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Quantifying Short-Term Seacliff Morphology of a Developed Coast:

San Diego County, California

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy
in
Structural Engineering
by
Adam Patrick Young

Committee in charge:

Professor Scott Ashford, Chair
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2006
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Chair

University of California, San Diego

2006
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Chapter 3, in full, is a reprint of the journal paper: Young, A. P. and Ashford, S. A., 2006. Application of Airborne LIDAR for Seacliff Volumetric Change and Beach-Sediment Budget Contributions. Journal of Coastal Research, 22(2), 307-318. The dissertation author was the primary investigator and author of this paper.

Chapter 4, in part, has been accepted for journal publication and will be titled as the following: Young, A. P. and Ashford, S. A., 2006. Performance Evaluation of Seacliff Erosion Control Methods, Shore and Beach. The dissertation author was the primary investigator and author of this paper.
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ABSTRACT OF THE DISSERTATION

Quantifying Short-Term Seacliff Morphology of a Developed Coast:

San Diego County, California

by

Adam Patrick Young

Doctor of Philosophy in Structural Engineering

University of California, San Diego, 2006

Professor Scott A. Ashford, Chair

Seacliff erosion and retreat in California threatens public and private property, coastal infrastructure, transportation corridors, and public safety. Seacliffs also contribute sediment to California beaches, which drive the coastal tourism economy. Thus, understanding the processes which govern seacliff erosion is paramount in protecting the coast and mitigating erosional issues. This research effort, focused on the Oceanside Littoral Cell, builds upon past projects and provides new insight into seacliff morphological processes.

This study utilized airborne and terrestrial LIDAR (LLight Detection And Ranging) and GIS (Geographic Information System) analysis to quantify short-term seacliff morphology and the effectiveness of erosion control methods. Additionally, the stability of cantilevered seacliffs was also explored using finite element analysis and elastic beam theory. Numerous field investigations and photographic surveys also provided indispensable information pertaining to erosional mechanisms.
It is difficult to make any long-term conclusions from the data given the relatively short study period. However, the results of the airborne LIDAR analysis indicate that seacliff sediment contributions were a significant sediment source of beach-sand in the Oceanside Littoral Cell for the study period, and that the relative percentage of annual seacliff sediment contribution was higher than found in previous studies. It was also found that converting volumetric erosion rates into linear retreat rates averages the erosion over the entire cliff face, thus reducing the episodic nature of cliff retreat measurements, and proving the efficacy of LIDAR in short-term studies. A comparison of cliff face retreat rates between unprotected and protected seacliffs indicated that erosion control methods that provided both lower and upper cliff protection performed better than methods which only provided partial protection. Additionally, the findings of this study suggested that properly controlling groundwater and surface runoff could reduce cliff erosion caused by subaerial processes.

Terrestrial LIDAR analysis demonstrated valuable applications at both a regional and site-specific level. The regional results illustrated that small erosional events, which may have previously gone unnoticed, may constitute a significant fraction of eroded material, underscoring the importance of evaluating short-term cliff morphology. The site-specific analysis of erosional hot spots, yielding individual failure volumes and profiles, allowed identification of landslide mechanisms, and permitted the back-calculation of soil properties from failure criteria. Recent advances
in LIDAR technology and use are not yet fully exploited and will provide further understanding of seacliff morphology in the future.
CHAPTER 1: Introduction
INTRODUCTION

The coastline is the unique interface of the ocean, land, and atmosphere where geologic processes can be observed on a human time scale. Each of these elements is important in controlling the erosional and depositional processes that shape our coastline. As the coastline became urbanized, the erosional processes have presented serious problems. Coastal erosion and seacliff retreat currently threaten coastal infrastructure, public safety, and the coastal tourism economy throughout much of California. These problems are likely to accelerate in the future if current projections of sea level rise become a reality. Many attempts to control seacliff erosion and retreat have had varying rates of success. This project seeks to better understand the short-term erosional processes affecting seacliffs and the effectiveness of erosion control devices. This research was conducted at the Jacobs School of Engineering, University of California San Diego, and was funded by California Sea Grant and the Coastal Environmental Quality Initiative. The specific goals of this research include:

- Identify erosion hot spots
- Quantify short-term retreat rates
- Evaluate the significance of subaerial and marine erosional processes
- Quantify seacliff sediment contributions to the littoral cell
- Evaluate seacliff stability
- Map erosion control devices
• Assess the effectiveness of erosion control devices

• Identify erosional processes

• Quantify seafloor morphology

The research objectives were addressed using a variety of methods including:

• Airborne LIDAR

• Terrestrial LIDAR

• GIS mapping and analysis

• Slope stability analysis

• Field investigation

• Digital photogrammetry

BACKGROUND

A significant body of research in the field of seafloor geomorphology has been conducted providing a strong foundation for this project. Texts by Trenhaile (1987) and Sunamura (1992) provide an extensive background in the geomorphic processes affecting the worlds’ seafloors. Hampton and Griggs (2004) also present a broad background in this discipline with a focus on coastal cliffs in the United States. Key works focusing specifically on the California seafloors include Griggs and Savoy (1985) and Griggs et al. (2005). Major research on the San Diego County seafloors
includes Kuhn and Shepard (1984), Flick (1994), U.S. Army Corp of Engineers - Coast of California Storm and Tidal Wave Studies (1983-1991), and Benumof (1999). Additionally, Collins (2004) provided a background in surveying seaclliffs utilizing terrestrial LIDAR. While these works are by no means a complete list of the previous research conducted in this field, they provided the fundamental background for this project. In addition to these vital sources of information, numerous journal papers and reports cited throughout this dissertation provided essential information indispensable to this research project.

PROJECT LOCATION AND DESCRIPTION

The project site, located in southern California, spans an 84 kilometer stretch of coastline known as the Oceanside Littoral Cell (Figure 1-1). This cell is categorized by narrow sand and cobble beaches backed by steep seaclliffs cut into uplifted marine terraces. Most of the rocks that constitute the lower portion of the cliffs are sedimentary rocks deposited on the continental shelf and the adjacent margin during the Eocene Epoch (Kennedy, 1975). Subsequently, wave erosion cut several terraces into these rocks during periods of changing sea level, after which Pleistocene sediments were deposited unconformably on top of the eroded Eocene sediments. Tectonic activity has raised many of the marine terraces above the current sea level, which now form a common feature along the region’s coastal plain. The formation of marine terraces is still an active process today. The most recent terrace started forming when sea level rise slowed to a relatively stationary position around 6000
years ago (Figure 1-2; Fairbanks, 1989). Waves cutting this actively forming marine terrace have produced the steep, unstable seacliffs exposed at today's shoreline. These seacliffs mark the landward boundary of the currently forming terrace platform and comprise 70% of the shoreline in the Oceanside Littoral Cell (Figure 1-3).

Figure 1-1. Map of the Oceanside Littoral Cell located in southern California.
Figure 1-2. Fairbanks (1989) sea level curve. Note, sea level rise significantly slowed about 6000 years ago to today's approximate position.
Figure 1-3. Seamounts mark the landward edge of the currently forming marine terrace. Note the wave cut platform exposed at the cliff base.

The Oceanside Littoral Cell has a long documented history of seamount erosion (Kuhn, 1980; Kuhn and Shepard, 1984). In fact, seamount erosion was first observed by the U.S. Coast and Geodetic Survey in 1884 (USCGS, 1889). From about that time to the present, the tidal gauge at San Diego Bay has recorded a mean sea level rise trend of 21.5 cm/century (Figure 1-4; NOAA, 2006), ensuring continued marine erosion of
unprotected seacliffs. Problems associated with seacliff erosion and retreat started to present problems as the region became rapidly developed during the 20th century. Figure 1-5 illustrates the dramatic rise in the region’s population, which has more than doubled three times between 1940 and 1990. In fact, population data (CIESIN, and CIAT, 2005) indicates that as of 2005, an estimated 1,411,000 people reside within the 6202 km² watershed of the Oceanside Littoral Cell, with the majority living along the coast (Figure 1-6). With the exception of the Camp Pendleton region, the entire coast is now densely populated and urbanized.

![San Diego Sea Level](image)

**Figure 1-4.** Recent sea level rise in San Diego Bay, Station ID: 9410170 (Figure source: NOAA, 2006).
Figure 1-5. Historical and projected population of San Diego County (U.S. Census Bureau, 2006 and SANDAG, 2006).
Figure 1-6. 2005 population density and areas affected by dams in the major watersheds of the Oceanside Littoral Cell.

The region’s urbanization and development has had major impacts on the coastline (Inman, 1976), including the damming of coastal rivers and construction of harbor jetties. Damming of the coastal watershed (Figure 1-6) has reduced the natural river beach-sediment supply by approximately 50% (Flick, 1994; Inman and Masters, 2005), while a series of harbor jetties built in Oceanside between 1942-1963 have interrupted the natural transport of beach sand. Additionally, coastal protective
structures have reduced the seacliff’s natural beach-sediment yield (Runyan and Griggs, 2003). The deficit in natural beach sediment supply has been supplemented by numerous beach replenishment projects, which started in the 1940’s, whereby over fifteen million cubic meters of sand have been placed in the Oceanside Littoral Cell (Flick, 2005). Despite these beach replenishment projects, waves continue to erode the seacliffs and currently threaten cliff top infrastructure (Figure 1-7).

Figure 1-7. Waves impacting the Solana Beach seacliffs, January 11, 2005.
OUTLINE OF THE DISSERTATION

The remainder of this dissertation consists of seven chapters. The next chapter (Chapter 2) describes an initial investigation of the effectiveness of erosion control devices by measuring short-term cliff top retreat using digital photogrammetry. This investigation was unable to accurately quantify cliff top retreat due to data gaps and the relative potential error associated with the data sets. Dissatisfied with the results using aerial photographs, a new methodology was adopted to address the research goals, which involved using LIDAR (Liight Detection And Ranging) data. While LIDAR data spans a relatively short time period (the first data set in the project area was collected in 1997), the precision and high point density of the data provides accurate three-dimensional analysis previously unobtainable using aerial photographs.

The third chapter describes using airborne LIDAR data to quantify seaciff volumetric change at a regional level, to back-calculate short-term retreat rates, and to evaluate seaciff beach-sediment contributions to a littoral cell. Building upon chapter three, the fourth chapter describes how airborne LIDAR data may also be used in a GIS environment to perform spatial analysis and evaluate the effectiveness of erosion control devices, as well as the roles of groundwater and drainage systems on seaciff erosion.

The fifth chapter describes a different approach to evaluating seaciff morphology using terrestrial LIDAR. Terrestrial LIDAR scanning provides extremely dense data and has many applications ranging from in-depth, site-specific analysis to regional morphological mapping. The sixth chapter explores the stability of
cantilevered seaclliffs by combining terrestrial LIDAR data, elastic beam theory, and finite element modeling. The seventh and final chapter provides a summary of the major conclusions resulting from this research.
CHAPTER 2: Evaluating the Effectiveness of Seacliff Erosion Control on a Developed Coastline Using Digital Photogrammetry
ABSTRACT

The instability and retreat of seacliffs in San Diego County has resulted in the construction of a wide variety of seacliff erosion control devices. The scope of this project was to regionally quantify the effectiveness of these different erosion control methods by evaluating short-term cliff retreat using digital photogrammetry. The study focused on a 17 kilometer stretch of coastline in northern San Diego County. Although several similar previous studies were successful at quantifying long-term cliff top retreat using digital photogrammetry, this study was unable to accurately quantify short-term retreat rates due to data quality, data gaps, seacliff development and alteration, and lack of required information. Measuring the short-term cliff retreat was necessary because the majority of control methods have been installed relatively recently. Due to the relatively small amount of retreat that occurs during a short time period in the study area, the quantifiable error exceeded the estimated short-term retreat rate. Additionally, major problems encountered included unidentifiable cliff edges causing data gaps, artificial shifts in cliff edge position, and an incomplete seacliff development history. Future research in this area could be improved by using higher quality data or choosing a different study area with additional available information.

INTRODUCTION

The instability and retreat of seacliffs in San Diego County threatens residential development and coastal infrastructure. As a result, much of the coast now
contains various types of erosion control devices ranging from small retaining walls to massive seawalls. The goal of this project was to evaluate how effective these erosion control devices have been at controlling cliff top retreat using digital photogrammetry. The study area consists of a 17 kilometer stretch of coastline located in northern San Diego County. This region was selected because it contains a wide variety of erosion control devices. The retreat rates of erosion controlled sealiffs could then be compared to previous studies by Benumof and Griggs (1999) and Moore et al. (1999) which have evaluated adjacent unprotected sealiffs.

Digital photogrammetry is commonly used to obtain geographic and topographic information from aerial photographs. This technique has been used to quantify long-term cliff top retreat in many areas throughout the world (Moore et al., 1999; Benumof and Griggs, 1999; Benumof et al., 2000; Moore and Griggs, 2002; Catalão et al., 2002; Zviely and Klein, 2004; Newsham et al., 2002), and short-term retreat in northern Monterey Bay, California (Hapke and Richmond, 2002).

While these previous studies were successful at accurately quantifying cliff top retreat at various time scales using digital photogrammetry, this study was unable to accurately quantify short-term retreat rates for several reasons, namely the original and digitized photograph quality, visual obstructions, ambiguous natural features, cliff top development, lack of information, and relatively small retreat rates. The combination of these problems resulted in unacceptable error and data gaps. This chapter outlines the difficulties encountered and reasons this project was unable to accurately quantify cliff top retreat for the developed sealiffs in the study area.
STUDY AREA

The study area consists of a 17 km stretch of coastline extending from Batiquitos Lagoon to Los Penasquitos Lagoon, which includes the cities of Del Mar, Solana Beach, and Encinitas (Figure 2-1). The study area is entirely within the Oceanside Littoral Cell located in Southern California. The Oceanside Littoral Cell spans an 84 kilometer stretch of coastline from Dana Point to La Jolla (Inman and Frautschy 1966). The project site is characterized by narrow sand and cobble beaches backed by seacliffs cut into uplifted marine terraces. Steep cliffs dominate the study area with occasional alternating lowlands at coastal river mouths and lagoons. The majority of the seacliffs are approximately 20 to 30 meters in height and are generally composed of two main geologic units. The lower unit consists of lithified Eocene mudstone, shale, sandstone, and siltstone (Kennedy, 1975). The lower unit is capped by unlithified Pleistocene terrace deposits. The lower unit is stronger and more resistant to erosion however both units are erodible. Long-term cliff top retreat rates in the study area range from 2-34 cm/yr, with a weighted average of approximately 10 cm/yr (Moore et al., 1999; Benumof and Griggs, 1999).
Figure 2-1. Map of the study area located in northern San Diego County.
METHODOLOGY

Eight sets of stereo photographs were obtained from various sources dating from 1932 to 2001 ranging in scale from 1:7200 to 1:20,000 (Table 2-1). All acquired photographs were contact prints with the exception of photographs provided by the University of California Santa Barbara (UCSB), which were in a digital format. The aerial photographs were scanned at 600 dpi (~42 microns) with a high resolution scanner resulting in a pixel resolution ranging from 0.303 to 0.842 meters. Ground control points were collected using a Trimble 5800 RTK DGPS survey system with centimeter level accuracy (Figure 2-2). A minimum of five control points were used for each overlapping set of stereo photographs.

Table 2-1. Aerial stereo photograph sets.

<table>
<thead>
<tr>
<th>Date</th>
<th>Source</th>
<th>Scale</th>
<th>Pixel Size (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1932</td>
<td>UCSB, Fairchild Collection</td>
<td>1:9600</td>
<td>0.404</td>
</tr>
<tr>
<td>1939</td>
<td>UCSB</td>
<td>1:20000</td>
<td>0.842</td>
</tr>
<tr>
<td>1946</td>
<td>UCSB, Fairchild Collection</td>
<td>1:7200</td>
<td>0.303</td>
</tr>
<tr>
<td>1970</td>
<td>California Coastal Commission</td>
<td>1:12000</td>
<td>0.505</td>
</tr>
<tr>
<td>1978</td>
<td>California Coastal Commission</td>
<td>1:12000</td>
<td>0.505</td>
</tr>
<tr>
<td>1986</td>
<td>California Coastal Commission</td>
<td>1:12000</td>
<td>0.505</td>
</tr>
<tr>
<td>1993</td>
<td>California Coastal Commission</td>
<td>1:12000</td>
<td>0.505</td>
</tr>
<tr>
<td>2001</td>
<td>UCSB, California Coastal Commission</td>
<td>1:12000</td>
<td>0.505</td>
</tr>
</tbody>
</table>
Figure 2-2. Example of ground control point collection.

Each photograph set was processed using Erdas Imagine 8.7 / Leica Photogrammetry Suite software (2003) to generated digital stereo pairs, and associated elevation models. A block bundle adjustment was used for triangulation, with the overall block RMS error kept below four pixels. After digital stereo pairs were created, digital elevation models were generated and edited. The final step was to digitize the cliff edge (Figure 2-3) by viewing the photographs three dimensionally with a monitor adapted for stereo viewing. This resulted in a series of two dimensional alongshore cliff top lines (Figure 2-4) which could be compared over time using GIS software and the Digital Shoreline Analysis System (Thieler et al., 2005).
Figure 2-3. Example of the 1932 digitized cliff top in northern Solana Beach.

Figure 2-4. Example of the series of cliff top lines in central Del Mar.
RESULTS AND DISCUSSION

The example of mapped cliff top results (Figure 2-4) illustrate that many of the cliff top positions intersect and do not retreat in the expected time sequence. For example, in some locations the 1986 cliff top position (green line) is landward of the 2001 cliff top position (violet line), indicating that the cliff top shifted seaward over time. In a natural setting this would not have been possible. This problem could not be rectified, therefore rendering the short-term retreat analysis inaccurate and incomplete. The problem of false cliff edges was created through a variety of causes discussed in the following sections. Dissatisfied with the results of measuring the short-term retreat, the long-term retreat (1932-2001) was measured for the Del Mar section, which amounted to an average of approximately 5 cm/yr.

Error Analysis and Data Gaps

The accuracy of retreat measurements is dependent on the quality of the data sources from which they are derived, and the ability to precisely locate the shoreline erosion reference feature. Quantifiable error associated with digital photogrammetry includes ground control point accuracy, block model accuracy, digital image resolution, and accuracy of the digital elevation model (Hapke, 2005; Moore, 2000; Thieler and Danforth, 1994; Anders and Byrnes, 1991, Crowell et al., 1991). In addition to these quantifiable errors, additional error and gaps in the data were
introduced by the inability to precisely locate the cliff edge, development of the cliff top and face, and an incomplete history of seacliff development.

