CHAPTER 230

Dune Damage Curves and Their Use to Estimate Dune Maintenance Costs

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Abstract

A beach profile numerical model is employed to calculate the change in dune cross-section for a wide range of increased, water level events. The volume loss in dune cross-section increases with relative increase in storm surge elevation above the design water level. These "damage curves" for dunes are analogous to rubble mound damage curves created by excessive wave energy above the design wave height.

The results are applied in the design of a protective, beach-dune structure (with buried seawall as a safety factor) at Dam Neck, Virginia for the US Navy. The damage curves are used to estimate annual dune maintenance costs and hence, total life-cycle costs for this "soft" alternative to shore protection. Interestingly, the dune-beach-buried seawall alternative costs less than a concrete structure using artifical units for armor.

Construction is complete and a three year monitoring project begun so that actual versus theoretical dune damage curves can be determined in the future.

1.0 Introduction

Dunes are "soft" coastal structures that quickly lose cross-sectional volume during elevated, storm surge events. Cross-shore sediment transport, beach profile models permit the development of dune "damage" curves showing the percent dune cross-sectional change, ΔV (damage) versus the relative storm surge level, S compared with the design storm surge, S_D. The dune damage curves can then be used in the classical, convolution integral method to compute annual dune maintenance costs. Life-cycle

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costs of the "soft" solution for coastal protection (dune-beach alternative) can then be compared with the "hard" alternatives (seawalls, dikes, etc.) on an equal, total annual cost per unit shoreline length basis.

The objective of this paper is to present the results of one analysis using the SBEACH model (Larsen and Kraus, 1989) for the design of a dune-beach restoration project to protect $95 million of structures and property at the US Navy's, Fleet Combat Training Center (FCTC), Dam Neck, Virginia. Section 2 briefly reviews the available models and key independent variables. The dune damage curves are summarized in Section 3 including safety factors used in dune design. Maintenance costs are determined in Section 4 and a cost comparison with an armored seawall design presented in Section 5. Construction of the entire project has recently been completed and a three year, beach profile monitoring project begun so that the theoretical versus actual dune damage curves can be determined in the future.

2.0 Beach - Dune Erosion Models

Recently, ten cross-shore sediment transport models have been evaluated by Schoonees and Theron (1995). The model developed by Larsen and Kraus, 1989 called SBEACH was found to be "acceptable" on its theoretical basis and in the "best group" category based on the extent of verification with prototype data. It allows sand overwash during elevated water level events so that the total, cross-shore sectional volume is conserved.

The probabilistic design of dunes with examples from the Netherlands are presented by van de Graaff (1989) as illustrated in Figure 1. It was learned (Table 1) that storm surge elevation accounted for about 83 percent of the total variance associated with dune erosion. Wave height, particle size, initial profile shape, storm duration and other factors were far less important. The change in dune cross-sectional area (per unit width) was primarily related to elevated water levels during storm surge events.

Dune damage curves are thus analogous to rubble mound damage curves created by excessive *wave energy* above the design, wave height.

3.0 Dune Damage Curves for Dam Neck, Virginia

Figure 2 shows the location of the Navy's FCTC at Dam Neck, Virginia on the Atlantic Ocean below the City of Virginia Beach.

Using a 50 ft. (15.2m) crest width at elevation +22ft (6.7m) above the City of Virginia Beach datum and 2:1 side slopes produces a unit volume of 30cy per foot ($75m^3/m$) above the one percent chance, storm surge event (9.1 ft., 2.8m). This dune cross-sectional (Figure 3) is essentially that originally designed by Headland (1991) and contains fifty percent more sand than the minimum requirement of 540 ft^3/ft ($50m^3/m$) as established by the Federal Emergency Management Agency (FEMA) for breaching of natural dunes.

