays. These costs are not, however, being reflected in the prices by which those who alter the environment are guided in making their decisions... The price per acre of marshlands, for example, are a vast understatement of the values that would be foregone with their destruction or serious alteration." Knetsch goes on to suggest a charge levied by the community for any destructive change of the environment. Even if such charges are not actually made, the cost to the community as a whole of changing the environment should be taken into account when assessing a design (the degree to which they are considered depends, of course, on point of view; an owner or developer will have a different point of view from that of a local authority, a conservationist or a neighbor).

As far as performance is concerned, the safety, serviceability and functional efficiency of a project are often closely interlinked. The function of a sea wall, for instance, is to keep the sea out, and if it fails in this function, it may affect the safety of people living behind it. One problem with performance factors is the difficulty of obtaining quantitative measures of performance; this could, however, be tackled with a probabilistic approach.

Environmental impact has been divided into two sub-headings: culture and ecology. Though the distinction is sometimes somewhat artificial, factors in the "culture" category are intended to apply to aspects normally affecting our perceptions and activities directly, while those in the category of ecology are concerned with aspects of nature. The sub-categorization of ecology into biological, physical and chemical is crude at best and must be revised and developed further to perhaps involve types of ecosystems. Some of the various environmental criteria are clearly interlinked since, for example, pollution might affect them all while moving sand would have more narrow repercussions.

All the listed factors should, in principle, be considered. Unfortunately, there is no existing methodology by which they can all be handled and compared, and often basic knowledge on many of them is lacking. To plan a project without considering them all runs the risk of sub-optimizing the project and yet a designer must produce a result.

4.7 Design Evaluation

If alternative designs are to be considered as solutions to a design problem, it is essential to be able to evaluate them in order to compare them rationally. It is also advisable to compare aspects of them to some standard figure, such as the cost per square foot of a bridge. Some measure of the comparative efficiency of a project is also required. This section of the report addresses the problem of providing quantitative measures of this sort which take into account a good deal more than the capital cost of the project.

In the previous section, a number of factors were discussed by which a project could be evaluated. In addition to cost, both performance and environmental impact factors were considered, though only in a qualitative way. However, apart perhaps from the very early stages of planning, it is important to be able to produce a single number or set of numbers to describe the worth or efficiency of a design. In the present section, we suggest ways of deriving a single design assessment parameter which takes into account all the evaluation factors which must be considered. However, remembering that the purpose of this report is to point the way ahead rather than produce definitive results, the ideas described are presented with a view to this being developed more thoroughly during the production of the proposed coastal engineering design handbook.

One common measure of value into which all the evaluation factors can be transformed is present-value cost (we shall give another measure later). The quantity describing the total characteristics of the design may be called the <u>worth</u> of the design. Designating it by W, we have:

$$W = C_c + \Delta C_c - C_p + C_e E$$

where C_c is a standard cost of a typical project of similar scope and purpose which includes the three items given under "cost" in Table 4.3; ΔC_c is the amount that an alternative design costs less than this standard; C_p is the cost of the three performance factors; and $C_e E$ is the cost value associated with the environmental impact of the design - of this, E is a number we shall call the <u>environmental attribute sum</u> (EAS) for the design and C_e is a <u>cost conversion factor</u> which brings the EAS into money terms.

Although this section of the report is primarily concerned with the more subjective evaluation of environmental impact, some mention must first be made of evaluating the strictly economic factors and the performance criteria necessary to obtain the total design worth. Capital cost, financing, running, maintenance and depreciation costs, and the strictly economic portion of hidden costs were discussed in the previous section and are relatively straightforward to obtain with the latter being discounted to present value.

Ascribing a dollar value to performance is much more difficult. One possible approach is to use subjective or even statistically-based probabilities. For example, suppose the estimated cost of repairs due to a ship running into a bridge is \$500,000 and that the probability of this happening in a year is estimated at 0.1. Then the cost per year would be 0.1 x 500,000 = \$50,000. This may be discounted to present value at an interest rate of, say, 5% and an assessed bridge life of 50 years to give a cost of \$913,000. Other safety problems (hurricanes, for instance), and even the effect of major design blunders can be dealt with in the same way.

Serviceability is concerned with the situation in which a facility normally performs satisfactorily but which becomes unserviceable or less serviceable for some reason: structural deflections which are too great, for instance, or a sea wall that has to be subjective as there is not normally any objective statistical data available. The cost effect of a lack of serviceability is not restricted to the cost of repair, however, and the cost of reducing the functional efficiency of the facility for a time must also be considered.

