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COASTAL PROTECTION STRUCTURES AND THEIR EFFECTIVENESS

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UNIVERSITY OF CALIFORNIA AT SANTA CRUZ

Joint publication of the State of California
Department of Boating and Waterways
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Design by Venetia Bradfield Griggs

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INTRODUCTION

The erosion or retreat of the shoreline is a continuing natural process along about 86% of California's 1100 miles of shoreline. Waves, tides, wind, storms, rain, and runoff combine to wear down and reshape this meeting place of land and sea. When the first permanent structures were built along the coast over a century ago, vacant land was readily available and houses were commonly located in relatively stable areas off the beaches and well away from unstable and eroding bluffs. However, as populations increased in coastal communities over the past two or three decades, the desire for unobstructed ocean views, convenient beach access and prestige induced many people to invest in property right at the ocean's edge.

After $18 million in coastal storm damage during the winter of 1978 and $100 million damage during 1983 storms, some Californians have begun to realize that there is an inherent economic risk in living on the beach, on active dunes, or on an eroding bluff. Geologically speaking, these are all temporary landforms which are subject to rapid and severe changes. This may not be obvious during the warm summer months when the beach is high and wide, but it will become clear with the arrival of the first severe winter storm.

Although erosion rates vary widely along the California coastline, in most cases it is only a matter of time before an oceanfront property owner feels the threat of storm damage and realizes some action is necessary. At this point there are really only four options: 1) do nothing and suffer the inevitable loss, 2) try to sell and pass the problem on to someone else, 3) move or relocate buildings and other improvements, or 4) attempt to control or reduce the erosion through some type of protective structure.

This manual deals with protective structures and their effectiveness in reducing storm damage and minimizing or halting shoreline erosion. The book is intended to help oceanfront property owners as well as the engineers and contractors who are called upon to design and build these structures. It will also aid planners in public agencies from whom permits for such structures must be obtained.

Coastal protection measures vary considerably in their cost, size, effectiveness, and life span. At one extreme, slabs of broken concrete or asphalt, or other construction debris have simply been dumped at the base of cliffs in an attempt to reduce wave impact. Most efforts of this sort have been relatively futile or very short lived. At the other extreme are massive, carefully engineered concrete seawalls, such as the O'Shaughnessy Seawall along Ocean Beach in San Francisco, which has functioned very effectively for over 50 years.

What should be made clear at the outset, however, is that on a rapidly eroding coastline, any protective structure built to withstand direct wave attack will probably fail eventually. Even a well-designed structure is likely to fail once its design life has been exceeded, especially if it has not been properly maintained. Engineers commonly think in terms of a 20 to 25 year life for a coastal protection structure. This should be clearly understood by the homeowner, but often is not.

Spending large amounts of money on the installation of a coastal engineering structure does not guarantee long-term, or in some cases, even short-term, protection for home and property. The exposure of a property to wave attack, the presence and geometry of a protective beach, the resistance of the seacliff or bluff to erosion, the presence or absence of a supporting bedrock platform beneath the beach as well as the specific design, construction and dimensions of the structure will all influence its effectiveness. During exceptional high tide and storm wave conditions, such as those of early 1983, protective structures which have survived for decades may fail virtually overnight. Some protective structures have fared far better than others. Our research indicates that for most types of structures, there are a number of precautions, alterations, or design criteria which, if utilized, can significantly improve the structure's effectiveness or extend its lifespan.

SCOPE

This publication presents an attempt to learn from the successes and failures of the past sixty years, and to apply these lessons in the planning and design of future coastal structures. Our assessment is based primarily on case histories of 32 sites scattered over 125 miles of the Central California coast (Figures 1 and 2 and Table 1). These sites include a wide variety of coastal environments, including high and low sea cliffs, pocket beaches, dune fields, and river mouths. Although local variations in wave climate and coastal geology must be taken into consideration, our findings should be applicable to other exposed coastlines. Although the Army Corps of Engineers has prepared a series of booklets for the homeowner, planner, and engineer (The *Low Cost Shore Protection* series), it is important to emphasize that the structures and recommendations in the Corp's reports are for low-energy coastlines, such as the Great Lakes.

This publication is divided into three major sections. First and foremost is the evaluation of five common types of coastal protection: concrete rubble, rip rap, concrete seawalls, wooden seawalls, and gunnite. For each type of protection, we present background information (including the results of previous field studies), our observations, and a summary of performance and behavior. A brief overview of other miscellaneous types of protection, and a review of the use of filter cloth are also included in this section.

The next section describes some general problems faced by virtually all seawalls—overtopping, undermining, and outflanking. The fourth section of the report contains a list of qualitative suggestions on how each type of protective structure could be improved, and a discussion of basic methods for avoiding damage to coastal property. This is followed by a conclusion and summary of the relative successes of rip rap, concrete, and wooden seawalls in various coastal environments.

From time to time new approaches or solutions to the coastal erosion problem will be proposed and marketed. We urge property owners or government officials who are trying to select the most appropriate erosion control measure to look carefully before spending money on untried or untested approaches for which little documentation exists. We have evaluated the types of structures that have been most commonly used along the California coast.

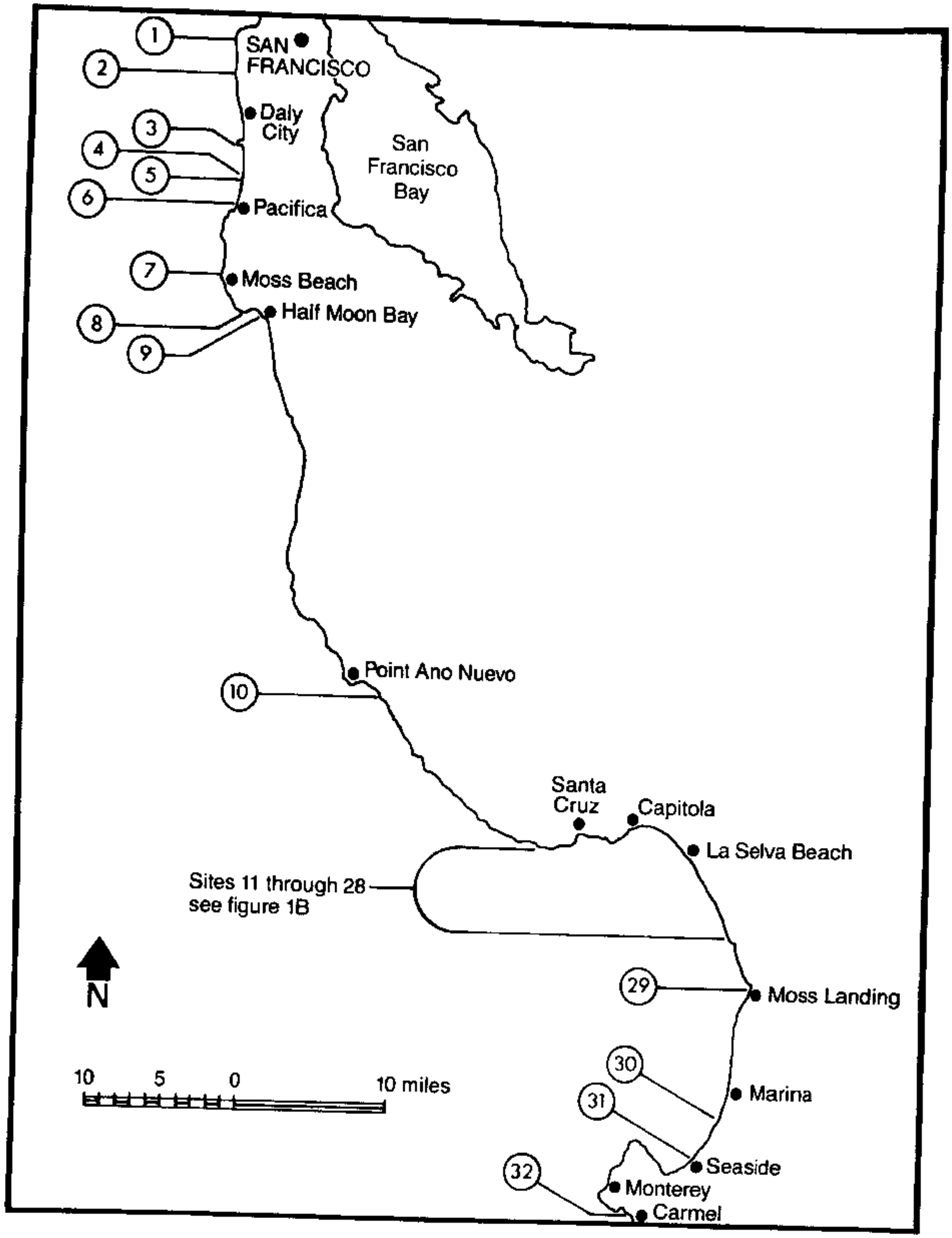


Figure I
Index map of locations for case study sites along the central California coast.

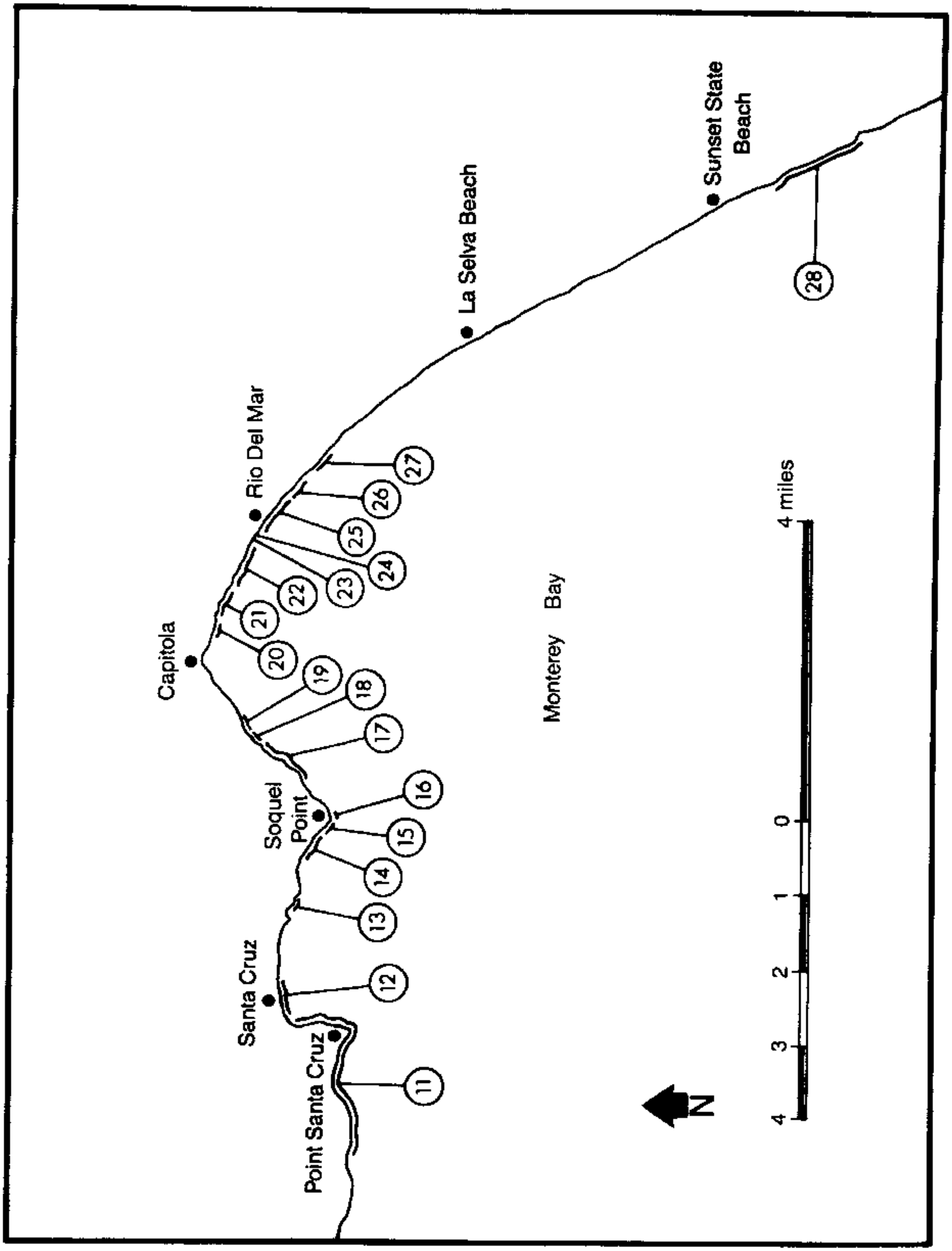


Figure 2
Index map for locations of case study sites in Santa Cruz County.

EVALUATION OF COASTAL PROTECTION MEASURES

CONCRETE RUBBLE

Background: Broken concrete and other construction debris are some of the oldest and cheapest, but least effective materials that have been dumped over seacliffs and onto beaches with the intent of protecting coastal property. These materials generally consist of loose dirt, flat concrete or asphalt slabs of various sizes, steel reinforcing rods, small stones, and occasionally pieces of wood or trash. At some locations, concrete slurry has been added to the debris, increasing its strength but not necessarily its stability.

Matthews (1934) states that flat revetment stones or slabs tend to settle parallel to the slope they are placed against, and may allow greater overtopping of the slope by splash and green water. Even when concrete rubble is stacked at a very low angle, the toe materials will still spread seaward. The Army Corps of Engineers (1956) determined that rubble and fill along the Santa Cruz County coastline was quickly removed when hit by waves. Their *Low Cost Shore Protection* study (1981) concludes that rubble is not generally useful as a revetment, and suggests that even if elongated pieces and flat slabs are removed from the debris, large quantities of material would be needed to provide significant coastal protection, even under low to moderate wave conditions. However, Moffatt and Nichols (1983) feel that selected concrete rubble is acceptable as an under-layer beneath armor stone.

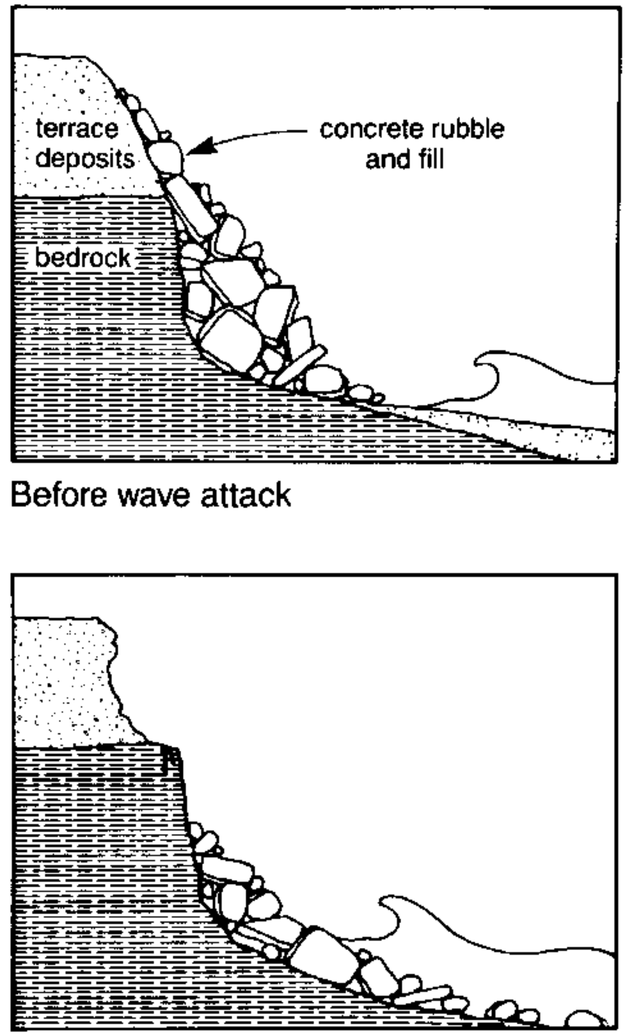
Figure 3
Concrete rubble and dirt have been dumped over the seacliff in an effort to slow erosion (Site II).