A nearshore survey taken in May, 1990 was considered representative for the existing bathymetric conditions in the model. The SBEACH model was run with eleven successively higher water level events to cover the return periods between 1

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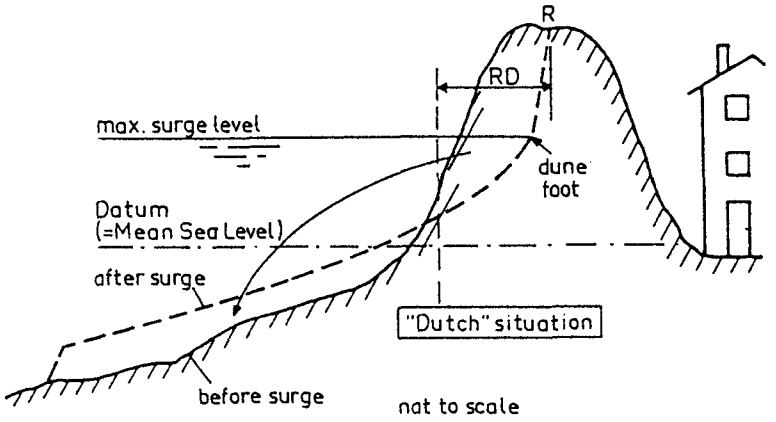

Figure 1 Schematic of Dune Erosion by Elevated Water Levels: Dutch Practice (from van de Graaff, 1986)

Table 1 Relative Importance of Independent Variables on Dune Erosion (from van de Graaff, 1986)

Contribution parameters to variance reliability function

Parameter	Contribution variance reliability function (%)
surge level	82.8
wave height	0.9
particle size	7.3
initial profile	1.3
surge duration	2.6
gust bump	0.0
accuracy computation	5.0

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A nearshore survey taken in May, 1990 was considered representative for the existing bathymetric conditions in the model. The SBEACH model was run with eleven successively higher water level events to cover the return periods between 1 on Southeastern Coastline, Atlantic Ocean and 1000 years (Table 2). Wave heights associated with these water levels were established from measured and extrapolated values at the Corps' FRF, Duck, NC. As illustrated in Figure 3, the original dune section was modified by sand moving offshore $\Delta V3$, sand overwash $\Delta V1$, and the dune volume $\Delta V2$. Dune damage is the volume change (loss) $\Delta V2$ and here after simply ΔV as found in Table 2. The total volume change above mean low water (MLW) accounted for all but less than 1cy per foot which moved offshore.

Dune Volume loss in cy/ft (ΔV in Table 2) and the percent loss (damage) are plotted against the S/S_D ratio as shown in Figure 4a and 4b, respectively. These curves are conservative in that they do not include the renourished beach in front of the dune as discussed blow.

