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Performance Evaluation of Seacliff Erosion Control Methods

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ABSTRACT

Seacliff-top property owners threatened by coastal erosion and retreat in California often choose to protect their property by installing erosion protection on or in the seacliffs. These protective measures have been implemented using a wide variety of techniques with various levels of success. This study quantified the short-term effectiveness of these erosion control devices for a 13 km section of the San Diego County coastline using airborne LIDAR and GIS spatial analysis over a six-year period. Erosion control methods were mapped and classified based on their location with respect to the cliff profile. The effectiveness of seacliff protection strategies was quantified by comparing the cliff face retreat rates of protected seacliffs against adjacent unprotected seacliffs. Overall, protective devices reduced the cliff face retreat by 42 percent. Seacliff protection was only partially effective because some methods did not provide defense against both marine and subaerial erosional processes. Seacliff erosion control methods that provided both lower and upper cliff protection performed better than methods which provided only partial protection. For example, areas with only cliff-toe protection were 31 percent effective, while areas combining lower and upper cliff protection were up to 58-75 percent effective. This study provides a new protection classification scheme and a methodology for regional first-order quantification on the effectiveness of seacliff protection methods.

INTRODUCTION

Seacliff retreat in California threatens residential structures, public property, and major transportation corridors. The rate of cliff retreat is controlled by the erosional forces, resisting cliff properties, and anthropogenic influences (Sunamura 1992). To reduce the threat and rate of retreat, cliff-top homeowners and government agencies have used a variety of erosion control methods ranging from beach replenishment to full cliff-height retaining walls. As of 2000, 177 km (10 percent) of the California coast has been structurally protected to some degree (Griggs et al. 2005). In many instances, erosion protection and cliff stabilization projects have been installed on or in the seacliffs (Figure 1). The objective of this paper is to quantify the performance of these seacliff protection methods using a comparative spatial analysis of erosion rates.

This study compared two airborne LIDAR (LIght Detection And Ranging) data sets spanning the six-year time period between April 1998 and April 2004 using GIS (Geographic Information System) spatial analysis. LIDAR scanners pulse a narrow, high frequency laser beam at the earth's surface and record the travel time and angle of each reflected pulse. Successive surveys can be used to quantify volumetric change over time. Although available LIDAR data covers a much shorter time scale compared to traditional methods that utilize historical maps and aerial photographs (years versus decades), the high point density of LIDAR data yields accurate, quantitative estimates of the eroded volume (Young and Ashford 2006). In addition, LIDAR provides a direct, three-dimensional erosion analysis, whereas traditional methods typically focus on two-dimensional retreat.

ADDITIONAL KEYWORDS: Shoreline changes, coastal armoring, seawalls, erosion rates, coastal erosion, coastal mapping, California, LIDAR.

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STUDY AREA

The study area (Figure 2) covers a 13-km stretch of coastline in northern San Diego County, California, extending from Cottonwood Creek to Los Peñasquitos Lagoon. The project area is located within the Oceanside Littoral Cell which extends from Dana Point to La Jolla (Inman and Frautschy 1966). This stretch of coastline consists of narrow sand and cobble beaches backed by steep seacliffs cut into uplifted marine terraces. Seacliffs mark the seaward edge of the marine terraces, and the landward boundary of the wave cut platform where the cliff-toe intersects the platform at approximately mean sea.

The majority of the seacliffs are approximately 20-30 m high, and are composed of two primary geologic units. The lower unit generally consists of either the Del Mar Formation or the Torrey Sandstone, both of which are lithified Eocene sedimentary rocks (Kennedy 1975). The upper unit is composed of unlithified Pleistocene marine terrace deposits, and extends throughout the study area. The lower Eocene-age unit is stronger and

Figure 1. Construction of a tied-back artificial rock seawall in Solana Beach.

more resistant to erosion; however, both units are erodible with long-term retreat rates estimated at 8-19 cm/yr (Benumof and Griggs 1999). The region also contains several artificial fills that have been placed during slope reconstruction efforts. The study area was divided into three sections (Cardiff, Solana Beach, and Del Mar), based on general stratigraphy and lagoon/creek incisions.

Cardiff Section

The Cardiff section extends from Cottonwood Creek to San Elijo Lagoon with the majority of the lower geologic unit composed of the Del Mar Formation, while a small portion of the most northerly seacliffs is composed of the Torrey Sandstone. The cliff-top in this section has been completely developed with residential structures, city and state parks, the Self-Realization Fellowship Temple, and California Pacific Coast Highway 101. At the southern end of this section, the terrace deposits were removed during the construction of the San Elijo State Campground.

Solana Beach Section

The Solana Beach section extends from San Elijo Lagoon to San Dieguito Lagoon, with the lower geologic unit mostly consisting of the Torrey Sandstone, which has been incised by several ancient river channels and filled with alluvium deposits (Kuhn 1977). The Del Mar Formation outcrops locally at both the southern and northern end of this section (Kuhn 1977). The cliff-top consists of single family residential units and multi-story condominium structures.

Del Mar Section

The Del Mar section extends from Power House Park to Los Peñasquitos Lagoon with the Del Mar Formation comprising the lower geologic unit. The cliff-top contains the North County Transit District rail corridor, which runs the full length of this section. Cliff failures in this section of coastline can threaten railway activity and have caused trains to derail in the past (Figure 3).

Climate and Oceanographic Setting

San Diego County has a semi-arid, Mediterranean climate characterized by mild, sometimes wet winters and warm, very dry summers. The region is influenced by the El Niño-Southern Oscillation which brings abnormally high winter precipitation. This study occurred during a relatively dry (27 percent below average precipitation) time period between two heavy rain seasons, after the 1997-1998 El Niño event (46 cm of rainfall) and before the 2004-2005 wet season event (55 cm of rainfall).

The San Diego coast receives waves from three primary sources: northern hemisphere swell, southern hemisphere swell, and local seas. Deep water waves undergo a complex transformation due to island shadowing, refraction, diffraction and shoaling before reaching the coastline. Tides are of the mixed semidiurnal type with a diurnal range of 1.62 m (La Jolla tidal gauge). The highest water level recorded was 2.33 m (MLLW datum) on 13 November 1997 (http://tidesandcurrents.noaa.gov/index.shtml).