Observations: Concrete rubble is often dumped along with dirt fill, which makes the resulting slope particularly vulnerable to wave attack (Figure 3). Although these materials appear deceptively stable in between storms, when attacked by wave splash, they frequently become unstable and will fail rapidly. Dirt between the large slabs or blocks of concrete washes away first, then the slabs themselves begin to slide downslope (see Figure 4). Typically, they fail by sliding down the slope face, parallel to the slope, and parallel to one another, like a stack of cards. Near the toe, they move out onto the beach at a very low angle of repose if large waves continue to push them around (Figure 5).

Under low wave conditions, concrete rubble with the flat pieces removed may reduce erosion at the toe of erodible slopes. Larger waves, however, will rapidly remove this debris. Under storm conditions, concrete slabs may become quite mobile. Large concrete slabs originally piled against a 30 foot high bluff at Milagra Valley near Pacifica were transported as far as 5000 feet upcoast during the 1983 storm season. Near the Twin Lakes Beach case study area, at Schwann Lagoon (Site No. 13 on Figure 2), rip rap was dumped directly on top of concrete rubble as an emergency measure during January 1983. Within the next two stormy weeks the rip rap was carried seaward as the rubble slid down beneath it. Similar seaward movement of concrete rubble beneath rip rap occurred at one location along West Cliff Drive (Site No. 11), at the ends of county streets near Twin Lakes Beach, and at several other locations in the Corcoran Lagoon case study area (Site No. 14).

Summary: Because rubble is often used during emergency situations, and is seldom engineered, its costs are difficult to determine. Since the material itself is usually free, and is often simply dumped at the shoreline, its cost depends primarily on the price of hauling the material to the site. However, except during low wave conditions, or where very large volumes are used, the benefits of this type of "protection" are also very low. In fact, the use of concrete rubble may generate unexpected future costs, first because it gives the appearance of protection, leading to a false sense of security and greater investment in endangered property, and second, because it must often be removed before any engineered structure can be built at the site. Its use as a *core stone* in rip rap walls is also of questionable value, unless its size and shape is carefully controlled. Even then, it may be easily displaced or removed, when the armor rock shifts or settles.

Figure 4
Typical failure of concrete rubble and fill.



Before wave attack

After partial erosion of fill

Figure 5
Concrete debris has been scattered across a low terrace by wave action (Site II).

☐ CONCRETE BLOCKS

Large concrete blocks have been placed on sand at at least four locations within the study region; (including Sites 4, 26, and 28) primarily for emergency protection. Property owners at two sites used 4 foot by 4 foot by 2 foot "Porta-Blocks," (a commercial product), while the others acquired large remnants from demolished concrete bridges and other large structures. Some concrete blocks up to three feet across that had been placed in the swash zone were scattered by waves, while others sank out of sight or were moved seaward. In each case, these large, unconnected blocks tilted seaward and sank partially into the sand during and after storms (Figure 6). Larger concrete blocks (six feet across and four feet high) also tilted seaward (Figure 7.)

In most cases, the blocks apparently did little to reduce coastal erosion or damage, because waves simply washed over and around them, especially after settlement occurred. Their seaward tilting indicates that the greatest scour took place at the seaward edge of these blocks, causing them to rotate.

Figure 6
Wave impact has undermined and scattered large concrete blocks stacked to protect a beach front home (Site 26).

Figure 7
Wave scour has led to sand removal and seaward tilting of large protective concrete blocks (Site 4).

☐ RIP RAP

Background: Rip rap revetments (engineered and non-engineered) are by far the most common structures used for protecting coastal property along the California coast. In this report, rip rap is used as a general term, referring to any large (usually 1 to 5 ton) rocks used for coastal protection. Until the late 1970s, such rocks were often just dumped over seacliffs or on top of the sand in front of endangered coastal property (Figure 8). This practice is still common during emergency situations. The resulting structures are referred to as "rubble revetments," or "rip rap seawalls" by the Army Corps of Engineers, but they are referred to in this report as *non-engineered rip rap. Engineered rip rap,* in contrast, incorporates carefully placed layers of different sizes of rock, excavated foundations or keyways, and/or filter cloth, and has been used with increasing frequency for small-scale protective structures over the last decade (Figure 9). Engineered rip rap is designed according to explicit assumptions regarding storm waves, scour depths, and water levels. Although non-engineered rip rap is more likely to be structurally damaged over time, both types can be susceptible to the same types of failure during storms.

Figure 8
Rip rap has been dumped on the beach as an emergency measure during the winter of 1983 to slow bluff erosion and protect a sewer line running beneath the beach.

Whether engineered or not, rip rap is used in two distinct ways: either as a *revetment* sloping up against, and supported on the landward side by soil or another structure, or piled in a self-supporting *rubble mound* of trapezoidal cross-section. The most common uses of rip rap are to protect erodible materials and structures from wave attack, and to reduce scour at the base of wood or concrete seawalls.

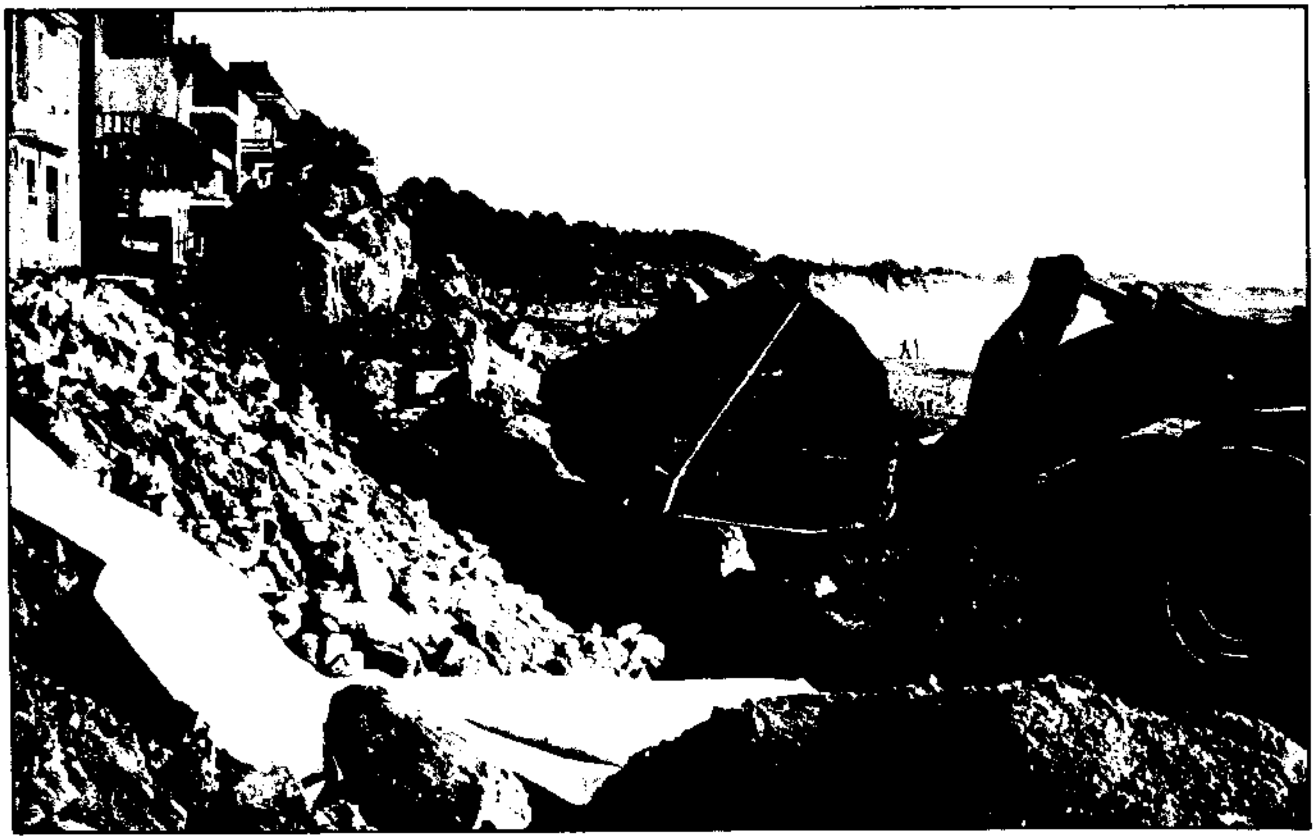


Figure 9
Emplacement of an engineered revetment using filter cloth, covered by small core stone, and larger cap rock (Site 24).

Previous reports have cited a number of advantages for rip rap seawalls:

a) They cost less to install than do concrete structures.
b) Their flexibility allows them to settle without massive or rapid structural failure.
c) They do not require special drainage systems.
d) They are easily maintained and modified.
e) They are resistant to damage by debris.
f) They absorb and dissipate wave energy, instead of reflecting it.
g) They allow less runup and overtopping than do vertical wood or concrete walls.

The Army Corps of Engineers (1956, 1982) have repeatedly shown properly installed rip rap to be one of the more cost-effective types of protection for individual homeowners. Their 1975 investigation of protection along the Great Lakes revealed the following typical causes of failure of rip rap:

a) scour at toe
b) outflanking
c) undersized rock
d) inadequate height
e) improper placement.

Settlement presents the biggest problem for all rip rap walls founded on sand. The Army Corps of Engineer's *Shore Protection Manual* (1977) recognizes this, stating that toe scour is an expected, "initial, short term effect." This manual also suggests that the problem can be mitigated by either building the wall high enough to take settlement into account, or by placing excess stone at the toe of the wall to fill the anticipated scour trough. Filter cloth is normally used in "engineered" walls as a method for reducing rip rap settlement.

Smith and Chapman (1982) present a different perspective, based on field observations during severe storms along the Australian coast. These authors watched five-ton rocks "completely disappear" into the sand in less than 150 seconds and documented the complete collapse of a previously-sound sixteen foot high rip rap wall in less than twenty minutes of heavy wave action. Their observations indicate that rip rap settlement is not primarily caused by sand removal at the toe, but results from toe stones sinking into a "fluidized" layer within the upper six feet of the sand (Figure 10). This would indicate that the maximum beach scour level is not the maximum depth to which rip rap can settle. Smith and Chapman add that after

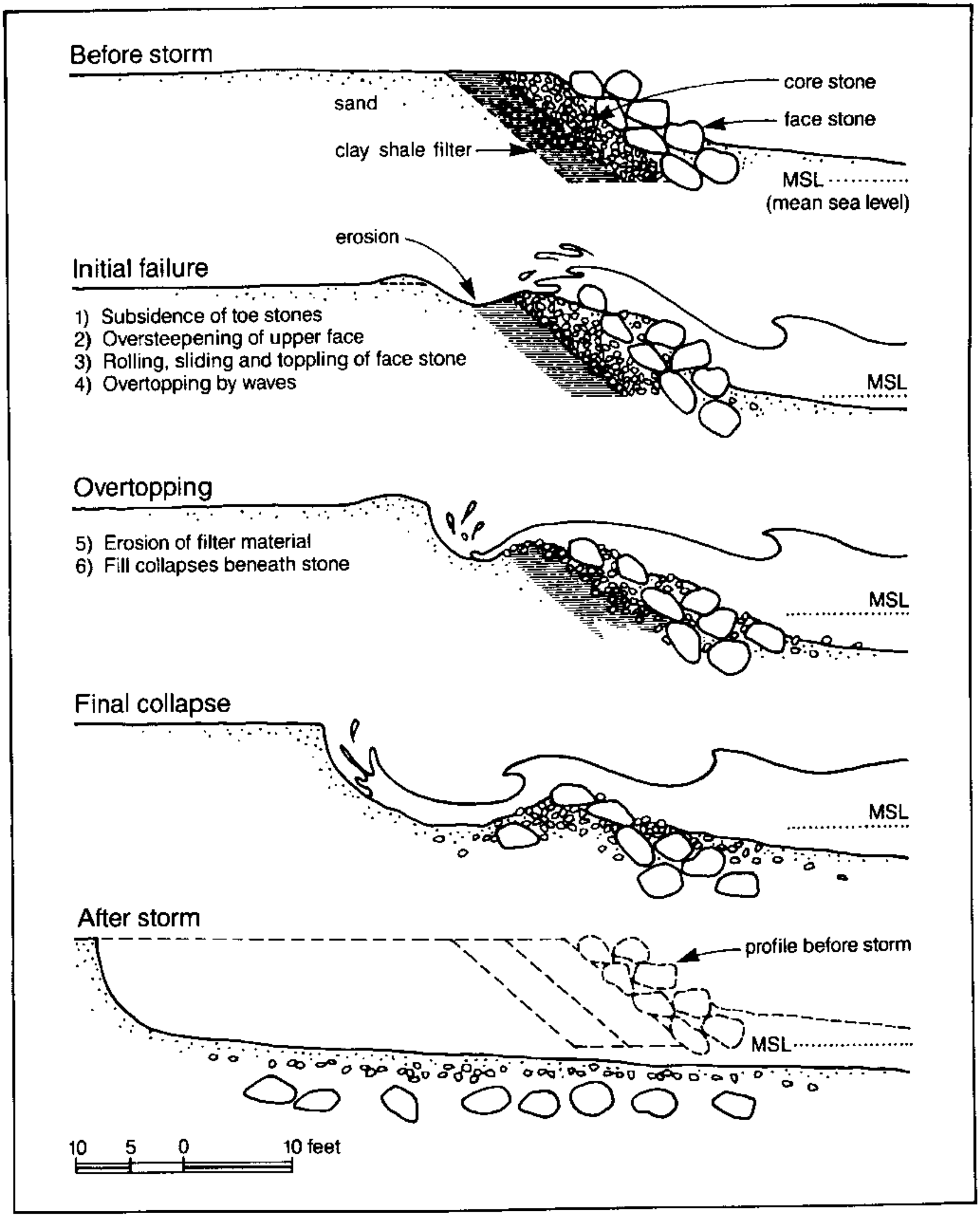


Figure 10
Collapse of a rip rap revetment along Australia coast (after Smith and Chapman (1982). Due to the availability of rock and difficulty of working in the surf zone, the Australian approach is often that settlement is expected and more rock will be added as needed.

several major storms, as more rip rap is added on top of the remains of the old walls, they should become relatively stable, until some future storm fluidizes sand to a greater depth. In Australia the expectation is that the rip rap wall will settle and the solution is simply to add additional rock. In California on the other hand, an engineered rip rap revetment is planned to resist that settlement. Nonetheless, with the exception of rip rap placed on a bedrock platform, virtually all rip rap observed does settle with time, requiring the addition of more rock.

Zeevaert (1983) describes a similar liquefaction process, which caused damage to a harbor jetty in Mexico. Moffatt and Nichols (1983) suggest that such settling is due to fine material "piping" upward through the structure, and that this process "could result in settlement of the upper layers of rock; particularly the large heavy armor stones." The Army Corps of Engineers (1977) state that, "When large quarrystones are placed directly on a sand foundation at depths where waves and currents act on the bottom (as in the surf zone), the rubble will settle into the sand until it reaches a depth below which the sand will not be disturbed by the currents. Large amounts of rubble may be required to allow for the loss of rubble due to settlement. This, in turn, can provide a stable foundation."