Unidentifiable Cliff Crest

Accurate cliff edge digitizing is dependent on correctly identifying the two dimensional cliff crest position. Digitizing proved to be problematic for several reasons including poor photograph quality, ambiguous natural features, and development of the cliff top. In several seacliff sections a definitive cliff edge was not evident due to poor photograph quality. Figure 2-5 shows an example of photograph wash in the 1939 aerial photograph of Cardiff in which the cliff edge could not be accurately located. Although vegetation and kelp on the beach provide some reference, the cliff edge could not be located due to lack of color contrast and poor lighting conditions. This type of problem was generally encountered with the older photographs.
Figure 2-5. An example of photograph wash in the 1939 aerial photograph in Cardiff.

In some instances, natural features such as vegetation and rounded cliff crests caused complications when identifying the cliff edge. Figure 2-6 shows an example where the cliff edge was blocked from vertical view by thick vegetation. In other areas, rounded cliff crests (Figure 2-7) caused ambiguity in the cliff edge detection due to an unclear break in slope. In both of these cases, the cliff edge position could not be precisely located and introduced gaps in the cliff edge digitizing.
Figure 2-6. Thick vegetation blocks the view of the cliff edge.

Figure 2-7. A rounded cliff top introduces uncertainty of the cliff crest position.
Cliff Top Development

Development of the cliff top can cause difficulty in locating the cliff edge, or may artificially shift the cliff edge seaward or landward. Much of the cliff top in Encinitas and Solana Beach is heavily developed, creating visual obstructions to the cliff edge. In Figure 2-8 the true cliff edge would be landward of the most seaward structure do to erosional undercutting of the foundation. In this case it is impossible to properly place the cliff edge using an aerial view. Visual obstruction problems were more common in recent photographs as the cliff top became increasingly developed with time.

![Figure 2-8. Cliff top structures block the view of the cliff edge.](image)
Artificial seaward and landward shifts of the cliff crest can be caused by artificial slope reconstruction (Figure 2-9 and 2-10) and grading the cliff top (Figure 2-11). Artificial slopes have been constructed in several parts of the study area. The largest slope reconstruction project (550 meters in length) occurred in 1960 (Kuhn and Shepard, 1984) between Swamis Beach Park and the San Elijo State Campground. Major cliff top grading projects have also occurred in Solana Beach and Cardiff. In southern Solana Beach, the cliff top was lowered 4.5 to 5.5 meters in 1971-1972 (Figure 2-12) associated with condominium construction (USACOE, 1987). At the southern end of Cardiff, a major portion of the cliff top was removed with the development of San Elijo State Campground around 1966. In some areas, this 1966 grading project removed all of the terrace deposits, significantly altering the cliff profile. The total extent of cliff top grading throughout the study area is currently unknown. These artificial shifts caused by development projects alter the natural cliff edge position resulting in incorrect natural cliff edge retreat rates.
Figure 2-9. The addition of backfill can cause the cliff crest to move seaward.

Figure 2-10. Cliff reconstruction can cause the cliff crest to move landward.
Figure 2-11. Cliff top grading can cause the cliff crest to move seaward.

Figure 2-12. Cliff top excavation and condominium construction in southern Solana Beach, 1972 (photograph courtesy of the California Coastal Commission).
Quantifiable Error

An assessment of the quantifiable error shows that the potential error exceeds estimated rate of retreat, resulting in unacceptable error. For example, consider the potential error of measured retreat between the 1993 and 2001 photograph sets. The pixel resolution for both photographs sets is approximately 50 cm. The resolution alone would result a potential measurement error of 12.5 cm/yr given the eight year time interval. Note that this does not include ground control point accuracy, block RMS, or accuracy of the digital elevation models. If we consider pixel resolution along with a block RMS of one pixel (a conservative estimate for digitized contact prints), this would result in a potential error of 30 cm/yr at the 95% confidence level. The weighted average long-term retreat rate in the study area is approximately 10 cm/yr (Moore et al., 1999). Assuming that the retreat rate between 1993 and 2001 sets is comparable to 10 cm/yr, then the potential error would greatly exceed any measured retreat. Note that these are conservative estimates, and do not take into account that the rate of retreat in erosion controlled areas would probably be significantly lower than the average long-term rate, thus making the potential error even greater. The relatively large potential error is at least in part due to the short time interval and relatively low retreat rates. For instance, had the time interval been 60 years in the above example, the potential error would be 3.7 cm/yr instead of 30 cm/yr. Therefore, long-term retreat rates tend to be more accurate compared to short-term retreat rates given the same data sources. However, to evaluate the effectiveness of recently constructed seacliff protection it is necessary to evaluate short-term retreat.
Erosion Control History

In order to evaluate the effectiveness of seafloor erosion devices, not only is the accurate rate of retreat necessary, but also a detailed history of construction, methods, and locations of cliff stabilization projects. To compare natural or uncontrolled seafloor to erosion controlled seafloor, it is necessary to know which cliff stabilization projects were present in each aerial photograph set. Due to the aerial photograph resolution, quality, and vertical angle, it was extremely difficult if not impossible to identify most erosion control structures in the aerial photographs. Although some construction history has been documented during the permitting process, the permit date does not necessarily correspond with the construction date, and there is currently no complete database of seafloor erosion control history available for the study area. This lack of necessary information presented a major problem when trying to evaluate the effectiveness of erosion control devices on a regional scale.

CONCLUSIONS AND RECOMMENDATIONS

Due to the potential error, data gaps, seafloor development, and lack of construction history, the effectiveness of erosion control devices could not accurately be quantified on a regional scale with the available data for the study area. This research may have been improved by utilizing a different study area with relatively high retreat rates thereby reducing potential error. A study location with higher quality data and additional resources could further the potential of accurately assessing
the effectiveness of control methods. For future research, oblique photographs should be obtained that correspond to the acquisition of aerial photographs. The oblique photographs could be used in combination with coastal development permits to map, date, and categorize seacliff stability projects, in order to develop a comprehensive seacliff development history. This information is paramount to any study attempting to quantify the effectiveness of erosion control structures. The digitizing data source quality could be improved by using diapositives (if available) scanned with a photogrammetric scanner (Hapke et al., 2000). In addition, the potential error could be reduced by using larger scale photographs (if available) scanned at a higher resolution. Most of the problems encountered during this research could not have been avoided for the study location, making this method locally inappropriate. For a further discussion of the effectiveness of erosion control devices, readers are referred to Chapter 4, which uses a different methodology and was successful at quantifying the effectiveness of erosion control devices on a regional scale.
CHAPTER 3: Application of Airborne LIDAR for Seacliff Volumetric Change and Beach-Sediment Budget Contributions
ABSTRACT

Coastal seacliff erosion in California threatens property and public safety, whereas coastal beach erosion threatens the coastal tourism economy. While coastal rivers, seacliffs, and gullies supply the majority of littoral material to California beaches, the relative contributions of these sources is coming into question. These beach-sediment sources must be accurately quantified to formulate proper solutions for coastal zone management.

This study evaluated the seacliff and coastal gully beach-sediment contributions to the Oceanside Littoral Cell using airborne LIDAR (Light Detection And Ranging). Seacliff and gully beach-sediment contributions were compared with coastal river beach-sediment contributions estimated in previous studies. This study took place over a relatively dry period from April 1998 to April 2004.

The results indicate seacliffs provided an estimated 67% of the beach-size sediment to the littoral cell, followed by gullies and rivers at 17% and 16%, respectively, over the period of the study. The total volumetric seacliff erosion rates were used to back calculate average annual seacliff face retreat rates for the study period. These rates ranged from 3.1 to 13.2 cm/yr and averaged 8.0 cm/yr for the Oceanside Littoral Cell.

Comparing these results to previous studies suggests that the relative seacliff sediment contributions may be higher that previously thought. Conversely, beach-sediment contributions from gullies were significantly lower compared with previous studies. This is likely due to the episodic nature of gullying and the relatively dry
study period. Nevertheless, the results of this study indicate that seafloor sediment contributions are a significant sediment source of beach-sand in the Oceanside Littoral Cell, and the relative annual seafloor beach-sand contribution is likely higher than previous studies indicate.

INTRODUCTION

Coastal cliff erosion is a serious problem, affecting 86% of the California coast (Griggs and Savoy, 1985). Erosion of seafloors, often manifested in the form of episodic slope failures, threatens public safety as well as public and private property. Seafloor erosion, however, is also a source of sediment to the beach, the erosion of which is a threat to the coastal tourism economy. In San Diego County alone, coastal tourism contributes in excess of $200 million a year to the local economy. The problems associated with seafloor and beach erosion will only increase if projections of sea level rise, ranging from 9 to 88 cm by 2100 (IPCC, 2001), become a reality.

The majority of littoral material supplied to California beaches comes from coastal rivers, seafloors, and gullies. In Southern California, all of these sediment sources are episodic in nature, as demonstrated by the seafloor failure in Figure 3-1, which delivered 890 m$^3$ of coarse sediment to the littoral system almost instantaneously. In order to formulate proper solutions to the problems associated with coastal beach erosion, the relative sediment source contributions to the beach-sand budget must be accurately quantified. Past efforts to evaluate volumetric change of seafloors and seafloor sediment yields have been accomplished using a variety of techniques including aerial photographs and topographic maps (Bowen and Inman,
1966; Robinson, 1988; Best and Griggs, 1991; Diener, 2000) empirical methods (Everts, 1990), long term cliff top erosion rates (Runyan and Griggs, 2003), and softcopy photogrammetry (Hapke, 2005).

![Image of sea cliff failure]

**Figure 3-1. Sea cliff failure in Solana Beach September 28, 2004.**

The objective of this paper is to evaluate the seacliff and gully littoral contributions using airborne LIDAR (LIght Detection And Ranging) for the Oceanside Littoral Cell during a relatively dry period between April 1998 and April 2004. LIDAR is a type of remote sensing used to collect topographic data. LIDAR sensors pulse a narrow, high frequency laser beam at the Earth’s surface and record the
reflection time and angle of each pulse. Advances in airborne LIDAR surveying allow accurate data to be collected over large areas. Successive surveys can be used to quantify volumetric change over time. Even though the available LIDAR data covers a much shorter time scale than other traditional methods (only a few years versus decades), its high resolution data yields quantitative estimates of the volume of total sediment liberated by the erosion process.

**STUDY AREA**

The Oceanside Littoral Cell located in the San Diego County region (Figure 3-2), spans an 84 kilometer stretch of coastline from Dana Point to La Jolla (Inman and Frautschy, 1966). The cell is categorized by narrow sand and cobble beaches backed by steep seacliffs cut into uplifted marine terraces. The majority of the Oceanside Littoral Cell contains both residential and commercial development on the cliff top, with the exceptions of the Camp Pendleton Military Reservation and San Onofre State Park. Steep cliffs characterize 70% of the study area with occasional alternating lowlands at coastal river mouths and lagoons. A majority of the seacliffs are approximately 25 meters in height, ranging from 2 to 110 meters high, and are generally composed of two primary geologic units. The lower unit consists of lithified Eocene and Miocene mudstone, shale, sandstone, and siltstone sedimentary rocks (Kennedy, 1975). The upper unit is composed of un lithified Pleistocene terrace deposits. The lower unit is stronger and more resistant to erosion; however both units are highly erodible, with long-term erosion rates of 8 to 43 cm/yr (Benumof and Griggs, 1999).
Figure 3-2. Study location map and section boundaries.
The study area was divided into ten sections based on general stratigraphy and major river incisions. The sections are shown in Figure 3-2 and described in Table 3-1 by the section boundary, cliff length within the section, average cliff height, percentage of beach-size sand in the cliffs, and the dominating erosional processes based on Emery and Kuhn’s (1982) seacliff classification (Figure 3-3) and section designation.
Table 3-1. Section descriptions for the Oceanside Littoral Cell.

<table>
<thead>
<tr>
<th>Section No.</th>
<th>Section Name</th>
<th>Southern End</th>
<th>Northern End</th>
<th>Length of Cliffs (m)</th>
<th>Average Cliff Height (m)</th>
<th>% of Beach-Size Sand in Seaciffs</th>
<th>Dominating Erosional Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Torrey Pines</td>
<td>SIO Campus</td>
<td>Penaquitos Lagoon</td>
<td>6,550</td>
<td>88.0</td>
<td>42(^1)</td>
<td>Marine(^4)</td>
</tr>
<tr>
<td>2</td>
<td>Del Mar</td>
<td>Penaquitos Lagoon</td>
<td>Power House Park</td>
<td>2,550</td>
<td>17.9</td>
<td>75(^2)</td>
<td>Equal(^4)</td>
</tr>
<tr>
<td>3</td>
<td>Solana Beach</td>
<td>San Dieguito River</td>
<td>San Elijo Lagoon</td>
<td>2,800</td>
<td>23.5</td>
<td>75(^2)</td>
<td>Equal(^4)</td>
</tr>
<tr>
<td>4</td>
<td>Cardiff</td>
<td>San Elijo Lagoon</td>
<td>Moonlight Beach</td>
<td>3,740</td>
<td>25.1</td>
<td>80(^2)</td>
<td>Equal(^4)</td>
</tr>
<tr>
<td>5</td>
<td>Leucadia</td>
<td>Moonlight Beach</td>
<td>Bataquitos Lagoon</td>
<td>3,980</td>
<td>26.0</td>
<td>80(^2)</td>
<td>Equal(^4)</td>
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<td>6</td>
<td>Carlsbad</td>
<td>Bataquitos Lagoon</td>
<td>Oak Avenue</td>
<td>6,910</td>
<td>16.5</td>
<td>80(^2)</td>
<td>Marine(^4)</td>
</tr>
<tr>
<td>7</td>
<td>Camp Pendleton</td>
<td>Santa Margarita River</td>
<td>Las Flores Creek</td>
<td>4,970</td>
<td>17.4</td>
<td>54(^4)</td>
<td>Subaerial(^6)</td>
</tr>
<tr>
<td>8</td>
<td>San Onofre</td>
<td>Las Flores Creek</td>
<td>San Onofre Creek</td>
<td>1,123</td>
<td>38.6</td>
<td>71(^1)</td>
<td>Subaerial(^6)</td>
</tr>
<tr>
<td>9</td>
<td>San Clemente</td>
<td>San Onofre Creek</td>
<td>Secunda Deshecha</td>
<td>7,130</td>
<td>28.6</td>
<td>80(^3)</td>
<td>Subaerial(^6)</td>
</tr>
<tr>
<td>10</td>
<td>Dana Point</td>
<td>Secunda Deshecha</td>
<td>San Juan Creek</td>
<td>3,830</td>
<td>37.2</td>
<td>80(^3)</td>
<td>Subaerial(^6)</td>
</tr>
</tbody>
</table>

\(^1\) Robinson (1988)
\(^2\) USACOE-LAD (1984)
\(^3\) Everts (1990)
\(^4\) Emery and Kuhn (1982)
Figure 3-3. Matrix of seafall profiles with respect to relative erodibility of the cliff top and cliff base, and the relative effectiveness of marine (M) versus subaerial (SA) erosion. Figure modified from Emery and Kuhn (1982).
In addition to quantifying the total volume of material eroded from the seacliffs during the study period, it is also of interest to estimate that portion of the volume that may remain on the beach. Very fine-grained sediments typically are not retained on the beach due to the high energy wave environment in this area. Therefore, it was necessary to determine the percentage of seacliff sediments that are large enough to remain in the littoral system. Hicks (1985) determined there is a sediment size diameter boundary or “littoral cut-off diameter” that describes whether a sediment grain is of sufficient size to be retained on the beach. Sediments with a diameter larger that the littoral cut-off diameter are retained on the beach, while sediments with a diameter smaller than the littoral cut-off diameter are not. The littoral cut-off diameter for the Oceanside Littoral Cell has been evaluated at 0.06 mm (Everts, 1990) and 0.0875 mm (Runyan and Griggs, 2003). The percentage of seacliffs sediments larger than the littoral cutoff diameter (%LCD) has been previously estimated for sections of the Oceanside Littoral Cell by Robinson (1988), U.S. Army Corp of Engineers (1984), Everts (1990) and Runyan and Griggs (2003). Values from these previous studies were selected that best correlate with the section boundaries used in this study.

The section between Carlsbad and Camp Pendleton (covering the City of Oceanside) was not included in this study. This section consists of heavily urbanized low relief seacliffs, beaches, river mouths, and lagoons. In this section the bluff face has either been heavily armored or built upon with residential development. Therefore the seacliffs in this section were assumed to not contribute significant amounts of beach-sand to littoral cell. The San Clemente and Data Point sections were analyzed,
but not included in any cell wide calculations. These sections are removed from wave action by the coastal railway and beach development, and therefore it is currently unclear if sediment from these sections actually enters the littoral system.

The Oceanside Littoral Cell 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. Waves that arrive at the coast provide energy, removing seacliff failure deposits and eroding exposed seacliffs at the base.