BACKGROUND

Previous studies on the effectiveness of seacliff protection have been both qualitative (e.g. Fulton-Bennett and Griggs 1986; Magoon *et al.* 1988; Storlazzi *et al.* 2000; Komar and McDougal 1988; Prior and Renwick 1980) and quantitative (e.g. Sunamura and Horikawa 1972; Clayton 1989; Carter *et al.* 2001). The results of these previous studies indicate that seacliff protection has been variously successful depending on the amount and type of protection used. Of particular interest to this paper are the studies (Komar and McDougal 1988; Prior and Renwick 1980) that indicate toe protection, which is commonly found in San Diego County, may not eliminate erosion problems. Our study sought to further investigate the performance of seacliff protection methods, using a quantitative GIS-based spatial analysis approach. This approach is similar to those of previous quantitative studies (Sunamura and Horikawa 1972; Clayton 1989) that compared natural retreat rates to those in protected areas.

METHODS

Classification and Mapping of Seacliff Protection Methods

Seacliff erosion protection methods were herein classified based on the location of the control device with respect to the seacliff profile (Figures 4 and 5). Type A projects are found at the cliff-toe and are used primarily to protect against wave impact. Type B projects are located on the lower cliff section and usually provide some lower seacliff support. Almost all Type B projects extend to the cliff-toe and provide protection from wave impact, therefore these structures were classified as Type AB.

Type C projects are located on the upper cliff and are used to provide upper cliff support and/or control subaerial erosion. Type D structures are located at the cliff-top and are usually used to provide support and/or prevent subaerial erosion at the crest of the seacliff. In some cases, Type D projects also served as a foundation for cliff-top structures.

Because the classification is based on the cliff profile, the protection category also corresponds to the upper and lower seacliff geologic units. For example, Type A and B control provide protection of the Eocene deposits, whereas Type C and D provide protection of the Pleistocene terrace deposits.

Seacliff erosion control projects were mapped (Figures 6, 7, and 8) for the beginning and end of the study period (April 1998 and April 2004) using oblique photographs (USGS 1998; Group Delta 1998, California Coastal Records Project), coastal maps (Flick 1994; Leighton and Associates 2001, 2003), personal communication (Lesley Ewing 2005), and field surveys. Each erosion control project was then designated as Type A, B, C, or D (Table 1) or various combinations based on the classification methodology described above.

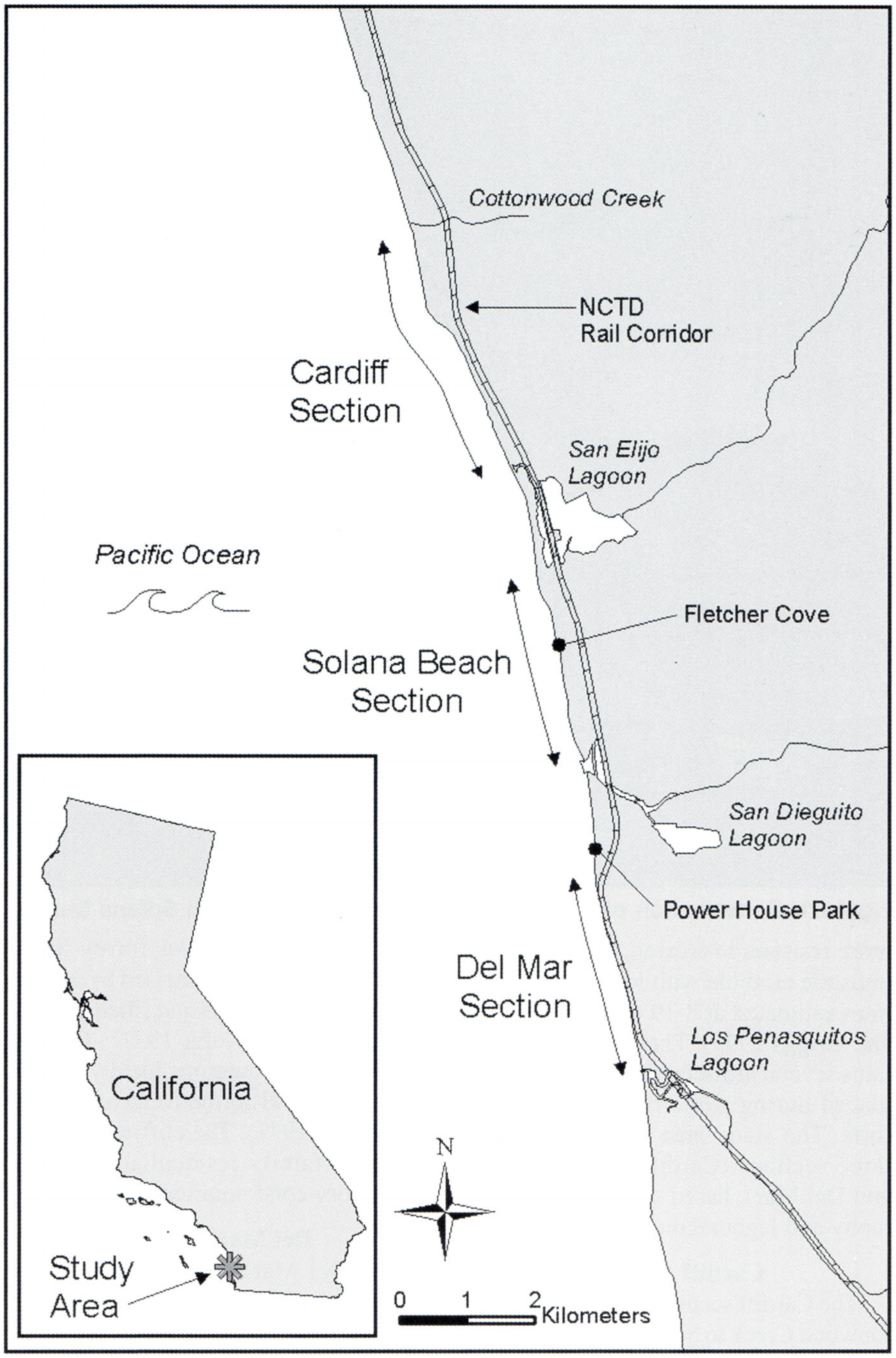


Figure 2. Study location map and section boundaries.

