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ABSTRACT

Each coastal disaster is followed by the inevitable debates of whether rebuilding is the right decision or not. Hurricanes Sandy and Katrina are good examples, as were the damaging El Niño events along the California coast in 1982-83 and 1997-98. Coastlines globally have been migrating landward since the last Ice Age ended about 18,000 years ago and all indications are that this trend will continue in the decades and centuries ahead, most likely at an increased pace as the rate of sea-level rise increases. Retreating from the shoreline is not a new approach and there are many communities and neighborhoods along both coasts of the U.S. and elsewhere where relocation has occurred and where formerly developed parcels are now underwater. Documenting these lost neighborhoods and those that are in the process of disappearing today is important in providing a longer term perspective of what we face as a state and as a nation. Coastlines are in constant flux, and with few exceptions, they are migrating inland, either gradually or more rapidly during extreme events. While there are short-term or temporary approaches that have been used for decades to hold back the ocean, these all have their limits. We need to begin to assess our vulnerabilities to future sea-level rise and begin to adapt or prepare for the inevitability of a changing shoreline.

ADDITIONAL INDEX WORDS: *Coastal erosion, shoreline retreat, California coast, coastal protection, armor, seawalls.*

INTRODUCTION

In the wake of Hurricane Sandy, there has been no shortage of articles, editorials, interviews and other written and spoken statements and opinions regarding either the need or the folly of rebuilding the destroyed and heavily damaged oceanfront communities of New Jersey and New York.

One representative example is an editorial from the January Newsletter of the American Shore and Beach Preservation Association (ASBPA), entitled “Retreat is not the Answer”:

> *People won’t walk away from their properties (or their fond memories of the coast) without a fight. The media was filled with stories of people who had grown up at the beach and then retired to their summer homes. Many wanted to pass on this experience to their children and grandchildren. That makes even the discussion of*

retreat an issue fraught with emotion and expense… something no government official wants to wade into unless there is an overwhelmingly good reason to do so (and, so far, storm damage does not seem to be that reason).

The economic hit from abandoning the coast would be enormous. First, there's the coastal economy — the juggernaut of tourist economic dollars, affordable recreation and a way of life would be lost. Entire oceanfront communities would have to be abandoned if retreaters had their way. Then there's the cost of acquiring all those properties, because if you don't want people to rebuild, you'd better be ready to buy that land to ensure it doesn't happen (and don't forget to pay for all the lawyers).

Add in the cost of physically retreating, the removal of structures and infrastructure to return that coast to a more "natural" state. Finally, there's the need to manage the land that's left, even at a minimal level… unless your plan is to turn it back to nature and banish people from ever setting foot on it again. In all likelihood, managing the new oceanfront would embrace some beach nourishment to ensure any recreational area remains big enough for recreation. All told, the real cost of retreat has never been calculated – and it will be shockingly enormous when someone finally does it.

An article and an opinion editorial in the New York Times, both from November 2013, provide a striking contrast in viewpoints:

As ocean waters warm, the Northeast is likely to face more Sandy-like storms. And as sea levels continue to rise, the surges of these future storms will be higher and even more deadly. We can't stop these powerful storms. But we can reduce the deaths and damage they cause.

Yet there is already a push to rebuild homes close to the beach and bring back the shorelines to where they were. The federal government encourages this: there will be billions available to replace roads, pipelines and other infrastructure…But this "let's come back stronger and better" attitude, although empowering, is the wrong approach to the increasing hazard of living close to the rising sea. Disaster will strike again. We should not simply replace all lost property and infrastructure. Instead, we need to take account of rising sea levels, intensifying storms and continuing shoreline erosion.

Across the nation, tens of billions of tax dollars have been spent on subsidizing coastal reconstruction in the aftermath of storms, usually with little consideration of whether it actually makes sense to keep rebuilding in disaster-prone areas. If history is any guide, a large fraction of the federal money allotted to New York, New Jersey and other states recovering from Hurricane Sandy- an amount that could exceed $30 billion- will be used in the same way. Tax money will go toward putting thing back as they were, essentially duplicating the vulnerability that existed before the hurricane.

A LONGER TERM PERSPECTIVE ON COASTAL EROSION

Along the English Channel, the Yorkshire coast of England has had a similar battle with the sea, but a much longer history in doing so. Records of the locations of coastal settlements in the United Kingdom go back almost 2000 years to the time of Roman occupation. While the Yorkshire coastline consists of clay bluffs, in contrast to the low-lying sandy barrier islands of the U.S. Atlantic coast, their problems are similar.