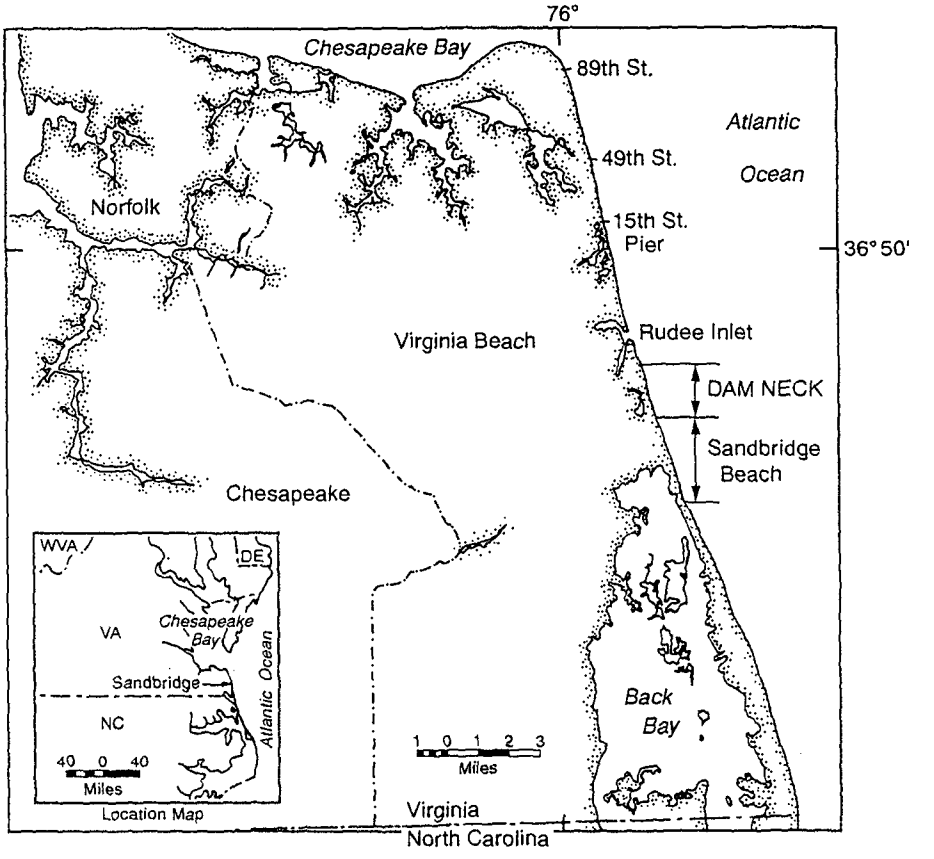

Figure 2 Location of US Navy, Fleet Combat Training Center, Dam Neck, Virginia on Southeastern Coastline, Atlantic Ocean

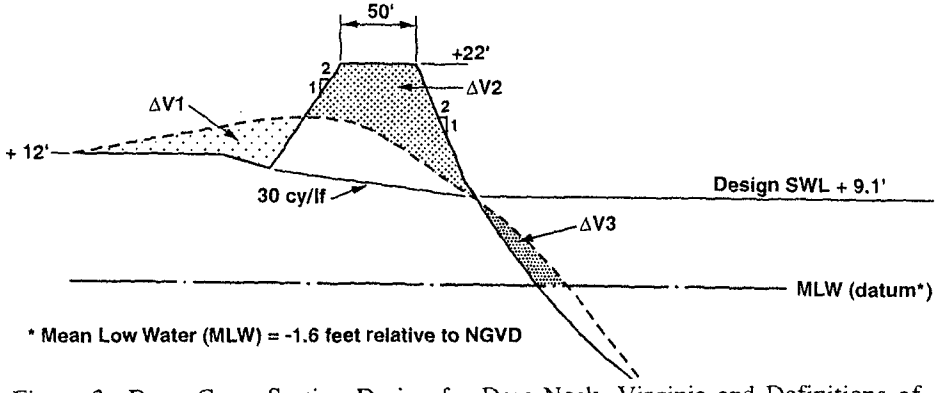

Figure 3 Dune Cross-Section Design for Dam Neck, Virginia and Definitions of Volume Change Regions, ΔV1, ΔV2 and ΔV3.

Table 2 Calculated ΔV Values for Various Water Elevations at Dam Neck, Virginia

Return Period in Year	Water Level, ft	S/S_D	H_{mo}, ft	T_p, sec	ΔV, cy/ft	ΔV_w, cy/ft	P, %	P_w, %
1	4.50	0.52	8.99	8.72	2.31	2.31	7.7	7.7
2	4.90	0.56	10.63	10.01	3.35	3.35	11.2	11.2
5	5.85	0.67	12.53	11.45	7.06	7.06	23.5	23.5
10	6.50	0.75	13.45	12.11	11.82	11.82	39.4	39.4
20	7.20	0.83	13.98	12.45	15.02	15.00	50.1	50.0
50	8.10	0.93	14.76	12.96	19.02	17.74	63.4	59.1
75	8.35	0.96	15.26	13.32	20.27	18.58	67.6	61.9
100	8.70	1.00	15.80	13.70	21.42	19.02	71.4	63.4
200	9.30	1.07	16.67	14.31	22.76	19.08	75.9	63.6
500	10.10	1.16	17.45	14.78	23.32	19.60	77.7	65.3
1000	10.70	1.23	18.18	15.25	23.40	19.68	78.0	65.6