Observations: We observed that, in general, the success rate of rip rap walls is marred by relatively high repair and maintenance requirements, and by the fact that significant property damage often occurs when these walls suffer even partial failure. Similarly, Smith and Chapman (1982) state that out of 12½ miles of (non-engineered type) rip rap installed along a stretch of Australian coastline since 1967, "nearly all... demonstrated at least some settlement and damage, and at least ½ mile was destroyed." Along the Central California coast, the collapse of entire structures was documented only at Sites 3, 27 and 28. More often the rip rap sank or toppled to a point at which continuous wave overtopping caused damage and erosion behind it.

Within the study region, at virtually every location where rip rap has been founded on sand, it has settled into that sand over time (Figures 1 and 2, Sites 3, 5, 6, 9, 11, 13, 14, 15, 20, 21, 26, 27, 28, 31). This settlement is often accompanied by a seaward movement of rocks at the toe of the structure. Such seaward movement is the result of a gradual or rapid undermining of the toe stones, which causes them to rotate seaward. A rotation of twenty to thirty degrees may drastically reduce the stability of rocks higher up on the wall. As each new block rotates, it destabilizes the stones above it, until the wall reaches a new, unstable configuration (Figure 11).

The rate and amount of rip rap settling varies considerably from one location to another. Often, corners, end sections and other localized segments of a single wall will settle, while the rest of the wall remains more or less intact. This may indicate an increased depth of scour or liquefaction in such areas, due to higher wave energy, current velocities, or a greater depth to the solid substrate. At a few sites, especially those underlain by wide, level bedrock platforms within a few feet of Mean Lower Low Water, settlement of the rock slows after a certain depth is reached. In other rocky areas, continuing settlement may be caused solely by offshore movement of the rocks within the sand, or over the exposed rock platform. However, in most cases, rip rap settlement appears to be reactivated each time a major storm arrives. At many locations rip rap has moved 5 to 10 feet vertically downward, and 10 to 30 feet horizontally seaward, during single storms.

Moffatt and Nichols (1983) suggest engineering excess rock into the toe of a rip rap wall, so that, "As sand is scoured from under the toe, the excess rock will drop into place and maintain toe support of the structure." This theoretical situation is shown in Figure 11A. As illustrated in Figures 11B and 11C, our observations indicate that this technique does not take into account the offshore movement of toe stones. When the toe drops, hinges, or fails, the rest of the wall will usually suffer at least partial failure and settlement, which often allows increased overtopping, erosion, or property damage behind the structure.

The second common failure mode for rip rap has been variously described as sliding, toppling, rolling, or plucking, and occurs when waves mobilize one or more armor stones in a wall, allowing them to move down to a new position of temporary stability. To prevent this type of failure, Moffatt and Nichols (1983) recommend avoiding smooth, rounded, elongate, or flattened stones, and carefully placing rocks so that they interlock with one another, and do not protrude from the face of the structure more than 18 inches. The *Shore Protection Manual* (Army Corps of Engineers, 1977) recommends that all rip rap subject to breaking waves be stacked at a slope of 1.5:1 (1.5 horizontal to 1 vertical, or 35 degrees) or less. Although a steeper wall will encroach less far onto the beach and initially will require less rock, such a wall is much more prone to toppling or plucking and subsequent collapse.

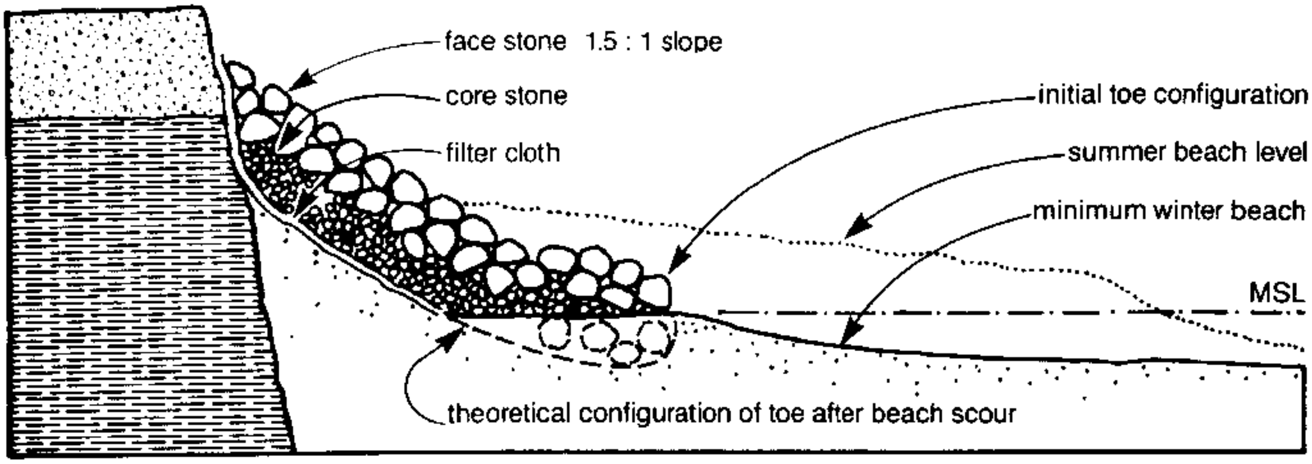


Figure IIa
Initial revetment configuration and theoretical "hinging" of revetment toe.

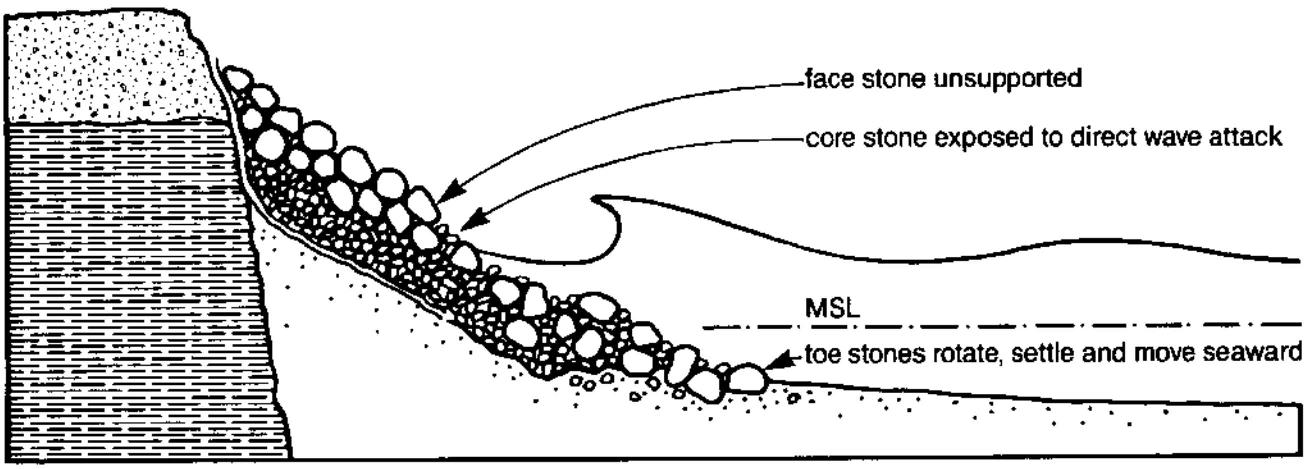


Figure IIB
Initial stages of observed toe failure (may be very rapid); note both seaward and downward movement of rock.

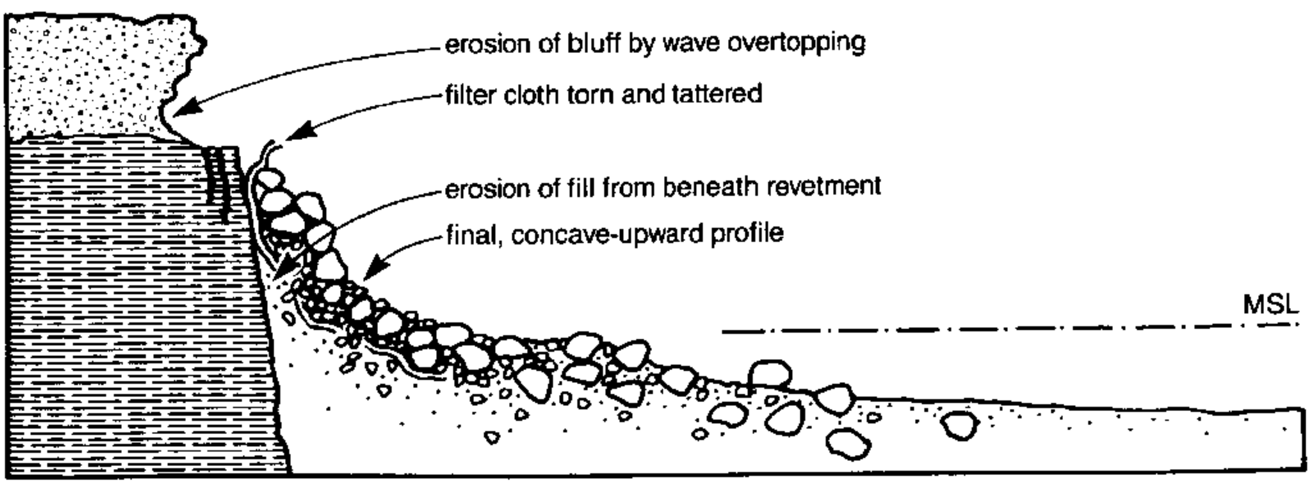


Figure IIC
Final states of observed revetment failure.

Rolling and plucking were observed primarily at sites where rip rap was stacked at slopes of 35 degrees (1.5:1) or steeper, and where stones less than 2 feet in diameter were exposed to direct wave action. After the severe 1983 storms, many damaged rip rap walls lay at slopes between 2:1 and 3:1. At least one engineered wall on bedrock (Site 16) settled from an original slope of 2:1 to a slope of 4.5:1. Rip rap stacked on narrow, seaward-sloping bedrock platforms is particularly susceptible to this type of failure, perhaps because a small rotation of the toe stones down slope will result in a relatively large vertical displacement. Founding the rip rap in an excavated keyway in the bedrock will provide a higher degree of safety, as long as the bedrock around the keyway does not erode away.

After their toe stones have rotated or settled, many rip rap walls assume a concave-upward profile (Figure 11C), in which the upper rocks are supported at a relatively steep angle, and are susceptible to toppling by large waves. This concave-upward profile, with its flattened toe, may cause waves to reform and break directly on the structure, especially during high tide.

A rip rap revetment, especially if only one or two stones thick, offers little protection for loose fill or sand behind and beneath it, unless it incorporates filter cloth or filter stone. Especially after settling of the rock, waves overtopping or outflanking rip rap often cause serious erosion of material behind the wall, even where filter material has been used. Where rip rap is stacked directly against loose fill, erosion behind the stone can result in catastrophic collapse of the wall and buildings behind it (as occurred at the south end of Site 27 in 1983). Also, filter cloth laid against a steep (greater than 2:1) slope can allow rip rap to slip down the slope when struck by large waves. In some cases, the toe of a rip rap wall has been placed in a trench excavated in bedrock or in "dense sand." This reduces spreading at the toe if the rocks are placed properly; but if the bedrock or dense sand is exposed to direct wave action (which is likely during severe storms), this trench may be eroded away at the toe, allowing the wall to settle as occurred at Site 5 in 1983.

Most engineered and non-engineered rip rap that we observed required additional stone after almost every moderate (say, 5 to 10 year recurrence interval) storm season. One central coast site required at least ten installments of rock and rubble over a thirty year period, and still suffered severe erosion during 1983 (Figure 12). Other engineered revetments, however have functioned well. For example, a rip rap revetment placed on bedrock in 1948 at Waddell Bluffs (Site 10) remains in excellent condition and has protected the highway as it was intended for over 35 years.

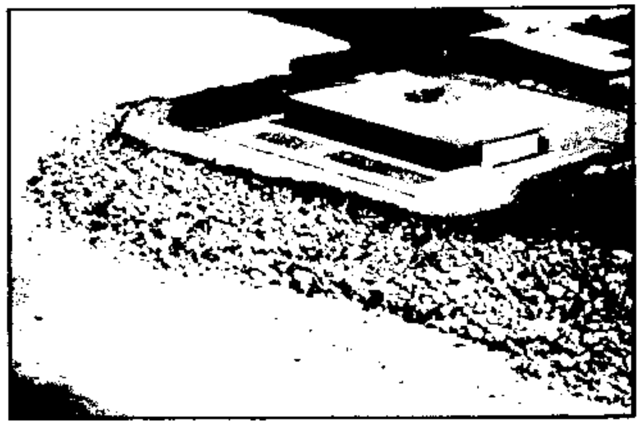


Figure 12
A total of 5500 tons of rip rap has been placed or replaced at this property 10 times over the past 30 years at a cost of over $150,000 (Site 14).

These more successful revetments may have survived for varying reasons, but there are similarities in their coastal environments. Most are founded on wide, flat, resistant bedrock platforms or surfaces (usually covered with sand) at depths within one to four feet of Mean Lower Low Water. These bedrock platforms force storm waves to break further offshore, even when the sand is completely removed, and they limit the depth to which scour can occur. Furthermore, because the rock surfaces are wide and level, erosion of bedrock keyways is less likely to be a problem.

However, even where such rip rap is successful in protecting the lower parts of seacliffs, the upper portions, especially unconsolidated terrace deposits, will often continue to fail because of gullying, debris slides, and other terrestrial erosion processes, as well as occasional wave splash overtopping. If bedrock erosion is completely halted, such upper-bluff retreat will probably decrease, except for erosion along isolated gullies.

Summary: Although rip rap is undoubtably the most common form of coastal protection in the study region, many of its alleged benefits may not hold during severe storm conditions:

1) Rip rap revetments do not always exhibit the coherent "flexibility" portrayed in some engineering publications (see Figure 11). Instead of settling as a cohesive unit, individual stones tend to separate as they rotate and/or settle, often moving seaward in the process. This causes the upper part of the wall to become less stable.

2) Rip rap walls may fail quite rapidly, often leaving behind gaps or arcuate landslide-like scarps of

oversteepened rip rap or exposed fill. Because many walls are designed as low as possible to minimize costs, even minor settling can allow significant overtopping, erosion, and damage behind the wall.

3) Rip rap revetments built over steep, loosely consolidated materials require carefully planned drainage systems to avoid erosion of material behind the rock. Numerous rip rap walls were outflanked or partially failed because of erosion from uncontrolled street or building runoff flowing behind or around them. Filter cloth is not always a practical solution to this problem, especially on slopes steeper than 2:1. Through-the-wall drainage pipes or conduits are often damaged as large rocks shift or settle.

4) Although, at most times, placing new rocks on top of old, settled ones is relatively simple, repairing a rip rap wall while it is being overwashed by storm waves is extremely difficult, and at many locations, beach access is impossible under such conditions.

5) Rip rap walls certainly reflect a smaller percent of wave energy than do vertical wood or concrete walls. However, during high tides and under certain wave conditions, reflected waves from rip rap walls have been observed to combine with incident waves, causing erosion and damage in adjacent areas, especially in small embayments.

Although a rip rap wall absorbs more wave energy than do relatively smooth, impermeable structures, it has a sloping seaward face. Because not all of the wave energy is absorbed, under high tide and storm wave conditions, waves running up a rip rap revetment can damage houses or erode the fill behind the rip rap (Figure 13).