There is an extraordinary record of Yorkshire's struggles against the waves documented in a book published a century ago, The Lost Towns of the Yorkshire Coast (1912). The author, Thomas Sheppard, documents the progressive disappearance of 28 towns over the past 2000 years (Figure 1). The list includes: Wilsthorpe, Auburn, Hartburn, Hyde, Withow, Cleton, Northope, Hornsea Burton, Hornsea Beck, Southorpe, Great Colden, Colden Parva, Ringborough, Monkwell, Sand-le-Mere, Waxhole, Owthorne by Sisterkirk, Newsome, Old Withernsea, Out Newton, Dimlington, Turmarr, Northorp, Hoton, Old Kilnsea, Ravenspurn, Ravenser Odd, and Old Aldborough. This is an impressive set of lost communities, which does make one wonder if there is any collective memory in the region.

A September 2012 article in The Guardian explains that the Yorkshire coast was being lost in 2012 at rates up to three times as fast as the previous year, and ascribes the sharply increasing rates of coastal retreat to a dry spring and a soggy summer (Figure 2). Average annual retreat of the boulder clay cliffs near the village of Aldborough has been about 1.7 m (5.5 feet), whereas over the past year the bluffs lost a startling 7m (22 feet).

New Jersey and New York are not alone in dealing with coastal hazards and shoreline retreat, nor is the Yorkshire coast. The difference is that in England they have been building on the coast for quite a few more centuries and they have kept track of their losses, whether castles or churches, it hasn't made any difference to the waves and they have all ended up in the sea.

One well cited example along the Atlantic coast of the magnitude of long-term retreat is the Cape Hatteras Lighthouse on North Carolina's Outer Banks, for which there is a well-documented history. At 61 m tall (200-feet) it is the nation's tallest lighthouse and the highest in the world that is constructed of brick.

Originally built in 1870 to warn passing ships of the shallow shoals known as the "Graveyard of the Atlantic", the lighthouse was originally built 457 meters (1500 feet) inland from the shoreline on the Cape Hatteras barrier island. In subsequent years it became apparent that the shoreline of the island was migrating and the ocean was coming closer to the light. By 1919, high water had encroached within 91m (300 feet) of the structure as shoreline retreated continued at an average rate of 7.5m/yr. (24ft/yr.). Waves first reached the base of the lighthouse in 1935, and in subsequent years, a number of engineering attempts were made, including dikes, groins, breakwaters, and wooden revetments, to protect the structure from hurricanes and large waves. None of these provided much long-term protection.

The National Park Service took over the lighthouse in 1935, and in 1999 decided to relocate the 4,830-ton lighthouse further inland. At a cost of about $12 million, the lighthouse was severed from its foundation, and moved on wheeled dollies along a specially constructed track 870m (2,900 feet) inland. At the historic rate of shoreline retreat, the lighthouse will be safe from wave attack for at least a century, although there is no guarantee that the retreat rate will not increase with an acceleration in the rate of sea-level rise.

In a recent book, The Rising Sea (2009), Pilkey and Young chronicle the histories of a number of American towns and villages that have succumbed to the sea over time. Isle Derniere (Lost Island), Louisiana (1856), Edingsville Beach, South Carolina (1893), Diamond City, North Carolina (1899), Thompson's Beach, New Jersey (1950), and Baytown's Brownwood Subdivision, Texas (1983), are some of the best examples of our past history of abandoning a retreating shoreline.

CALIFORNIA'S RETREATING COASTLINE

The 1760 km (1100 mile) coastline of California includes 1) lowlands with estuaries, lagoons, dunes and beaches, but also 2) steep mountains and 3) lower relief coastal cliffs and bluffs (Figures 3-5). Coastal retreat and the challenges this has posed to infrastructure and development have been well documented (Griggs, Patsch and Savoy, 2005; Hapke and Reid, 2007; and Hapke, et al., 2006). California has the longest coastline in the lower 48 states and is also the most populated state in the nation with 38 million people. Sixty-seven percent of the population reside in coastal counties, and many of them live virtually on the edge or as close as they can get to the water (Figure 3).

Following World War II, California's population, particularly in coastal counties, exploded (Figure 6). Development of cliffs, bluffs and beachfront areas attracted new residents and immigrants who were happy to trade the weather elsewhere for the sunny skies and moderate climate of central and southern California. The state's population nearly doubled from about 8 million in 1945 to nearly 16 million in 1960, and has continued to add about a half a million new residents each year in the following decades.

The period between 1945 and about 1978, however, was a cool Pacific Decadal Oscillation (PDO) cycle (Figure 7), characterized by a relatively calm coastal climate overall. This meant fewer large El Niño Southern Oscillation (ENSO) events with their accompanying damaging coastal storms, lower rainfall, and therefore less coastal erosion and flooding. This period of benign coastal climate coincided with the time of most rapid growth in California, particularly in coastal counties. Subdivisions and development occurred along the coastline and people moved closer to the edge. Not that these areas hadn't been built on in earlier decades, but the construction intensified with significant new coastal development during this calm interval.