San Diego has a semi-arid, Mediterranean climate characterized by mild, sometimes wet winters and warm, very dry summers (Miller, 2005). San Diego is also influenced by the El Niño Southern Oscillation and the Pacific Decadal Oscillation. Strong El Niño events are associated with anomalously high precipitation during the winter rainy season. The rainy season of San Diego begins in the fall and ends in spring. For the purposes of this paper, we assume that the study period (April 1998 through April 2004) covers water years 1999 - 2004 (i.e. October 1, 1998, through September 30, 2004). This is a reasonable assumption because negligible precipitation occurred between April and October 1998, and April and September 2004.
BACKGROUND

Previous studies of the Oceanside Littoral Cell evaluated seacliff and gully sediment contributions to the littoral cell using topographic maps (Robinson, 1988), empirical methods (Everts, 1990), and long term erosion rates (USACOE-LAD, 2003; Runyan and Griggs, 2003). A summary of results from these studies and others is shown in Table 3-2.
Table 3-2. Summary of annual beach-sediment contributions to the Oceanside Littoral Cell from previous studies.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Torrey Pines</td>
<td>Seaciffs, Gullies, Terraces</td>
<td>Natural</td>
<td>42,300</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Camp Pendleton</td>
<td>Seaciffs, Gullies, Terraces</td>
<td>Natural</td>
<td>90,300</td>
<td>---</td>
<td>---</td>
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<td>---</td>
</tr>
<tr>
<td>San Onofre</td>
<td>Seaciffs, Gullies, Terraces</td>
<td>Natural</td>
<td>138,200</td>
<td>---</td>
<td>---</td>
<td>---</td>
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</tr>
<tr>
<td>Solana Beach</td>
<td>Seaciffs</td>
<td>Actual</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
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<td>---</td>
</tr>
<tr>
<td>Cardiff</td>
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<td>---</td>
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<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Leucadia</td>
<td>Seaciffs</td>
<td>Actual</td>
<td>---</td>
<td>---</td>
<td>4,168</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Oceanside Littoral Cell</td>
<td>Seaciffs</td>
<td>Natural</td>
<td>---</td>
<td>32,900</td>
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<td>---</td>
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</tr>
<tr>
<td>Oceanside Littoral Cell</td>
<td>Seaciffs</td>
<td>Actual</td>
<td>---</td>
<td>---</td>
<td>42,000</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Oceanside Littoral Cell</td>
<td>Gullies, Terraces</td>
<td>Both</td>
<td>---</td>
<td>---</td>
<td>219,400</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Oceanside Littoral Cell</td>
<td>Gullies</td>
<td>Natural</td>
<td>---</td>
<td>296,700</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Oceanside Littoral Cell</td>
<td>Terraces</td>
<td>Natural</td>
<td>---</td>
<td>4,000</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Oceanside Littoral Cell</td>
<td>Coastal Rivers</td>
<td>Actual</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>101,000</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Oceanside Littoral Cell</td>
<td>Coastal Rivers</td>
<td>Actual (Dry)</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>19,100</td>
</tr>
<tr>
<td>Oceanside Littoral Cell</td>
<td>Coastal Rivers</td>
<td>Actual (Wet)</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>293,000</td>
</tr>
<tr>
<td>Oceanside Littoral Cell</td>
<td>Coastal Rivers</td>
<td>Actual (Avg)</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>122,000</td>
</tr>
</tbody>
</table>
Robinson (1988) evaluated three sections using topographic maps from 1889 (scale 1:10,000) and 1968 (scale 1:24,000): San Onofre, Camp Pendleton, and Torrey Pines. These sections approximately covered between 450 and 900 meters from the coast inland. Elevation contours were digitized from the maps into $X,Y,Z$ data and gridded into 8 meter cells. Robinson (1988) then evaluated the volumetric change and calculated the beach-sediment yield based on the $\%$LCD in each section.

Everts (1990) developed an empirical method to hindcast and forecast linear seaciff toe retreat rates for the Oceanside Littoral Cell. The average annual seaciff toe retreat rates were calculated based on the frequency probability of storm events and associated seaciff toe retreat. The linear toe retreat rates ranged from 1.5 to 9 cm/yr. The annual seaciff toe retreat rates were then used to calculate the natural annual seaciff beach-sediment contribution (i.e. excluding the effect of seaciff stabilization) to the littoral cell by using the following general equation:

$$Q_s = L_c \cdot R_t \cdot H_c \cdot \%\text{LCD} \quad \text{(Equation 3-1)}$$

$Q_s$ = Natural annual seaciff sediment yield  
$L_c$ = Length of seaciffs  
$R_t$ = Linear rate of seaciff retreat  
$H_c$ = Average height of seaciffs  
$\%\text{LCD}$ = Percent of seaciff sediments with a diameter greater than the littoral cut-off diameter
USACOE-LAD (2003) also used the general form of Equation 3-1 to calculate the annual sediment yields for Solana Beach and Encinitas. The average seacliff top retreat rates estimated by USACOE-LAD (2003) ranged from 7.6 to 37.0 cm/yr. This study assumed that the cliff top would retreat to create a more stable slope, and therefore the annual beach-sediment volumes were reduced by one half to account for this equilibrium. Since shoreline protection reduces the amount of littoral material supplied to the beaches, the natural annual beach-sediment contributions were adjusted downward to account for the percentage of protective devices, thus resulting in the actual contribution.

Runyan and Griggs (2003) calculated natural seacliff contributions to the Oceanside Littoral Cell using long term (40 to 60 years) seacliff top retreat rates from both Benumof and Griggs (1999) and Moore et al. (1999). These linear seacliff top retreat rates ranged from 10 to 20 cm/yr. Seacliff beach-sediment yields were then calculated using the general form of Equation 3-1. Runyan and Griggs (2003) calculated the annual gully volume by subtracting their natural annual seacliff beach-sand volume from Robinson’s (1988) combined seacliff and gully annual beach-sand volume. Runyan and Griggs (2003) also calculated the actual annual seacliff volume by reducing their natural annual beach-sand volume based on the percentage of shoreline armoring in each section.

The surfaces of coastal terraces can provide beach-sand to littoral system by means of subaerial erosion and small stream transportation. The terrace degradation sediment yield was estimated by Everts (1990) at 4000 m$^3$/yr for the Oceanside
Littoral Cell. For the purposes of this study, terrace surface yields were assumed to be negligible in the overall sediment budget due to the dry study period and relatively low volume reported by Everts (1990).

Rivers can provide a significant amount of beach-sand to the littoral cell. However, the natural average annual sediment load of California coastal rivers has been significantly reduced by the development of the coastal watershed through flood control and water storage dams (Inman and Brush, 1973; Brownlie and Taylor, 1981; Griggs, 1987; Flick, 1993; Inman and Jenkins, 1999; Willis et al., 2002). These studies indicate that the natural beach-sediment load of coastal rivers in the Oceanside Littoral Cell has been reduced by approximately one half. Flick (1993) summarized several studies which estimate the actual long term average annual coastal river beach-sediment flux to the Oceanside Littoral Cell at 112,000-203,000 m³/yr. A more recent study by Willis et al., (2002) estimates the actual beach-sediment flux at 101,000 m³/yr. It should be noted that the fluvial beach-sediment delivery to the littoral system is highly episodic in California. Inman and Jenkins (1999) found that the average annual sediment flux during wet periods is five times higher compared to dry periods for California rivers, and that this episodicity is even more pronounced in Southern California. In fact, Inman and Masters (2005, http://coastalchange.ucsd.edu) estimate the fluvial beach-sand flux in the Oceanside Littoral Cell for dry and wet periods at 19,100 m³/yr and 293,000 m³/yr respectively, which is approximately a 15 times difference for wet and dry periods.
Based on the studies presented above, the total annual amount of beach-sediment contribution from all natural sources combined (rivers, seacliffs, gullies, and terraces) would appear range from just over 350,000 m³/yr to nearly 550,000 m³/yr. Of this total, the contribution of seacliff erosion is on the order of 10 to 15 percent, which is in agreement with conventional wisdom, while gully erosion appears to be the most significant source of beach-sediment. It should be noted, however, that the contributions of gullies noted in Everts (1990) and Runyan and Griggs (2003) are directly related to the initial estimates of Robinson (1988). The data presented by Robinson (1988) is based on interpretation of old topographic maps and dominated by a limited number of extreme gully erosion events caused by altered drainage patterns associated with the construction of coastal highways in the Camp Pendleton and San Onofre sections. Kuhn and Shepard (1984) documented several of these events including the formation of a new canyon in the San Onofre section which eroded landward 140 meters between 1968 and 1980, and Dead Dog Canyon in the Camp Pendleton section which eroded landward 230 meters between 1932-1980. Below, we use airborne LIDAR data to quantify the combined contributions of seacliffs and gullies over the six-year study period as an independent benchmark of the conventional wisdom, and then compare the LIDAR-developed contributions to estimates of river beach-sediment contributions for the study period.
METHODOLOGY

Topographic Change

In order to evaluate the topographic change of the seacliffs, two airborne LIDAR data sets were used which span a six year time period. The older data set was collected in April 1998 using NASA’s Airborne Topographic Mapper (ATM, 1998). This survey was downloaded from NOAA’s Coastal Services Center website (www.csc.noaa.gov). The second data set was collected in April 2004. This data set was 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. The original point densities of the 1998 and 2004 data were 0.9 and 3.3 points per m², respectively. The X,Y,Z point data were interpolated into 0.5 meter resolution grids using ESRI ArcINFO 3-D Analyst (2004). Grid interpolation was completed using inverse distance weighting.

After grid interpolation, the Oceanside Littoral Cell was divided into ten sections for analysis. The change in elevation was evaluated for each section by subtracting the 2004 grid from the 1998 grid (Equation 3-2). This procedure results in a grid showing the change in elevation over time. Negative cells indicate erosion and positive cells indicate accretion.
\[ Z_{\text{Change}} = Z_{1998} - Z_{2004} \quad \text{(Equation 3-2)} \]

\( Z_{\text{Change}} \) = Cell change in elevation

\( Z_{2004} \) = Cell elevation in 2004

\( Z_{1998} \) = Cell elevation in 1998

Figure 3-4 shows the central portion of the Solana Beach grid displayed under a transparent shaded relief. The red areas in this figure indicate areas where significant erosion occurred during the study period. This figure shows numerous distinct upper seacliff failures as well as several sections of lower seacliff retreat. These calculations were performed using data from the base of the 1998 seacliff landward. No changes in beach volumes are included.
Figure 3-4. Erosion grid of central Solana Beach where red cells represent seaciff erosion that occurred between April 1998 and April 2004. Several upper cliff failures and sections of lower cliff retreat are shown in this figure.
The potential error in the change grid can be primarily attributed to LIDAR measurement error, interpolation error, and vegetation. Error evaluation was done by computing the root mean square (RMS) which describes the average magnitude of change between the two data sets. Typical vertical RMS error for quantifying beach changes using airborne topographic LIDAR is 15 cm (Sallenger et al., 2003). This RMS value was not deemed to accurately quantify the error in this study, since it focused on high relief cliffs with partial vegetation in some areas. Therefore the RMS error was evaluated using a 400 meter representative control section in Encinitas between Swami’s and San Elijo State Beach. The control section consists of a partially vegetated slope and was assumed to have no significant change over the time period, as it was stabilized in 1960 using a rock revetment at the base, slope grading, and surface drainage control (Kuhn and Shepard, 1984). The vertical RMS for this section was calculated using Equation 3-3 (Federal Geographic Data Committee, 1998).

\[
\text{RMS}_z = \sqrt{\frac{\sum_{i=1}^{n} (za_i - zb_i)^2}{n}}
\]

(Equation 3-3)

\(za_i = \text{Cell elevation in 2004}\)

\(zb_i = \text{Cell elevation in 1998}\)

\(n = \text{Number of cells}\)
The RMS$_Z$ of the control section was calculated at 21 cm. This value was then used as a threshold of acceptable error for each cell. Each cliff section was isolated from the beach and cliff top development by clipping the change grids along the seacliff base and cliff top. Next, cells that showed erosion of 21 cm or more ($-\infty < \text{cells} < -21 \text{ cm}$ from Equation 3-2) were extracted from each section to produce a new erosion-only grid.

RMS$_Z$ values were then calculated for each erosion grid. Statistical error for each section was calculated as a ratio based on the RMS$_Z$ of the control section, using Equation 3-4 (Zhang et al., 2005). Table 3-3 summarizes the RMS$_Z$ and percent error for each section and weighted cell average.

\[
\text{Percent Error} = \frac{\text{RMS}_Z(\text{Control Section})}{\text{RMS}_Z(\text{Seacliff Section})} \quad \text{(Equation 3-4)}
\]

<table>
<thead>
<tr>
<th>Section Name</th>
<th>RMS (m)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Section</td>
<td>0.21</td>
<td>---</td>
</tr>
<tr>
<td>Torrey Pines</td>
<td>1.28</td>
<td>16.4 (± 8.2)</td>
</tr>
<tr>
<td>Del Mar</td>
<td>1.07</td>
<td>19.7 (± 9.9)</td>
</tr>
<tr>
<td>Solana Beach</td>
<td>2.12</td>
<td>9.9 (± 5.0)</td>
</tr>
<tr>
<td>Cardiff</td>
<td>1.20</td>
<td>17.5 (± 8.8)</td>
</tr>
<tr>
<td>Leucadia</td>
<td>1.32</td>
<td>15.9 (± 8.0)</td>
</tr>
<tr>
<td>Carlsbad</td>
<td>0.81</td>
<td>25.9 (± 13.0)</td>
</tr>
<tr>
<td>Camp Pendelton</td>
<td>0.75</td>
<td>28.1 (± 14.1)</td>
</tr>
<tr>
<td>San Onofre</td>
<td>1.43</td>
<td>14.6 (± 7.3)</td>
</tr>
<tr>
<td>San Clemente</td>
<td>1.42</td>
<td>14.7 (± 7.4)</td>
</tr>
<tr>
<td>Dana Point</td>
<td>1.31</td>
<td>16.0 (± 8.0)</td>
</tr>
<tr>
<td>Oceanside Littoral Cell</td>
<td>1.32</td>
<td>16.0 (± 8.0)</td>
</tr>
</tbody>
</table>
Other error in the grids may have come from interpolating over sharp edges or vegetation. Aerial LiDAR typically does not capture over vertical surfaces such as seacaves or notches. Therefore, changes that occurred in these areas were not evaluated. Complete LiDAR coverage was not available for Las Pulgas Canyon and a small portion of the Torrey Pines section and these areas were also not evaluated. The total eroded volumes were calculated for each section by summing the volumes of negative cells less than the threshold value of -21 cm. Cells that showed erosion values between 0 and -21 cm were removed to compensate for possible grid interpolation error.

Gullies were clipped out of the erosion grids to quantify the eroded gully volume. Gullies were removed from the total seaciff eroded volume because, although they did contribute beach-sediment to the littoral cell, they do not contribute to the eroded volume of the seaciff face. Gullies in each section were identified using the generated digital elevation models and aerial photographs. For this project gullies were defined as areas where significant subaerial erosion occurred due to concentrated terrace runoff and piping. This included extensive gully networks, coastal ravines, and canyons. An example of a well developed gully network is shown in Figure 3-5. Subtracting the gully volumes from the total eroded volume in each section produced a seaciff erosion volume.
Figure 3-5. Example of the identification and boundary of an extensive gully network in the Camp Pendleton section. (A) shaded relief map. (B) aerial photograph.

Areas that showed significant accretion and were determined to be landslide talus deposits were added to the eroded volume for correction. These volumes were added back in to the corresponding seacliff or gully section because they have not yet entered the littoral system. Talus deposits were identified as accretion areas found below significantly eroded areas. These deposits typically conformed to the shape of alluvial fan deposits, and were found at the base of the seacliff or in the bottom of the gullies. Coastal construction that occurred during the study period also resulted in some accretion areas. These areas were separated from the talus deposits and were not added to the eroded volume. Corrections were also made in heavily vegetated areas by removing the cells.
The total eroded volumes of seaciffis and gullies were then reduced to quantify the contribution of beach-sand size material, based on the %LCD values from Table 3-1. These volumes were then divided by the six-year time span to produce average annual sediment volumes of beach-sand size material. Table 3-4 shows a section summary of the total and reduced for %LCD annual volumes. Section volumes were summed to quantify the average annual seaciff and gully beach-sediment contributions to the entire littoral cell. Note that the San Clemente and Dana Point sections were excluded from this calculation for reasons previously discussed.

<table>
<thead>
<tr>
<th>Section Name</th>
<th>Average Annual Volume of Total Eroded Sediment</th>
<th>Average Annual Volume of Beach-Sand Content (Total Reduced for %LCD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gully (m$^3$/yr)</td>
<td>Seaciff (m$^3$/yr)</td>
</tr>
<tr>
<td>Torrey Pines</td>
<td>8,300</td>
<td>26,400</td>
</tr>
<tr>
<td>Del Mar</td>
<td>600</td>
<td>4,900</td>
</tr>
<tr>
<td>Solana Beach</td>
<td>0</td>
<td>8,300</td>
</tr>
<tr>
<td>Cardiff</td>
<td>0</td>
<td>5,800</td>
</tr>
<tr>
<td>Leucadia</td>
<td>0</td>
<td>5,900</td>
</tr>
<tr>
<td>Carlsbad</td>
<td>0</td>
<td>4,000</td>
</tr>
<tr>
<td>Camp Pendelton</td>
<td>7,600</td>
<td>5,500</td>
</tr>
<tr>
<td>San Onofre</td>
<td>16,700</td>
<td>57,100</td>
</tr>
<tr>
<td>Oceanside Littoral Cell*</td>
<td>33,200</td>
<td>117,900</td>
</tr>
<tr>
<td>San Clemente*</td>
<td>4,700</td>
<td>7,600</td>
</tr>
<tr>
<td>Dana Point*</td>
<td>0</td>
<td>4,500</td>
</tr>
</tbody>
</table>

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Seacliff Beach-Sediment Contribution and Retreat Rate

Figure 3-6 shows the actual average annual beach-sediment contributions from the seacliffs per meter of cliff length for each section, as well as for the entire littoral cell. These values were calculated based on Equation 3-5. Error bars in Figure 3-6 were calculated based on the percent error values from Table 3-3. The weighted average of seacliff beach-sediment volume per length of cliff for the entire Oceanside cell was calculated based on the section seacliff length.

Figure 3-6. Actual average annual seacliff beach-sediment contributions per cliff length for the study area between April 1998 and April 2004.
\[ R_{vs} = \frac{(V_{st} \times \%LCD)}{(L_c \times T)} \]  

(Equation 3-5)

\[ R_{vs} = \text{Volumetric rate of sand contribution per length of seacliffs} \]
\[ V_{st} = \text{Total eroded volume from seacliffs} \]
\[ \%LCD = \text{Percent of seacliff sediments with a diameter greater than the littoral cut-off diameter} \]
\[ L_c = \text{Length of seacliffs (including armored sections)} \]
\[ T = \text{Time span} \]

Figure 3-7 shows the actual average annual rate of seacliff face retreat for each section. The linear rate of cliff face retreat was calculated for each section based on Equation 3-1. This equation was rearranged to back-calculate the actual average annual rate of seacliff face retreat and is shown as Equation 3-6. A weighted average of seacliff face retreat for the entire Oceanside cell was calculated based the section seacliff length. Error bars in Figure 3-7 were calculated based on the percent error values from Table 3-3.
Figure 3-7. Actual average annual rate of seacliff face retreat for the study area between April 1998 and April 2004.

\[ R_t = \frac{V_{rt}}{(H_c \times L_c \times T)} \]  \hspace{1cm} \text{(Equation 3-6)}

\( R_t \) = Linear rate of cliff face retreat

\( V_{rt} \) = Total eroded volume from seacliffs

\( H_c \) = Average seacliff height

\( L_c \) = Length of seacliffs (including armored sections)

\( T \) = Time span
The average section seacliff heights used in Equation 3-6 were evaluated by taking a profile parallel to the shoreline along the cliff using the ESRI ArcINFO (2004) profiler. The profiles were then averaged over the seacliff length to produce an average cliff height. These values are shown in Table 3-1.