Where maintained, rip rap has proven relatively effective in slowing erosion, but maintenance costs, even for engineered rip rap, are usually quite high. For example, the total weight of rock necessary to protect individual bluff-top lots in the Santa Cruz area over the last ten to fifteen years ranges from 500 to 2000 tons, or approximately ten to twenty-five tons per foot of ocean frontage. At todays average cost of $35 to $45 or more per ton, these walls may cost perhaps a third as much as the value of the property they are protecting. The Army Corps of Engineers generally uses a 1% per year estimate of maintenance requirements for rip rap. However, after a storm of roughly ten-year recurrence interval (Feb. 1980), engineered structures along the Central California coast required repairs totaling 20 to 40% of their construction costs, (2 to 4% per year) and non-engineered structures required repairs totaling between 50% and 150% of construction costs (5 to 15% per year).

Figure 13
During extreme high tides in the winter of 1983 waves washed over this engineered revetment and damaged these ocean front homes (Site 27).

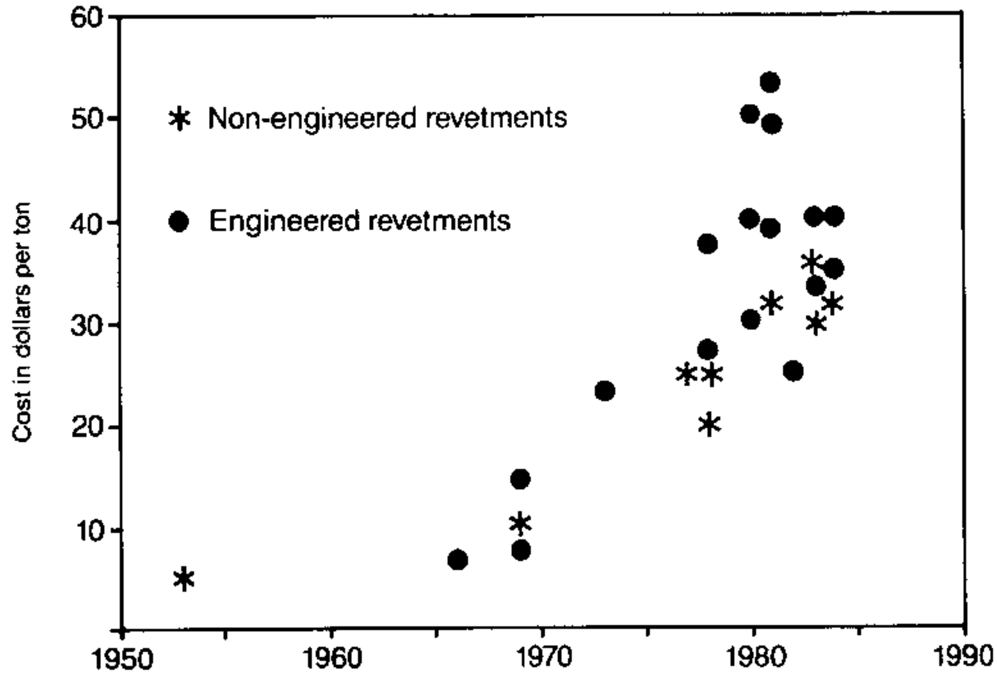


Figure 14
Increasing costs of engineered and non-engineered rip rap (not corrected for inflation.)

Within the study area, the cost of rip rap has roughly tripled or quadrupled in the last 15 years (Figure 14). Non-engineered rip rap expenses reflect primarily the costs of quarrying and transporting armor stone; but emergency rock costs may be somewhat higher, due to shortages of locally available stone and higher emplacement costs under storm conditions. The former factor may account for the high rip rap costs observed in 1981. Engineered rip rap costs include the costs of design, careful placement (labor intensive), and fill and filter materials. These add about $10 to $20 per ton to the total cost of the wall, making engineered rip rap about 30 to 60% more expensive than non-engineered rip rap, at the present time (1984).

Although engineered rip rap on sand has relatively high maintenance costs, it is not likely to be a complete loss, as many non-engineered rip rap walls have been. Engineered walls have settled 5 feet or more in single storms, but some non-engineered walls have virtually disappeared, settling 8 to 10 feet, and being dispersed by the waves.

Engineered rip rap walls founded on wide, level resistant bedrock surfaces have required much less repair, especially in relatively low energy environments. However, virtually all rip rap on seaward-sloping, uneven, and/or erodible rock surfaces required maintenance, after rocks moved offshore during storms.

CONCRETE SEAWALLS

Background: Concrete seawalls are commonly used to protect loose fill or sand against wave attack; they must also support the weight of this fill, and for this reason, are sometimes referred to as concrete bulkheads. In some cases, they also protect the foundations of structures which are built on this fill. Concrete seawalls are continuous, rigid structures, whose vertical or concave faces reflect wave energy upward, downward, and back out to sea. This reflection of energy may lead to greater wave overtopping and toe scour near smooth concrete walls than near permeable rip rap walls.

There are three major types of concrete seawalls: Gravity walls, which are self-supporting, balancing anticipated horizontal forces by their sheer mass; Cantilever walls, which rely on support from a deep foundation; and Tie-back walls, which are braced by cables or rods tied to anchors in the fill behind them. Concrete tie-back and gravity walls are usually poured in place. Most cantilever walls (and some tie-back walls) are constructed of prefabricated concrete sheet piles, jetted into the sand.

Army Corps of Engineers (1975) lists the following as typical causes of failure for concrete seawalls fronting the Great Lakes:

a) loss of foundation support
b) inadequate penetration

c) scour at toe
d) outflanking
e) inadequate height.

Observations: These causes of failure are also typical for west coast walls. Loss of fill behind walls due to piping (the subsurface removal of loose sediment, soil, or fill, due to water flowing through voids or holes), gullying, and/or undermining are also prevalent. Although the *Shore Protection Manual* (Army Corps of Engineers, 1977) states that failure of rigid seawalls is most likely to be catastrophic, many walls in the study region were endangered by a gradual removal of fill over several days or storm periods. Several concrete walls survived undermining or loss of fill because property owners had the time and money to add new fill and toe protection, preventing structural failure.

The O'Shaughnessy Seawall in San Francisco (Figure 15), completed in 1929 at a cost of $575,000, is the single most successful protective structure within the study region. This massive concrete wall has survived the test of time because it incorporates design and construction elements that prevent each of the typical causes of failure. At present day costs of approximately $4000 per linear foot, this wall would be economically impractical for most property owners today, but its design elements are still highly relevant.

O'Shaughnessy (1924) states that careful attention to the concrete mix and size of aggregate is imperative, so that the concrete will be as impervious as possible. The Army Corps of Engineers (1982) also stresses the need for good quality control in the concrete, and their Shore Protection Manual (1977) states that a low water to cement ratio is most resistant to exposure to seawater. Similarly, careful precautions should be taken so that metal reinforcing rods will not come in contact with salt water. Davis and Rutherford (1985) document the importance of carefully controlling

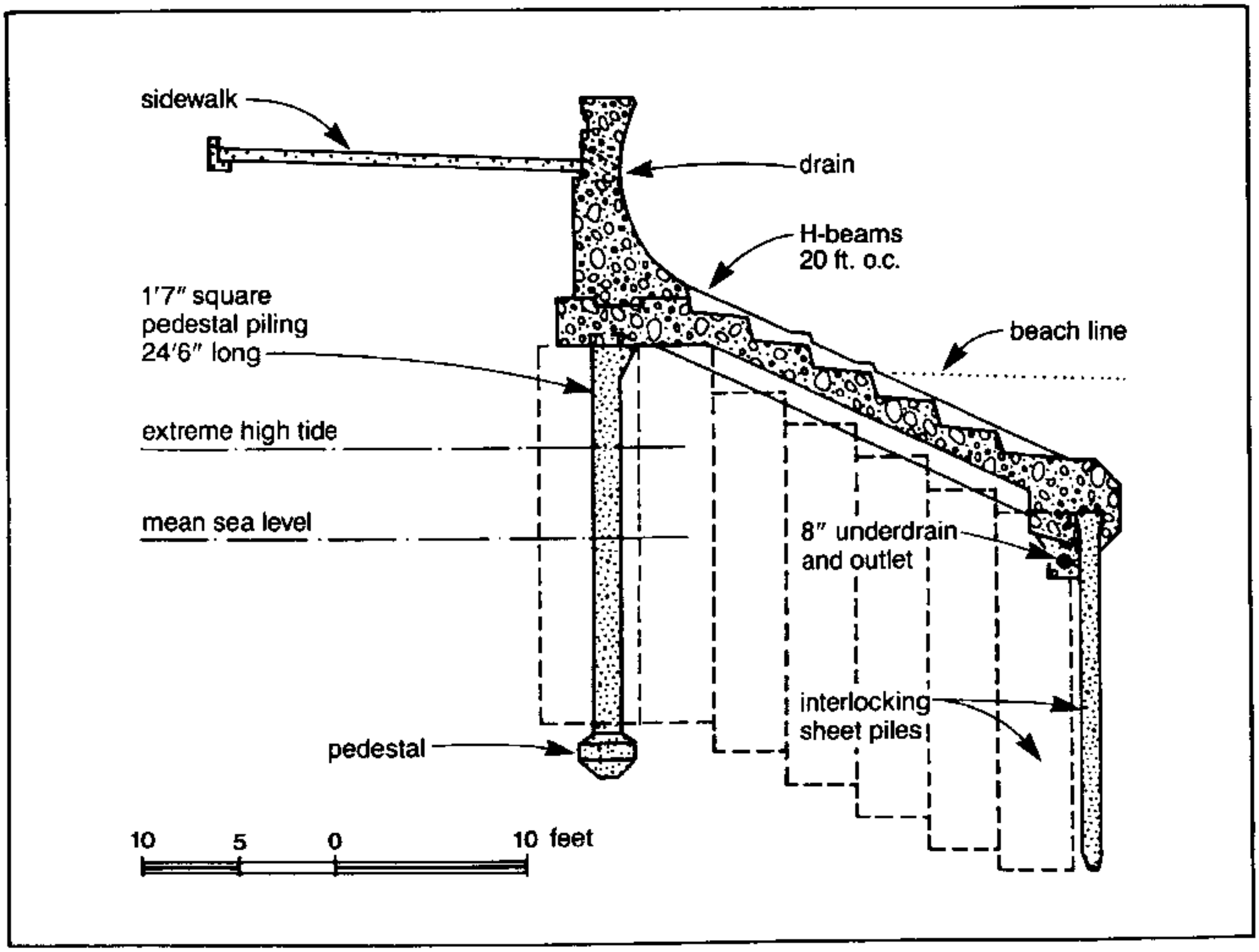


Figure 15
The O'Shaughnessy seawall in cross-section (Site I- see also Figure 16).

Figure 16
Northern end of O'Shaughnessy seawall in San Francisco showing concrete deterioration and rusting of exposed steel reinforcing rod (Site I).

the concrete mix as well as the type of reinforcing steel. The use of epoxy-coated rebar and at least 2 to 3 inches of concrete cover over the steel is strongly recommended for marine exposure. Flaking and cracking present long-term hazards to concrete walls and their steel reinforcing. Abrasion by cobbles has been a significant problem for some British seawalls. Damaged portions of concrete walls must be grouted or repaired, to prevent saltwater seepage from weakening materials or causing piping of fill. This was done regularly at the O'Shaughnessy wall until the late 1960s, when it was discontinued due to budget constraints. Over 20 years of abrasion at the northern end of the walls has exposed the steel reinforcing rod, which is now rusting (Figure 16).

Most concrete walls on this open coast have suffered from other problems, however, before their strength has been significantly reduced by degradation of the concrete. Those few concrete walls that did crack were built before 1960, often using poor materials, and were only six to eight inches thick.

The simple massiveness of concrete walls contributes to their resistance to wave attack (the O'Shaughnessy wall weighs about 12 tons per linear foot). However, this weight must be supported by a foundation well below the level of disturbance by waves, or undermining will cause the wall to tilt or even fail. The O'Shaughnessy wall is supported at its seaward edge by concrete sheet pilings, and at its inland side by concrete pedestal pilings (see Figure 15) to depths of -18 feet MSL and -16 feet MSL, respectively. These supports not only counteract the downward weight of the wall, but resist hydrostatic forces, without relying on buried anchors or "deadmen" in fill behind the wall.

Figure 17
Concrete seawall in northern Monterey Bay in January 1983 showing individual precast concrete spans bolted to concrete piers (Site 26).

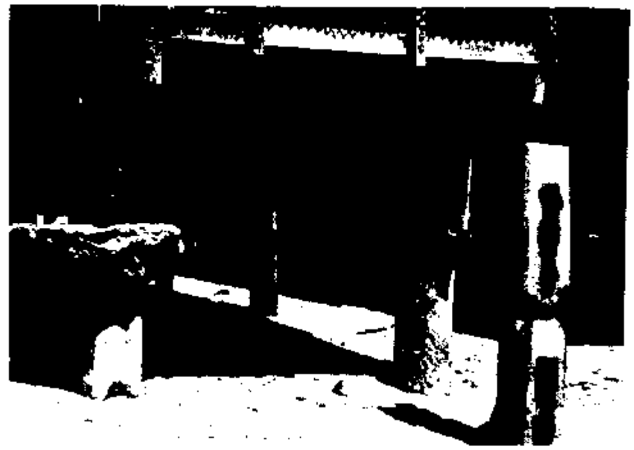


Figure 18
Concrete pier following wall failure showing deformation of concrete and extent of beach scour beneath house.

Scour at the toe of a vertical or concave-face concrete wall is common, because of the shape of the wall, and because the concrete is relatively impermeable, and highly reflective of wave energy. Rip rap is often installed at the base of concrete walls to reduce the reflected wave energy that is believed to cause scour. As with rip rap seawalls, the maximum scour depth in front of a vertical wall during storm conditions cannot always be predicted. Such scour will result in deeper water at the base of the wall during high tide, and will in theory, allow larger waves to break closer to shore. Depending upon the configuration of the wall, wave reflection at the flanks could also produce accelerated erosion to either side of the wall. To date, no comprehensive study using field measurements to document the importance or magnitude of either of these processes has been carried out.

The O'Shaughnessy wall incorporates several elements whose purpose is to reduce damage due to scour. The lower twelve feet of the wall forms a series of large steps to disperse wave energy at the toe. Both Matthews (1934) and the Army Corps of Engineers (1977) recommend this design where cost and space permit. The deep, interlocking sheet piles beneath the San Francisco wall have apparently prevented any significant loss of sand from under the structure.

Sand loss from under or behind a number of concrete walls has been documented along the central coast. Only one of these walls actually collapsed (Figure 17 and 18), although several hung suspended, bridge-like, over the scoured areas, until emergency rip rap or fill could be placed in front of or behind them (Figure 19 and 20).

Concrete walls founded on bedrock encountered similar problems when the bedrock eroded out from around or beneath them during various storms. Most concrete walls studied toppled seaward when they failed, due to erosion of sand or bedrock at their toes, and/or the active pressures of fill and water behind them. Concrete walls have also been poured on bedrock platforms or connected to eroding cliffs. Where the bedrock is less resistant than the concrete, which is almost always the case, the support or foundation for the wall has been removed, leading to undermining or outflanking (Figure 21).