The climate shift in 1978 to a warm PDO cycle (Figure 7) brought more frequent and intense ENSO events with widespread storm damage. This came as a surprise to many private property owners, as well as local government and state agency staff, who hadn't experienced such events in their short memories. The winters of 1978, 1982-83 and 1997-98 were particularly damaging, and brought the long-term stability of these oceanfront homes, businesses and infrastructure into question.

While the issues of "retreat" or "hold the line and resist the advance of the ocean" are still being fiercely debated as evidenced from the references in the beginning of this article, there is in fact, already a long history of disappearing or lost neighborhoods and retreat along California's coastline.

DIFFERENT TYPES OF COASTAL RETREAT

When speaking of coastal erosion or coastal retreat, it is important to distinguish between several different processes, as these will affect the long-term decisions we as a society make on the most appropriate response at any particular location.

Seasonal beach retreat. Along California's coast, and indeed along most coastlines, beaches come and go or accrete and erode on a seasonal basis in response to changing wave climate. While the extent of these year-to-year changes varies depending upon the actual winter and summer wave conditions, fluctuations in beach width are expected and predictable (Figures 8a & b).

Long-term beach retreat. Where sand delivery to the shoreline has been reduced, where sand has been mined or removed, or where large engineering structures have impounded or diverted large volumes of sand, beaches can undergo progressive narrowing over time. Beaches can also advance and retreat in response to PDO climate cycles (Figure 9; Orme, et al, 2011).

Shoreline migration. With a long-term rise in sea level, shorelines that have no barriers on their landward edges will simply migrate or advance inland. This is not a problem unless development has occurred on or landward of those beaches, such as along many of the Atlantic and Gulf Coast barrier islands, or along many of California's beach front developments. In these cases, passive erosion takes place, where the beaches are progressively narrowed or gradually flooded as sea level continues to rise. Back beach barriers, whether seawalls, revetments, bulkheads, homes, highways, hotels or any other structures, will prevent a beach from advancing landward, but the beach can also return if the barrier is removed (Figures 10a & b).

Cliff or bluff erosion. Virtually all coastal cliffs or bluffs in California are eroding. Rates may vary from mm/year to meters/year, depending upon the nature or strength of the cliff or bluff forming materials, the presence of absence of a protective beach, and the combined physical forces acting on those cliffs or bluffs (waves, tides, rainfall and runoff, storm, etc.). Within our lifetimes, these losses are permanent and not recoverable.

Each of these processes can present problems or threats to coastline development depending upon how close to the shoreline or the bluff edge the development has encroached, the rate of retreat or erosion, the elevation of the development above sea level, and the nature of the physical processes impinging on the shoreline at any particular location.

CASE STUDIES OF SOME LOST CALIFORNIA NEIGHBORHOODS

Big Lagoon, Humboldt County

In 1929, about 60 beach cottages were built on the low terrace at the south end of Big Lagoon along the Humboldt County coast in northern California (Figure 11); fifteen of these were within 30-40 feet of the bluff edge. During the winter of 1935-36 and again in the winter of 1939-40, unfavorable combinations of storm waves and high tides removed the entire beach. All of the most vulnerable cottages were gone by November 1941, probably having been relocated farther inland. Up to 20 m (60 ft) of bluff were lost between 1931 and 1941. During the 1941-42 winter, the lack of a protective beach encouraged further bluff retreat, reaching up to 10 m (30 ft) by February 1942 (Griggs, et al., 2005).

These disastrous winters were followed by a long period of generally benign conditions, from the mid-1940s to the late 1970s, now understood as a cool and calm PDO cycle, characterized by few large El Niño events, and with fewer intense storms, less wave energy and erosion along the California coast. In 1962, parcels for the Big Lagoon/Ocean View subdivision were laid out along the top of the bluffs to the south of the original community, but on the same low eroding terrace (Figure 12). In subsequent years, additional homes were built along the bluff top to the south on Oceanview Drive. Long-term average erosion rates of the low bluffs south of the Big Lagoon development have been very high, ranging from 0.45 to 1.4 m per year.

With the transition to a warm PDO cycle in 1978, the coast of California entered a period of more intense and frequent El Niño events, accompanied by elevated sea levels and large waves. Erosion of the bluffs again increased. The 1982-83 El Niño winter waves and elevated water levels cut back the cliffs up to 10 m in another catastrophic erosion event. Two more cottages had to be moved and sand was stripped away below the cliffs bordering the new subdivision, threatening many new bluff top homes. Erosion continued during the 1983-84 winter, with up to 10 m of additional erosion at the north end of the community. One cottage that sat over 27 m from the bluff edge in 1931 was within three meters of the edge by 1985, an average retreat rate of o.4m per year for over 50 years.