The graphical representation of Equation 3-6 is shown in Figure 3-8. The geometry of this figure shows that Equation 3-6 is independent of the slope angle. Note that Equation 3-6 describes the average rate of retreat over the entire cliff face. This does not represent the actual seacliff top or seacliff base rate of retreat.

![Figure 3-8](image)

**Figure 3-8.** Typical seacliff geometry and the geometric relationship between seacliff retreat and the total eroded seacliff volume.
Precipitation and Coastal River Beach-Sediment Contributions

The Oceanside Marina rain gauge (#046377) was chosen as a representative rainfall indicator for the cell. This gauge was selected because it is centrally located and has a 60 year record to compare past precipitation with that of the study period. Monthly rainfall amounts were obtained from the Western Regional Climate Center website (www.wrcc.dri.edu). Monthly precipitation values were added to obtain annual values for each water year, extending from October 1-September 30 of the later year. The average annual rainfall at the Oceanside Marina is 25.7 cm based on water years 1954 to 2004. The annual precipitation during the study period is shown in Figure 3-9. This figure shows that the study occurred during a relatively dry time period. Statistically, rainfall during the study time frame was 27% below average. The study period occurred between two heavy rain years, after the El Niño 1997-98 event (46 cm) and before the 2004-2005 wet season (55 cm, 3rd wettest year in San Diego’s recorded history).
Figure 3-9. Precipitation at Oceanside marina for water years 1999 to 2004 (monthly values obtained from the Western Regional Climate Center website, www.wrcc.dri.edu).

Because this study spanned a relatively dry period, and given the episodic nature California river sediment flux (Inman and Jenkins, 1999), the average annual fluvial beach-sediment contributions reported in the background section would be over-estimates of the beach-sediment flux for the study time period. Therefore, it was required to estimate the beach-sediment flux for the dry study period so a proper comparison could be made to the seacliff and gully beach-sediment contributions.

Initially, an attempt was made to calculate the sediment flux using annual river flows and sediment rating curves. Unfortunately, many of the flow data were not available...
during the study time period. Therefore, the annual beach-sediment for the study period was assumed to correlate with the dry average annual beach-sand flux reported by Inman and Masters (2005, http://coastalchange.ucsd.edu) of 19,100 m³/yr (average of dry years from 1943-1977).

RESULTS

Based on the airborne LIDAR data, seacliffs and gullies yielded 76,900 m³/yr and 20,000 m³/yr of beach-sediment, respectively, during the study period (Table 3-4). The majority of the beach-sediment from both the seacliffs and gullies originated from the San Onofre section. The volumetric rate of beach-sediment yield per length of shoreline ranged from 0.47 (Carlsbad) to 3.61 (San Onofre) m³/m-yr with a weighted average of 1.80 m³/m-yr for the entire Oceanside Littoral Cell (Figure 3-6). Figure 3-7 shows that the linear rate of seacliff face retreat ranged from 3.1 to 13.2 cm/yr with a weighted average for the littoral cell of 8.0 cm/yr. The highest seacliff face retreat rates were found in the Del Mar, Solana Beach, and San Onofre sections, which were all greater than 10 cm/yr. Statistical error for each section ranged from 9.9 to 25.9 %, with an overall weighted cell average of 16.0 % (Table 3-3).

DISCUSSION AND CONCLUSIONS

Figure 3-10 shows the estimated percentage of beach-sediment contributions from seacliffs, gullies, and rivers during the study period (excluding artificial
nourishment). Seacliffs produced the majority of beach-sediment at 67%, followed by
gullies and rivers at 17% and 16% respectively. These percentages would likely
change significantly during wet periods when all beach-sediment source volumes
would increase appreciably, though how the relative volumes would change is not well
understood. The average annual rate of river beach-sediment volumes has been
estimated at 101,000 to 203,000 m$^3$/yr (Flick, 1993; Willis et al., 2002). Even using
the upper bound of these annual rates, the percent of seaciff contributions is still
significant. Increasing the seaciff yield marginally for more average climatic
conditions and using recently evaluated average annual river beach-sediment yields of
101,000 m$^3$/yr (Willis et al., 2002) would put the seaciff beach-sediment
contributions upwards of 50% of the beach-sediment budget. This level of
contribution from the seaciffs is supported by recent research by Haas (2005) based
on sediment provenance analysis of beach-sand in the study area.
Figure 3-10. Estimated percentage of beach-sediment contributions to the Oceanside Littoral Cell for the study area between April 1998 and April 2004 (a statistically dry period).

Figure 3-11 shows the percentage of beach-sediment contributions based on Emery and Kuhn's (1982) profile classification (Figure 3-3) from Table 3-1. This figure shows that areas controlled by subaerial erosion produced the majority of the beach-sediment. It should be noted that even though subaerial processes dominated, marine erosion is important in controlling the rate of erosion. If wave action were not present, seaciff material would not be removed from the base of the cliffs, the cliffs would become relatively stable, and thereby the retreat rate would be reduced. This conclusion is supported by the fact that the rates of seaciff retreat for the Dana Point and San Clemente sections were two of the three lowest sections evaluated. These sections are removed from wave action, and therefore only subaerial processes are acting in these locations.
Figure 3-11. Seacliff beach-sediment contributions classified by the dominating section erosional process for the study area between April 1998 and April 2004. This figure is based on profile classification (Figure 3-3) and designation from Emery and Kuhn (1982).

Figure 3-12 compares the average annual beach-sediment yields from various sources calculated in this study and previous studies. During this study period seacliffs yielded 76,900 m$^3$/yr of beach-sediment. This is significantly higher that the previously estimated rates of 32,000 m$^3$/yr (Everts, 1990) and 42,000 m$^3$/yr (Runyan and Griggs, 2003). Given the dry period of this study, these results suggest that seacliff beach-sediment contributions may be higher than previously thought. Gullies yielded 20,000 m$^3$/yr of sediment during the study period, which is significantly lower than reported from other studies. This is likely due to the episodic nature of gullyng. Robinson’s study covered a time period where several severe gully events occurred as a result of altered drainage patterns associated with the construction of coastal
highways. These large gully events did not compare in magnitude to any gully events in this study. We suggest that average annual gully beach-sediment contribution reported in previous studies should be reconsidered for future studies unless more severe gully events occur in the future.
Figure 3-12. Comparison of average annual beach-sediment contributions to the Oceanside Littoral Cell from previous studies compared with this study. Values computed in this study represent the short term 6 year dry period, while other studies represent long term averages.
The seacliffs face retreat rates ranged from 3.1 to 13.2 cm/yr, with a weighted cell average of 8.0 cm/yr. These rates are at the low end of long-term rates ranging from 1.5 to 43.0 cm/yr (Everts, 1990; Benumof and Griggs, 1999; Runyan and Griggs, 2003). A comparison of seacliff retreat rates for the Oceanside Littoral Cell is shown in Figure 3-13. Note that the long-term rates from previous studies represent the natural rate of cliff top (Runyan and Griggs, 2003) and cliff toe (Everts, 1990) retreat, while the rates calculated in this study represent the short-term actual cliff face retreat in the partially armored condition. Figure 3-14 shows how different studies measure the retreat of a seacliff, and a comparison of the measured retreat for an idealized erosion sequence. This figure shows how it is critical to understand where the retreat is being measured and why retreat rates may not be directly comparable. This figure also shows how using the cliff face retreat measurement as described in this study averages the failure area over the cliff face, thereby removing some of the episodic nature retreat measurements. Comparing the retreat measurements through the retreat cycle shows that, the three measurement techniques are not equal until the erosion cycle has been completed. It should be noted that the retreat rates calculated in this study were averaged over the entire cliff section including armored areas. Therefore the natural rate of retreat would be significantly higher in heavily armored sections. The relatively low rates found in this study are likely due to the partially armored condition, and the dry climate study period.
Figure 3-13. Comparison of average annual seacliff retreat rates from previous studies used to calculate average annual seacliff beach-sediment contributions to the Oceanside Littoral Cell and retreat rates back calculated in this study.
Figure 3-14. (A, B, C) Comparison of the techniques used to measure cliff retreat. (D) Comparison of how retreat measurements vary with an idealized erosion sequence. Note, using the average cliff face method removes some of the episodicity of the measured retreat.
A comparison of the average annual seacliff beach-sediment yields and cliff retreat rates from this study, Everts (1990), and Runyan and Griggs (2003) reveals a discrepancy. Because all of these studies used the same general form of Equation 3-1 the retreat rates and beach-sediment volumes should correlate in size with one another. This is not case where the beach-sediment volume calculated in this study is larger that reported by Runyan and Griggs (2003), yet the retreat rate of this study is smaller than Runyan and Griggs (2003). The main reason for this discrepancy comes from the significant differences in cliff height used by this study and Runyan and Griggs (2003).

Given the relatively short study time period and the episodic nature of cliff failures, it is difficult to make any long-term conclusions. The seacliff and gully beach-sediment contributions could be viewed as lower bounds, given the relatively dry climate of the study period. Nevertheless, the results of this study indicate that seacliff beach-sediment contributions are significant beach-sand source in the Oceanside Littoral Cell. This study also suggests that the relative seacliff beach-sand contribution may be significantly higher due to a possible over estimation of annual gully beach-sand contributions for current conditions.

This study also demonstrates that airborne LIDAR analysis can be used to quantify seacliff and gully beach-sediment contributions on a large scale. Further research should be conducted to quantify volumetric changes during wet periods. A comparison of dry and wet time periods could be used to quantify the episodic nature of seacliff retreat. Additional research should also be conducted to more accurately
quantify the effects of marine versus subaerial erosion processes. Now that a baseline for the Oceanside Littoral Cell has been established, future airborne LIDAR scanning can be used to evaluate the longer term rates of seacliff erosion.

ACKNOWLEDGMENTS

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This chapter, in full, is a reprint of the journal paper: Young, A. P. and Ashford, S. A., 2006. Application of Airborne LIDAR for Seacliff Volumetric Change and Beach-Sediment Budget Contributions. *Journal of Coastal Research*, 22(2), 307-318. The dissertation author was the primary investigator and author of this paper.
CHAPTER 4: Performance Evaluation of Seacliff Erosion Control Methods
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 shoreline using airborne LIDAR and GIS spatial analysis over a six year period. Erosion control methods were mapped and then 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 to adjacent unprotected seacliffs. Overall, protective devices reduced the cliff face retreat by 42%. 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 only provided partial protection. For example, areas with only cliff-toe protection were 31% effective, while areas combining lower and upper cliff protection were up to 58-75% effective. This study also investigated the role of subsurface and surface drainage conditions, both of which increased cliff face erosion. Seacliffs affected by groundwater seepage eroded faster, while surface runoff directed onto the cliff face caused accelerated erosion in localized areas. These findings suggest that properly controlling groundwater and surface runoff could reduce the rate of cliff face retreat. 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%) 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 4-1 shows an example in which cliff top homeowners have chosen to protect their property by constructing a tied-back artificial rock seawall. The objective of this portion of the study was to quantify the performance of seacliff protective methods that have been installed on or in the seacliffs.
This study utilized two airborne LIDAR (Lighg 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 (years versus decades) compared to traditional methods that utilize historical maps and aerial photographs, the high point density of LIDAR data yields highly accurate, quantitative estimates of the volume of total sediment liberated by the erosion process (Young and
Ashford, 2006). In addition, LIDAR provides a direct, three dimensional erosion analysis, whereas traditional methods typically focus on two dimensional shoreline retreat.

**STUDY AREA**

The study area (Figure 4-2) covers a 13 kilometer 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 sea cliffs cut into uplifted marine terraces. Sea cliffs 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 level.

The majority of the sea cliffs are approximately 20-30 m in height, 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 un lithified Pleistocene marine terrace deposits, and extends throughout the entire study area. The lower Eocene-age unit is stronger and more resistant to erosion; however, both units are erodible, with long-term retreat rates estimated at 8 to 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 (Figure 4-2) was divided into three
sections (Cardiff, Solana Beach, and Del Mar) based on general stratigraphy and lagoon/creek incisions.

Figure 4-2. Study location map and section boundaries.
Cardiff Section

The Cardiff section extends from Cottonwood Creek to San Elijo Lagoon with cliffs ranging in height from 6-36 m. The majority of the lower geologic unit is 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 for a variety of uses including 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 the San Dieguito Lagoon, with cliffs ranging in height from 10-28 m. The lower geologic unit mostly consists of the Torrey Sandstone, but 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 north of Fletcher Cove consists of dense single-family residential units, and the cliff top south of Fletcher Cove consists of several multi-story condominium structures.
Del Mar Section

The Del Mar section extends from Power House Park at 15th Street, Del Mar to Los Peñasquitos Lagoon. The cliffs range in height from 6-24 m, and the lower geologic unit consists of the Del Mar Formation. The cliff top contains the North County Transit District rail corridor (Figure 4-3), which runs the full length of this section. The railway tracks were realigned in 1910 on the cliff top to allow for the development of the city of Del Mar and reduce the railway track grade, significantly altering the natural surface drainage pathways. Cliff failures in this section of coastline can threaten railway activity and have caused a train to derail (Figure 4-4) in the past (Kuhn and Shepard, 1984).

Figure 4-3. The Amtrak Surfliner in passage along The North County Transit Department rail corridor on the cliff top in Del Mar.
Climate and Oceanographic Setting

San Diego County has a semi-arid, Mediterranean climate characterized by mild, sometimes wet winters and warm, very dry summers (Miller, 2005). The region is influenced by the El Niño Southern Oscillation and the Pacific Decadal Oscillation. Strong El Niño events are associated with anomalously high precipitation during the winter rainy season (November through April). This study occurred during a relatively dry time period. Statistically, rainfall was 27% below the long-term average of 26 cm/yr. The study period occurred directly between two heavy rain seasons, after the 1997-98 El Niño event (46 cm) and before the 2004-05 wet winter season (55 cm).
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. Waves that arrive at the coast provide energy, which removes seacliff failure deposits and erodes the lower portions of exposed seacliffs. Tides are of the mixed semi-diurnal type with a diurnal range of 1.62 m (La Jolla Tidal Station). The highest water level recorded was 2.33 m (MLLW datum) on November 13, 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., 1981). Fulton-Bennett and Griggs (1986) provided an extensive review of the effectiveness of coastal protection on the central California coast. They outlined several failure mechanisms and suggested improved design criteria that could extend the structures’ design life or improve performance. Based on case studies, they concluded that concrete seawalls were the most effective, riprap was more effective that wooden seawalls, and placing riprap in front of walls improved performance. Magoon et al. (1988) investigated the performance of rubble mound seawalls in Santa Cruz County,
California and found that 90% of the structures were still in good condition after 25 years. The remaining 10% failed due to the erosion of landward material, erosion at the ends, toe scour, or inadequate design height. Wiegel (2002) also inspected one of the same structures in 1998 after the 1997-98 El Niño event and noted that it remained in good condition after 37 years. Storlazzi et al. (2000) investigated why the 1982-83 El Niño was significantly more damaging than the 1997-98 event along the central California coast. These authors concluded that, although a secondary factor, the increased amount of shoreline protection built after the 1982-83 event was partially effective in reducing damage done by the 1997-98 El Niño. Komar and McDougal (1988) provide a review of protection structures along the Oregon coast and indicate that while some structures have been effective, others that were improperly designed have not. They also point out that only adding toe protection to stop marine erosion may not be enough to halt the cliff retreat, at least in the short-term. Prior and Renwick (1980) also found that eliminating marine erosion does not immediately reduce upslope mass movements of the coastal slopes in France. In addition, they noted that in some cases, underestimating the magnitude of upslope mass movements has resulted in damage to the protection structures.

A quantitative study by Sunamura and Horikawa (1972) used aerial photographs to measure the toe retreat of the Byobuguara cliffs in Japan over a 10 year period. They compared natural retreat rates to those in areas protected by seawalls and found that the retreat rates were reduced from 100 cm/yr (natural) to 5-30 cm/yr (protected). Clayton (1989) also compared natural toe retreat rates to those of
protected sections. Clayton (1989) used aerial photographs of seacliffs in Norfolk, England, over a seven-year time period and found that unprotected sections retreated at 70 cm/yr while those protected by seawalls and revetments retreated at 8 cm/yr and 30 cm/yr, respectively. Carter et al. (1981) used a regional approach to investigate the influence of shore protection along a 300 km cliffed portion of the Ohio shoreline of Lake Erie. They used maps and aerial photographs to map the shoreline positions from 1876-1973. During the study period the number of shore protection structures increased from 60 to 3600, while the length of cliffs retreating at 30-90 cm/yr decreased from 76 km to 54 km, and cliffs retreating at less than 30 cm/yr increased from 151 km to 171 km. These results indicate that as the amount of shore protection increased, the retreat rates decreased.

Several seacliff erosion studies have found that subsurface groundwater can lead to increased cliff erosion or cliff instability (e.g. Bryan and Price, 1980; Turner, 1981; Kuhn and Shepard, 1984; Norris and Back, 1990; Benumof and Griggs, 1999; Hampton, 2002). Sorben and Sherrod (1977) have estimated that over-irrigation of landscaping in sub-divisions in the San Diego area is equivalent to receiving 130-150 cm of rain per year. This is almost six times the natural annual rainfall and has significantly increased local groundwater levels. Poorly designed or failed surface drainage systems can also lead to direct cliff erosion (Kuhn and Shepard, 1984).

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 research 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 erosional problems. This study sought to further the investigation of the performance of seaciff protection, 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. In addition to evaluating seaciff protection, this portion of the study also investigates the role of both subsurface and surface drainage conditions, which affect seaciff erosion in San Diego County (Turner, 1981; Kuhn and Shepard, 1984; Benumof and Griggs, 1999).

**METHODOLOGY**

**Classification and Mapping of Seaciff Protection Methods**

Seaciff erosion protection methods were classified based on the location of the control device with respect to the seaciff profile (Figure 4-5 and 4-6). 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 seaciff 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 seaciff. 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, located on the lower cliff, provide protection of the Eocene deposits, whereas Type C and D, located on the upper cliff, provide protection of the Pleistocene terrace deposits.

**Figure 4-5. Seacliff erosion control classification based on the location with respect to the seacliff profile.**
Figure 4-6. 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.