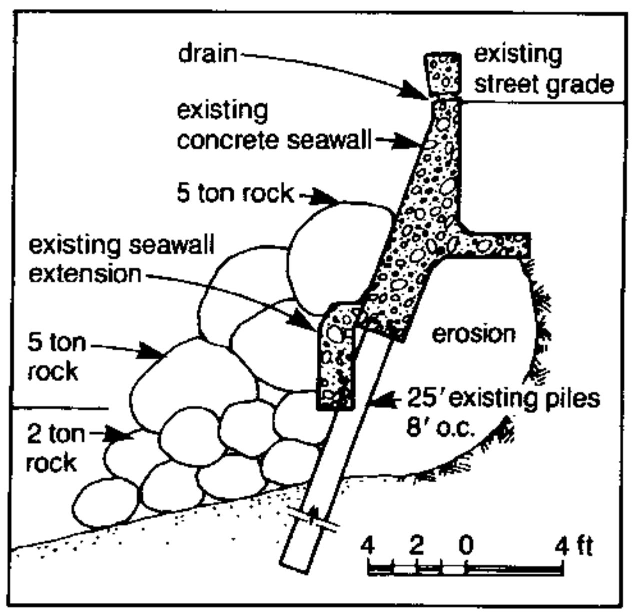


Figure 19
Erosion beneath concrete seawall and proposed rip rap at Rockaway Beach (Site 6).

Concrete seawalls built on sandy beaches lost fill both from underneath when sand levels dropped (Figure 22), and from behind the wall by piping. This piping takes place after fill behind the wall becomes saturated by wave splash, spray, and in some cases, groundwater. Under such saturated conditions, piping occurs due to concentration of flow at small openings, and the resulting fluid velocities are great enough to erode granular material. The process is often self-perpetuating, because as the zone of erosion enlarges, the seepage path is shortened, and hydraulic gradients increase.

Where drains or weep holes have been included within a seawall to allow for drainage from behind the wall, or where partially open joints exist between panels, it is critical that a system be utilized that prevents piping of sand or fill through these openings. Some combination of an impermeable surface behind the wall and/or graded fill and filter cloth as well as perforated caps or plugs over the weep holes is strongly recommended in order to minimize or eliminate piping under conditions of severe wave overtopping.

At Holiday Inn, in Monterey (Site No. 31), sand washed out through small (less than 0.25 inch) gaps between tongue-in-groove concrete panels, creating collapse pits a meter or two across in the fill behind the wall. The cracks were grouted when the wall was originally built in 1968, but some joints may not have been fully grouted, sand levels in 1983 may have dropped to below the level of the grout, and/or the grout itself may have become brittle and cracked with age.

A new concrete sheet pile seawall placed at Site No. 26 in late 1985 was severely damaged when exposed to storm waves within a month of construction. Severe wave scour dropped sand levels below four inch diameter weep holes and exposed approximately 12 vertical feet of the wall (Figure 23).

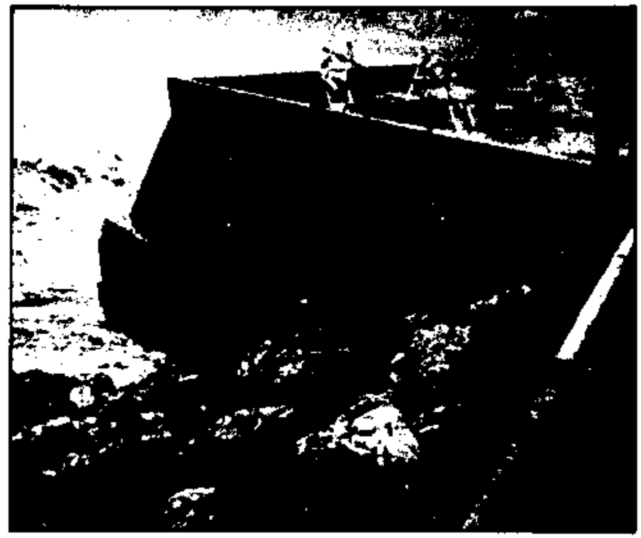


Figure 20
South portion of undermined seawall (March 21, 1972).

Figure 21
Outflanking of a short concrete seawall and undercutting of a sidewalk occurred during severe storm conditions (Site II).

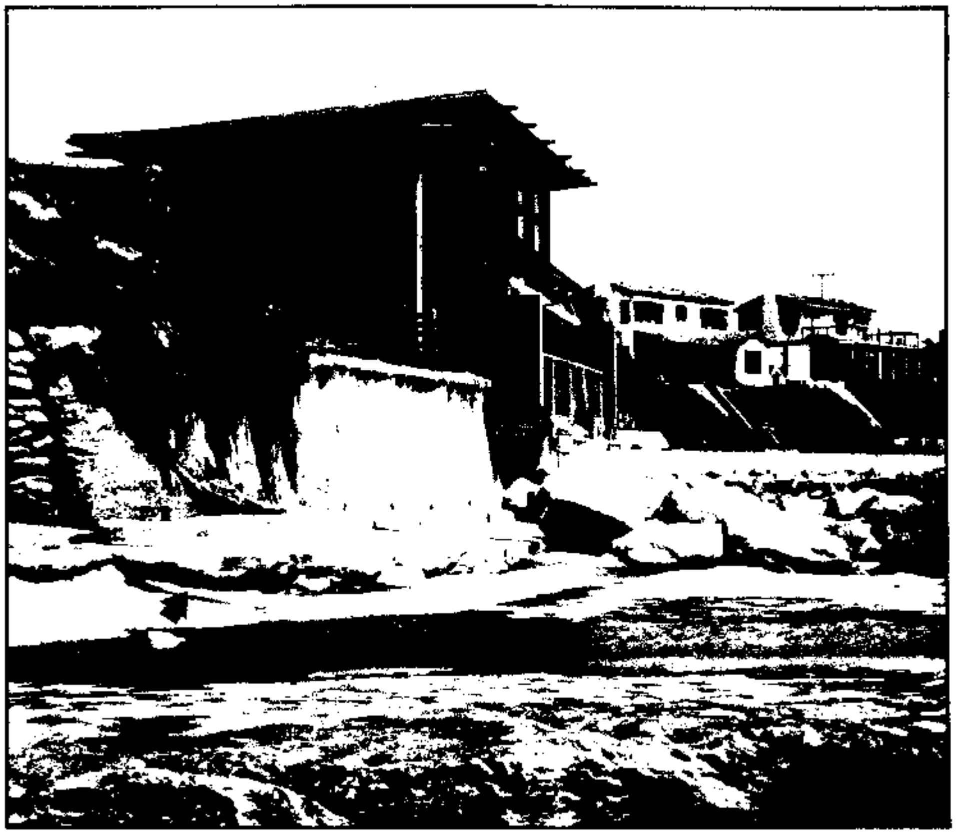


Figure 22
Scour beneath the base of a concrete seawall (at arrow) (Site 16).

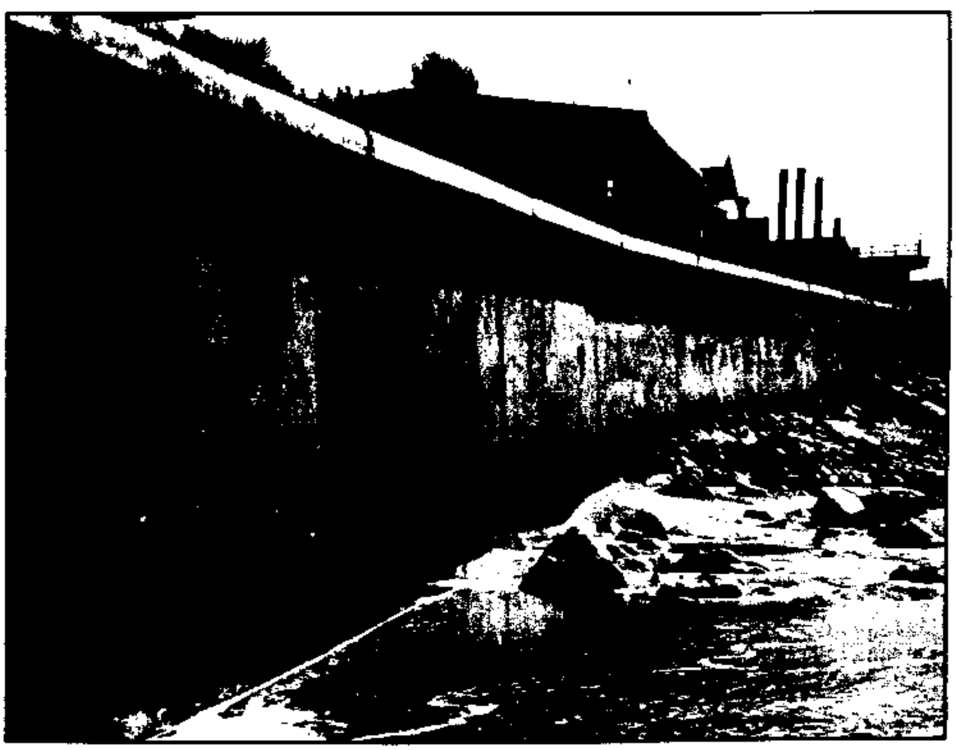


Figure 23
Wave scour has lowered beach sand levels in front of a concrete sheet pile seawall to approximately +4 feet MLLW and exposed weep holes.

Wave overtopping and vibration of the wall due to wave impact initiated piping through the weep holes forming large collapse pits behind the wall. Without the support behind the upper wall, continuing wave impact completely cracked a number of the eight inch thick, 26 foot wide panels (Figure 24). Despite the use of filter cloth and gravel behind the wall, piping of the sand through the weep holes occurred. Perforated plugs were placed within the weep holes in an attempt to halt the piping by retaining the gravel pack.

The O'Shaughnessy wall relies on a twenty-foot-wide concrete sidewalk and a foot or more of impervious, high quality clay underneath the sidewalk to keep spray from seeping behind the wall (Figure 17). Water drains rapidly off of the sidewalk through oversized drainage holes, so that it will not pond on top of the wall. Ponding of overtopping seawater or land runoff is commonly observed behind walls during large storms. During repeated overtopping, even drainage materials such as sand and gravel can become temporarily saturated. This factor needs to be more completely addressed by providing adequate surface drainage in the design of impermeable structures.

There is a general belief that concave-faced concrete walls will prevent or greatly reduce overtopping and damage by wave splash (Figure 25). Recurved seawalls, which have an overhanging section at their top, may reduce overtopping, if properly designed with respect to still water levels and maximum wave heights. Under moderate-size waves and no wind, spray does not travel as far inland behind concave walls as behind straight, vertical walls. However, under storm conditions, with high tides, large waves, and an onshore wind, Fitzgerald (1981) observed that the largest waves hitting a recurved concrete wall sent 50 foot high jets of water and debris upward, filling streets and damaging houses behind the wall. These near-vertical jets have been observed in front of almost all vertical seawalls when high tides and low sand levels allow waves to reach them. These jets may reach heights perhaps two to three times the height of the original wave and will allow spray and splash to overtop almost any structure, if blown inland by strong winds.

The Army Corps of Engineers (1977) acknowledges the problem of overtopping during onshore winds, and suggests that rip rap at the base of the wall will reduce it (Figure 20). Fitzgerald (1981) observed that after rip rap was placed at the base of a concave wall, overtopping due to high waves without wind became more frequent, but that the spray and gravel did not appear to be thrown with as much force. Where erodible material is exposed to wave action, the force of the spray may not be as critical in causing erosion as its volume and persistence. Where this is the case, overtopping with rip rap in place can still cause serious erosion.

Figure 24
Loss of fill behind upper portion of seawall through piping and wave impact led to cracking and failure of portions of this new concrete wall.

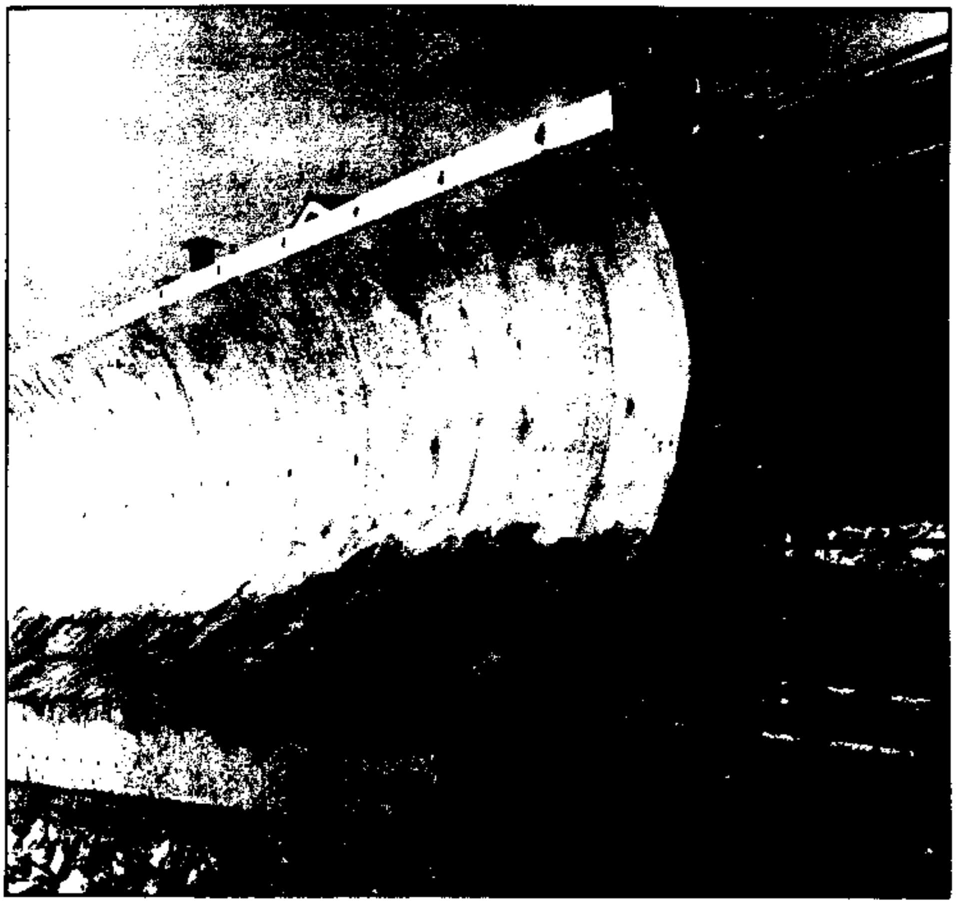


Figure 25
Curved face concrete seawall with rip rap under construction (Site 27).

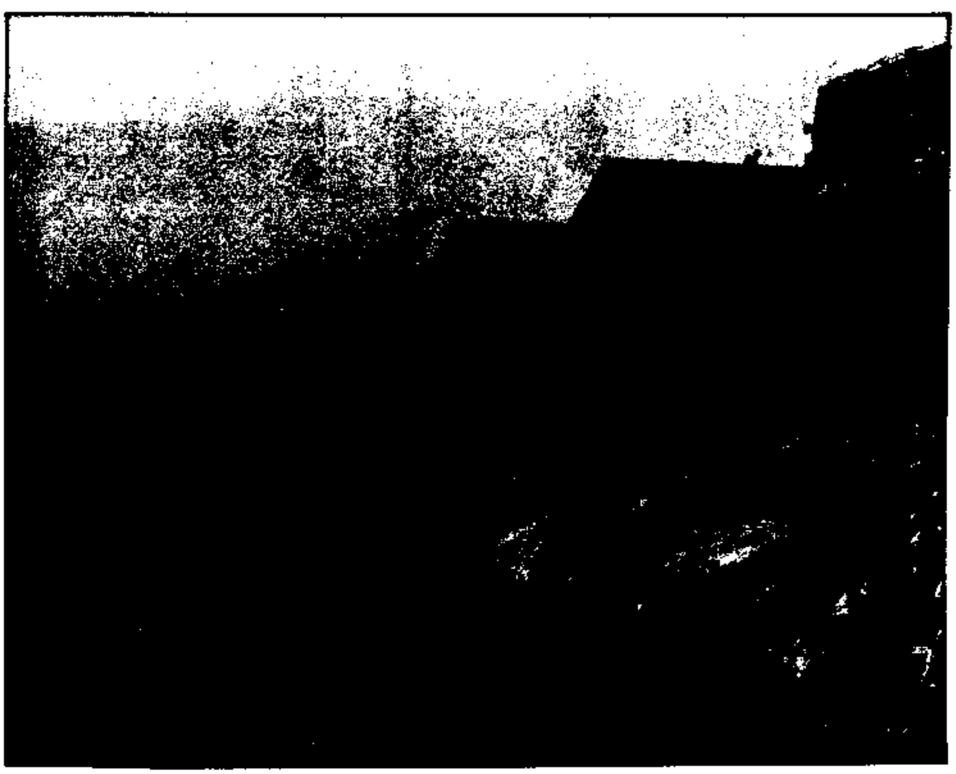


Figure 26
Curved face concrete seawall with rip rap for protection against scour (Site 27).