Topographic and Volumetric Change

Topographic change of the seacliffs was evaluated using airborne LIDAR collected in April 1998 (ATM 1998) and April 2004 (provided by the Southern California Beach Processes Study, operated by the Scripps Institution of Oceanography). Both data sets were obtained in X,Y,Z format and interpolated into 0.5 m resolution grids using ArcINFO 3-D Analyst (ESRI 2004). Then, grid subtraction produced the topographic change.

The potential error of the topographic change grids can be primarily attributed to LIDAR measurement error, interpolation error, and vegetation. This error was evaluated by comparing a representative control section to each study section resulting in the percent error for Cardiff, Solana Beach, and Del Mar at ± 8.8 percent, ± 5.0 percent, and, ± 9.9 percent, respectively (Young and Ashford 2006). Aerial LIDAR does not capture over-vertical surfaces such as sea caves or notches, and thus were not evaluated. Corrections were made in heavily vegetated areas by removing the cells. After

Figure 3. Train derailment in 1941 along the Del Mar seacliffs (photo courtesy of the Encinitas Historical Society).

editing, the cliffs in each section were extracted from the vertical change grids and converted to volumetric change grids.

GIS Spatial Analysis

The first step was to divide each volumetric change grid into 2 m-wide compartments with ArcINFO (ESRI 2004) shape-files (Figure 9). Next, summing the volumetric change cells within each compartment produced individual compartment eroded volumes. The compartment shape-files were then intersected with the digital elevation model to find the cliff height of each compartment. The final step was to classify each compartment by intersecting the compartment shape-files with the seacliff erosion control locations.

Seacliff Retreat Rate

The linear rate of cliff face retreat was calculated for each seacliff compartment (Equation 1) and plotted alongshore for each study section (Figures 6, 7, and 8).

$R_l = V_{st} / (H_c * L_c * T)$ (Equation 1)

R_l = Linear rate of cliff face retreat
V_{st} = Total eroded volume from seacliff within the compartment
H_c = Seacliff height in the compartment
L_c = Length of seacliff compartment (2 m)
T = Time span (6 years)

Equation 1 is independent of the slope angle (Figure 10), describes the average rate of retreat over the entire cliff face, and reduces the episodic nature of retreat measurements (Young and Ashford 2006). This method does not represent the actual seacliff top or seacliff base retreat rate.

Quantifying the Effectiveness of Seacliff Protection

The effectiveness of each seacliff protection method was evaluated by comparing the retreat of protected seacliffs to unprotected seacliffs in the same section (Equation 2). Negative results of Equation 2 indicate the protected seacliffs retreated more than the unprotected seacliffs.

$E_c = [(R_U - R_P) / R_U] * 100\ \%$ (Equation 2)

E_c = Effectiveness of control type
R_U = Average retreat rate of unprotected seacliffs
R_P = Average retreat rate of protected seacliffs (sorted by control type)

Seacliff compartments that changed control classification due to seacliff protection construction during the time period were removed from the analysis. This accounted for approximately 7 percent of the total study length.

RESULTS AND DISCUSSION

Overall, the bulk of seacliff protection consisted of Types A, AB, ABC, and ABCD (Figure 11). The majority of additional protection was constructed in Solana Beach, consisting of Type A notch in-fills and Type AB artificial rock seawalls. The Solana Beach section increased from 33 percent to 44 percent controlled, while Cardiff had essentially no change at 42 percent controlled, and Del Mar increased slightly from 16 percent to 17 percent controlled (Figure 12).

The effectiveness of control (Table 2) for the Cardiff, Solana Beach, and Del Mar sections range from -71 percent to 73 percent, -127 percent to 84 percent, and 15 percent to 83 percent respectively. The weighted average of seacliff retreat reduction for the entire study area ranged from -71 percent to 75 percent. Overall, sections with some type of protection reduced the retreat rate by 42 percent in Cardiff, 35 percent in Solana Beach, and 58 percent in Del Mar. Variation in local geologic conditions, topography, and wave energy may have locally affected the rate of cliff erosion, but were assumed uniform within each section in order to make a comparison of protected and unprotected areas.

The results indicate that the erosion control methods had a wide range of effectiveness. Many control methods failed

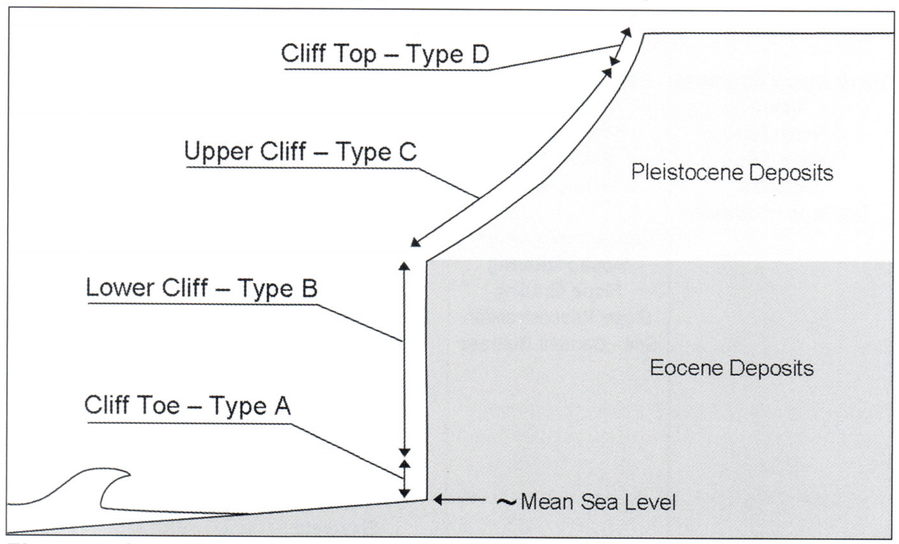


Figure 4. Seacliff erosion control classification based on the location with respect to the seacliff profile.