Seacliff erosion control projects were mapped for the beginning and end of the study period (April 1998 and April 2004). The April 1998 data set was mapped using April 1998 USGS oblique photographs, June 1998 oblique photographs (Group Delta, 1998), and coastal maps (Leighton and Associates, 2001, 2003; Flick, 1994). The April 2004 data set was mapped using October 2004 oblique photographs (California Records Project), coastal maps (Leighton and Associates, 2001, 2003), and multiple
field surveys conducted throughout the study period. Several sections of riprap were
documented in the April 1998 oblique photographs of Solana Beach. These riprap
structures were removed from the mapping because they were placed temporarily for
the 1997-98 El Niño and removed in summer of 1998 (Lesley Ewing, personal
communication 9/2/2005). After all erosion control projects were mapped they were
then designated as Type A, B, C, and D or various combinations based on the
classification methodology described above. Table 4-1 summarizes the different types
of protection mapped in the study area and how they were classified.

Table 4-1. Classification of seaciff erosion control devices

<table>
<thead>
<tr>
<th>Type A</th>
<th>Type B</th>
<th>Type C</th>
<th>Type D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wave Impact Structures</strong></td>
<td><strong>Retention Structures</strong></td>
<td><strong>Retention Structures</strong></td>
<td><strong>Retention Structures</strong></td>
</tr>
<tr>
<td>Riprap</td>
<td>Seawalls</td>
<td>Retaining Walls</td>
<td>Retaining Walls</td>
</tr>
<tr>
<td>Notch Fills</td>
<td>Retaining Walls</td>
<td>Post and Board</td>
<td>Post and Board</td>
</tr>
<tr>
<td>Cave Fills</td>
<td>Soldier Piles</td>
<td>Crib Walls</td>
<td>Crib Walls</td>
</tr>
<tr>
<td>Seawalls</td>
<td>Rock Bolts</td>
<td>Tire Walls</td>
<td>Soldier Piles</td>
</tr>
<tr>
<td>Drainage Headwalls</td>
<td><strong>Slope Improvement</strong></td>
<td>Soldier Piles</td>
<td><strong>Slope Covering</strong></td>
</tr>
<tr>
<td></td>
<td>Slope Flattening</td>
<td>Rock Bolts</td>
<td>Gunnite</td>
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<td></td>
<td>Slope Grading</td>
<td></td>
<td>Shotcrete</td>
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<tr>
<td></td>
<td><strong>Slope Improvement</strong></td>
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<td></td>
<td>Slope Reconstruction</td>
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<tr>
<td></td>
<td>Soil - Cement Buttress</td>
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Classification and Mapping of Drainage Conditions

The subsurface and surface drainage conditions, including groundwater seepage, dewatering systems, and surface drainage outlets were mapped in the study area. Perched groundwater conditions form when groundwater encounters a relatively impermeable layer within the seacliffs. When this occurs, groundwater moves horizontally and seeps out onto the cliff face. The Del Mar Formation, which is relatively impermeable, commonly causes groundwater seepage in the Cardiff and Del Mar sections. The Torrey Sandstone is relatively permeable and therefore generally does not cause groundwater seepage except in a few localized areas where claystone seams exist within the Torrey Sandstone. Groundwater seepage was mapped using annotated October 2001 oblique photographs (TerraCosta Consulting Group, 2002), coastal maps (Leighton and Associates, 2001, 2003), and field investigations conducted throughout the study period. It was assumed that there were no changes in the locations of groundwater seepage over the study period.

Dewatering at the Self Realization Fellowship in the Cardiff section was mapped by Turner (1981). These drains were installed after the winter storms in 1980 (Kuhn and Shepard, 1984). The effective extent of this dewatering system was estimated using the locations of monitoring wells affected by the subdrain system (Turner, 1981), where wells down gradient of the subdrain system showed a significant decrease in groundwater levels. Kuhn and Shepard (1984) documented another dewatering system in the Cardiff section along the coast where the Pacific Coast Highway 101 runs along the cliff top between Swami’s Beach City Park and
San Elijo State Park. This cliff section experienced a large landslide in April 1958, collapsing a section of the highway. As part of the repairs performed in 1960, subsurface drains were installed inland from the cliffs and connected to pipes running down the cliff face to remove groundwater (Kuhn and Shepard, 1984). Dewatering systems in the Del Mar section were mapped using coastal maps (Leighton and Associates, 2001, 2003). Most of these drains were installed during a drainage improvement project completed in 1998 (Leighton and Associates, 2003). Figure 4-7 shows a typical example of a dewatering pipe.
Figure 4-7. Typical seaciff profile and drainage system classification.
The dewatering system at the Self Realization Fellowship uses pumps to remove the groundwater, making it an active dewatering system, while the dewatering system in Del Mar utilizes gravity to remove the groundwater, making it a passive dewatering system. Kuhn and Shepard (1984) did not indicate whether the dewatering system along the Pacific Coast Highway 101 in Cardiff is active or passive.

Surface drainage pipes were mapped using April 1998 oblique photographs (USGS) and field investigations. These outlets were classified based on the location of the outlet with respect to the seaciff. Figure 4-7 shows how the three types of pipes were classified. Type I drainage pipes collect surface runoff and channel it down the cliff face. Type II drainage pipes are installed below the cliff surface and the outflow is directed on to the cliff face. Type III drainage pipes are also installed below the cliff surface but the outflow is directed at the base of the cliff onto the beach.

**Topographic and Volumetric Change**

Topographic change of the seaciffs 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 meter 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%, ±5.0%, and ± 9.9%, respectively (Table 3-3). Aerial LIDAR does not capture over-vertical surfaces such as seacaves or notches, and these feature were therefore not evaluated. Corrections were made in heavily vegetated areas by removing the cells. After 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 of the GIS spatial analysis was to divide each seaciff volumetric erosion grid into two-meter wide compartments. This was accomplished using an ArcINFO (ESRI, 2004) shapefile (Figure 4-8). In areas where the coastline curved, the compartments were constructed to be two meters wide across the center (halfway between the cliff top and cliff base) of the seaciffs. Next, each compartment was intersected with the volumetric erosion grid using GIS spatial analysis. This procedure resulted in the summation of the cell values from the volumetric erosion grid within each compartment. The compartment shapefile was then intersected with the digital elevation model to find the highest elevation (seaciff height) within each compartment. These values were plotted along the length of each section and edited for outliers caused by vegetation. The final step was to classify each compartment for various seaciff erosion control combinations.
Figure 4-8. Two meter wide seacliff compartment polygons (A) displayed over an aerial photograph in the Solana Beach section and (B) displayed over the erosion grid of the same area. Note the dark areas showing significant erosion during the study period.
Sealiff Retreat Rate

The cliff retreat rate was calculated for each sealiff compartment using the cliff face retreat method (Equation 3-6) as described in the previous chapter.

Quantifying the Effectiveness of Sealiff Protection

The effectiveness of each sealiff protection method was evaluated by comparing the retreat of protected sealiffs to unprotected sealiffs in the same section. This calculation is shown in Equation 4-1.

\[
\left( \frac{R_U - R_P}{R_U} \right) \times 100 \%
\]

(Equation 4-1)

\(R_U = \text{Average Retreat Rate of Unprotected Sealiffs}\)

\(R_P = \text{Average Retreat Rate of Protected Sealiffs (Sorted by Control Type)}\)

The application of Equation 4-1 results in the following:

\(R_P = 0 \quad \rightarrow \quad 100\% \text{ effective}\)

\(R_P = R_U \quad \rightarrow \quad 0\% \text{ effective}\)

\(R_P = 2R_U \quad \rightarrow \quad -100\% \text{ effective}\)
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% of the total study section length.

RESULTS AND DISCUSSION

The detailed results in Cardiff, Solana Beach, and Del Mar are shown in Figures 4-9, 4-10, and 4-11 respectively. These figures illustrate the spatial relationships between a shaded relief map of the section (Figures 4-9A, 4-10A, and 4-11A), cliff face retreat rates (Figures 4-9B, 4-10B, and 4-11B), erosion control methods (Figures 4-9C, 4-10C, and 4-11C), drainage conditions (Figures 4-9D, 4-10D, and 4-11d), and geology (Figures 4-9E, 4-10E, and 4-11E).
Figure 4-9. Details of the Cardiff section (A) shaded relief map (B) average annual seafloor face retreat during the study period (C) classified locations of seafloor erosion control measures for the beginning and end of the study period (D) classified drainage conditions (E) general geology and cliff height along the section.
Figure 4-10. Details of the Solana Beach section (A) shaded relief map (B) average annual seaciff face retreat during the study period (C) classified locations of seaciff erosion control measures for the beginning and end of the study period (D) classified drainage conditions (E) general geology and cliff height along the section.
Figure 4-11. Details of the Del Mar section (A) shaded relief map (B) average annual seaciff face retreat during the study period (C) classified locations of seaciff erosion control measures for the beginning and end of the study period (D) classified drainage conditions (E) general geology and cliff height along the section.
Seacliff Erosion Control

All combinations of control types were located except BD and BCD (Figure 4-12). Overall, the bulk of seacliff protection consisted of Types A, AB, ABC, and ABCD. Figure 4-13 shows the percentages of each section length that contain various types of combinations of control, as well as areas with no protection, at the beginning and at the end of the study period. These results indicate that the majority of additional protection was constructed in Solana Beach, and little overall change occurred in the Del Mar and Cardiff sections. The Solana Beach section increased from 33% to 44% controlled, while Cardiff had essentially no change at 42% controlled, and Del Mar increased slightly from 16% to 17% controlled. The majority of additional protection in Solana Beach consisted of Type A and B combinations, most commonly Type A notch infills and Type AB artificial rock seawalls.
Figure 4-12. Detailed results of the erosion control mapping and classification for the entire study, at the beginning and end of the study period.

Figure 4-13. General results of the erosion control mapping and classification for the three study areas, at the beginning and end of the study period.
The effectiveness of control (Table 4-2) for the Cardiff, Solana Beach, and Del Mar sections range from -71% to 73%, -127% to 84%, and 15% to 83% respectively. The weighted average of seaciff retreat reduction for the entire study area ranged from -71% to 75%. Overall, sections with some type of protection reduced the retreat rate by 42% in Cardiff, 35% in Solana Beach, and 58% 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.

Table 4-2. Effectiveness of seaciff erosion control devices evaluated by comparing the retreat rate during the study period of protected seaciffs to unprotected seaciffs (Equation 4-1 results)

<table>
<thead>
<tr>
<th>Type of Seaciff Erosion Control</th>
<th>Cardiff</th>
<th>Solana Beach</th>
<th>Del Mar</th>
<th>Weighted Average Seaciff Retreat Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Seaciff Retreat Reduction (%)</td>
<td>Length Evaluated (m)</td>
<td>Seaciff Retreat Reduction (%)</td>
<td>Length Evaluated (m)</td>
</tr>
<tr>
<td>A</td>
<td>35</td>
<td>862</td>
<td>21</td>
<td>374</td>
</tr>
<tr>
<td>B</td>
<td>-71</td>
<td>4</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>C</td>
<td>40</td>
<td>42</td>
<td>-127</td>
<td>14</td>
</tr>
<tr>
<td>D</td>
<td>23</td>
<td>8</td>
<td>-76</td>
<td>42</td>
</tr>
<tr>
<td>AB</td>
<td>--</td>
<td>--</td>
<td>74</td>
<td>160</td>
</tr>
<tr>
<td>AC</td>
<td>58</td>
<td>62</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>AD</td>
<td>--</td>
<td>--</td>
<td>45</td>
<td>36</td>
</tr>
<tr>
<td>BC</td>
<td>66</td>
<td>16</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>CD</td>
<td>53</td>
<td>16</td>
<td>-98</td>
<td>18</td>
</tr>
<tr>
<td>ABC</td>
<td>52</td>
<td>448</td>
<td>81</td>
<td>92</td>
</tr>
<tr>
<td>ABD</td>
<td>--</td>
<td>--</td>
<td>65</td>
<td>12</td>
</tr>
<tr>
<td>ACD</td>
<td>73</td>
<td>4</td>
<td>-46</td>
<td>8</td>
</tr>
<tr>
<td>ABCD</td>
<td>56</td>
<td>32</td>
<td>84</td>
<td>88</td>
</tr>
<tr>
<td>A Combinations</td>
<td>42</td>
<td>1408</td>
<td>47</td>
<td>772</td>
</tr>
<tr>
<td>B Combinations</td>
<td>61</td>
<td>500</td>
<td>78</td>
<td>352</td>
</tr>
<tr>
<td>C Combinations</td>
<td>52</td>
<td>620</td>
<td>50</td>
<td>220</td>
</tr>
<tr>
<td>D Combinations</td>
<td>52</td>
<td>60</td>
<td>22</td>
<td>204</td>
</tr>
<tr>
<td>Any Combination</td>
<td>42</td>
<td>1494</td>
<td>36</td>
<td>844</td>
</tr>
</tbody>
</table>
The results in Table 4-2 indicate that the erosion control methods had a wide range of effectiveness. Many control methods failed 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% effective while Type AB, ABC, and ABCD were 74%, 58%, and 75% effective, respectively. The most effective type of control was Type ABCD which was 100% effective in some localized areas where the protection consisted of a completely artificially hardened seacliff (Figure 4-6D).

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 4-14). In this example a notch infill was placed to prevent marine erosion but failed to prevent upper cliff erosion despite the cliff being partially controlled. Type A and B structures may also be overtopped during large wave and high tide events (Figure 4-15) and thus may not provide complete protection from marine erosional processes. Figure 4-16 shows another marine erosion mechanism associated with Type A control. In this example, a cave infill was outflanked at both ends. This resulted in the formation of a temporary sea arch (Figure 4-16A). The arch subsequently failed, resulting in an upper seacliff failure that left the remnant infill isolated on the beach (Figure 4-16B). Undermining and poor maintenance of protective devices also caused
localized erosional problems. 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% effective while Type AB, ABC, and ABCD were 74%, 58%, and 75% effective respectively.

Figure 4-14. 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.
Figure 4-15. Waves impacting the seacliffs in Solana Beach and overtopping seawalls.

Figure 4-16. Cave infill in Solana Beach where (A) outflanking created a temporary sea arch and (B) the arch collapsed leaving behind the remnant infill isolated on the beach.
Drainage Conditions

Figures 4-9D and 4-11D show that little seepage is occurring at the two locations with dewatering systems in the Cardiff section, while localized seepage is still occurring in the dewatered areas in the Del Mar section. Figure 4-17 shows the average annual seacliff face retreat rates for seepage, no seepage, and dewatered areas in the Cardiff and Del Mar sections. The rates of retreat in the Cardiff section were 7 cm/yr, 6 cm/yr, and 4 cm/yr for seepage, no seepage, and dewatered areas respectively. In Del Mar the retreat rates were 11 cm/yr, 9 cm/yr, and 11 cm/yr for seepage, no seepage, and dewatered areas respectively. Figure 4-17 illustrates that areas affected by groundwater seepage had higher retreat rates than those without seepage in both Cardiff and Del Mar. This figure also shows that dewatering systems in Cardiff were relatively successful and dewatered areas had lower cliff face retreat rate than areas affected by seepage. Conversely, both seepage and dewatered areas in Del Mar had basically the same rate of retreat, indicating that the dewatering system in Del Mar was unsuccessful at reducing the retreat rate during the study period. The ineffectiveness of the Del Mar dewatering system can be at least partially attributed to the outlet location of the dewatering pipes, as well as pipes that have been broken during slope failures. Many outlets of the Del Mar dewatering system exit and drain onto the middle of the cliff face, causing surface erosion on the lower seacliff (Figure 4-18A and 4-18B). Although some pipes are still in place and continue to remove groundwater, numerous pipes have been broken in mass movements (Figure 4-18C) and now drain groundwater directly onto the slope (Figure 4-18D).
Figure 4-17. Average annual seacliff face retreat for areas with seepage, no seepage, and dewatering for the Cardiff and Del Mar sections.
Figure 4-18. Typical dewatering pipe in the Del Mar (A & B) draining on to the cliff face. (C) A small slope failure causing the pipe to break and fall to the beach. (D) The broken pipe continuing to drain groundwater directly on to the cliff face causing surface erosion.
Broken and inadequately maintained surface drainage systems have also contributed to accelerated erosion in at least five locations in Cardiff and one in Del Mar. Figure 4-19 shows three examples in Cardiff where broken pipes have caused concentrated surface runoff to be directed onto the cliff face, causing increased erosion. Another notable surface drainage feature contributing to increased erosion is located in Del Mar (Figure 4-20). At this location surface water is concentrated, and the flow is directed over the cliff top into a catch basin located at the cliff toe (Figure 4-20A). Only partial seacliff protection is being provided for the concentrated surface flow, resulting in increased direct channel erosion and localized cliff failures (Figure 3-20B). In addition, this area is subject to water ponding on the cliff top, which contributes to the poor surface drainage conditions.

Figure 4-19. Examples of failed surface drainage systems causing accelerated erosion in Cardiff. (A&B) Failed Type I pipe. (C) Failed Type II pipe that was converted to a Type III which failed during the study period.
CONCLUSIONS

This research provides a new methodology to quantify the effectiveness of seashore erosion control devices using airborne LIDAR and detailed GIS spatial analysis, as well as a new method of seashore erosion protection classification based on cliff face profile. This approach demonstrates that the effectiveness of seashore protection strategies can be quantified by comparing the cliff face retreat rates of protected and unprotected seashores on a regional scale.
Given the relatively short study time 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. Seacliff erosion control methods that provided both lower and upper cliff protection performed better than methods which only provided partial protection. Overall, protective devices reduced the cliff face retreat by 42%. Partial seacliff erosion protection was effective at decreasing erosion during the study period, but failed to eliminate all erosional processes affecting the seacliffs. This conclusion is supported by previous studies (Komar and McDougal, 1988; Prior and Renwick, 1980) that indicate that partial seacliff protection may not be sufficient in eliminating erosional problems.

Both subsurface and surface drainage conditions contributed to the increase of erosional processes during the study period. Seacliffs affected by groundwater seepage eroded 19% and 25% faster in Cardiff and Del Mar, respectively, compared to adjacent seacliffs unaffected by seepage, while surface runoff directed onto the cliff face caused accelerated erosion in localized areas. These findings are supported by previous studies (Turner, 1981; Kuhn and Shepard, 1984; Benumof and Griggs, 1999) that reported similar conclusions for the study area. Proper control of groundwater and
surface runoff could therefore reduce the rate of retreat. This could be accomplished by (1) reducing groundwater sources, (2) installing active dewatering systems, (3) regularly maintaining drainage systems, and (4) directing water flow away from the cliff face.