ΔV = Volume Loss Without Seawall
ΔV_w = Volume Loss With Seawall
P = Percent Damage Without Seawall
P_w = Percent Damage With Seawall
$(P, P_w) = 100*(\Delta V, \Delta V_w)/V$, V=Total Volume of the Dune, 30 cy/ft

Dutch design practice for dunes (TAW, 1984) includes a safety factor or "remanent" dune volume remaining after a major storm event. Headland (1991) replaced this minimum remanent volume by an equivalent volume of rubble-mound seawall buried beneath the dune. Should a second major storm occur the same winter season, the buried seawall will be in place to protect the structures behind the dune. A similar buried seawall structure as shown in Figure 5 has been incorporated in the constructed project. Its effect on the damage curve is ΔV_w in Table 2 as illustrated in Figure 4b. The buried seawall acts to reduce dune volume loss at high water level events.

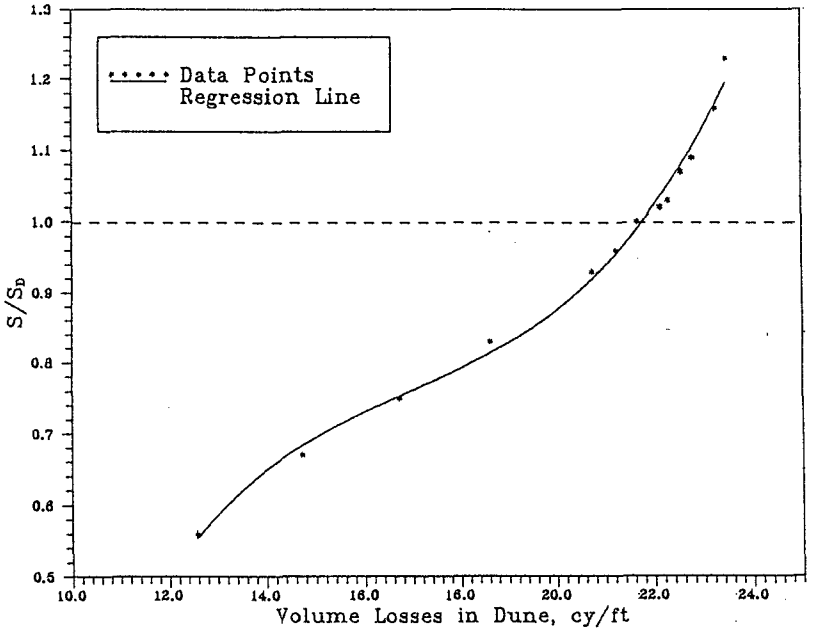

Figure 4a Dune Volume Loss (cy/ft) Versus S/S_D

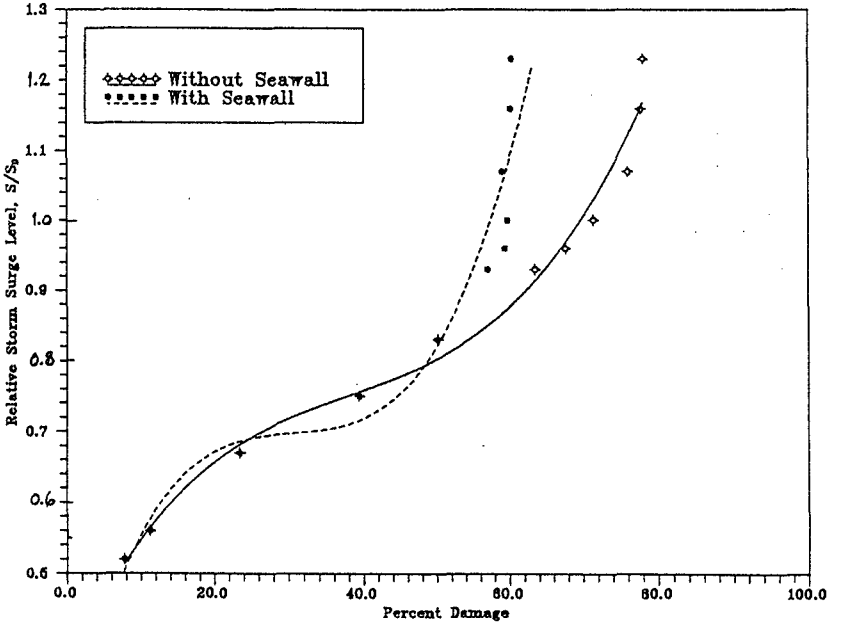

Figure 4b Dune Damage Curve: Percent Loss Versus S/S_D

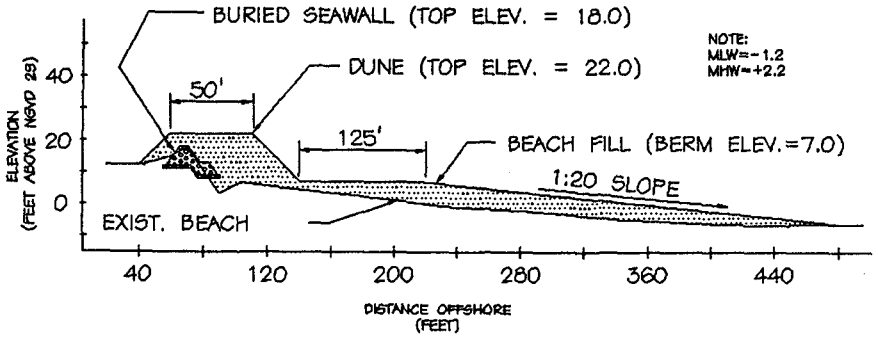

Figure 5 Dune-Beach-Buried Seawall Design for Dam Neck, VA

However, as illustrated in Figure 6, a major reduction in dune volume loss (percent damage) occurs when the beach is also renourished seaward of the dune. As an example, when the constructed beach width is 75ft (23m) damage curves for a design width after equilibration of 40 ft (12m) and with one-half life remaining of 20 ft (6m) are presented in Figure 6. Dune maintenance costs are obviously impacted by the volume of beach remaining over time to protect the dune system. The results of these computations are summarized in Table 3.

4.0 Dune Maintenance Costs

Simply stated, higher water elevations produce greater damage but have lower probabilities of occurrence each year. Annual dune maintenance costs are computed using the classical, convolution integral method of Kreeke and Paape, 1964 as illustrated in Figure 7. The dune damage curve was divided into eight subregions with damage greater than 70 percent requiring complete rebuilding of the dune structure. the storm surge probability curve was also divided into eight comparable subregions and then annual dune repair costs computed. As shown, subregion 2 for 10 - 20 percent damage from storms in the 0.2 - 0.35 probability of occurrence range accounted for the highest increment of maintenance expense. The total annual repair costs per unit foot of dune summed to about $74 per foot (Table 4).

Using a 25 year design life and 9.5 percent interest rate in the present worth method of economic analysis resulted in annual dune maintenance costs of $695 per foot. The value is conservative because the damage curve *without* the protective beach (Figure 4b) was used in the analysis. This can also be considered as a safety factor in the design and economic analysis.

Monitoring of the entire dune system and beach to closure depth will provide the requisite feedback information over a three year period to insure that dune maintenance is performed at appropriate intervals.