Functional efficiency deals with the way in which the design being considered can fulfill the task for which it was intended. For example, the function of a bridge is to carry vehicles: if the toll booth design is poor, fewer vehicles can use the bridge in a given time passed and it is less functionally efficient. If the design efficiency is easily measured or estimated, it can be translated to economic terms by a linear cost relationship. For example, suppose poor design reduced the maximum flow of cars across a bridge or increased the time they took to cross it. Taking the total estimated cost of the bridge as a measure of the value placed on the specified maximum number of cars being able to cross the bridge, then the ratio of the number that fall short to the design maximum number, multiplied by the total estimated cost, gives the cost of the functional efficiency (or lack of it) of the design. This item could either be positive or negative. A subjective estimate of the fractional loss of efficiency could also be made, and once again this could be applied to the total estimated cost of the project to provide the cost of a drop in functionary efficiency.

In order to assess the environmental-impact contribution to the design evaluation, the environmental attribute sum E of Eq. 1 has to be found. This may be effected by making subjective judgements and weighing them in different ways. This is best explained by an example, which may be assumed to have been applied to an initial design which is to be assessed for the Chesapeake Bay

Bridge Tunnel. Table 4.4 shows a weighting and averaging scheme set out in block form. The cultural impact factors are separated from the environmental impact factors. The various categories are divided up as in Table 4.3 into aesthetics, recreation and so on. The aim of the scheme is to try to evaluate the proposed design according to various representative points of view, and then to combine the evaluations of the different points of view into a single parameter. Take, for example, the first three columns collectively headed "Engineer." In the first column are put the weights to be applied to the various factors; thus, aesthetics is given a weight of 1 meaning that it is felt to be of fair importance, and it is also thought that the project will not affect health in any way. There are only three possible weighting factors: 2, 1, 0. In the next column, the engineer enters his subjective judgments of the value or merit of the design using a scale running from 0 to 5. These scores may be called the attributes assigned to the proposal. They are next multiplied by the weights and summed. Dividing the sum of the weighted scores by 5 times the sum of the weights (i.e., the maximum possible) gives a percentage figure, called in the table the weighted sum. If all scores (all attributes) were 5, then the weighted sum would be 100.

This procedure is carried out for various viewpoints. In this simple case, the points of view of the engineer, the owner, a local body authority and a conservationist are considered, but more could be brought in if more diversity is necessary. The scores and weightings could be made by the real owner, an actual conservationist and so on, requested to participate (see Section 4.9), or more probably they could all be made by the engineer himself playing the roles of the other actors in the matter - an idea suggested by an unpublished paper by Rosenblueth on Ethical Optimization.

The next step is to average the weighted sums for the different points of view. This may be done as a straight average, as in the row marked "cross-weighted sums 1," or the different viewpoints may themselves be given weights (called cross-weights here) and the weighted average taken. The cross-weights used in the table range from 5 to 1, but of course, any range could be used to accentuate or de-emphasize a particular viewpoint. The cross-weighted averages (divided by 100) are labeled E1 and E2. They are themselves averaged in the bottom right-hand corner to give a numerical value for E.

In Eq. 1, the value of C_c could be used for C_e, but the terms are left distinct in case a different value of C_e would be desired in converting the subjective evaluation parameter E into a dollar value.

In Table 4.4, it is important to note that the individual cross-weighted sums are also of interest in that if one is markedly different from the others, as is the value of 140 for the

		Engineer			Owner			Local Body			Conservationist				
		Weight	Score	W. Score	Weight	Score	W. Score	Weight	Score	W. Score	Weight	Score	W. Score		
cultural impact	aesthetic	1	3	3	1	3	3	2	4	8	2	2	4		
	recreation	2	3	6	1	2	2	2	4	8	1	2	2		
	health	0	-	-	0	-	-	0	-	-	0	-	-		
	sociological	2	4	8	2	4	8	2	5	10	1	2	2		
	historical-scientific	2	4	8	1	2	2	1	3	3	0	2	0		
	sums	7		25	5		15	7		29	4		8		
	weighted sum	71			60			83			40				E1
	cross weights 1	5			5			5			5			20	0.63
	cross weighted sums 1	355			300			415			200			1270	
	cross weights 2	5			5			3			3			16	0.64
	cross weighted sums 2	355			300			249			120			1024	

Weighting:

2 very important
1 fairly important
0 unimportant

Scoring:

5 excellent
4 very good
3 good
2 passable
1 poor
0 very bad

		Engineer			Owner			Local Body			Conservationist					E
		Weight	Score	W. Score	Weight	Score	W. Score	Weight	Score	W. Score	Weight	Score	W. Score		E2	Averages of E1 and E2
ecological impact	physical	2	3	6	1	4	4	2	3	6	2	2	4			
	chemical	0	-	-	0	-	-	0	-	-	1	1	1			
	biological	1	5	5	1	4	4	2	3	6	2	1	2			
	sums	3		11	2		8	4		12	5		7			
	weighted sum	73			80			60			28					
	cross weights 1	5			5			5			5			20	0.60	0.615
	cross weighted sums 1	365			400			300			140			1205		
	cross weights 2	4			3			2			5			14	0.57	0.605
	cross weighted sums 2	292			240			120			140			792		

Cross-Weighting:

5 much weight
4 much weight
3 much weight
2 much weight
1 little weight

Table 4.4: Evaluation of Environmental Impact

conservationist's cross-weighted sum for ecological impact, the reasons for this and the possible future implications for the project must be carefully considered by the design engineer.

In the handbook we have envisaged, it should be possible to develop a system of weights for the procedure of Table 4.4 associating the shore type classification of Table 4.1 with the facility type classification of Table 4.2. However, as both tables would need to be considerably revised and expanded from their present tentative forms, to check this hypothesis, such guidelines for a weighting scheme have not been attempted in this report.

Finally, it must be said that although only the environmental impact portion of the total cost defined by Eq. 1 has been treated using subjective weightings and scores, the performance aspects of cost and even the economic factors themselves could be dealt with in a similar way, ending up with an evaluative number for the project rather than a summed cost figure. This alternative procedure might have very considerable advantages at the early planning stages of the project when design alternatives would be too tentative for a reliable cost appraisal. It might be advantageous as well at later design stages. If, for instance, a comparison of efficiency was being carried out between the proposed design and some already-existing projects elsewhere, the use of attribute sums would avoid the problem of having to discount costs to present value and also that of somehow comparing projects of different magnitudes; for the attribute sum is, unlike cost (which is an absolute term), a semi-subjective measure of efficiency.

4.8 Checklists

One way of helping the solution generation aspect of the design process is to use checklists as a source of ideas. This technique has been suggested by Osborn(24) and advocated by Hall(25) and others. The idea is to start with some very tentative proposals for design solutions, and then to use the checklist to generate ideas for modifying them, and to produce alternative solution proposals. A tentative general checklist aimed at construction in the coastal zone is as follows:

offshore
at shore
back from shore
wider
deeper
longer
narrower
smaller
larger
substitute
rearrange
modify
reverse
combine
adapt
harmonize
continuous
piles
boating
marina
marine borers
corrosion
collision
tsunami
earthquake
scour
streamline
shoals
rescue
vegetation
fauna
take around
take over
take under
fill
dredge
swimming
groynes
stronger
energy absorbing
build above
build below
more protection
more access
stabilize
float
sink
buoy
insects
erosion
sand source
pollution
recoverable
less people
more people
breakwater

Table 4.5: Design Aid Checklist

In addition, Table 4.2 and the list of evaluation factors in Table 4.3 can be used as checklists, though their function is somewhat different. More specific checklists for particular facilities would be included in the handbook or the manuals.

4.9 Gaming

Since World War II, decision games, previously used by the military in the form of war games, have been used by management and in other operations research situations. A decision game is a simulation modeling of a situation in which a number of "players" form part of the model. The players may, in fact, be those taking part in the decision-making of the real situation being modeled or they may be others playing roles. One of the main advantages of gaming is that the players learn about the interactions in the situation they are simulating. In many ways, the evaluation procedure outlined in Section 4.7 is such a game.

There is evidently a place for the use of gaming in the planning stages of a large shore construction project. If, for instance, a crossing of the mouth of Delaware Bay would be contemplated, a game, if it were readily available, could help the project planners to more fully understand the complex interactions between the various interest groups involved.

However, a game must be developed carefully, and its design takes a considerable amount of time and effort in itself. The necessary preliminary structure and documentation for a Coastal Project Game could be a useful section in our proposed coastal engineering handbook, together with an explanation and the results of a played example. Some comments on gaming are given by Ackoff and Sasieni(26).

4.10 System Balances

At some stage in the design process, probably during Phase II, the facility to be constructed must be considered as a system, and all interactions of the system with its environment (using "environment" in the technical sense of that-which-is-not-the-system) must be checked both qualitatively and quantitatively. This must be done not only for the project as it is expected to be when built, but also during the construction phase when pollution and the need for access by heavy machinery can cause severe interactions with the environment.