Summary: Concrete walls, in general, have proved to be the most durable type of protection structure within the study region. Although their initial costs are relatively high compared to rip rap and wooden walls, if they are well designed, their maintenance costs may be relatively low. The total costs for one concrete seawall fronted with rip rap built in the central Monterey Bay (Site No. 27) in 1983, reached almost $3000 per linear foot, an extreme value (Figure 26). At another location (Site No. 26, Figures 23 and 24) a concrete sheet pile seawall was completed in 1985 for $750/linear foot.

Figure 27
Low concrete seawall at base of eroding bluff in pocket beach.

The relatively high costs of well-engineered concrete seawalls, which extend both high enough to prevent significant overtopping and deep enough such that they are not endangered by scour, have virtually eliminated this type of structure from consideration by the average homeowner. Homeowner groups and assessment districts have been formed, and (in the past) public agencies have been recruited to finance projects of this sort. It is important here to stress the need for a continuous coherent wall or approach in contrast to every homeowner building their own individual structure. In such a situation the entire structure is only as strong as the weakest link. The damage along much of Beach Drive south (Site No. 26) in 1983 was due to failure of an entire group of different and unconnected walls (Figures 6, 19A-B, 31 and 32).

Beach access may also pose limitations for seawall construction. Concrete seawalls are usually built along straight, low-lying stretches of coast, and houses, roads, or other improvements are often built on the fill behind the wall. Although some small concrete seawalls have been built in front of cliffed pocket beach areas (Figure 27), the access required for construction is often a major limitation.

The two most critical problems observed in concrete wall design are, first, preventing loss of fill from behind, around and underneath the wall, and second, maintaining the wall's stability and rigidity if such a loss does occur. Concrete walls incorporating deep (at least 8 to 10 feet below MLLW), interlocking sheet piles in sand have generally been successful in sandy areas; walls based on individual pilings and those founded in exposed bedrock have proven less durable. The latter two types tend to lose fill or foundation support from underneath, as the sand or bedrock is removed by wave action. This creates a need for expensive repair, maintenance, and often rip rap toe protection. If rigid enough, concrete walls may survive such undermining by remaining suspended, bridge-like, over the eroded area, but repeated, expensive maintenance will be necessary.

Even recurved concave-faced concrete walls are likely to be overtopped by damaging wave splash during storms, especially those accompanied by onshore winds. A wide concrete apron shoreward of the wall and oversized drainage holes will help reduce damage or erosion caused by this overtopping, and will reduce ponding. However, careful design, inspection, and maintenance are necessary to insure that piping does not undermine paved areas behind concrete walls. Such undermining may be virtually undetectable from the surface.

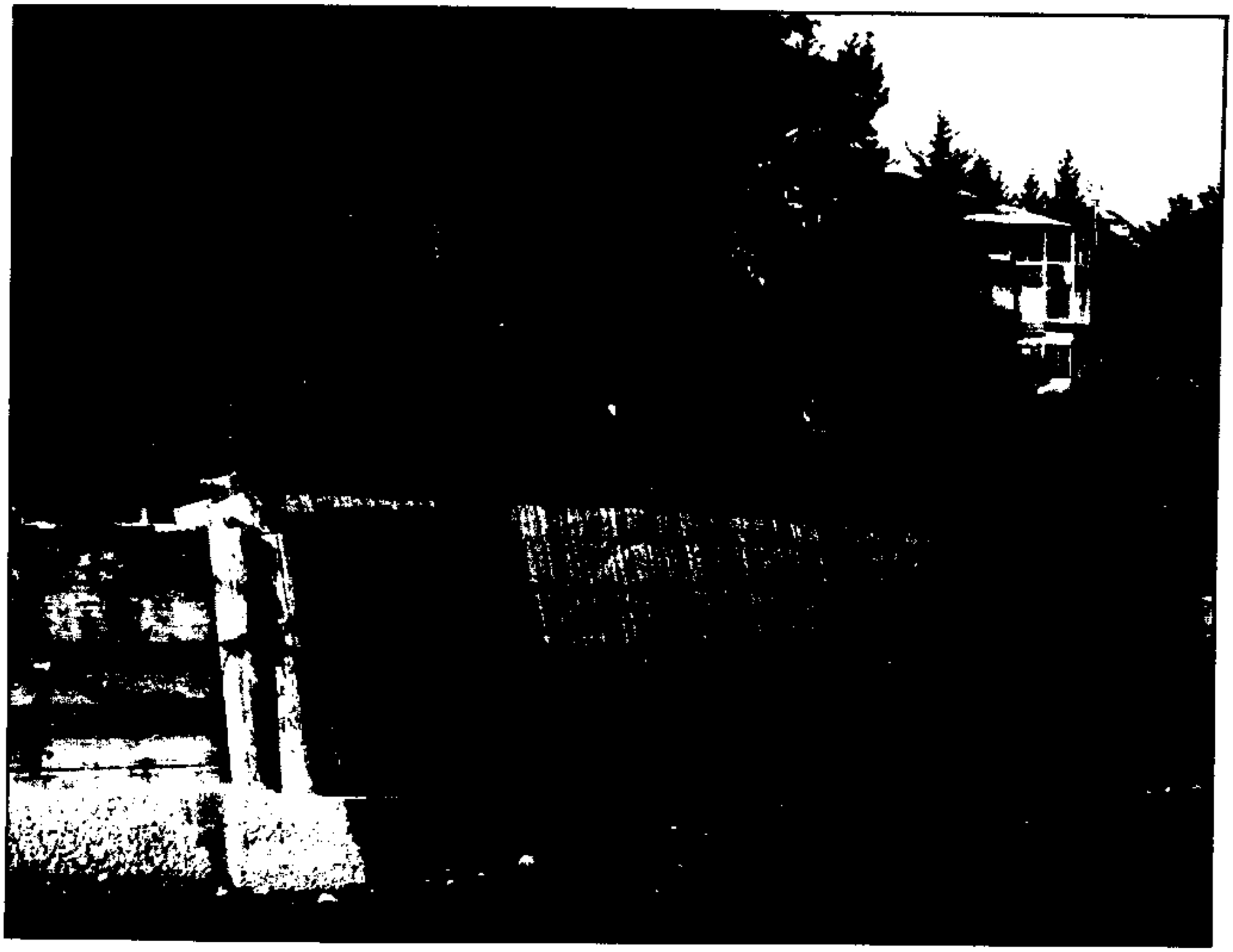


Figure 28
Several types of timber seawalls set in concrete. Inclined wall is of Wakefield type with lagging vertical as opposed to horizontal (see Figure 46 for close-up of undercutting of house in upper right).

WOODEN SEAWALLS

Background: Wooden seawalls are used for purposes similar to concrete seawalls, and may behave as bulkheads, holding back fill materials. Their effect on incoming waves is also similar to that of concrete walls, and they suffer from many of the same problems of undermining and overtopping. They are often cheaper to install than concrete, however, which probably accounts for their continued use.

Numerous designs for wood walls have been tried over the years, including the use of railroad ties and steel H-beams as vertical members. Wakefield piling bulkheads use vertical boards deeply imbedded in the sand in a tongue-in-groove arrangement, and reinforced with one or more horizontal planks on their seaward faces (Figure 28). These walls were relatively common between the turn of the century and the 1950s. Currently, the most common design within the study region incorporates vertical wooden pilings six to eight feet apart imbedded in the sand with horizontal boards (usually 3 or 4 inches by 12 inches in cross section) nailed or bolted to the landward side of the pilings. In the last decade, such walls have also incorporated filter cloth behind the horizontal wooden planks or lagging, and tie-backs into the fill behind the wall.

The Army Corps of Engineers (1956) observed that wooden walls appeared to be effective when new, but disintegrated rapidly. Their *Low Cost Shore Protection* study (1982), which deals with more protected environments than the exposed Pacific coast, found wooden walls to be most successful if treated properly to reduce rot, fastened together with corrosion-resistant bolts, and sealed from sand leakage using filter cloth or other means. Chemical treatment of wood walls is a critical necessity, but even pressure-treated wood loses its resistance to decay after about ten to twenty years of exposure to salt water and spray (Moffatt and Nichols, 1968, 1983). Smith and Chapman (1982) describe a typical failure sequence for wood walls (without filter material) as shown in Figure 29.

Observations: Wooden walls are highly vulnerable to battering by floating logs and debris, which are common along the Central and Northern Coast of California. Rip rap placed in front of the wall may minimize this problem; virtually the only wood walls within the study region which were not heavily damaged in 1983 were those augmented with rip rap to the top of the wall.

Damage to many wooden walls, with and without rip rap, was accompanied by a drop in sand levels to below the lowest boards on the walls, similar to that shown in Figure 29. This problem can be difficult to remedy, because attaching boards to the pilings is difficult or very expensive below the water table of the beach. Wakefield piling walls were somewhat more successful in this respect, and were less likely to fail catastrophically when their fill was removed by overtopping or outflanking.

Damage to many wooden walls was initiated when floating debris (such as large redwood logs) cracked or broke horizontal planks, allowing fill to erode out at these points, despite the presence of filter cloth (Figure 30). Piping can also pose a problem for wood walls. Extensive wave overtopping during 1983 storms in northern Monterey Bay produced loss of fill behind timber walls as water flowed seaward beneath and through sidewalks and paved areas. At one location (where timber lagging or wood planks were backed by two layers of filter cloth separated by a gravel layer) deflection of a cantilever wall during extreme wave conditions apparently liquified or compressed the fill behind the wall, which led to

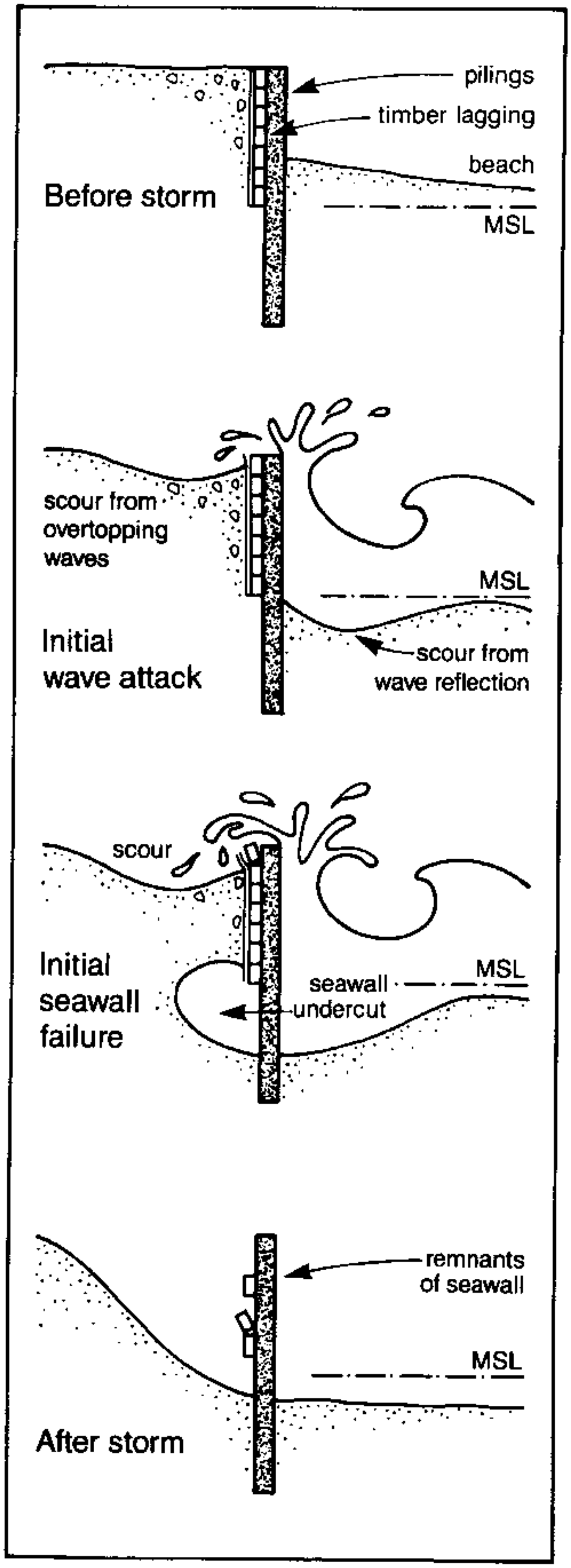


Figure 29
Typical failure mode of wooden seawall in cross-section (After Smith and Chapman, 1982)

Figure 30
Total loss of lagging from a timber bulkhead or wooden seawall. Despite presence of filter cloth, fill was removed followed by asphalt collapse.

Figure 31
Overtopping of this seawall and clogging of drain system led to piping through underlying fill and collapse of pavement (Site 25).

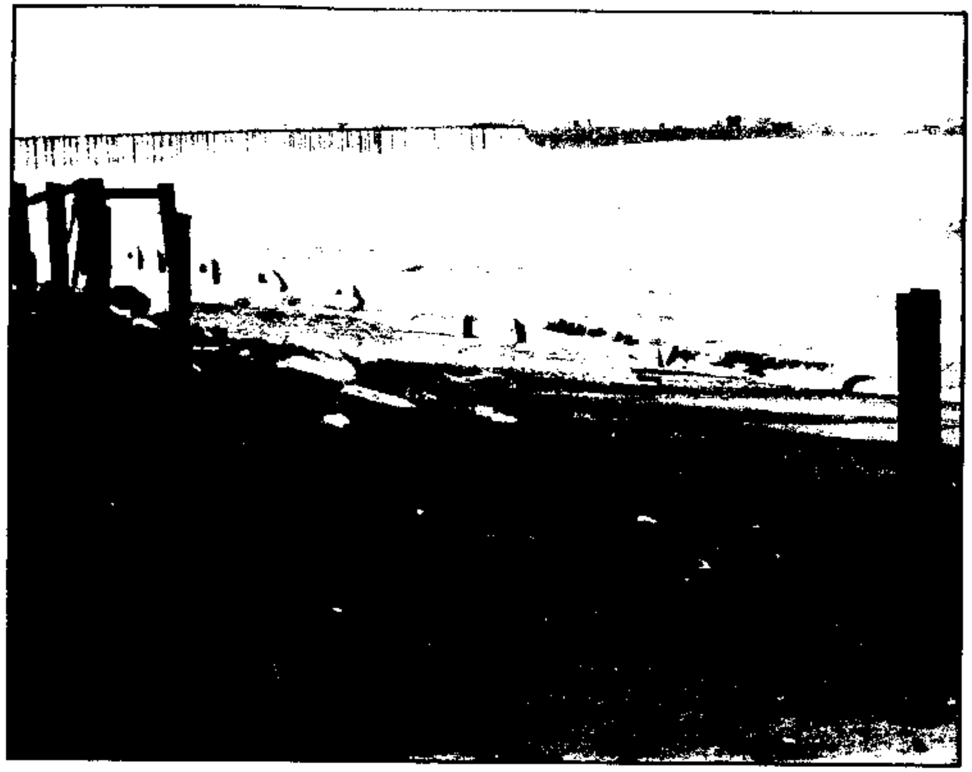


Figure 32
Loss of timber lagging and failure of pilings. This wooden wall was heavily damaged within four months of completion. Note remnants of two earlier walls in the surf zone (Site 22).