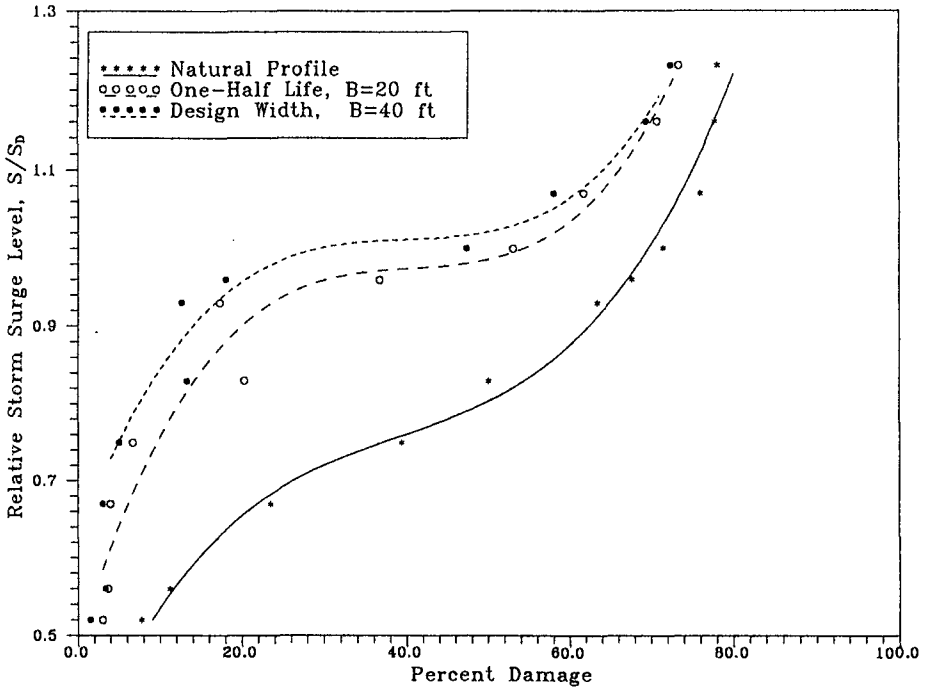

Figure 6 Effect of Beach Renourishment on Dune Damage Curves (Example for design beach width of 40 feet)

5.0 Cost Comparison With Armored Seawall

The dune damage curves used to compute dune repair costs permitted total, life-cycle cost estimates to be made for the dune-beach-buried seawall system (DBBS). Initial, unit costs for the dune of \$15/cy or \$450 per foot together with the maintenance costs of \$695 per foot produced a total cost of \$1145 per foot for the dune system. Using an offshore borrow area (Sandbridge shoal) for beach renourishment, one renourishment after 10 -12 years and realistic, unit cost estimates for sand and rubble materials (buried seawall), the "soft" alternative system totalled about \$1820 per foot on a annual, life-cycle cost basis.

The original, engineering study (Cummings and Basco, 1995) also considered a conventional, large armor unit, revetment structure as the "hard" solution for storm damage mitigation.

Table 3 Summarized Computations of ΔV Values for Various Water Elevations at Dam Neck, Virginia

Return period in year	Water Level, ft	S/S_D	H_{mo}, ft	T_p, sec	Volume Loss, cy/ft					Percent Damage, %				
					ΔV	ΔV_{20}	ΔV_{30}	ΔV_{40}	ΔV_{65}	P	P_{20}	P_{30}	P_{40}	P_{65}
1	4.50	0.52	8.99	8.72	2.31	0.90	0.80	0.80	0.60	7.70	3.00	2.67	1.43	2.00
2	4.90	0.56	10.63	10.01	3.35	1.10	1.00	1.00	0.90	11.20	3.67	3.33	3.33	3.00
5	5.85	0.67	12.53	11.45	7.06	1.20	0.90	0.90	1.10	23.50	4.00	3.00	3.00	3.67
10	6.50	0.75	13.45	12:11	11.82	2.00	1.60	1.50	1.30	39.40	6.67	5.33	5.00	4.33
20	7.20	0.83	13.98	12.45	15.02	6.10	4.40	4.00	1.90	50.10	20.33	14.67	13.33	6.33
50	8.10	0.93	14.76	12.96	19.02	5.20	4.20	3.80	2.60	63.40	17.33	14.00	12.67	8.67
75	8.35	0.96	15.26	13.32	20.27	11.00	7.40	5.40	2.90	67.60	36.67	24.67	18.00	9.67
100	8.70	1.00	15.80	13.70	21.42	15.90	14.60	14.20	12.70	71.40	53.00	48.67	47.33	42.33
200	9.30	1.07	16.67	14.31	22.76	18.50	17.60	17.40	16.10	75.90	61.67	58.67	58.00	53.67
500	10.10	1.16	17.45	14.78	23.32	21.20	20.80	20.80	20.00	77.70	70.67	69.33	69.33	66.67
1,000	10.70	1.23	18.18	15.25	23.40	22.00	21.80	21.70	21.80	78.00	73.33	72.67	72.33	71.00