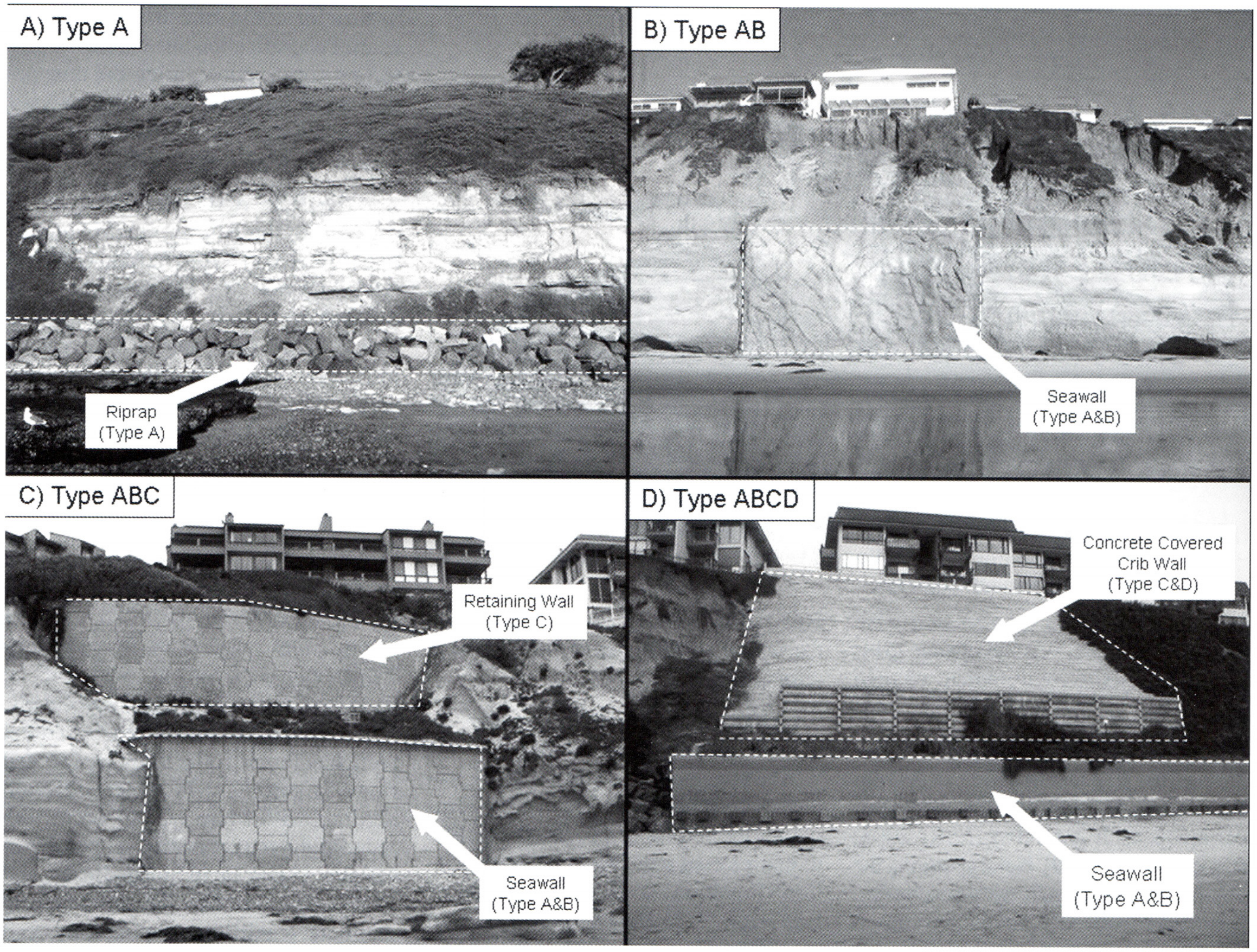


Figure 5. Examples of erosion control classification (A) Type A — riprap in the Cardiff section. (B) Type AB — tied-back artificial rock wall in Solana Beach. (C) Type ABC — a seawall and upper cliff retaining wall in Solana Beach. (D) Type ABCD — a seawall and concrete-covered crib wall retention system in Solana Beach.

to provide protection against both marine and subaerial erosional processes leading to continued erosion in semi-protected areas. Protection methods that used a combination of strategies to protect against both marine and subaerial erosion were the most successful. For example, over the entire study area Type A was 31 percent effective while Type AB, ABC, and ABCD were 74 percent, 58 percent, and 75 percent effective, respectively. The most effective type of control was Type ABCD which was 100 percent effective in some localized areas where the protection consisted of a completely artificially hardened seacliff (Figure 5D).

Type A	Type B	Type C	Type D
Wave Impact Structures	*Retention Structures*	*Retention Structures*	*Retention Structures*
Riprap	Seawalls	Retaining Walls	Retaining Walls
Notch Fills	Retaining Walls	Post and Board	Post and Board
Cave Fills	Soldier Piles	Crib Walls	Crib Walls
Seawalls	Rock Bolts	Tire Walls	Soldier Piles
Drainage Headwalls		Soldier Piles	
	Slope Improvement	Rock Bolts	*Slope Covering*
	Slope Flattening		Gunnite
	Slope Grading	*Slope Improvement*	Shotcrete
	Slope Reconstruction	Slope Reconstruction	
	Soil - Cement Buttress	Slope Flattening	
		Slope Grading	
		Soil - Cement Buttress	
		Geogrid	
		Slope Covering	
		Gunnite	
		Shotcrete	
		Jute Matting	

Table 1. Classification of Seacliff Erosion Control Devices.