During the large 1997-98 El Niño, eleven additional homes were threatened by accelerated bluff failure as a 15-meter stretch of one yard dropped and a section of roadway dropped into the ocean (Figure 13). Humboldt County tagged several structures as unsafe to occupy and some have been removed.

While the beach fronting the bluffs will accrete and erode depending upon wave and tidal conditions and sediment supply, the long-term trend is clear from the bluff erosion rates and the temporary accumulation of talus at the base of the slope. The bluffs will continue to retreat and houses closest to the bluff edge will eventually have to be relocated or demolished. The erosion problems at Big Lagoon have been readily identifiable for decades and demonstrate the importance of determining long-term bluff erosion rates prior to creating oceanfront lots and building new homes.

Gleason Beach, Sonoma County

This steep and unstable section of Sonoma County coastline is underlain by the rocks of the Franciscan complex, which is a mélange (French for mixture) of rock types, some quite weak and erodible, and others more resistant, that persist as the offshore sea stacks provide some protection to the steep cliffs (Figure 14). The homes either built on or protected by the resistant rock types (generally at either end of this development) have fared far better than those in the middle that were built on sheared and weakened sandstone, siltstone and shale.

Gleason Beach (Figure 11) is a clear example where the problems of building too close to an eroding sea cliff have become all too apparent. Twenty-one homes were originally built in the 1930s on a narrow strip of marine terrace between Highway 1 and the cliff edge beginning. Septic tanks were built on the beach perched behind concrete seawalls. While there are some a few resistant areas of bedrock in the section of melange, most of the cliffs have continued to fail from a combination of winter high tides and wave run-up, as well as rainfall and runoff, which have produced shallow landslides and failure of the underlying materials. Only 10 of the original homes remain and the rest have now been destroyed or demolished such that only portions of concrete foundations and seawalls still remain (Figure 15). The San Andreas Fault runs virtually along the shoreline here, which contributes to the long-term instability of this eroding cliff top.

Bolinas Bluffs, Marin County

Located approximately 40 km north of San Francisco, the Bolinas Peninsula forms the southernmost extension of the larger Point Reyes Peninsula (Figure 11). Most of the peninsula is a broad, flat plateau or marine terrace that is bordered by steep seacliffs 40 to 60 m high. In 1880 the first summer home subdivision was developed in what is now the town of Bolinas. Since that time, seacliff erosion has been a continuing hazard.

The entire cliff appears to be a nearly continuous zone of landslides (Figure 16). Resistant, wave-truncated outcrops of shale at beach level create a narrow, shingle-covered tidal platform. As is common throughout the area, most retreat occurs during the wet winter months. Groundwater seeps can be seen along the base of the seacliff during winter and spring. Most of this water originates from rainfall percolating through the fractured bedrock underlying the marine terrace. Heavy winter rains also tend to cause gullying of the cliff face.

Surveys of the position of the cliff edge, which began in 1913, show that erosion has continued at average rates of several cm/year on the west to over a meter per year to the east where the mudstone is more fractured and less competent. Attacking waves cause landslides by undercutting the base of the cliffs. Failure is facilitated by increased subsurface flow of water and saturation due to septic effluent from cliff-top homes as well as winter rainfall.

The combination of inherent bedrock weakness, groundwater seepage, and wave attack leads to rapid cliff recession. Since the area was initially subdivided in 1927, many of the original oceanfront lots, the fronting Ocean Parkway, and several homes have been either partially removed or damaged by cliff erosion.

The cliffs just west of the entrance to Bolinas Lagoon support the most densely developed residential area in Bolinas, with 20 houses located on the brow of the cliff, some of which are precariously perched on the face (Figure 17). With each winter the location of the homes, road, and utilities located at the terrace edge becomes increasingly hazardous. This is not a new problem; the hazards resulting from wave attack and erosion have threatened Bolinas for over 100 years.

In an attempt to stabilize the beach and halt cliff erosion, bulkheads and groins were first emplaced in the 1880s beneath the cliffs backing the beach. These early wooden structures were regularly maintained by the community for many years and provided a beach of sufficient width to shield the cliff base from wave attack. Winter storms, however, have gradually destroyed many of the protective structures in addition to some homes.

During the prolonged and intense rains of the January 1982 storms, significant cliff failure occurred. Four homes along Terrace Avenue above Bolinas Beach were irreparably damaged and subsequently condemned. With the winter wave attack of 1983, one cliff-top home was completely destroyed and several others suffered damage (Figure 18). The effects of cliff erosion have been damaging to this community. Had the geological conditions been evaluated prior to development, much of the erosion "problem" could have been forestalled through better planning and setbacks. An 1882 plot of the Terrace Avenue area shows the road at one location as situated 27 to 39 m inland of the cliff edge; in 2005 the same road was at the edge of the cliff.