Notes :

S_D = Design Storm Surge Level, ft
S/S_D = Relative Storm Surge Level
H_{mo} = Significant Wave Height, ft
T_p = Spectral Peak Period, sec
ΔV, P = Volume Loss and Percent Damage Without Any Beach Renourishment
ΔV_{40}, P_{40} = Volume Loss and Percent Damage on Design Beach Width, B=40 ft under 75 ft Construction Beach Width
ΔV_{20}, P_{20} = Volume Loss and Percent Damage on One-Half Life Width, B'=20 ft under 75 ft Construction Beach Width
ΔV_{65}, P_{65} = Volume Loss and Percent Damage on Design Beach Width, B=65 ft under 125 ft Construction Beach Width
ΔV_{30}, P_{30} = Volume Loss and Percent Damage on One-Half Life Width, B'=30 ft under 125 ft Construction Beach Width
P=100*ΔV/V, V=Total Volume of the Dune, ≈ 30 cy/ft.

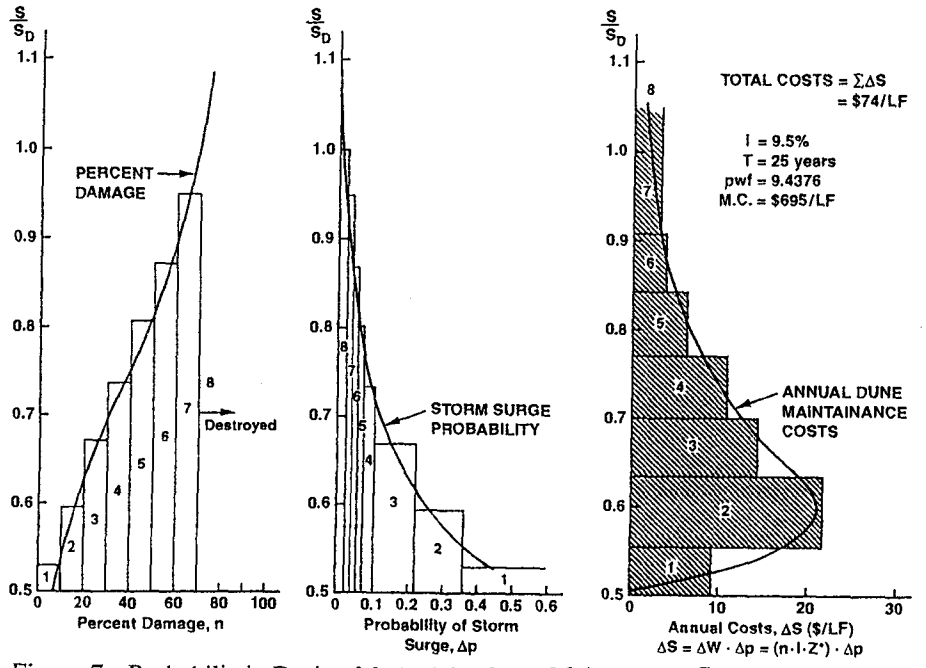

Figure 7 Probabilistic Design Method for Dune Maintenance Costs

Table 4 Dune Maintenance Costs

Region	Storm Surge Elev.*, S feet	Percent Damage (Average) n	Storm Probability Difference Δp	Dune Repair Costs ΔW = n.I.Z $	Annual Dune Maint. Costs, $ ΔS = Δp . ΔW
1	4.57	5	0.42	22.50	9.45
2	5.18	15	0.32	67.50	21.60
3	5.83	25	0.125	112.50	14.06
4	6.39	35	0.068	157.50	10.71
5	7.00	45	0.030	202.50	6.08
6	7.57	55	0.015	247.50	3.71
7	8.27	65	0.012	292.00	3.51
8	> 8.7	> 100 destroyed	0.010	450.00 rebuild	4.50
* ZERO DATUM (NGVD)				∑ΔS	73.62

Z = repair cost factor (say 1)

INITIAL COSTS, I.C.
IC = $15/cy * 30 cy/LF = $450/LF

MAINTENANCE COSTS, M.C.
i = 9.5%
T = 25 yrs
pwf = 9.4376
MC = $73.62 * 9.4376 = $695/LF

TOTAL COSTS, T.C.
TC = IC + MC
= $450/LF + $695/LF
TC = $1145/LF

For a proper design study, the water depths at the toe of the stone revetment were estimated as those at the *end* of the 25 year design life. The historic, long term erosion rate, seasonal beach variations and toe scour during storms were all considered to determine the design water depth. In effect, at the end of 25 years, the beach would be gone in front of the seawall and the design water depth would be far different than today's conditions. The SBEACH model and others were used to calculate the surf zone wave conditions and design wave height for the armor layer. Artificial armor units (core-loc) were selected and resulted in total costs (minimal maintenance) of about $2350 per foot.