It is difficult to determine all the specific reasons why the control measures failed to prevent erosion, but several reasons were identified from field investigations and photographic evidence. Type A control, which generally does not provide upper cliff structural support, failed to prevent upper cliff landslides in several locations (Figure 13). Additionally, Type A and AB control methods were subject to overtopping and outflanking throughout the study area. Undermining and poor maintenance of protective devices also caused localized erosional problems. Both surface and subsurface drainage systems (which coincide with many erosion controlled areas) acceler-

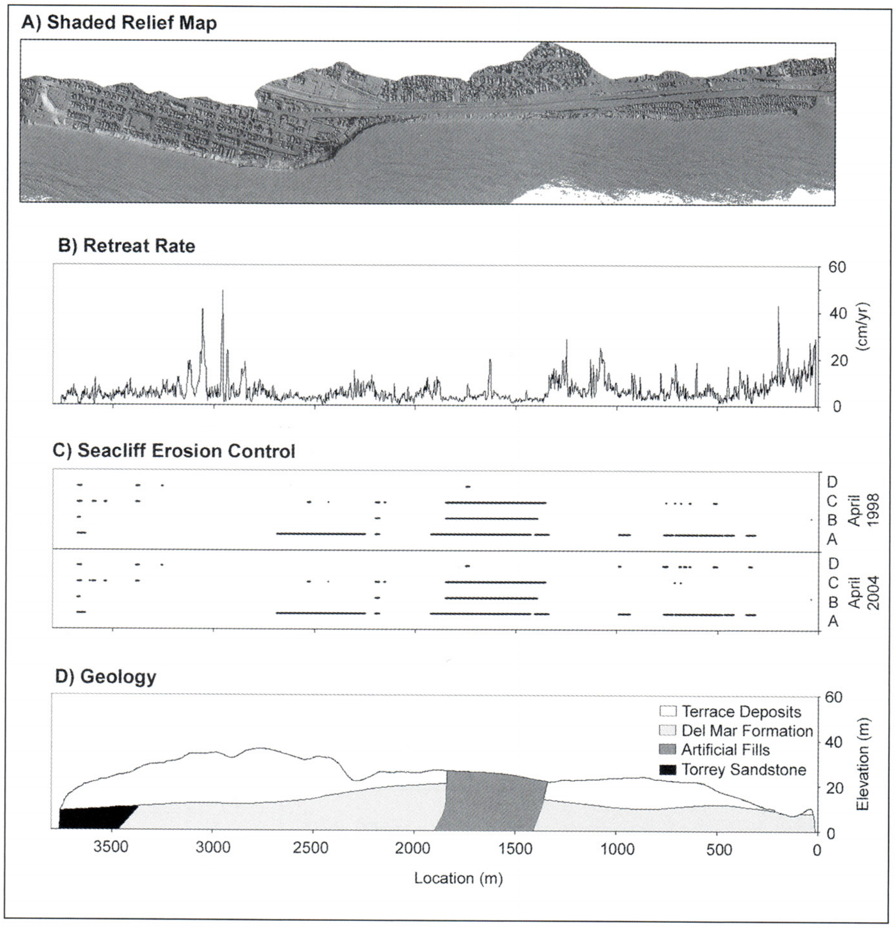
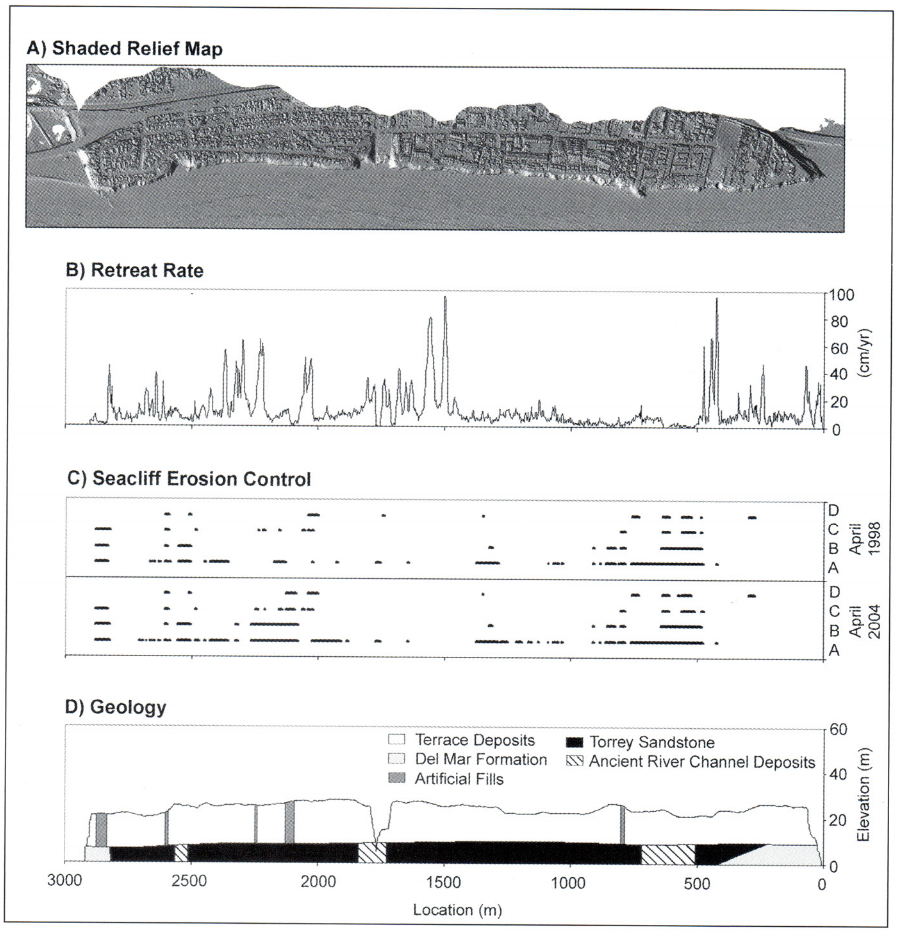


Figure 6. Details of the Cardiff section (A) shaded relief map (B) average annual seacliff face retreat during the study period (C) classified locations of seacliff erosion control measures for the beginning and end of the study period (D) general geology and cliff height along the section.



ated erosion when the systems had failed, poorly situated outlets, or not been maintained.