Figure 33
Removal of lagging and collapse of wooden seawall due to scour and wave impact (Site 26).

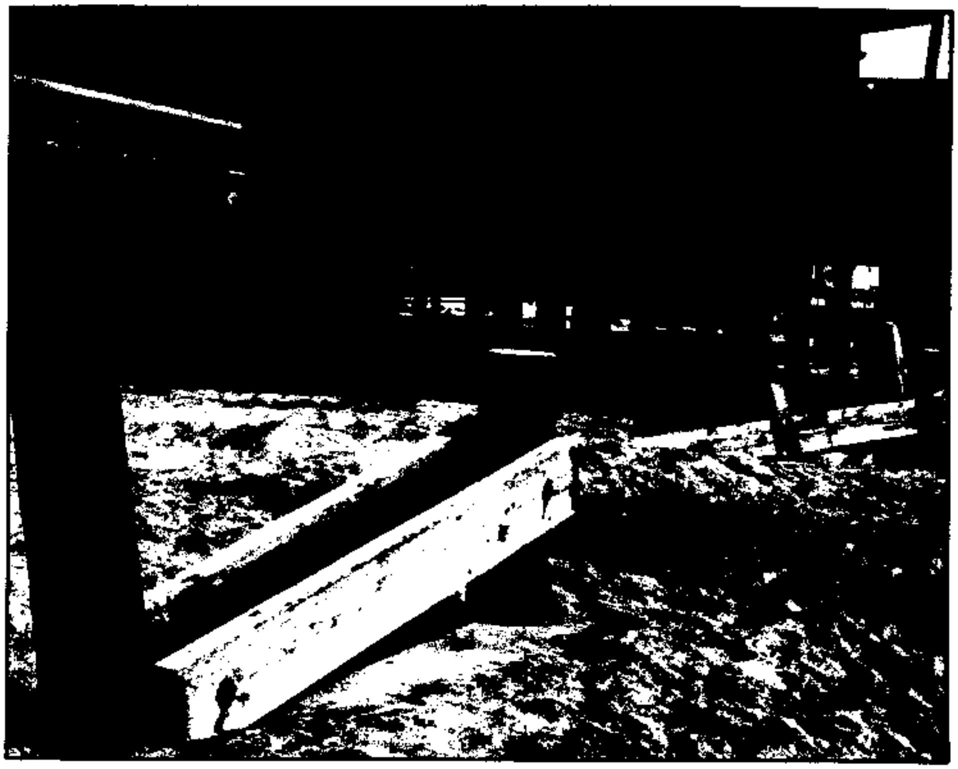


Figure 34
Scour led to settling of steel and concrete pilings and loss of lagging support (Site 26).

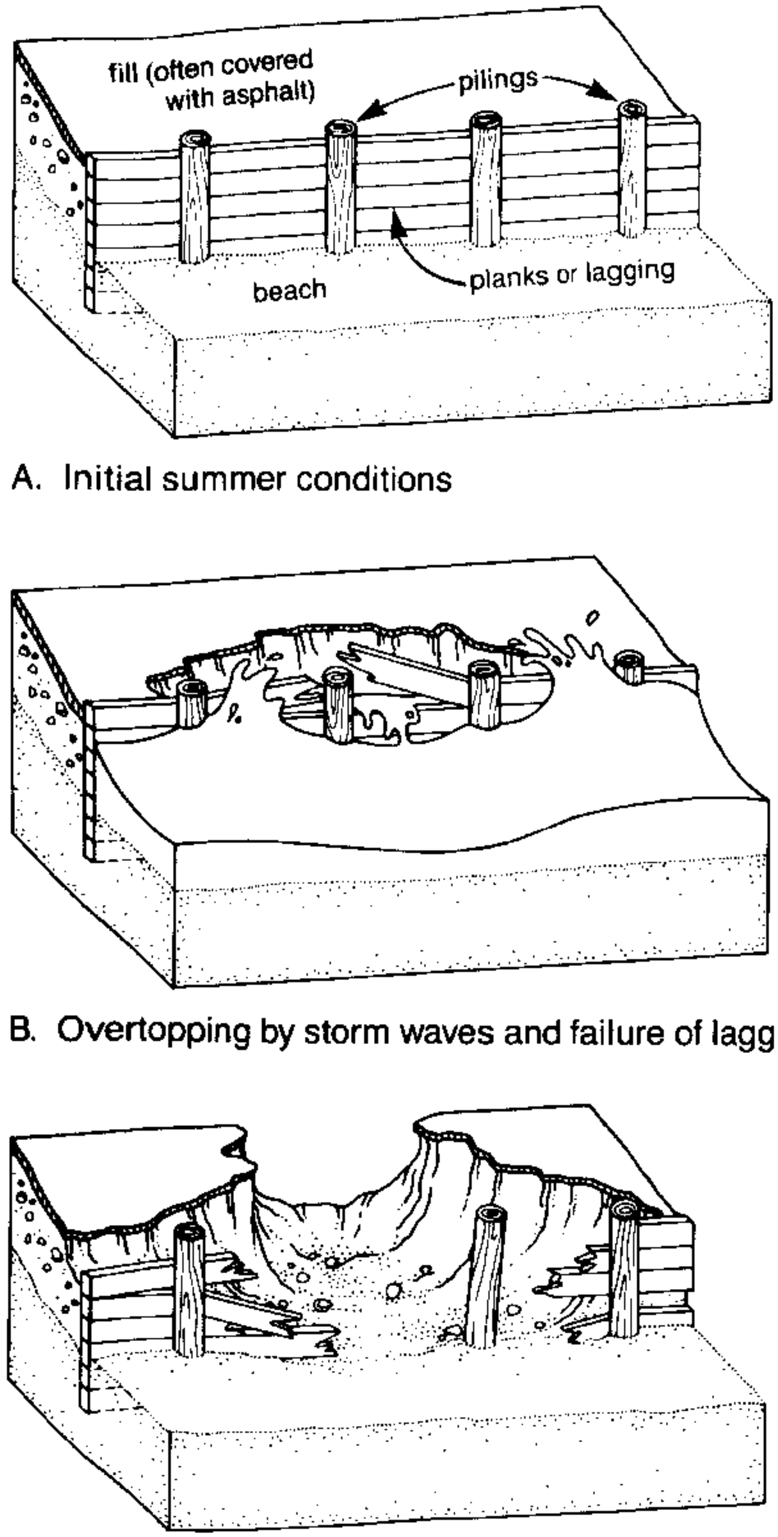
settlement and buckling of the asphalt pavement and concrete sidewalk (Figure 31). Wave overtopping followed by return flow through the cracks in the asphalt and concrete initiated piping of the fill, which compounded the problem. The wall itself however, remained intact. In such a location, tie-backs might have limited wall deflection if they weren't exposed by loss of fill. Sewer lines and other utilities in the area did not permit installation of tie-backs, however.

At many sites, vertical wood pilings had been driven deep enough, and were not undermined, but some were broken by logs and debris in 1983. The U.S. Army Corps of Engineers (1977) states that drag forces on vertical cylindrical pilings are relatively low, which may explain how they can survive, while the rest of a wall is demolished by waves. There are other examples, however, where large numbers of pilings have been broken off at beach level by large logs (Figure 32). At other locations, scour and battering led to loss of piling support and subsequent seawall collapse, detachment of lagging, or complete loss of fill (Figures 33 and 34).

Once the fill begins to erode from behind a wooden wall, the uppermost planks are almost immediately separated from the pilings by waves, either because bolts or nails are pulled out, or (more commonly) the boards are splintered by wave forces (Figure 33). This allows additional overtopping to erode fill on either side of the damaged area, causing gullying behind the wall and progressive failure (Figure 35). However, where wooden walls are fronted by rip rap, even though some fill may erode, the planks often stay in place at levels below the top of the rip rap. Where rip rap in front of wood walls settles or has not been piled to the top of the walls in the first place, both walls and property may be damaged. In the more successful cases, the wooden wall may provide a better support for the rip rap than would fill alone, and the rip rap appears to provide protection from battering and scour for the wood wall.

Historical data indicates that even treated wooden walls more than twenty years old may appear sound, but are often internally weak. They will continue to stand for decades, until a severe storm tests their strength, and then they may fail catastrophically. These recurring problems (and costs) are perhaps best illustrated at Seacliff State Beach, where major damage to walls and facilities and partial or complete reconstruction has occurred at least seven times over the last sixty years (see Griggs and Johnson, 1983; Figure 32).

Figure 35
Progressive lateral failure of wood seawall.



A. Initial summer conditions

B. Overtopping by storm waves and failure of lagging

C. Failure of wall and loss of fill

Figure 36
Seawall consisting of steel I-beams, 6 inch thick timber lagging and curved concrete cap withstood overtopping during 1983 storms (Site No. 25). The failure of the stairway at several locations was caused by wave uplift on the stairway and repeated deflection of the wall during extreme wave conditions.

Summary: Wooden walls, no matter how well designed, will usually decay after ten to twenty years in the surf zone. They are generally less expensive than either rip rap or concrete walls of the same height, but have a relatively poor ability to resist wave forces and battering by floating debris. They also have similar problems of overtopping and loss of fill as do concrete walls, but are more likely to fail catastrophically, as horizontal boards are undermined and/or removed. Their vertical pilings often survive storms however, and older walls incorporating deep interlocking vertical wooden planks may have had relatively longer lifetimes.

Because wooden walls are often relatively low and easily damaged, filter cloth behind them is often torn or removed by wave action. However, wooden walls that have been protected by rip rap revetments of at least equal height as the wood wall have survived recent storms with relatively less damage, although overtopping and settling of the rip rap still presented problems at these locations.

The utilization of Epoxy-coated steel I beams (which constrain the lagging) and 6-inch-thick timbers (Figure 36—Site No. 25) proved far more able to withstand the wave and debris impact during the 1983 storms than did wood pilings with 2 to 3 inch timber lagging (Figures 30 and 32, Site No. 22), although loss of fill behind the wall at Site No. 25 was still a problem.

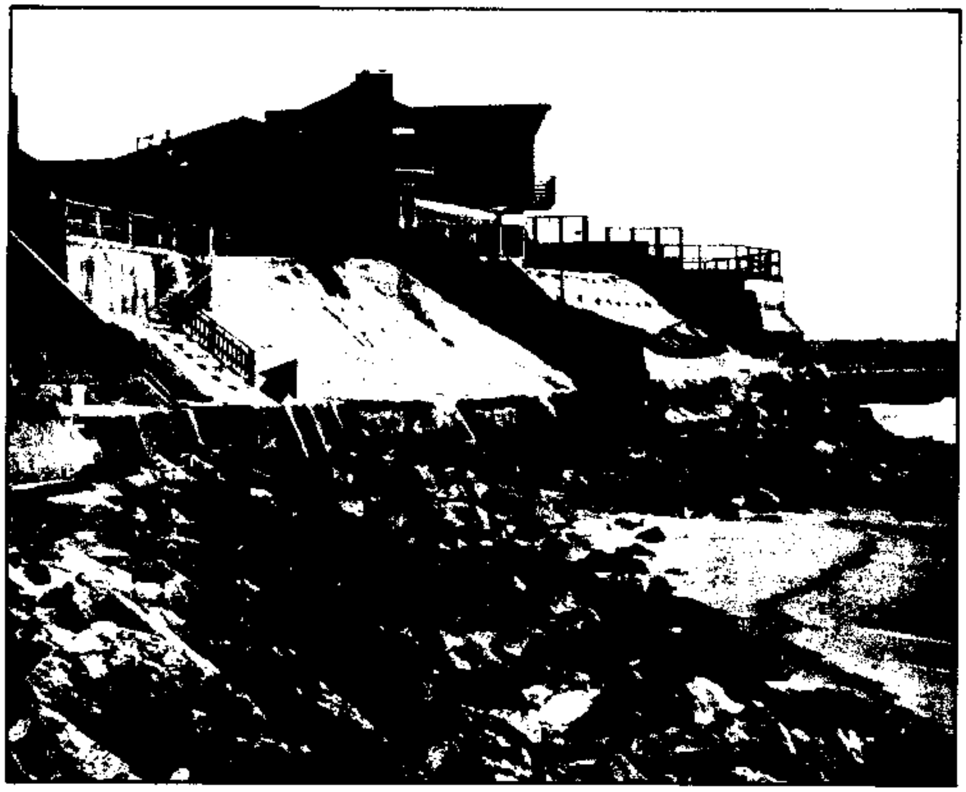


Figure 37
Concrete seawall fronted by rip rap in foreground and gunnite protected slopes in background (arrow) (Site 16).

GUNNITE

Gunnite consists of viscous concrete sprayed or trowelled over a steel mesh and/or reinforcing rod framework, and is often laid over relatively steep, erodible slopes (Figure 37). It has most commonly been used to protect terrace deposits and erodible bedrock from erosion by wave splash and spray, as well as by surface runoff. The coastal protection literature seldom mentions gunnite, probably because it is not viewed as a stable long-term solution to erosion problems. However, with continued maintenance and patching, gunnite at some sites (Site No. 16 for example) has lasted for 10 to 20 years. At each of these sites, waves only reach the gunnite during the highest tides and most severe storms. Along San Francisco's Great Highway, a low, engineered, steel wall coated with gunnite has survived from 1941 to the present, although it has been buried by sand much of that time.

A Gunnite Contractor's Association brochure states that gunnite's primary advantage is that it forms extremely strong bonds with clean, solid surfaces, such as rock, concrete, or steel. In fact, these bonds are often stronger than the base material itself. There are still many problems, however, in adhering gunnite to weak, loose, powdery materials, such as terrace deposits. Such materials allow the gunnite to be undercut if water is allowed to flow between them and gunnite. In addition, gunnite generally does not work well as an earth retaining structure, and thus should not be placed in locations where it may eventually function as such.

The Contractor's brochure makes three important recommendations for gunnite in coastal areas:

1) Extend the coverage as far below low tide as possible;
2) Use a carefully engineered system of tie-rods and wire mesh to anchor the gunnite in loose materials.
3) Install subsurface cut-off walls and/or drains to keep water from undermining the concrete facing or exerting high hydrostatic pressures.

Davis and Rutherford (1985) have successfully utilized epoxy-coated reinforcing bar with gunnite or shotcrete to prolong the life of a structure; they specify, however that the aggregate size and nozzle pressure must be limited and carefully controlled during placement to prevent abrasion of the epoxy coating.

Gunnite at all the sites along the central coast has required maintenance and repair. Cracking, puncturing, and abrasion of the surface may result in water leaking under the gunnite, causing gullying or piping in the fill behind. Erosion at the toe by wave action can also present problems. At one location, an entire gunnite wall failed by peeling off the slope after it was undermined when rip rap moved away from the toe.