Pacifica, San Mateo County

Pacifica, which is about 16 km south of the San Francisco's Golden Gate, is within easy commuting distance of San Francisco (Figure 11). Over the past 30 years it has become densely populated with homes, apartments, businesses, and a mobile home park, all built close to the bluff edge on a 15-30m high marine terrace. Photographs from the 1970s show eroding and unvegetated bluffs (Figure 19), but the only armor at that time was a retaining wall and riprap protecting the mobile home park and some scattered concrete slabs that had been dumped at the base of the bluff. Houses along the Esplanade (right side of Figure 19) were close to the bluff edge at that time, and ample evidence existed for recent bluff failure. The Esplanade area has a well-documented history of coastal change that provides a useful long-term perspective (Griggs et al. 2005). According to older maps, this fragile coast had been relatively stable from 1853 to 1946. When 12 houses were built on the seaward side of Esplanade Drive in 1949, the 20m high coastal bluff was still 50m west of the street.

Between 1941 and 1970, 10m or more of bluff retreat occurred, with mobile home park construction taking place in 1966–67. By 1969, riprap and concrete rubble that had been placed at the base of the low bluff had been washed away by wave action. Around 1970 a timber bulkhead fronted by riprap was constructed, but within several years, additional rock had to be placed at the north end due to outflanking.

During the elevated sea levels and repeated high tides and storm wave attack of the 1983 El Niño winter, waves rapidly eroded the weak, unconsolidated materials making up the bluffs, threatening a number of structures. In February, the timber wall was breached, extreme beach scour occurred, and the riprap collapsed, followed by bulkhead failure. Wave attack, bulkhead destruction, and bluff erosion continued, and by March 1983, 23 mobile homes were moved to prevent further losses (Figure 20). The bluff was cut back 12m at the southern end of the mobile-home park and 25m at the north end, where a three-story building was moved back to prevent damage (Figure 21). To the south, a group of eleven homes along the oceanfront Esplanade were threatened by accelerated bluff erosion. Within a year, a rock revetment had been constructed at the base of the bluff to protect the homes (Figure 22).

The new revetment settled into the sand beach over time, despite the use of filter cloth and careful layering of the rocks. By the time the high tides and storm waves of the next large El Niño arrived in early 1998, there was little of the rock left to protect the weak bluffs. High tides and large waves again combined to remove about 12m of bluff, despite the efforts of the homeowners to install additional rock. Heavy equipment working under emergency conditions on the beach was damaged when caught by high tide. Continued bluff erosion through March and April led to undercutting of house foundations (Figure 23), condemnation of all but two homes, and the ultimate demolition of 10 homes in April 1998.

Losses at this location were among the most dramatic along the California coast during the 1997–98 winter and provided evidence of the potential limitations of riprap or revetments placed on deep sand foundations, as well as the ability of heavy surf to strip sand from narrow beaches and directly attack soft bluff materials already weakened by groundwater saturation. Breaking waves undercut the bluff face, inducing block falls and slumps in the oversteepened bluff. Following demolition of the homes, additional riprap, funded by the Federal Emergency Management Agency (FEMA), was placed at the base of the bluff along the entire Esplanade even though most of the houses were now gone (Figure 24). A concrete caisson structure combined with riprap was built to protecting the mobile home park, but a portion of it was damaged as some of the piles rotated seaward (Figure 25).

Winter waves during a weak El Niño in the winter of 2002–3 eroded six to ten meters of the poorly consolidated bluffs at the north end of Pacifica and threatened several large apartment complexes on the bluff top. Emergency rock was brought in to protect the toe of the bluff below the apartments (Figure 26), and a request was made in early 2003 for a permit to place 2,500 tons of 6–8-ton stones along the base of the eroding bluffs below a group of townhouses, directly to the north. By 2010, continued erosion had reached the front edge of the apartment buildings leading to postings as unsafe to occupy. Emergency tiebacks and gunite were used to try to stabilize the foundations with additional rock placed at the base of the bluff (Figure 27).

Almost the entire 2.5 km bluff frontage of Pacifica has now been armored with riprap, seawalls, gunite, or some combination. These high, weak bluffs are unstable under wave attack, yet the bluffs have been nearly completely urbanized. Erosion problems can be expected here in the future, and more property and structures will be threatened and gradually lost.

Seal Cove, San Mateo County

The small residential community of Seal Cove in San Mateo County (Figure 11) is built on an uplifted marine terrace fronted by a 25 to 30m high, steep coastal cliff eroded into weak sandstones and mudstones. There is no significant beach along this stretch of coastline so that waves attack the base of the cliff year around, leading to long-term average erosion rates of about 30cm/year. A number of residential lots have been lost and three homes located on the cliff edge in the 1972 aerial photographs have been removed or destroyed by continuing bluff retreat (Figure 28).