CONCLUSIONS

This research provides a new methodology to quantify the effectiveness of seacliff erosion control devices using airborne LIDAR and detailed GIS spatial analysis, as well as a new method of seacliff erosion protection classification based on cliff face profile. This approach demonstrates that the effectiveness of seacliff protection strategies can be quantified by comparing the cliff face retreat rates of protected and unprotected seacliffs on a regional scale.

Given the short-term study period and the episodic nature of large cliff failures, it is difficult to make any long-term conclusions. Nevertheless, the results of this study indicate that seacliff erosion control was only partially effective during the study period because some measures did not provide protection against both marine and subaerial erosional processes. In addition, some erosion control methods were subject to wave overtopping, outflanking, and undermining, while poorly maintained and failed drainage systems adversely affected the retreat in some protected areas. Erosion control methods that provided both lower and upper cliff protection performed better than methods which only provided partial protection. Partial seacliff erosion protection was effective at decreasing erosion, but failed to eliminate all erosion. Overall, protective devices reduced the cliff face retreat by 42 percent.

Figure 7. Details of the Solana Beach section (A) shaded relief map (B) average annual seacliff face retreat during the study period (C) classified locations of seacliff erosion control measures for the beginning and end of the study period (D) general geology and cliff height along the section.

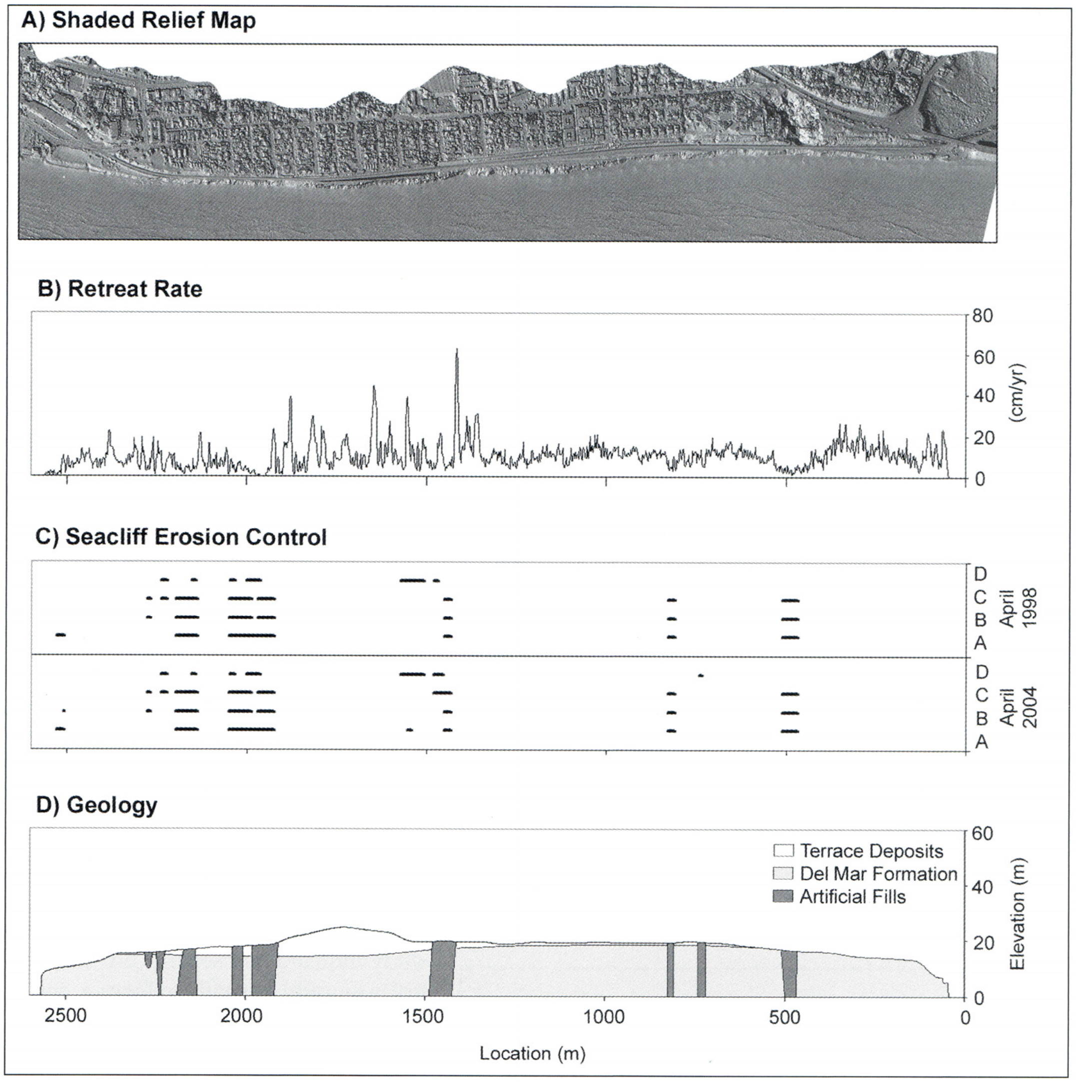
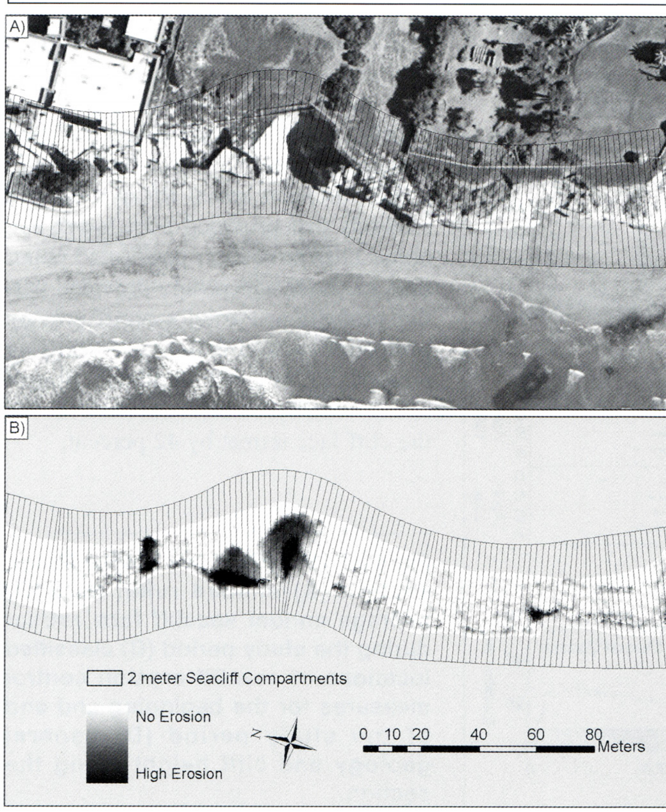