The movement of tangible things must be recorded and a balance into and out of the system must be maintained. System balances can be checked during both construction and operation for the following quantities separately:

1. mass,
2. energy,
3. people,
4. water,
5. vehicles.

It is necessary, for instance, that the mass of the input of raw materials into a plant should be equal to the mass of both finished and waste products coming out of the plant. The point of making this check is to make sure that there is no secondary outflow of mass in the form of, say, pollution. An energy balance will ensure that the necessary allowance has been made for the removal of degraded energy in the form of heat.

The handbook should expand the concept of system balance and give some explanatory examples.

In these tasks, it is envisaged that the design engineers will probably call in specialists in order to do the jobs; but they themselves should know enough about the problems to be suitably knowledgeable. Therefore, a handbook should provide them with sufficient description, guidelines, and references to further information to guide and interpret the work or be capable of doing it themselves in reasonably simple cases. Two levels of information are needed. The first of the two categories refers to Phase I of the design process where a number of alternative proposals are under consideration, while the second applies to the situation in which major decisions as to the site situation have been made, but there are many design alternatives still to be considered.

The proposed handbook sections should outline fairly carefully what information will actually be required for design evaluation in Phases I and II, so that an investigation produces sufficient information for the purpose while not going into unnecessary detail and producing information that is not required.

4.11 The Place of Simulation Models

Very real help may sometimes be obtained in the understanding of the action of a complex situation by the development of computer simulation models. Such models are particularly useful at the preliminary planning stage. The idea is to model the situation as a system consisting of a number of interacting subsystems connected by flows of various sorts which move between the various parts of the system in a constrained way, the rate of flow being determined by the "pressure" between the parts. Various computer languages exist which make the computer aspect of simulation modeling relatively simple, such as the program DYNAMO which was used for Forrester's book Urban Dynamics (27).

4.12 Other Handbook Items

The handbook should also contain major sections on information gathering which are not outlined here. There should include:

1. Aids for the carrying out of initial environmental studies for the entire area for which the project is proposed, including alternative construction sites.

2. Means for carrying out detailed studies, both cultural and ecological, for the chosen site or sites and gathering detailed physical data on currents, waves, storms, soil conditions, sediment transport and so forth.

5. CONCLUSION

5.1 A Case for Case Studies

It is peculiar that engineering of all the major professions neglects the case-study approach in professional training. Many convincing reasons can be advanced why this occurs but few that it should. It is recognized by engineers that the study of failures is highly rewarding from the limited viewpoint of structural design but there is the pervasive tendency to avoid overall critical analysis of mediocre, good, and even excellent work. The case-study presented illustrates that the engineer has as much to learn from studying successful facilities as he does from unsuccessful ones. Moreover, such study requires and thereby encourages a broader view of his design function, so essential if he is to retain overall responsibility in the building of public works.

Actually, the review of the Chesapeake Bay Bridge and Tunnel as an example of a particular type of marine structure and the discussion of viaducts in general serves a dual purpose. Firstly, it points up the need for new methods of design and suggests aids that might be developed for the engineer in this area. Secondly, at the same time, the information from this sort of example is seen, in itself, to be an aid for any future design of such facilities by:

1. providing help in understanding the overall problem
2. highlighting areas which must not be overlooked and where special information may be necessary
3. giving a broader view to help generate new ideas
4. illustrating criteria and methods for evaluation
5. helping to provide standards for judgment.

Thus, case studies of this sort aid throughout the development of new strategy for effective design and, if continuing research to study other types of facilities is undertaken, can be of great importance.

5.2 Handbook Outline

It is easier by far to show need for a new and broader design approach by studying existing facilities than it is to meet this need with specific recommendations and guidelines. While case studies do valuable service defining the problems with existing standard practice and suggesting possible solutions after the fact, they do not in themselves provide a formalized procedure or specific aids for the designer seeking new strategies for engineering development in the coastal zone.

To accomplish this task, a handbook is suggested which would incorporate a number of related design aids with examples and commentary. The development of such a handbook would be a major task as would the organization of secondary manual volumes giving more specific information and case studies for the different types of marine facilities.

A general outline for such an effort is suggested in this report. In order to formulate this outline, the nature of the design process was first analyzed briefly and various design areas were isolated in which the engineer could be given assistance. A series of design aids were then suggested in a general format along with examples to illustrate in a tentative way how these aids might actually be formulated. It is felt that the idea of a handbook appears to be entirely feasible if developed along the lines suggested and would be expected to be extremely useful to the designer of marine facilities at a time when ever-increasing emphasis is being put on the cultural and ecological significance of large engineering works.

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