ACKNOWLEDGMENTS

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CHAPTER 5: Applications of Mobile Terrestrial LIDAR
Scanning in Seacliff Morphology Studies
INTRODUCTION

Terrestrial (or ground-based) LIDAR (LIght Detection And Ranging) is a relatively new surveying tool that has only recently been applied to coastal morphology studies. Although this new tool is only in recent use, the highly accurate and complex surface models produced provide new insight into processes of seacliff morphology. One of the major drawbacks of stationary terrestrial laser scanning is that only a relatively small area can be surveyed when compared to other types of remote sensing (aerial and oblique photographs, airborne LIDAR, IFSAR). In this study, a terrestrial LIDAR scanner was mounted on a mobile surveying platform which significantly increased the length of coastline which could be covered.

Terrestrial laser scanning has several advantages over airborne remote sensing techniques. Due to the steep nature of seaciffs and considerable sensor-to-cliff distance, airborne sensors have a lower resolution on the cliff face when compared to ground-based methods. The high resolution and accuracy of terrestrial LIDAR allows seaciff volumetric change to be quantified at the centimeter level. Volumetric seaciff morphology literally provides additional dimensions compared to some traditional methods that focus on one and two dimensional change. These additional dimensions present a new scope in understanding the processes governing seaciff morphology. In addition, because terrestrial methods operate by side-scanning, geologic features such as sea caves and wave cut notches are captured, whereas they are hidden from airborne sensors. Ground-based surveying can be performed on short notice, thus obtaining valuable data after important events that may otherwise be lost.
This chapter explores the methods and applications of mobile terrestrial LIDAR scanning in evaluating seacliff morphology on both a regional and site-specific scale. The regional applications investigated include volumetric changes, spatial analysis, landslide volume frequency, and back-calculated retreat rates. The site-specific analysis investigated individual landslides and potential failure mechanisms. Lastly, future applications of terrestrial LIDAR are also discussed.

BACKGROUND

Using laser scanning technology to monitor seacliff morphology is a relatively new technique compared to traditional methods (oblique and aerial photographs, historical maps, and direct field measurements). Total stations can be used to collect laser point data on a point-by-point basis from the ground, and is applicable to relatively small projects (Gulyaev and Buckeridge, 2004). Terrestrial laser data also may be collected using stationary high-frequency (250-8000 Hz) laser scanners that can detect centimeter level changes (Collins, 2004; Collins and Sitar, 2004; Lim et al., 2005; Rosser et al., 2005). These high frequency LIDAR scanners allow for rapid data collection, thereby increasing the potential scope of projects, while producing very high point density. In addition to terrestrial laser scanning methods, airborne LIDAR can also be used to quantify seacliff morphology (Young and Ashford, 2006). When compared with terrestrial laser scanning methods, the major drawbacks of airborne scanning include; cost, accuracy, point density, and the inability to capture over-vertical surfaces, while the foremost advantage is the length of coastline that may
be surveyed. This research project utilized a mobile-terrestrial method which incorporates the advantages of terrestrial scanning, and although not as rapid as airborne surveys, permits swift surveying of significant coastal lengths.

**STUDY AREA**

The study area consists of a 17 km stretch of coastline extending from Batiquitos Lagoon to Los Peñasquitos Lagoon which covers the cities of Del Mar, Solana Beach, and Encinitas (Figure 5-1). The study area is entirely within the Oceanside Littoral Cell located in Southern California, which spans an 84 kilometer stretch of coastline from Dana Point to La Jolla (Inman and Frautschy, 1966). The project site is categorized by narrow sand and cobble beaches backed by steep seacliffs cut into uplifted marine terraces. Steep cliffs characterize the study area with occasional alternating lowlands at coastal river mouths and lagoons. Most of the seacliffs are approximately 20 to 30 meters in height, and are generally composed of two main geologic units. The lower unit consists of lithified Eocene mudstone, shale, sandstone, and siltstone (Kennedy, 1975). The lower unit is capped by unlithified Pleistocene terrace deposits. The lower unit is stronger and more resistant to erosion however both units are highly erodible, with long-term cliff top retreat rates of 8 to 19 cm/yr (Benumof and Griggs, 1999).
Figure 5-1. Study area location map.
METHODOLOGY

Figure 5-2 illustrates a schematic diagram of a typical LIDAR system. LIDAR scanners operate by transmitting and receiving light pulses reflected off of a target surface. The light is transmitted by a pulsed diode laser directed by an oscillating mirror and rotating scanner head. The reflected pulse is received by a small telescope that focuses the light onto a detector. The travel time and transmission angle of each light pulse is measured by the LIDAR scanner and then converted into an “X,Y,Z” position with signal processing. The result of each scan is a “point cloud” (Figure 5-3) of X,Y,Z data with positions relative to the scanner setup location. After point clouds are generated, the raw data is post-processed in a series of steps to create georeferenced digital terrain models (DTMs). Using sequential DTMs of the same site, seaciff morphology may be quantified using a variety of methods on both a regional and site-specific basis.
Figure 5-2. Schematic diagram of a typical terrestrial 3D laser scanning system.

Figure 5-2. Typical terrestrial LIDAR point cloud, Solana Beach, CA.
Data Collection

Terrestrial LIDAR surveys for this research project were conducted at approximately six month intervals starting in May 2004 and ending in October 2005 (May 2004, September 2004, April 2005, and October 2005). Surveys were performed during negative and low tides to maximize the available beach width and scanning time. Scanning during low tides generally offered a 4-6 hour window of scan time, whereby the study area could be completely scanned in 3-4 days. Scan setups were located approximately 30-70 meters from the cliff base and spaced 50-100 meters apart. The LIDAR scanner will only collect data that is within the line of sight from the scanner. Therefore, when scanning complex cliff features, care should be taken not to miss portions of the seacliff that may be shadowed (Figure 5-3). The shadowing effect necessitates scans to be spaced closely so that complete cliff coverage is attained. The overall pace of data collection generally proceeded at 1.0-1.5 km/hr. The mobile terrestrial scanning system consists of three main components: the LIDAR scanner, a differential global positioning system (DGPS), and a mobile platform. Figure 5-4 shows the typical mobile terrestrial scanning setup.
Figure 5-3. (A & B) Individual point clouds of scans 1 and 2 showing shadowed zones created by a complex cliff feature (C) Combined point clouds of scan 1 and 2 showing the elimination of the shadow zones.
Figure 5-4. Typical setup of the mobile terrestrial LIDAR scanning system.

*LIDAR Scanner*

Current terrestrial LIDAR systems collect data at rates of 4000 to 12,000 points per second with a vertical angular view of 80° and a horizontal view spanning 360°. A typical seaciff scan collects approximately 1,000,000 points in under five minutes with a point density of about 10-15 centimeters on the cliff face. Current scanners typically have a range of several hundred meters with an accuracy of a few
centimeters. Two different scanners were used during this research project, the Riegl LMS-Z210 and the I-Site 4400. The data acquisition rates for the Riegl and I-Site scanners are 8000 and 4400 Hz, respectively. The I-Site 4400, a relatively new scanner, incorporates a digital tilt compensator and a high resolution digital panoramic camera. The digital images are acquired during the scan and automatically registered to point cloud, which may then be easily draped over the scan data to provide a fully rectified three dimensional image.

**DGPS**

With the use of a DGPS, each scan can be georeferenced to real world coordinates with centimeter level accuracy. DGPS employs two GPS receivers, a base station receiver and a rover receiver. The base station is set up on a known benchmark and sends correction information through a radio transmitter to the rover receiver. The rover receiver is mounted centrally above the LIDAR scanner at known vertical distance to obtain the scanner origin. In order for the rover GPS to receive corrections from the base station, the base station radio antenna must lie within the line of sight of the rover location. Therefore, optimal base station locations consisted of high elevation benchmarks near the cliff crest and seaward positions such as the end of the Scripps Institution of Oceanography’s pier. This study utilized a Trimble 5800 RTK DGPS to make the transformation to real world coordinates.
Mobile Platform

The LIDAR scanner and rover GPS are mounted on a mobile platform. In this study, four wheel drive vehicles with roof racks were utilized. During each scan, the LIDAR scanner must not vibrate in order to collect accurate data. Therefore the vehicle must be turned off and people inside the vehicle should exit to reduce any movement. Additionally, consideration should be taken when selecting a scan setup location. The vehicle should be parked at a sufficient distance from the ocean so that an incoming wave does not impact the vehicle and cause the scanner to move. Furthermore, the LIDAR scanner should not use the vehicle as a power source. Because the vehicle is not on during scanning, there is little time for the vehicle battery to recharge. Using a raised mobile platform permits the scanning equipment to remain powered between setup locations, eliminating equipment setup and boot time. This significantly reduces the time interval between scans from approximately twenty minutes (for stationary terrestrial scanning) to five minutes, allowing for rapid data collection (1.0-1.5 km/hr).

Post Processing

Post processing the raw survey scans must be done to produce accurate three dimensional surfaces. Post processing consists of editing, georeferencing, and generating surfaces using specialized software. Figure 5-5 illustrates the major steps involved in turning raw point data into georeferenced DTMs. Editing removes
anomalous points and filters high density point areas, as point clouds are sometimes excessively dense and slow the software processing speed. Each scan must then be georeferenced to convert the data to real world coordinates using DGPS, the scanner inclination sensor, and surface registration. After the data is georeferenced three dimensional DTM s are generated using various triangulation and/or gridding techniques. The final step consists of merging the individual DTM s together through a fusion process creating a comprehensive DTM of the survey area. For this project, terrestrial LIDAR software, I-Site Studio 2.4 (I-Site, 2004), was used for the post-processing procedure.
Figure 5-5. Major steps of post-processing terrestrial LIDAR data.
Editing

After the survey has been completed each scan must be edited to assure accurate surface generation. During the scanning process anomalous points are sometimes collected and should be removed. Other points that should be removed include people, birds, vehicles, or other points that do not indicate the true land surface. The raw point files are typically very dense around the scanner origin. These dense areas can be filtered to reduce the file size and create faster software processing without significantly affecting the surface accuracy. Filtering uses minimum separation, in which a minimum separation between points is assigned and all points closer than the specified distance are removed. Filtering the scans for this project used a minimum separation of 10 cm.

Georeferencing

Initially each scan collects X,Y,Z point data in relative coordinates to the scanner. Therefore each scan should be georeferenced to real world coordinates. A variety of methods are used for georeferencing including DGPS, scan control points, and baseline surveys. For the DGPS method, a rover GPS is mounted on the scanner and collects a coordinate for each scanner origin position. Utilizing either a level compensator or backsighting will determine the scanner x-y plane orientation. The point cloud is translated into real world coordinates by combining the scanner origin and x-y plane orientation with surface registration. Surface registration finds the best fit between two overlapping adjacent point clouds, and then rotates the data into place.
Another georeferencing alternative is to collect GPS control points within each scan. This may be accurately accomplished by installing driveway reflectors at several locations spread throughout the target surface area (Collins, 2004). The reflector points are then surveyed and georeferenced by identifying and selecting the highly reflective points in the point cloud. A further georeferencing technique uses baseline surfaces and surface registration. If a prior survey of the site has been established and georeferenced, then some features may be selected as baseline surfaces. These surfaces should consist of fixed structures, for example seawalls, cliff top houses, roads, etc. The baseline surfaces serve as known locations that the surface registration processes can employ to georeference the raw scan data. Note that the baseline georeferencing technique is only applicable to urbanized shorelines with multiple fixed structures spread throughout the study site. Utilizing more than one georeferencing technique for a survey is possible and may also improve the overall accuracy. Scan georeferencing for this research project used both the DGPS and baseline techniques.

*Surface Generation*

After editing and georeferencing each scan, the final post-processing step is to produce surface models. For this project, digital terrain models were created using spherical triangulation (I-Site, 2004), which allows for surface modeling of overhanging surfaces. In other words, the software allows multiple Z positions for a given X,Y coordinate, thus enabling the modeling of complex coast features such as
seacaves and notches. After triangulating each point cloud into separate DTMs, the DTMs are then merged together into a fusion surface. Figure 5-6 displays a fusion surface of northern Solana Beach, illustrating the complex coastal features modeled using the spherical triangulation. The ability to surface model these complex overhanging features is fundamental to investigating the role of marine erosion.

![Image](image_url)

**Figure 5-6. A fusion surface of northern Solana Beach illustrating the ability to model complex coastal features.**

In addition to using the spherical triangulation and fusion surfacing, a 700 m long section in southern Del Mar was gridded into a digital elevation model using ArcINFO (ESRI, 2004). These grids were created using inverse distance weighting point interpolation and a 20 cm grid resolution. Although some detail was lost in the gridding procedure when compared to the fusion surface, grids provide an
environment for detailed GIS spatial analysis. Gridded surfaces only allow one Z position for a given X-Y grid cell, and therefore do not support surface modeling of overhangs. The fusion surfaces of this section in southern Del Mar lacked overhanging features, and therefore provided a suitable application of topographical gridding.

**Morphological Analysis**

Once georeferenced surfaces have been produced, several types of morphological analysis may be performed on a regional and site-specific basis. One type of analysis unitizes consecutive LIDAR surveys of the same coastal section to quantify volumetric change over time. The first step in volumetric change analysis is to identify areas that have either eroded or accreted between surveys, by displaying the more recent surface as a color coded distance (or spectrum distance) from the previous surface. For example, Figure 5-7 displays the erosion (red) and accretion (blue) that occurred between September 2004 and April 2005 for a section in southern Del Mar, with a spectrum distance scale of ± 2.5 meters. The yellowish points in Figure 5-7 are background point clouds and were left in the image for reference (note several houses in the upper-left of the figure). After eroded areas have been identified, they may be selected and isolated for either regional or site-specific morphological analysis.
Figure 5-7. Oblique view of southern Del Mar, illustrating the areas of erosion and accretion that occurred between September 2004 and April 2005.

**Regional Analysis**

To demonstrate the applications of regional morphological analysis, a 700 meter long section of southern Del Mar was selected. This coastal segment experienced a significant amount of erosion between September 2004 and April 2005 as shown in Figure 5-7. The time frame encompassed the 2004-05 winter wet season, when the study area received over twice (57 cm) the average yearly amount of precipitation (Western Regional Climate Center).
Regional volumetric analysis was performed using GIS spatial analysis similar to the procedure described in the previous chapter. In essence, digital elevation models were clipped to isolate the cliff face and talus deposits and then subtracted from one another to evaluate the change in elevation over time. Next, one meter wide coastal compartments were used to quantify the volumetric change alongshore. Figure 5-8 illustrates the positive volumetric change (blue line, accretion), negative volumetric change (red line, erosion), and net volumetric change (difference between accretion and erosion, green line). The positive volumetric change represents areas where eroded material was deposited down slope or on the beach.

Significant landslides (> 10 m³) were then visually identified in the color-coded surface changes model, and the individual failure volumes calculated. Figure 5-9 illustrates the locations and volumes of the significant landslides that occurred during the six month period. Lastly, the rate of cliff face retreat/advance was back-calculated by dividing the eroded/accreted compartment volume by the compartment width (one meter) and the compartment cliff height. Note that this calculation represents the average retreat/advance over the entire cliff face and does not represent the change of the actual cliff top or base. Figure 5-10 displays the alongshore cliff face retreat/advance rate and net change (difference between retreat and advance) that occurred during the six month period.
Figure 5-8. Alongshore volumetric change in southern Del Mar that occurred during the 2004-05 wet winter season (September 2004 through April 2005).
Figure 5-9. Location and volume of the significant individual landslides (> 10 m³) that occurred between September 2004 and April 2005.
Figure 5-10. Alongshore cliff face retreat / advance rate that occurred during the six month period (September 2004 through April 2005) in southern Del Mar.
Site Specific Analysis

To demonstrate the applications of site-specific analysis, two eroded locations were selected and isolated for investigation. One site consisted of a large lower cliff failure in Solana Beach (site T1), and the other was a progressive failure in Del Mar (site D1). Photographs of the conditions before and after the T1 landslide are shown in Figures 5-11 and 5-12, respectively. Figure 5-13 illustrates the topographical change that occurred between May 2004 and September 2004. The total T1 failure volume was evaluated by isolating the failure plane and calculating the volumetric change between surveys.

Figure 5-11. Conditions before the T1 landslide, Solana Beach, May 2004.
Figure 5-12. Conditions after the T1 landslide, Solana Beach, September 2004.

Erosion and Accretion Areas of Failure

Figure 5-13. Digital change model of site T1 between May 2004 to September 2004, where orange represents erosion and blue represents accretion.
Additional insight into the T1 failure may be gained by extracting profiles from the digital surfaces. Figure 5-14 shows a typical profile before the T1 landslide, with the failure plane demarcated.

![Profile of Failure Section Before September 2004 Failure (Solana Beach)](image)

**Figure 5-14.** Typical profile before the T1 landslide, failure plane location, and average failure dimensions.

Both photographic and LIDAR surveys of site D1 reveal a series of failures between September 2004 and October 2005. Figures 5-15 through 5-19 illustrate the photographic sequence of erosion that occurred from January 11 through September
16, 2005. Reference point X, in Figures 5-15 through 5-19 represents the location of a concrete pad and pull-up bar located on the cliff top (the pull-up bar fell off the cliff, as shown in Figure 5-17).

Figure 5-15. Site D1, January 11 2005.
Figure 5-18. Site D1, July 18, 2005.

Figure 5-19. Site D1, September 16, 2005. Note perched groundwater, seepage, and water draining down the lower cliff face.
The erosional sequence at site D1 was captured by three terrestrial LIDAR surveys and therefore two surface change models. Figures 5-20 (September 2004 to April 2005) and 5-21 (April 2005 to October 2005) illustrate the digital model of surface changes at site D1. Note, Figures 5-20 and 5-21 are shown from the same perspective. The erosion occurring at site D1 between September 2004 and April 2005 (Figure 5-20) affected both the lower and upper cliff independently and therefore the eroded volumes were calculated separately. Due to the progressive erosion at site D1 the calculated eroded volumes do not represent individual landslide events, but the total eroded volume between surveys for a specific cliff zone.