Figure 8 (left). Details of the Del Mar section (A) shaded relief map (B) average annual seacliff face retreat during the study period (C) classified locations of seacliff erosion control measures for the beginning and end of the study period (D) general geology and cliff height along the section.

Figure 10 (below). Visual representation of how seacliff face retreat was calculated. Note: This shows the equation is independent of slope angle.



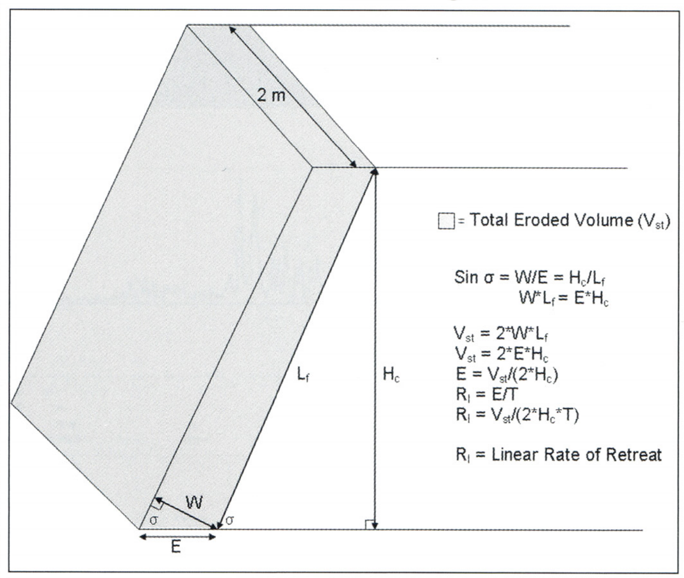


Figure 9 (left). Two-meter wide sea-cliff compartment polygons (A) displayed over an aerial photograph in the Solana Beach section and (B) over the erosion grid of the same area. Note the dark areas showing significant erosion during the study period.

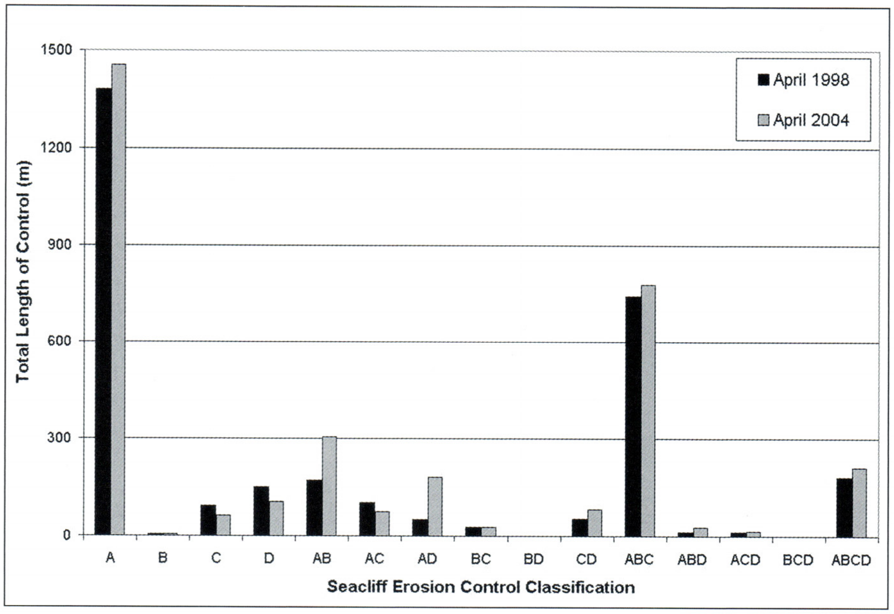


Figure 11. Detailed results of the erosion control mapping and classification for the entire study, at the beginning and end of the study period.

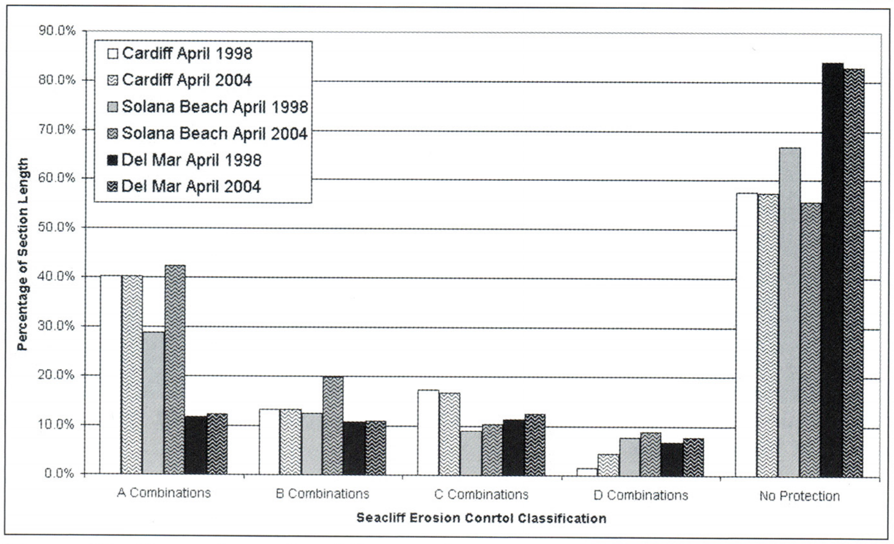


Figure 12. General results of the erosion control mapping and classification for the three study areas, at the beginning and end of the study period.