Although cliff erosion is a serious problem in Seal Cove, an even greater hazard is seaward movement and headward expansion of the large landslide on which part of the community is built. This slope failure has badly damaged a number of homes and threatens others, as well as roads in the area. A second large landslide south of Seal Cove is also active and is expanding northward; here blocks up to 60m wide are slowly sliding seaward. Wave erosion at the base of the steep cliffs and groundwater infiltration from above contribute to the instability in this area. The road closest to the cliff that provided access to the homes is now damaged and impassable (Figure 29).

Depot Hill, Santa Cruz County

Depot Hill, in the village of Capitola on the northern edge of Monterey Bay (Figure 11), saw its first grand old Victorian homes built in the late 1800s. While the original houses were built well back from the cliff edge, within a few decades an ocean front street had been built and lots on the inland side created. Before long, summer homes had been built on many of these parcels, although they were originally separated from the 25m high vertical seacliff by Grand Avenue, a sidewalk with benches known as Lover's Lane, and a row of Monterey cypress trees. By the 1940s, the row of trees and the sidewalk had fallen away and in subsequent years Grand Avenue was threatened and eventually undermined.

The cliffs fronting Depot Hill are highly failure prone for a combination of reasons. The underlying bedrock consists of mudstone, siltstone and sandstone, which is capped by 8 m of poorly consolidated marine terrace sands. The bedrock is extensively jointed in several directions, the dominant trend being northeast-southwest, dipping or tilting about 80 degrees seaward, which is the trend followed by the cliffed coastline here. There is a weak layer exposed at the base of the bluff, which as it is eroded by wave attack, leads to loss of support for the overlying joint bounded blocks, which subsequently fail (Figure 30). Groundwater from both landscape watering on the developed cliff top terrace, as well as winter rainfall, percolate down to the bedrock and then move seaward towards the bluff edge. This flow penetrates into the joints, increasing the pore pressure and weakening the rock. As a result of the orientation of the coastline here, littoral drift doesn't allow sand to accumulate at the base of the cliff such that high tides and wave runup reach the base of the cliff virtually every day.

Large blocks, a few to as much as three meters thick, fail regularly producing average long-term erosion rates of about 30cm/yr (Griggs and Johnson, 1979; Griggs et al., 2005).

Several houses have been relocated from the cliff edge to parcels further inland (Figure 31). During the 1989 Loma Prieta earthquake, cliff failure led to loss of support for some of the concrete caissons supporting a cliff-top apartment complex and also cracked the slab and walls. Several units were subsequently demolished (Figure 32). Grand Avenue, the former cliff top roadway is now nearly completely gone and erosion continues. While there have been numerous proposals over the years to stabilize the 25m high cliffs, no project has ever been agreed upon and approved.

Stilwell Hall, Fort Ord, Monterey County

The smooth, gently curved shoreline of Monterey Bay with its wide sandy beaches (Figure 33) suggests an equilibrium coast, or one essentially in balance with the forces or processes acting upon it. Although this may be the long-term picture, historical and photographic records combined with recent measurements and observations indicate that the shoreline is dynamic here as elsewhere. The beaches advance and retreat, and the frontal dunes along the central and southern portions of the bay are periodically eroded back and subsequently rebuild.

Erosion along the southern coastline of the bay is the most severe. The entire 25 km of southern Monterey Bay shoreline from Moss Landing to Monterey consists of essentially unconsolidated Pleistocene dunes that when reached by waves are highly erosion prone. Measurements from aerial photographs taken over the past 40 to 50 years indicate average retreat rates of the sandy bluffs of about 0.6 to over 2m per year (Griggs et al., 2006). An important contributing factor to erosion along the southern shoreline of the bay has been a century of sand mining, directly from the beach (Figure 34). At continuing removal rates of about 150,000 m3/yr, a strong case has been made that this volume is equivalent to the volume of sand being eroded from the bluffs each year along the southern bay shoreline (Griggs and Jones, 1985; Thornton, 2007).

Stilwell Hall, a World War II soldiers club near the bluff edge at the former Ft. Ord military base, was built overlooking the bay during the early 1940s (Figure 11). As erosion proceeded at about 2m/yr, the army repeatedly dumped rock and broken concrete onto the beach in front of the structure in attempts to slow or halt erosion and save the historic building (Figure 35). By early 1984, the edge of the eroding bluff was within 5m of the structure, which lead the Army Corps of Engineers to prepare a feasibility study analyzing all options for the building. Based on the high rate of regional erosion, the conclusion reached was that complete relocation, reconstruction or demolition was far more cost-effective than trying to halt bluff erosion. The entire military base was ultimately decommissioned as a Department of Defense cost saving measure, leaving Stilwell Hall perched high above the beach on what was rapidly becoming a peninsula. The California Department of Parks and Recreation ultimately took ownership of the property, and the structure was subsequently demolished and all rock and concrete from the beach removed. While the armoring had led to a well-documented case of passive erosion, with the removal of the rock and concrete a beach has returned (Figure 10b).