Figure 5-20. Site D1 surface change model from September 2004 to April 2005.
Figure 5-21. Site D1 surface change model from April 2005 to October 2005 (Same perspective as Figure 5-20).
RESULTS AND DISCUSSION

Table 5-1 lists the total volumetric and average linear change that occurred in southern Del Mar between September 2004 and April 2005 from the regional morphological analysis. The total eroded and accreted volumes for the 700 meter section were 1310 m³ and 900 m³, respectively, with an overall net change of 410 m³ (erosion). The average linear changes of the cliff face for the six month period were 13.0 cm (retreat) and 8.6 cm (gain), with a net change of 4.4 cm (retreat). The significant amount of accreted volume indicates that wave action during the study period was not sufficient to remove talus deposits, and although a large amount of material was eroded from the seacliffs, the majority of it had not yet entered the littoral system. Furthermore, this suggests that subaerial erosional processes, as opposed to marine, dominated during the time period. This result is expected due to the unusually high amount of precipitation occurring over the 2004-05 winter wet season.

Table 5-1. Summary of changes that occurred in southern Del Mar from September 2004 to April 2005

<table>
<thead>
<tr>
<th></th>
<th>Total Volumetric Change (m³)</th>
<th>Average Linear Change (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negative (Erosion)</td>
<td>1310</td>
<td>13.0</td>
</tr>
<tr>
<td>Positive (Accretion)</td>
<td>900</td>
<td>8.6</td>
</tr>
<tr>
<td>Net Change</td>
<td>410</td>
<td>4.4</td>
</tr>
</tbody>
</table>
Figure 5-22 displays the cumulative contribution of eroded compartment volumes. The median compartment eroded volume was approximately 2.5 m$^3$, which indicates that relatively small erosional events yielded a significant amount of material. This result is also corroborated by the results displayed in Figure 5-23, which shows the percent contributions of the significant landslides (identified in Figure 5-9) to the total section eroded volume. The results in Figure 5-23 confirm that the larger the landslide volume, the less it contributed to the total eroded section volume. This is an interesting result because even though 20 landslides larger than 10 m$^3$ occurred over the six month period, they only accounted for 60% of the total eroded volume. This suggests that a significant amount of the seaciff beach-sediment contributions may be coming from small landslide events and weathering, which generally go unnoticed.
Figure 5-22. Cumulative contribution of compartment eroded volumes.

Figure 5-23. Percentage contributions of significant landslides to the total section eroded volume (1310 m$^3$).
The site-specific morphological analysis of site T1 indicates that the lower cliff failed in a single event with a failure volume of 890 m³. The profile in Figure 5-14 shows that a well developed wave cut notch had developed at the cliff base prior to the September 2004 failure, creating a cantilevered lower cliff profile. The well developed notch reveals that marine erosion at the cliff base was responsible for creating the unstable cliff profile that led to the failure. The volumetric change and profile data of an individual landslide, such as the T1 failure, provides an opportunity to back-calculate the soil properties for a particular site. Further investigation of this application is explored in the following chapter.

Examination of the progressive failure at site D1 suggests that groundwater was the responsible erosion mechanism. Evidence of perched groundwater and seepage may be seen clearly in Figure 5-19. Perched groundwater conditions form when groundwater percolating downward encounters a relatively impermeable layer within the seacliffs. When this occurs, groundwater moves horizontally, and seeps out on to the cliff face. The Del Mar Formation, which comprises the lower seacliff at site D1, is relatively impermeable, thus causing groundwater seepage. The seepage at site D1 likely initiated the progressive failure by removing cliff material at the geologic contact of the Del Mar formation and upper cliff terrace deposits (Figures 5-20 and 5-24). In turn, this caused instability and failure of the upper seacliff (Figures 5-16 through 4-19), resulting in 170 m³ and 340 m³ of upper cliff erosion between September 2004 to April 2005 (Figure 5-19) and April 2005 to October 2005 (Figure 5-20), respectively.
In addition to causing upper cliff instability by removing material at the base of the terrace deposits, groundwater draining down the cliff face caused direct erosion on the lower cliff (Figure 5-19). Broken dewatering pipes at site D1 provided an additional source of water draining down the lower cliff face (Figure 5-25). In combination, these two water sources caused at least 140 m$^3$ of erosion at site D1 from September 2004 to April 2005 (Figure 5-19).
Figure 5-25. Broken dewatering pipe draining onto the lower cliff face at site D1.

FUTURE APPLICATIONS

In addition to the applications of terrestrial LIDAR discussed thus far, many others exist. The newest generation of terrestrial LIDAR scanners now incorporates a high resolution panoramic camera. These scanners acquire a digital image during the laser scan which is automatically georeferenced to the point cloud, and allows instantaneous image rectification and draping. Figure 5-26 illustrates an example of an image draped over a point cloud in northern Solana Beach. Image draping adds a new dimension to terrestrial LIDAR surveying and presents an opportunity to produce high resolution 3D maps of any identifiable features, which might include stratigraphy, vegetation, protective structures, or geology (Figure 5-27).
Figure 5-26. High resolution image drape in northern Solana Beach.

Figure 5-27. High resolution 3D geologic and structural mapping in northern Solana Beach.
As illustrated in Figure 5-6, terrestrial LIDAR has the ability to model over-vertical coastal features, but typically does not capture the cliff top surface. Conversely, airborne LIDAR captures the cliff top, but not over-vertical features. Merging these two data sets provides a complete seacliff terrain model (Figure 5-28). In the future, high resolution bathymetric data could also be integrated. This will provide a complete coastal terrain model, and further our understanding of the dynamics and interactions within the coastal system.

![Diagram of merged airborne and terrestrial surfaces](image)

**Figure 5-28.** Merging airborne and terrestrial surface models provides a complete seacliff terrain model.
CONCLUSIONS

This chapter demonstrates some of the applications of mobile terrestrial LIDAR in seafloor morphology studies on both a regional and site-specific basis. Utilizing a mobile platform provides a new technique for data collection, significantly increasing the scope of possible monitoring sites. Terrestrial LIDAR offers a method to survey and model over-vertical features (for example seacaves and notches), which are fundamental to investigations of marine erosional processes. The high point density of the terrestrial LIDAR data yields high resolution digital terrain models with which both large and small seafloor changes can be quantified.

The regional analysis in southern Del Mar illustrates the ability to quantify short-term volumetric and linear change. In addition, applying GIS spatial analysis facilitates visualization of the alongshore cliff morphology. The results from the study period indicate that southern Del Mar was dominated by subaerial erosional processes and that small erosional events, which may have previously gone unnoticed, constituted a significant fraction of seafloor erosion. Site-specific analysis of erosional hot spots may be used to evaluate individual failure volumes, failure profiles, and identify landslide mechanisms. Failure criteria obtained from individual landslide analysis yields data applicable to back-calculating soil properties, a topic explored in the following chapter. Advances in terrestrial LIDAR technology and use are providing future applications not yet exploited and will provide further insight into seafloor morphology studies.
CHAPTER 6: Investigation of the Cantilever Failure Mode of Seacliffs
INTRODUCTION

Major seacliff failures are episodic in both time and distribution, and may occur through a variety of mechanisms. Large cliff failures in California threaten residential structures, public property, and major transportation corridors. Therefore it is vital to understand the causes of failure so that they can best be mitigated. One type of failure is caused by marine erosion at the cliff base. Waves that impact the base of exposed seacliffs apply both hydraulic and pneumatic pressure, eroding the cliff base and form wave cut notches (Figure 6-1). In addition, large waves can mobilize beach sediment and cobbles, further eroding the notch through abrasion (Figure 6-2). The notch formation results in a cantilevered cliff profile (Figure 6-3), which may become unstable over time as the notch depth increases, leading to a catastrophic failure (Figure 6-4). The objective of this chapter is to investigate the instability of cantilevered seacliffs. This was accomplished by analyzing two failures that occurred in Solana Beach, CA, using terrestrial LIDAR, cantilever beam theory, and finite element slope analysis software.
Figure 6-1. A wave cut notch at the cliff base in Encinitas, CA.

Figure 6-2. Evidence of beach sand abrasion in Solana Beach, CA.
Figure 6-3. Cantilevered cliff section in Solana Beach, CA before failure.

Figure 6-4. Large cliff failure in Solana Beach, CA (same location as Figure 6-3).
BACKGROUND

The stability of cantilevered cliffs has been previously studied by Robinson (1970) and Hampton (2002). Both studies applied Timoshenko and Goodier’s (1951) cantilever beam theory to evaluate the maximum tensile stress on the potential failure plane. Using cantilever beam theory, the normal stress ($\sigma_x$) at point y (Figure 6-5) on plane a-a’ may be determined by Equation 6-1 for a rectangular cross section, where $W$ represents the gravity load of the block ($W = 2cN\gamma$). Assuming that a cantilevered block would fail in tension at the point of maximum developed tensile stress (-y = c, point a), Robinson (1970) determined a dimensional ratio (Equation 6-2) that would cause tensile failure.

$$\sigma_x = \frac{3}{4} \left( \frac{W}{c^3} \right) \frac{N}{y} \quad \text{(Equation 6-1)}$$

$$\frac{N}{c} = \left( \frac{2\sigma_x}{3\gamma c} \right)^{0.5} \quad \text{(Equation 6-2)}$$

Figure 6-5. Dimensions of Robinson’s (1970) cantilever model.
Hampton (2002) analyzed the sensitivity of the cantilever model to the level of sediment saturation. The sensitivity was evaluated by combining the maximum tensile stress induced by bending with a regression equation for normalized cohesion, assuming a tensile strength equal to one half of the cohesion (Sitar et al., 1980). The results indicate that as the percentage of saturation increases, the maximum stable notch depth abruptly decreases.

In addition to tensile stress caused by bending of the cantilevered block, additional tensile stress can develop in steep cliffs from the gravitational body load, and unloading may result in stress release fracturing (Sitar and Clough, 1983). Sitar and Clough (1983) used finite element analysis to evaluate the stresses in vertical cliffs under static conditions, and found a tension zone located along the cliff face and crest. The zone of tension corresponds well with observations of tensile cracks commonly found just behind the crest of steep cliffs (Figure 6-6 and Figure 6-7).
Figure 6-6. Well developed tension cracks in steep seacliffs, Baja California, Mexico.
Figure 6-7. Tension cracks along the rim of Kilauea Caldera, Hawaii.

The objective of this chapter is to evaluate stresses induced by both the cantilever mode and gravitational body load for cantilevered seacliffs commonly found in Solana Beach, CA. In addition, stresses caused by overburden loads above the cantilevered block will also be considered.

STUDY AREA

The seacliffs studied for this project are located in Solana Beach, CA (Figure 6-8), where the lower portion of the cliffs commonly forms a cantilevered profile. The cliffs are composed of two primary geologic units, both of which are sedimentary
deposits, but vary considerably in their strength characteristics. The lower unit, named Torrey Sandstone, is coarse-grained and well-cemented, and was deposited 47-49 million years ago in the Eocene epoch (Kennedy, 1975). The upper unit consists of marine terrace deposits, which lie unconformably atop the Torrey Sandstone. The marine terrace deposits are approximately 120,000 years old (Pleistocene), weakly-cemented, and fine-medium grained. Both units are permeable and erodible, however the Torrey Sandstone is relatively more resistant to erosion. The Torrey Sandstone is approximately 8-10 meters in height above the terrace platform and stands vertically, or temporarily over-vertical when a notch develops. The terrace deposits are approximately 10-15 meters in thickness and form upper cliff slope angles of 35°-50°.
Figure 6-8. Digital elevation model of the study area, and locations of two cantilevered failures (T1 & T2).
Two cantilevered cliff failures that occurred recently in the study area (locations T1 and T2 in Figure 6-8), were analyzed for this portion of the project. Failure T1 occurred in September 2004 and is shown in Figures 6-3 (before failure) and 5-4 (after failure). Figures 6-9 and 6-10 show failure location T2 before and after the cliff collapse, which occurred in April 2005. Failure T1 was significantly larger than T2, however both failures had a cantilevered lower cliff profile with similar geologic conditions.

Figure 6-9. Site T2 conditions before failure. Note the well developed cantilevered profile in the lower seacliff.
Figure 6-10. Site T2 after April 2005 failure (same location as Figure 6-9).

METHODOLOGY

Failure analysis of sites T1 and T2 combined digital terrain surface modeling derived from terrestrial LIDAR, field site investigation, elastic beam theory, and finite element stress modeling. Using this combined approach, the maximum mobilized stresses can be back-calculated along the failure surface. Successive terrestrial LIDAR surveys may be used to identify and quantify the surface changes in seaciffs over time. After quantifying the surface changes for sites T1 and T2, the calculated average failure dimensions were incorporated into elastic beam theory of cantilevers and finite element stress models. It should be noted that finite element models indicate the stress distributions derived from elastic cantilever beam theory tend to
break down when the ratio of notch depth to height of the cantilever block (N/2c from Figure 6-5) becomes small, and the stress distributions may be more appropriately evaluated by modeling the cantilever block using deep beam theory. Nevertheless, elastic cantilever beam theory was used in this analysis for simplicity, and to build upon the methodologies of Robinson (1970) and Hampton (2002) to investigate cantilevered seacliff failures. The loads contributing to stress considered in the finite element models consisted of the Torrey Sandstone body load and over burden caused by the terrace deposits. Both materials were assumed to have linear elastic behavior, an estimated unit weight of 18 kN/m$^3$, and a Poisson’s ratio (v) of 0.3 for the Torrey Sandstone. Additional factors which may have caused stress, include fatigue and wave induced cyclic flexing of seacliffs (Adams et al. 2005) were not incorporated in this analysis.

**Terrestrial LIDAR**

Terrestrial LIDAR was collected in May 2004, September 2004, and April 2005, and processed into georeferenced 3-D terrain models using the procedure described in Chapter 5. Failures T1 and T2 were then identified by evaluating the surface change between each LIDAR data set. Figures 6-11 and 6-12 show the surface change models of failures T1 and T2 respectively; red areas indicate erosion, and blue areas indicate accretion. For both failures, LIDAR data collection occurred within one week of the actual cliff collapse (September 2004 for site T1, and April 2005 for site T2).
Figure 6-11. Surface change model of site T1 between May 2004 and September 2004.

Figure 6-12. Surface change model of site T2 between September 2004 and April 2005.
Surface models of failures T1 and T2 were extracted for individual slide analysis. The total failure volume of each landslide was evaluated by isolating the failure plane and calculating the volumetric change between surveys. The average notch depth was calculated using the average dimensions of the slide plane, and total failure volume (Equation 6-3).

\[ N = \frac{V}{(H \times L)} \quad \text{(Equation 6-3)} \]

N = average notch depth
V = total failure volume
H = average height of failure plane
L = average length of failure plane

Additional insight into the landslides was gained by extracting typical profiles from the surface models before and after the failures occurred. These profiles along with the average failure dimensions are shown in Figures 6-13 and 6-14. Both the T1 and T2 profiles reveal a cantilevered configuration of the Torrey Sandstone in which the failure plane was approximately vertical where it intersected the most landward location of the notch.
Figure 6-13. Typical profile before failure (April 2004), failure plane location, and average failure dimensions of site T1.

Figure 6-14. Typical profile before failure (September 2004), failure plane location, and average failure dimensions of site T2.
Site Investigation

One of the main differences between failures T1 and T2 was that the failure plane of T2 had developed a crack prior to the failure. The evidence of this crack was identified in a post failure site survey, during which significant weathering could be seen on the upper portions of the Torrey Sandstone failure plane. Unexposed Torrey Sandstone is light brown, whitish, or gray in color. When the sandstone becomes exposed to weathering the oxidation of minerals turns the material to a dark brown or reddish color. Figure 6-15 shows a photograph of the T2 failure surface and the zone of weathering identified by darker brown and reddish areas compared to the lighter brown, white, and gray unweathered areas. Weathering on the failure plane indicates that a crack has partially formed, exposing the rock. The average depth of the crack was estimated during the post failure survey at 1.5 meters. A combined summary of average failure dimensions, volume, and crack depth is shown in Table 6-1.
Figure 6-15. Weathering on the T2 failure plane indicating the formation of a crack prior to failure.

Table 6-1. Average failure dimensions and volumes of sites T1 and T2.