Type of Seacliff Erosion Control	Cardiff Seacliff Retreat Reduction (%)	Cardiff Length Evaluated (m)	Solana Beach Seacliff Retreat Reduction (%)	Solana Beach Length Evaluated (m)	Del Mar Seacliff Retreat Reduction (%)	Del Mar Length Evaluated (m)	Weighted Average Seacliff Retreat Reduction (%)
A	35	862	21	374	83	20	31
B	-71	4	---	---	---	---	-71
C	40	42	-127	14	---	---	-2
D	23	8	-76	42	15	54	-21
AB	---	---	74	160	---	---	74
AC	58	62	---	---	---	---	58
AD	---	---	45	36	82	14	55
BC	66	16	---	---	67	12	67
CD	53	16	-98	18	46	18	-1
ABC	52	448	81	92	62	202	58
ABD	---	---	65	12	---	---	65
ACD	73	4	-46	8	---	---	-6
ABCD	56	32	84	88	71	60	75
A Combinations	42	1408	47	772	66	296	46
B Combinations	51	500	78	352	64	274	63
C Combinations	52	620	50	220	63	292	54
D Combinations	52	60	22	204	48	144	35
Any Combination	42	1494	35	844	58	380	42

Table 2. Effectiveness of Seacliff Erosion Control Devices Evaluated by Comparing the Retreat Rate During the Study Period of Protected Seacliffs to Unprotected Seacliffs (Equation 5 Results).

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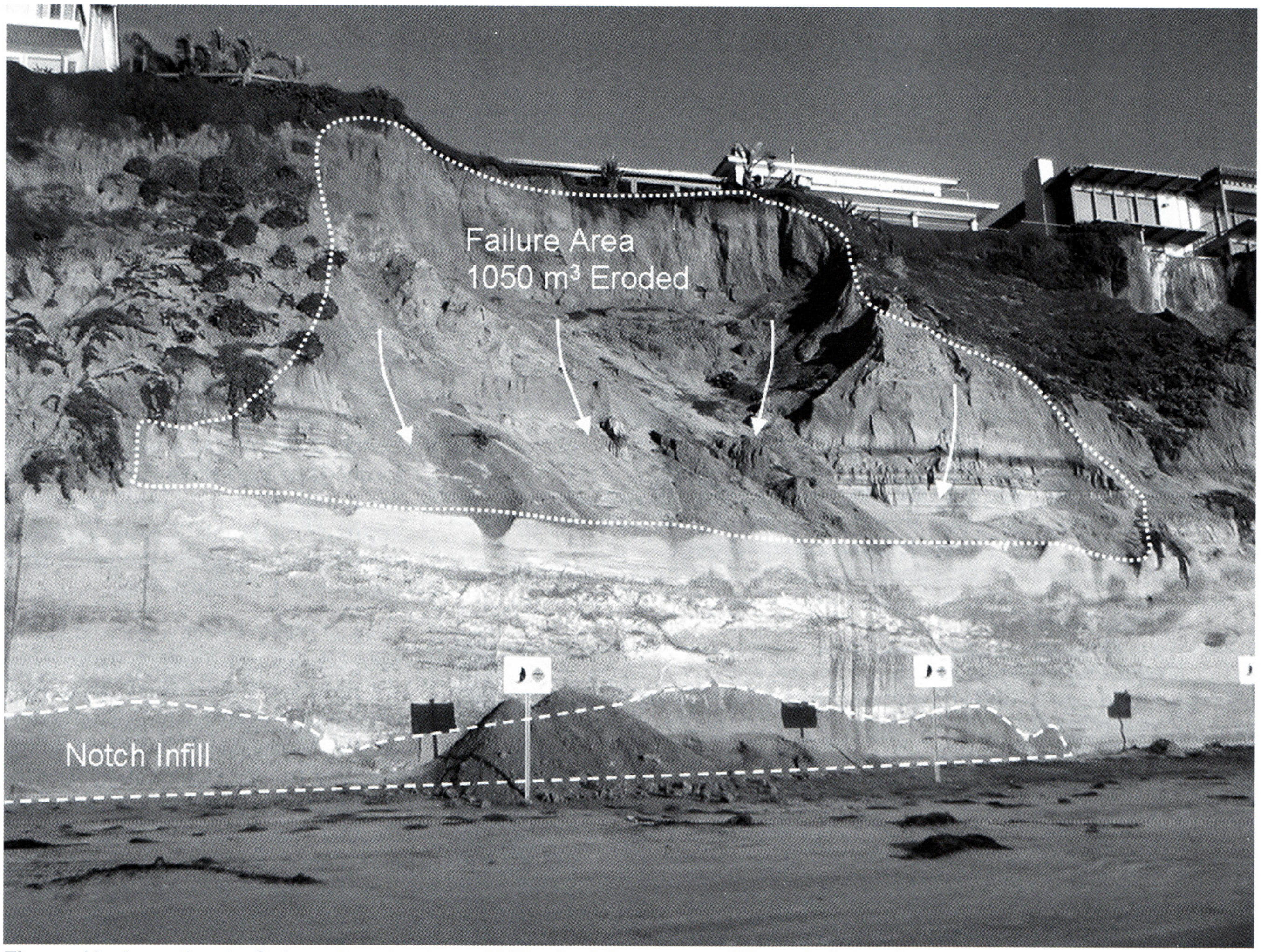

Figure 13. A section in Solana Beach where 1050 m^3 of the upper cliff eroded despite a notch infill that was used to prevent erosion. Note recently failed material at the cliff base.

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