Isla Vista, Santa Barbara County

Isla Vista (Figure 11) is the student community for the adjacent University of California Santa Barbara campus and is home to about 15,000 college students living primarily in apartments. The 12m high seacliffs in this area are made up of the Sisquoc formation, which consists dominantly of shale and siltstone. The beaches here narrowed during the severe El Niño events of the last three decades and have never returned to their historic widths, such that waves frequently reach the base of the cliff at high tides. The offshore Channel Islands play an important role, however, in sheltering much of this coastline from direct wave attack.

The Isla Vista seacliff area was essentially undeveloped until the 1940s and 1950s when homes and apartments began to be built following the conversion of the terrace immediately to the east from a World War II Marine Corps base to the University of California Santa Barbara campus. By the 1980s, many of the oceanfront parcels had been built out with small, typically two-story apartment complexes. Many of these units were built nearly to the cliff edge, often with decks extending to or cantilevered over the edge, which had great appeal to students (Figure 36).

Because of the narrowed beaches over the past several decades, erosion has proceeded at average rates of between 15 and 30cm per year (Griggs, et al, 2005). While a few low-budget timber seawalls have been constructed, for the most part the cliffs are unprotected and erosion has proceeded to undercut the decks, foundations and exposed and destroyed the concrete caissons supporting some of the structures (Figure 37). As cliff erosion had proceeded, the overhanging decks and the front units of a number of apartments have gradually been removed or demolished (Figure 38). The neighborhood is getting smaller and this is likely to continue well into the future.

Carpinteria, Ventura County

Following the construction of the Santa Barbara harbor breakwater between 1928 and 1930, sand began to accumulate upcoast of the breakwater, eventually widening the beach to as much as 250m (Figure 39). This area of former seafloor now supports a college stadium, several large parking lots, park facilities and a number of buildings associated with the harbor complex. While the upcoast beaches widened, the beaches as far east as Carpinteria (Figure 11), about 20km downcoast, suffered varying degrees of sand deprivation and subsequently, erosion. There was a well-documented erosion wave that migrated downcoast at about 1.7 km/yr (Wiegel, 1965). The greatest impact was along the low sand spit that encloses the Carpinteria salt marsh where erosion removed the protective beach that led to the loss of foundation support and collapse of a number of homes (Figure 40). In January 1940, the beach at Sand Point in Carpinteria eroded landward 75m and caused over $2 million in property damage. Ultimately, riprap was brought in to protect this shoreline, but the initial damage had been done and property and houses had been damaged and, in some cases, destroyed.

West Newport Beach, Orange County

The shoreline at Newport Beach is a highly developed, low-lying sand spit in Orange County (Figure 11). The low spit has been attacked intermittently and overwashed by waves from tropical storms off Baja California and the southern hemisphere. The coastline faces nearly south and therefore lacks protection from the offshore Channel Islands like much of the rest of southern California. Beach homes and cottages were undermined during 1934 when the beach was severely eroded (Figure 41; Kuhn and Shepard). In the summer of 1965, the beach eroded 50m before being stabilized by sandbags just a few meters from property lines. Similar severe erosion occurred in 1968.

The greatest threats have been at West Newport Beach, and this area has been subject to numerous shoreline protection and nourishment efforts, primarily as a result of Corps of Engineers regional projects. Rock and sheet pile groins were installed in the 1960s and 1970s (Figure 42), and several nourishment projects have added more than 1.2 million m3 of sand to this beach. In 1991, another one million m3 were dredged from the Santa Ana River and used to create an offshore mound. Some of this sand migrated landward to widen this beach. Groins have helped to widen and stabilize the shoreline but large southern swells are still hazardous to the expensive beachfront development. Sea-level rise will only exacerbate the existing risks.

Encinitas, San Diego County

In 1938, the Self-Realization Fellowship constructed a temple on the bluffs at Encinitas (Figure 11), just 3-5m back from the cliff edge, where it had a spectacular view of the Pacific (Figure 43). Known as “Swamis”, the temple was built by Paramahansa Yogananda, a native of India, who was widely revered at the time as a pre-eminent spiritual leader.

Cliffs are unstable in the area as a result of both wave attack at the base of the bluff during high tides, and also a result of landslide prone cliff materials. In 1942, just four years after completion, the Golden Lotus Temple collapsed and slid downslope as the bluff failed from a combination of large waves and heavy rainfall (Figure 44). The temple was dismantled and hauled away, and today a plaque marks the original location.