<table>
<thead>
<tr>
<th>Site Name</th>
<th>T1</th>
<th>T2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure Date</td>
<td>September 2004</td>
<td>April 2005</td>
</tr>
<tr>
<td>Eroded Volume (m³)</td>
<td>890</td>
<td>300</td>
</tr>
<tr>
<td>Width of Failure (m)</td>
<td>47.5</td>
<td>25.0</td>
</tr>
<tr>
<td>Height of Failure (m)</td>
<td>7.5</td>
<td>6.0</td>
</tr>
<tr>
<td>Average Notch Depth (m)</td>
<td>2.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Crack Depth (m)</td>
<td>---</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Elastic Beam Theory

Using the average failure dimensions, each failure was modeled as a cantilevered block using elastic beam theory (Timoshenko and Goodier, 1951) to derive the resultant bending stresses along the failure plane. Gravitational loading of the cantilevered block causes bending, where both normal and shear stresses are developed along the failure plane. The amount of normal ($\sigma_x$) and shear stress ($\tau_{s_y}$) along the failure plane is expressed in Equations 6-4 and 6-5, respectively. A graphical representation and axis orientation of Equations 6-4 and 6-5 is illustrated in Figure 6-16.

\[
\sigma_x = \frac{My}{I} \quad \text{(Equation 6-4)}
\]

\[
\tau_{s_y} = \frac{W}{2I} \left( \frac{H^2}{4} - y^2 \right) \quad \text{(Equation 6-5)}
\]

\[M = \text{Moment magnitude} = W^*(N/2) \quad \text{(Equation 6-6)}\]

\[W = \text{Weight of cantilevered block} = bHN_y \quad \text{(Equation 6-7)}\]

\[I = \text{Moment of inertia} = \frac{bH^3}{12} \quad \text{(rectangular cross section)} \quad \text{(Equation 6-8)}\]

\[H = \text{Height of cantilevered block}\]

\[N = \text{Notch depth}\]
\( \gamma = \text{unit weight of rock mass} \)

\( b = \text{a unit length (for two dimensional analysis)} \)

\( c = (H/2) \)  

(Equation 6-9)

---

**Figure 6-16.** Graphical illustration of the resultant normal and shear stresses for an elastic cantilevered beam.
The maximum normal stress ($\sigma_x$) occurs where $y = \pm c$ (Equation 6-10), and may be simplified to Equation 6-11 through the substitution of Equations 6-6 through 6-9.

$$\max \sigma_x = \pm \frac{Mc}{I} \quad \text{(Equation 6-10)}$$

$$\max \sigma_x = \pm \frac{3N^2\gamma}{H} \quad \text{(Equation 6-11)}$$

The maximum shear stress ($\tau_{xy}$) along failure plane a-a’ occurs at $y = 0$ (Equation 6-12). Simplification of Equation 6-12 using Equation 6-8 leads to Equation 6-13, which shows that the maximum shear stress ($\tau_{xy}$) is one and a half times greater than the average shear stress ($W/bH$) over the cross section of the failure plane ($bH$).

$$\max \tau_{xy} = \frac{WH^2}{8I} \quad \text{(Equation 6-12)}$$

$$\max \tau_{xy} = \frac{3}{2} \frac{W}{bH} \quad \text{(Equation 6-13)}$$

The maximum shear stress ($\tau_{xy}$) may be further simplified to Equation 6-14 using the weight of the cantilevered block (Equation 6-7). Equation 6-14 reveals that the maximum shear stress ($\tau_{xy}$) is only dependant on the notch depth and material unit weight.
\[ \max \tau_{xy} = \frac{3N\gamma}{2} \]  \hspace{1cm} (Equation 6-14)

The equations above (Equations 6-5 and 6-8 through 6-14) are valid for a cantilevered block without a pre-existing crack and were therefore applied to failure T1. In the case of failure T2, the equations must be modified to account for the developed crack. The maximum normal stress \( \sigma_x \) in the cracked cantilever model occurs where \( y = \pm c' \) described by Equation 6-15.

\[ \max \sigma_x = \pm \frac{Mc'}{I} \]  \hspace{1cm} (Equation 6-15)

\( I = \) Moment of inertia

\[ = \frac{b(H')^3}{12} \]  \hspace{1cm} (Equation 6-16)

\( H' = H - \) crack depth \hspace{1cm} (Equation 6-17)

\( c' = (H'/2) \) \hspace{1cm} (Equation 6-18)

Solving for maximum normal stress \( \sigma_x \) using the above equations (Equations 6-6, 6-7, and 6-15 through 6-18) produces Equation 6-19, which describes the relationship between maximum normal stress \( \sigma_x \) and the average failure dimensions for the crack model.
\[
\max \sigma_x = \pm \frac{3HN^2\gamma}{(H')^2} \quad \text{(Equation 6-19)}
\]

The developed shear stress \(\tau_{xy}\) along failure plane a-a' for the crack model is described by Equation 6-20, where the maximum shear stress \(\tau_{xy}\) occurs at \(y = 0\) (Equation 6-21). Substitution (Equations 6-7 and 6-16) yields Equation 6-22, which reveals the relationship between maximum shear stress \(\tau_{xy}\) and average failure dimensions for the cracked cantilever model.

\[
\tau_{xy} = \frac{W}{2I} \left( \frac{(H')^2}{4} - y^2 \right) \quad \text{(Equation 6-20)}
\]

\[
\max \tau_{xy} = \frac{W(H')^2}{8I} \quad \text{(Equation 6-21)}
\]

\[
\max \tau_{xy} = \left( \frac{3N\lambda}{2} \right) \left( \frac{H}{H'} \right) \quad \text{(Equation 6-22)}
\]

**Resultant Body and Terrace Deposit Load Stresses**

In addition to stresses caused by bending of the cantilevered block, stresses are also derived from the gravitational body load of the Torrey Sandstone and the overburden terrace deposit load. These additional stresses were quantified using Sigma/W (GeoStudio, 2004) finite element stress modeling software. Figure 6-17 illustrates the normalized minimum principle \(\sigma_3\) stresses induced from a body load.
(ν = 0.3) in a vertical cliff. This figure shows that the cliff crest is in a state of tension, where the maximum tensile stress (-σ₁) is located approximately at a distance of one third the cliff height from the cliff face and has a value approximately equal to 0.03σ₃/γH.

Figure 6-17. Normalized minimum principle stresses (σ₃) resulting from the gravitational body load in a vertical cliff.

Figure 6-18 illustrates the resultant minimum principle stresses (σ₃) resulting from the overburden terrace deposit load (γ = 18.0 kN/m³) for a vertical, 8.0 meter
high cliff with material properties of \( v = 0.3 \), and \( \gamma = 18.0 \text{ kN/m}^3 \). The slope of the terrace deposits (assumed 41° for the model) creates a differential vertical load, resulting in additional tension in the cliff crest and along the cliff face.

Figure 6-18. Minimum principle stresses \((\sigma_3)\) induced by the terrace deposit load in a vertical cliff.
The stresses evaluated in Figures 6-17 and 6-18 both indicate additional tensile stress is developed by the gravitational body and terrace loads and should be included in the overall evaluation of maximum tension stress. Furthermore, these loads produce vertical ($\sigma_z$) and shear stresses ($\tau_{xy}$) and need to be quantified in order to evaluate the overall stress conditions at the time of failure T1 and T2.

Using the average failure dimensions generated from terrestrial LIDAR, both failure T1 and T2 were modeled in the finite element environment to quantify the resultant stresses induced by the body and terrace deposit loads. Figures 6-19 and 6-20 show the dimensions of finite element models T1 and T2, respectively. Note that the wave cut notch was not used in the finite element models because the stresses induced by the cantilevered configuration were addressed by the elastic beam theory stress evaluation.
Figure 6-19. Dimensions and loading conditions of the finite element model T1.

Figure 6-20. Dimensions and loading conditions of the finite element model T2.
Stress Superposition

The overall stress conditions of failures T1 and T2 were evaluated by combining the resultant stresses of the three loading models (cantilever, body, and terrace deposit). In each loading case, the horizontal ($\sigma_x$), vertical ($\sigma_y$), and shear ($\tau_{xy}$) stresses were evaluated along the failure plane a-a'. Superimposing these stresses for each loading case resulted in the total horizontal ($\sigma_x$), vertical ($\sigma_y$), and shear ($\tau_{xy}$) stress. Figures 6-21 through 6-26 illustrate the resultant stresses of each loading case and the superimposed total stress for the failure planes at site T1 and T2.

![Figure 6-21. Resultant horizontal stresses ($\sigma_x$) along the T1 failure plane for each load and the superimposed total.](image-url)
Figure 6-22. Resultant vertical stresses ($\sigma_y$) along the T1 failure plane for each load and the superimposed total.

Figure 6-23. Resultant shear stresses ($\tau_{xy}$) along the T1 failure plane for each load and the superimposed total.
Figure 6-24. Resultant horizontal stresses ($\sigma_x$) along the T2 failure plane for each load and the superimposed total.

Figure 6-25. Resultant vertical stresses ($\sigma_y$) along the T2 failure plane for each load and the superimposed total.
Figure 6-26. Resultant shear stresses ($\tau_{xy}$) along the T2 failure plane for each load and the superimposed total.

The next step was to calculate the minimum principle stress ($\sigma_3$), maximum principle stress ($\sigma_1$), and maximum shear stress ($\tau_{\text{max}}$) on the failure planes of T1 and T2 using Mohr’s Circle (Mohr, 1882). Mohr’s Circle depicts the graphical relationship between stresses for a soil element (Figure 6-27). Figures 6-28 and 6-29 illustrate the calculated principle stresses ($\sigma_3, \sigma_1$) and maximum shear stress ($\tau_{\text{max}}$) for failure planes T1, and T2, respectively.
Figure 6-27. Geometry of Mohr's Circle (Mohr, 1882) and relationship between stresses on a soil element.
Figure 6-28. Principle stresses \((\sigma_3, \sigma_1)\) and maximum shear stress \((\tau_{\text{max}})\) along the T1 failure plane a-a'.

Figure 6-29. Principle stresses \((\sigma_3, \sigma_1)\) and maximum shear stress \((\tau_{\text{max}})\) along the T2 failure plane a-a'.
RESULTS AND DISCUSSION

While all loads contributed to the total horizontal stress (\( \sigma_x \)) developed at sites T1 (Figure 5-21) and T2 (Figure 5-24), the majority of the horizontal tensile stress was caused by the cantilever load. Note, that relatively little horizontal stress (\( \sigma_x \)) was caused by the body and terrace loads at site T2 (Figure 5-24). Conversely, the majority of the total vertical stress (\( \sigma_y \)) developed at sites T1 (Figure 5-22) and T2 (Figure 5-25) was due to the body load, while the cantilever load contributed no vertical stress (\( \sigma_y \)). Similar to the horizontal stress conditions, all loads contributed to the total shear stress (\( \tau_{xy} \)) at sites T1 (Figure 5-23) and T-2 (Figure 5-26), but the overwhelming majority was caused by the cantilever load.

Of particular interest are the maximum tensile (\( \sigma_{3 \text{ min}} \)) and shear (\( \tau_{\text{max}} \)) stresses, which were the likely cause of the cantilevered failures. When these stresses exceed the strength of the Torrey Sandstone, failure is imminent. Figures 6-28 and 6-29 show that approximately 75% of the failure plane was in a state of tension, where the maximum tensile stress occurred at \(- y_{\text{max}}\) (the highest failure plane location). At both sites T1 and T2 the maximum developed shear stress (\( \tau_{\text{max}} \)) occurred just below the central \((y = 0)\) cantilevered axis (Figures 6-28 and 6-29), with the minimum shear stress occurring at \(\pm y_{\text{max}}\). Table 6-2 lists the largest calculated principle and shear stresses along the failure planes at sites T1 and T2.
Table 6-2. Summary of the largest stresses along failure planes at sites T1 and T2

<table>
<thead>
<tr>
<th></th>
<th>T 1</th>
<th>T 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Largest Stress on Failure Plane (kPa)</td>
<td>Location on Failure Plane (m)</td>
</tr>
<tr>
<td>Minimum Principle Stress ($\sigma_3$)</td>
<td>-58</td>
<td>3.75</td>
</tr>
<tr>
<td>Maximum Principle Stress ($\sigma_1$)</td>
<td>191</td>
<td>-2.80</td>
</tr>
<tr>
<td>Maximum Shear Stress ($\tau_{\text{max}}$)</td>
<td>93</td>
<td>-1.25</td>
</tr>
</tbody>
</table>

If sites T1 and/or T2 failed in tension, then the failure would have originated at $y_{\text{max}}$ and propagated down the failure plane. Given this scenario, the back-calculated maximum tensile strength of the Torrey Sandstone would be 58 and 62 kPa for sites T1 and T2, respectively. There is strong evidence for a tensile failure mechanism at site T2 where a tension crack had formed prior to failure. Alternatively, if sites T1 and/or T2 failed in shear, then the failure likely originated just below the central ($y = 0$) cantilevered axis. Assuming a shear failure scenario, the back-calculated maximum shear strength of the Torrey Sandstone would be 93 and 88 kPa for sites T1 and T2, respectively. A third possibility is that these failures may have occurred in a combined tensile/shear mode. In all three failure modes (tensile, shear, or combination) the load contributing the majority of the stress was caused by the cantilever load.
Additional insight into the cliff failures at sites T1 and T2 may be gained through laboratory testing. A review of several geotechnical studies (Earth Systems Design Group, 1992a, 1992b, 1993; Owens Consultants, 1989; GeoSoils, 1997) that performed laboratory tests indicate that the Torrey Sandstone exhibits a wide range of strength characteristics. Eleven tests were completed by these studies and reported cohesion in the range 0-224 kPa and angles of internal friction (\(\phi\)) of 21-61° (Table 6-3).

**Table 6-3. Torrey Sandstone properties from laboratory testing**

<table>
<thead>
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<th>Test Number</th>
<th>Cohesion (kPa)</th>
<th>Phi ((\phi))</th>
<th>Source</th>
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<td>27</td>
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<td>GeoSoils, 1997</td>
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<td>77</td>
<td>45.5°</td>
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<td>45.5°</td>
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<tr>
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Comparing the shear failure envelopes of the laboratory tests and the Mohr’s circles for the maximum derived shear locations at sites T1 and T2 (Figure 6-30) indicates that the back-calculated shear strengths correlate with the lower range of reported failure envelopes. Three of the eleven testing failure envelopes (test numbers
1, 2, and 3) intersect the T1 and T2 Mohr's circles indicating strengths less than the back-calculated stresses, and would have predicted shear failure prior to the maximum potential shear stresses at both sites. Of the remaining eight testing failure envelopes, four (test numbers 8, 9, 10, and 11) illustrate much higher strength criteria and would not have predicted shear failures at sites T1 and T2, while the other four (test numbers 4, 5, 6, and 7) correspond fairly well with the back-calculated failure stresses.

Figure 6-30. Torrey Sandstone shear failure envelopes from laboratory tests and the back-calculated shear failure criteria of sites T1 and T2.
Assuming that the tensile strength is approximately equal to one half the cohesion (Sitar et al., 1980), the laboratory tests may also be compared to the back-calculated strengths of sites T1 and T2. Figure 6-31 illustrates that seven (test numbers 1-7) of the eleven laboratory tests had tensile strengths less than the back-calculated values and would have predicted a tensile failure prior to the actual cliff collapses at sites T1 and T2. The remaining four laboratory tests (test numbers 8-11) had tensile strengths that exceeded the back-calculated values and would not have predicted a tensile failure.

![Graph showing tensile strength comparison](image)

**Figure 6-31.** Estimated tensile strength of the laboratory tests and back-calculated maximum tensile stress at sites T1 and T2.
It is difficult to determine the exact failure mechanisms of T1 and T2 without more information. Nevertheless, given that seven of eleven laboratory tests would have predicted a tensile failure, compared to three in shear (Figure 6-30 and 6-31), there is some evidence that sites T1 and T2 failed in tension rather than shear. Further insight into these landslides could be gained through additional laboratory testing that simulates the back-calculated maximum failure stress conditions. The failure mode may be determined if the samples demonstrate a tendency to fail in a particular manner. Data from future cantilevered failures in the Torrey Sandstone could also be integrated to refine this analysis and may yield results leading to the exact determination of various failure modes and failure prediction modeling.

CONCLUSIONS

This chapter demonstrates that integrating terrestrial LIDAR and geotechnical stress analysis may be used to gain valuable insight into cantilevered seacliff failures. The side-scanning capability of terrestrial LIDAR allows for over-vertical terrain modeling vital to the investigation of cantilevered seacliffs. Failure profiles generated from the LIDAR models can be used with geotechnical stress analysis to back-calculate stresses along a failure plane. Superimposing stresses induced by cantilever bending, gravitational body load, and overburden loads provides a methodology to calculate the principle and maximum shear stresses at the time of failure. For the two cantilevered failures analyzed it is difficult to determine the exact mode of failure.
without more data, however the developed tension crack at site T2 and a comparison with laboratory derived strengths present evidence that both sites T1 and T2 failed in tension. Further insight into the mechanisms of cantilever failures could be gained through additional laboratory testing and new data from future cantilevered cliff failures.
CHAPTER 7: Summary of the Dissertation
SUMMARY OF THE DISSERTATION

Seacliff erosion is a natural process controlled by erosional forces (marine and subaerial) and resisting cliff material properties. Seacliff erosion and retreat is not a problem until it interacts with society. As in many other populated locations throughout the world, seacliff erosion and retreat is a problem in San Diego County, CA because it threatens human development, recreation, and safety. This problem has resulted in the intentional alteration of the natural seacliff erosional processes through the use of construction erosion control devices. Additionally, development has resulted in the unintentional alteration of natural seacliff erosion through raising groundwater levels and altering natural drainage systems, reducing a source of beach sediment which provides natural protection against marine erosional forces. Furthermore, the construction of shore-perpendicular structures can block littoral transport, thus reducing the down coast beach width, permitting wave attack at the cliff base. Seacliff erosion will continue to be a problem in the future wherever it interacts with society, and the problem will likely be exacerbated if the current predictions of accelerated sea level rise become a reality. It is therefore paramount to further our understanding of both the natural seacliff erosion and the anthropogenic influences on the coastline.

This dissertation sought to advance our knowledge on the quantification and processes that govern short-term seacliff morphology of a developed coast. Both airborne and terrestrial LIDAR were shown to be valuable tools that provide a level of regional detail previously unattainable using traditional methods to quantify coastal
changes. Integrating these new coastal mapping tools with GIS spatial analysis and geotechnical investigation provides a novel approach to understanding and measuring seacliff morphology and stabilization.

Utilizing airborne LIDAR to evaluate the volumetric seacliff change in the Oceanside Littoral Cell yielded surprising results. These results indicated that seacliffs were a significant source of beach-sediment during the study period and that the percentage of annual seacliff beach-sediment contributions may be larger than previously thought. It was also found that volumetric erosion rates could be converted to linear retreat rates, providing a new method to quantify cliff retreat. This method averages the erosion over the entire cliff face, thus reducing the episodic nature of cliff retreat measurements, and proving the efficacy of LIDAR in short-term studies. Incorporating GIS spatial analysis and the use of coastal compartments permitted the reduction of regional data to the local level affording a first-order evaluation of erosion control methods and the effects of drainage conditions. These findings indicated that erosion control methods that provided both upper and lower cliff protection performed better than methods which only provided partial protection. Most erosion control methods were effective at reducing the natural retreat rate, but many projects failed to eliminate erosion because they did not provide proper protection against both marine and subaerial processes. Additionally, it was found that properly controlling groundwater and surface runoff conditions could reduce cliff erosion caused by subaerial processes.
Terrestrial LIDAR scanning provides a new technique to digitally model seacliffs with centimeter level resolution. The side-looking orientation of the scanner allows for surface modeling of over-vertical coastal features such as seacaves and notches, which is fundamental to understanding the role of marine erosional processes on seacliffs. Utilizing a mobile scanner platform offered an innovative approach to ground-based scanning, facilitating data collection at a regional level. Regional results illustrated that small erosional events, which may have previously gone unnoticed, may constitute a significant fraction of eroded material, underscoring the importance of quantifying short-term seacliff morphology. At the site-specific level, terrestrial LIDAR presents an opportunity to perform detailed analysis on erosion hot spots and individual landslides. These investigations yielded individual cliff failure volumes, profiles, and the identification of both marine and subaerial erosion mechanisms. Combining geotechnical analysis with terrestrial LIDAR landslide data can be used to back-calculate soil properties and stresses along a failure plane. The in-depth examination of two cantilevered cliff failures revealed that the majority of the induced stress results from the cantilever configuration and that the cliff materials probably failed in tension.

Both airborne and terrestrial LIDAR offer high resolution three dimensional mapping with noteworthy applications in short-term seacliff modeling. Combining these two approaches allows for the entire cliff face, cliff-top, and subaerial beach to be captured producing a more complete coastal surface model. In the future, high resolution bathymetric data could also be added to complete the coastal surface model.
Recent advances in LIDAR technology and use are not yet fully exploited and will provide a greater understanding of seaciff morphology and the role that cliffs have in the coastal system.
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