Interestingly, the dune-beach-buried seawall alternative costs *less* than a concrete structure using artificial units for armor. This was primarily because the lowered beach elevations at the end of the design life permitted in large waves to directly attack the armor units with no beach remaining. Full details can be found in Cummings and Basco, 1997.

Costs are only one criteria in the decision matrix for choosing the "soft" or "hard" alternative for shore protection. Table 5 summarizes these decision criteria at Dam Neck. The only advantage of the armored revetment is lower annual maintenance costs. All others favored the dune-beach-buried seawall system. The primary benefits of this design are also that:

- a beach is present in the year 2020 at the end of the design life;
- the new sand spreads north and south to benefit all Dam Neck;
- the permitting agencies favor the "soft" alternative;
- the general public favors the "soft" alternative;
- the Navy's image will be enhanced by these efforts to protect/improve the environment.

6.0 Recommendations

Research is needed to develop generic damage curves and equations for use by coastal engineers for a wide range of practical applications. This dune design information could be developed through the systematic application of numerical models (e.g. SBEACH) plus confirmation of the results using large scale laboratory experiments and field data. The influence of the beach width should be quantified and design recommendations presented to aid the coastal engineer in dune design.

More case studies are needed comparing the life-cycle, costs of "soft" versus "hard" solutions for shore protection.

Table 5 "Soft" Versus "Hard" Alternatives for Storm Damage Mitigation

	ALTERNATIVE	
	"SOFT" Beach/Dune Buried Seawall	"HARD" Armored Revetment
• Shore Protection	✔	✔
• Economics - Initial Costs	✔	
Maintenance Costs		✔
Total Costs	✔	
• Environmental Consequences	✔	
• Recreation and Aesthetics	✔	
• Permit Application	✔	
• Public Perceptions	✔	
• Navy's Image	✔	
Combined Total	✔	

7.0 Acknowledgement

The authors wish to acknowledge the original contributions of John Headland (1991, 1992) for the buried seawall concept. Discussions with Professor van de Graaff, Delft Technical University are also appreciated. The project has been completed by Glenn and Sadler, consulting engineers, Norfolk, Virginia under the supervision of Mr. Robert E. Cummings, Jr.. The first author of this paper served as a special consultant on this project.

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