Following the collapse of the temple, the fellowship's monks and nuns consulted with experts and came up with a plan in the 1980s they believed would save the site. It involved a combination of geology and engineering and included: 1] installing wells and pumps to lower ground water on the site; 2] planting deep-rooted vegetation on the bluff face; and 3] Building a 1,500 foot long riprap revetment at the toe of the bluffs to dissipate wave energy. Overall their approach has survived subsequent wave attack and heavy rainfall that has caused bluff failure elsewhere along the Encinitas coast (Figure 45).

Southwest Fisheries Sciences Center (NOAA), La Jolla, San Diego County

A National Marine Fisheries Service Laboratory (Figure 11) was built in the early 1960s on the edge of a 60m high cliff at the north end of the Scripps Institution of Oceanography (Figure 46). The sedimentary rock making up the seacliff is fractured and highly permeable, and is also characterized by a steeply seaward dipping joint set and relatively high groundwater seepage. As a result, many small and large mass movements have occurred, including translational block slides and slab failures. One large slide mass lies directly below the building (Figure 46). Just to the north, a 180m long slide in 1982 brought an estimated 1.8 million m3 of rock, sand and soil onto the beach. An earlier landslide in 1949 was even larger and extended alongshore for approximately 500m (Griggs, et al. 2005).

Soon after the Fisheries Laboratory was built it was determined that the facility straddled an active landslide whose movement was correlated with distant earthquakes. Shifts of several cm in the most seaward building soon became evident (Griggs, et al., 2005). Average long-term cliff top erosion rates have been documented at about 30cm/yr (Benumof and Griggs, 2000).

The facility sits atop an eroding coastal cliff, with future failure over time being inevitable. This erosion has placed two of the four buildings in the complex within 6m of the cliff's edge, and forced NOAA to implement plans to abandon the two buildings and move into temporary offsite leased space. The relocation of staff from these two buildings was completed on June 2008 and federal money was appropriated to build a new building directly inland from the existing building, which is now under construction (Figure 47).

DISCUSSION AND CONCLUSIONS

Many coastal areas around the U.S. are threatened by a combination of winter wave attack, high tides, storm surges as well as periodic extreme events (hurricanes and ENSO, for example). Although global sea level is rising at what appears to be an increasing rate based on satellite altimetry measurements made since 1993 (NRC, 2012), it will be the extreme events such as Hurricanes Sandy and Katrina or the El Niños of 1982-83 and 1997-98, that will pose the greatest risks to coastal development over at least the next several decades. The past history of shoreline retreat and the loss of buildings, neighborhoods, and entire communities has been well documented. There are expensive lessons here that should be heeded.

Throughout the last century, the most common response to an eroding coastline was armor along the West Coast and beach nourishment and armoring along the East and Gulf coasts. Today the hold-the-line view is being tempered by both a well- documented increase in the rate of global sea-level rise, a growing awareness of climate change, as well as a number of very costly coastal natural disasters. Despite this history, there are still differing views on how to respond, as expressed in the introduction to this article. The greatest difference in approaches are understandably those of coastal business or shoreline homeowner on the one hand, who don't want to give up their oceanfront property and homes, and the coastal scientists, on the other hand, who are well aware of the long-term retreat trends.

In California, ten percent of the entire 1760 km coastline has now been armored, with fully 1/3 of the coastline of the four most populated Southern California counties now protected (Griggs, 2010). The California Coastal Commission, which is the statewide permitting agency for new development or seawalls, has developed a general policy of discouraging additional armor unless primary structures are in imminent danger.

While there is a general attitude among oceanfront property owners of resisting retreat and rebuilding, often with federal disaster relief funding, in the UK retreat has been going on for centuries, and in California, we have been retreating for decades. There are examples from one end of the state to the other of lost or disappearing neighborhoods, whether streets, homes or other buildings. All indications are that sea-level rise rates in the future will increase. There are also some indication that wave heights are increasing along the west coast (Storlazzi and Wingfield, 2005; Ruggiero, Komar and Allen, 2010; Seymour, 2011).

The combination of a long and well-documented history of cliff erosion and shoreline retreat, rising sea level and a likely increase in the frequency and height of storm waves, suggests that we need to begin to plan for adapting and preparing for a different future. The state of California has just released new sea-level rise guidelines to be used by all state agencies (CO-CAT, 2013), and the state's Ocean Protection Council has just issued a Request for Proposals to communities for $2.5 million in funds to support the development of sea-level rise adaptation plans. The California Energy Commission's Public Interest Environmental Research Program funded a study that has now been published by the state's Ocean Sciences Trust, Adapting to Sea-Level Rise: A Guide for California's Coastal Communities (Russell and Griggs, 2013 & 2012). The state of California has lost a number of oceanfront structures over the past century, but is taking the lead in beginning to prepare for the future risks faced by all coastal communities.

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