Erosion along the sides (outflanking) of gunnite is also a common problem and can progress underneath the material, causing either gradual or catastrophic failure. Lateral erosion is a serious threat because gunnite has typically been applied to individual properties leaving adjacent cliffs unprotected. Protecting such flanks is often difficult. Gunnite presents a particular problem because it may be seriously weakened by loss of fill from behind, yet outwardly appear intact. However, where maintained diligently, gunnite appears to have temporarily slowed erosion of loose materials.

Figure 38
Seawall consisting of concrete filled sacks which has been outflanked (Site II).

MISCELLANEOUS STRUCTURES

The coastal protection measures described thus far are those most commonly used along the central California coast, but many other approaches have been taken as well. A few of these less common types are described below, and comments on their advantages and limitations are given. Because too few of these structures have been observed, generalizations cannot be made on their historical effectiveness.

Masonry Walls: Masonry walls have been used for centuries in England and Europe, and a few exist along California's central coast. Some of these California walls are quite old, dating from the nineteen twenties and thirties. Most are founded on relatively resistant bedrock, and are only exposed to wave action during severe storms. These rigid, vertical walls may behave similarly to the concrete walls, although they may have less internal strength than reinforced concrete. Like concrete walls, bedrock erosion behind or under the wall would eventually cause most difficulties.

Steel Bulkheads: Sheet steel bulkheads have been extensively used in sheltered waterways, but are relatively rare in this open-coast region. One sheet-pile wall coated with gunnite has survived since 1941 near San Francisco's Great Highway, though it has been buried under sand much of that time. The remnants of a sheet steel wall, built in the 1920s (?), are occasionally visible at low tide at Seacliff State Beach. Deep sheet-steel walls may be relatively resistant to undermining by beach scour (if placed deep enough) but the metal may be rapidly degraded by salt water and air. Certain types of treated or coated steel, such as "Mariner Steel" are formulated to survive in the harsh marine environment, but even these will probably have limited lifetimes compared with concrete walls. Another problem with sheet steel seawalls is how to provide adequate drainage of fill behind the wall. One solution would be to provide drainage through the wall; another would be to tie the steel into a concrete apron, so that all water would be drained over the face of the wall rather than collecting behind it.

Concrete Sand Bags: Concrete-filled sacks placed over steel reinforcing rods have been used to protect terrace deposits and sea cliffs (Figure 38). Some of these walls have been outflanked, in part because they allowed water to collect and then run off to either side, even where shallow flanking walls were used. Surface runoff from streets and sidewalks combined with water from overtopping waves to cause these problems. Several walls of this type failed completely in 1983, and others were threatened. Those which were not exposed to frequent wave splash did not suffer from severe outflanking problems. The stability of the foundation material beneath these walls is also an important factor in their survival.

Gabions: Rock-filled wire cages, or *gabions*, normally used for stream bank protection, were used as emergency slope protection at some sites during 1983 storms. None of these gabion walls have experienced severe storm conditions since their installation, so their effectiveness remains to be seen. Their lifetimes will be limited by abrasion and corrosion of the wire mesh, as well as the stability of the surface upon which they are placed (sand, bedrock, etc.), and severity of wave conditions.

Cribbing: An interlocking system of concrete or wooden rails, cribbing is commonly used to support potentially unstable highway cuts. It has also been used to protect terrace deposits at several points within the study area. Where these structures did not experience direct wave attack; they performed relatively well. One wall apparently failed because the wood beams were old and the fill had become saturated by overtopping. One recently-installed crib wall relies upon a single layer of filter cloth to retain fill in a potentially high wave-impact setting. This filter cloth, though not yet reached by waves, has already been torn by vandals and burrowing animals. It appears that this wall will be quite vulnerable to loss of fill when wave conditions such as those of 1983 recur. Closed-face cribbing would certainly be more appropriate for coastal environments, but still is vulnerable to loss of fill initiated by overtopping and outflanking. Light-weight cribbing members might also be moved by severe, direct wave attack.

Figure 39
Steeply stacked rip rap on filter cloth collapsed onto beach as beach sand was scoured during heavy wave attack.

FILTER CLOTH

Background: In the past decade, the use of filter cloth in coastal protection structures has greatly increased. The term filter cloth is used to refer to a wide variety of synthetic materials whose primary purpose is to permit the passage of water, while preventing the transport of sand, or in some cases, silt-size particles. By relieving hydrostatic or seepage pressures, (the pressure from the accumulated water) filter cloth is supposed to eliminate piping of soils or sand from underneath or behind seawalls, and to reduce forces on the walls themselves (Moffatt and Nichols, 1983). It must also resist clogging, abrasion, and degradation by saltwater and sunlight. Common coastal applications of filter cloth are for lining for the landward side of wooden seawalls, and behind and underneath rip rap, sometimes in combination with a layer of smaller core stone, gravel or gabion-rock.

The durability of various types of filter cloth varies greatly, in part due to a lack of standardization (Moffatt and Nichols, 1983). Of the three major types, woven, non-woven, and slit film, woven materials are generally better for harsh environments (Moffatt and Nichols, 1983), and are less likely to clog than the felt-like non-woven fabrics (Dunham and Barrett, 1974).

Many authors stress the need for careful selection and placement of filter cloth, especially for use underneath rip rap. To reduce the possibility of piping between adjacent sheets of filter cloth under saturated conditions, Moffatt and Nichols (1983) suggest at least 36" of overlap, and that the material not be placed on slopes steeper than 2.5:1. In addition, Dunham and Barrett (1974) state that if the material protected by a standard mesh filter is made up of more then 50% silt and clay (which could easily apply to estuarine and terrace deposits), the filter should be underlain by a six-inch layer of sand, to prevent piping or clogging.

When rip rap is placed over filter cloth, the fabric must be loosely placed, but without creases or folds, and the stone should not be dropped from a height of more than one foot (Moffatt and Nichols, 1983). Dunham and Barrett (1974) state that, for rock weighing more than two tons (which includes most rip rap in this study region), a layer of smaller filter stone directly over the cloth is necessary to prevent tearing of the cloth (Figure 9). They add that at least two layers of rip rap should always be used, or under cyclic wave attack, "a pumping action can be expected to develop, which will displace the stone and the soil under the cloth, thus exposing the cloth to the full brunt of the attack."

Once in place, filter cloth is most vulnerable at the top and the toe of a structure. Moffatt and Nichols (1983) suggest that at the toe, and wherever filter does not cover an entire slope, it must be keyed in a trench.

Observations: It is difficult to tell how adequately and under what conditions filter cloth has achieved its purpose at the study sites. At least three or four walls in which rip rap was installed over filter cloth have suffered from some settlement. At one northern Monterey Bay site (Site No. 20), a carefully engineered rip rap revetment with filter cloth sank approximately one to three feet during the first year after it was installed. It was repaired, and sank an additional two to three feet in 1983. At several other sites low rip rap revetments apparently slid down the slopes against which they were piled, leaving the exposed filter material to be damaged by waves and debris (Figure 39). The total settlement may have been reduced by the use of filter cloth at these sites, but differences in design and environmental conditions make comparisons with walls at other locations difficult.

Not only is the quality of filter material quite variable, but it is frequently used in ways that may do more harm than good. For example, filter material has been placed over steep (greater than 2.5:1) erodible slopes, at many sites. In some cases, this rip rap has moved down the slope, possibly because the cloth reduced friction between the rock and the slope. Once the rip rap slides, the exposed filter material is vulnerable to wave attack. However, there are few, if any satisfactory methods for protecting slopes behind rip rap from splash erosion.

Where exposed directly and repeatedly to sunlight or storm waves, almost all filter cloth weakens rapidly, and is likely to tear. At least three different types of filter cloth were observed in the field which could be torn with bare hands after being in place only one to three years. Tearing of filter cloth is very difficult to avoid when placing rip rap. However, the effects of relatively small gaps or tears can be quite important, especially where piping is likely to occur.

Summary: In sandy foundations, where both filter cloth and rock are installed deeply and carefully, the cloth may reduce the amount of settling of stones. However, filter cloth probably will not, by itself, reduce seaward movement of toe stones, nor will it protect steep, erodible materials above and behind the wall from erosion by significant amounts of wave splash. In all seawalls, the filter material will remain intact only as long as it is not directly exposed to wave attack. Even behind rigid seawalls, because its permeability is small relative to the amount of water that can overtop such structures, filter cloth may not be able to effectively reduce hydrostatic pressures under storm conditions.

GENERAL PROBLEMS

OVERTOPPING

Overtopping is defined as the transport of significant quantities of ocean water over the top of a seawall, either as greenwater, splash, or spray. Overtopping causes damage in several ways, by exerting direct vertical and horizontal forces, and by eroding material from behind walls.

In most coastal environments it is not practical to build a seawall that will not be overtopped during severe storm conditions. At many sites, cost is a limiting factor. For example, for a rip rap revetment with a triangular cross section, and fixed seaward slope, the volume (and cost) of rock required is proportional to the square of the height. Where property behind the wall is at a relatively low elevation (less than 15 to 20 feet above Mean Lower Low Water), aesthetic and beach access problems may limit seawall height. Few coastal residents or cities are willing to build seawalls which will significantly block their view of the ocean.

Standard runup calculations for seawalls typically consider only the frequency of overtopping by greenwater. The height of this runup is usually calculated using empirical or theoretical formulae based on water depth, beach slope, significant wave height, wave period, maximum expected sea level, and the type of structure involved. Unfortunately, these calculations often ignore the potential effects of overtopping by wave splash, and the erodibility of materials behind and above the seawall.

Vertical Forces: Both greenwater and wave splash can exert strong upward, vertical forces on structures and materials near the crests of seawalls, especially those with vertical faces (Figure 36). Where moderately deep water lies in front of a vertical seawall, even relatively small (3 to 4 foot high) breaking waves can send jets of water up to twenty feet in the air. In high-surf conditions, the vertical forces exerted by such jets have destroyed overhanging decks and floors of ocean-front homes.

At several sites, vertical wave forces have lifted rip rap and other rocks up to one to two feet across from the base of vertical walls and erosion scarps, and thrown them inland. Where vertical seawalls or rock cliffs face deep water, waves have broken off immense blocks of stone (up to 50 cu. ft.) from the crest of the wall or bluff, and rolled them landward.

Horizontal Forces: Water overtopping seawalls in the form of greenwater or splash can also exert significant horizontal forces on structures or materials behind the wall. Matthews (1934) documents damage to buildings twenty feet inland from vertical masonry seawalls. Where low seawalls are overtopped by whitewater bores, these bores may cause great flooding and property damage hundreds of feet inland. This damage may be increased if floating logs and debris are floated or thrown over the wall (Figure 40).

Rip rap walls are generally assumed to have a lower runup coefficient than smooth concrete or timber walls. However, because of their sloping seaward face, splash or greenwater overtopping rip rap walls may have a greater horizontal component of velocity than splash over vertical walls of the same height. Wave splash has been observed to travel further inland at locations where rip rap has been placed than where waves hit vertical bluffs. Waves overtopping high rip rap (19 feet above MLLW) knocked out entire home fronts at Via Gaviota in northern Monterey Bay, during storms in 1983 (Figure 41).

Erosion of materials above and behind seawalls is one of the most widespread problems observed, perhaps because it can be caused by greenwater, wave splash, and even spray. The effect of very large volumes of runoff water on coastal structures has often been underestimated and should always be considered in designing those structures.

Erosion behind seawalls is a complex process, combining direct wave action, falling splash and spray, subsurface piping, and gullying by surface runoff. Saturation of soils may play a major part in the last two processes.

Figure 40
These logs were thrown over a vertical wooden seawall at Seacliff State Beach (Site No. 22) during the winter of 1983.

Frequent inundation of soils and sand by wave splash and spray (and often rain) can create temporarily saturated conditions within the upper layers of soil, resulting in ponding behind seawalls. This occurred behind virtually every vertical seawall observed during the storms of 1983, even those with filter cloth and other "through the wall" drainage systems. If ponding is severe, water will begin spilling over the side or front of a seawall, in some cases causing loss of fill or outflanking. Once saturated, soils become increasingly susceptible to gullying and piping. Both these processes tend to follow paths of least resistance, gullying being most likely around the flanks and low portions of seawalls, and piping occurring at minute cracks, joints, tears in filter cloth, or other regions of concentrated flow.

Where water cannot exit directly, it may flow behind a seawall, parallel to shore, for hundreds of feet, before finding a weakness or gap in the barrier (Site No. 25, 1983). To counter this problem, the O'Shaughnessy Seawall incorporates a series of deep cutoff walls at right angles to the main wall, at one hundred-foot intervals, so that if one section of the wall failed or was undermined, it would be less likely to affect adjacent sections.

UNDERMINING

Undermining of seawalls occurs when foundation material (usually sand, fill, or rock) is removed by waves. This may take place not only when beach sand is scoured or fluidized, but also where bedrock erodes rapidly during storms. In either case, the result of undermining is often rapid loss of fill from behind a wall, and in some cases, structural failure. Undermining of rigid walls can be difficult to recognize, since it may remove subsurface material, while leaving visible portions of a wall and paved surfaces behind the wall intact. Undermining of rip rap walls is more obvious, since these "flexible" structures will settle into the undermined area.

Predicting the level to which a beach may be scoured, and the exact wave conditions which will cause scour is difficult, at best. Coastal engineers have used a variety of "scour depths" in designing seawalls. Most of these are within 3 feet of the Mean Sea Level in the Monterey Bay area (where 0 feet Mean Sea Level equals approximately +3' Mean Lower Low Water). However, rip rap has been observed to settle to depths of five to ten feet below Mean Sea Level, as it moves seaward under wave attack.

Figure 41
House fronts placed at the top of an engineered rip rap revetment without setbacks were seriously damaged as waves washed up the ramp formed by the rock during an extreme high tide (Site 27).

Since there are no widely accepted formulas for calculating these depths, estimates based on field observations made during or (more commonly) after storms are used. Because of the rapid rate at which beaches may be rebuilt after being scoured under severe storm conditions, observations made days after a high tide period (when the beach is not inundated by storm waves) may be misleading. In areas where bedrock is deep, borings are often used to determine the depth of storm lag deposits, consisting of gravel and cobbles. However, several such layers are often encountered, and in the absence of accurate dating methods, the selection of a design or expected scour depth can be quite uncertain.

The depths to which scour occurs depend heavily on how far landward or seaward a structure is located on the beach profile. Within this zone, the depth of beach scour and liquefaction should increase rapidly with increasing distance seaward. Thus, there is an inherent problem in any solution that involves moving a structure seaward—the amount of energy it receives and the scour at its base will be greatly increased. For example, one rip rap revetment in northern Monterey Bay (Site No. 27) was designed for a scour depth of 0 feet MLLW, and a height of 19 feet MLLW—equal to or greater than those of adjacent walls. However, because this wall was approximately 100 feet seaward of the other walls in the area, it suffered much more severe overtopping and undermining during 1983, and ultimately failed altogether.

One of the most controversial questions relating to beach scour is whether seawalls lead to sand loss in front of them. The Army Corps of Engineers (1977, 1981) indicates that toe scour can be expected in front of a seawall, and Smith and Chapman (1982) describe such an effect in front of rip rap walls in Australia. Observations along the central coast of California have turned up no conclusive evidence that seawalls caused beaches to become narrower over time at any of the study sites. However, this effect is difficult to observe using primarily qualitative data. It might also be quite transitory, only occurring during storms and high tides, when the greatest wave energy is exerted at the base of the wall. In any case, rip rap seawalls, because they are so wide relative to vertical structures, can cover significant portions of sandy beaches, making them less usable for recreation and somewhat hazardous for public access. The summer beaches at many locations have not gone away, but may simply build up against the cliffs, under the revetments, as if the rocks were not there.

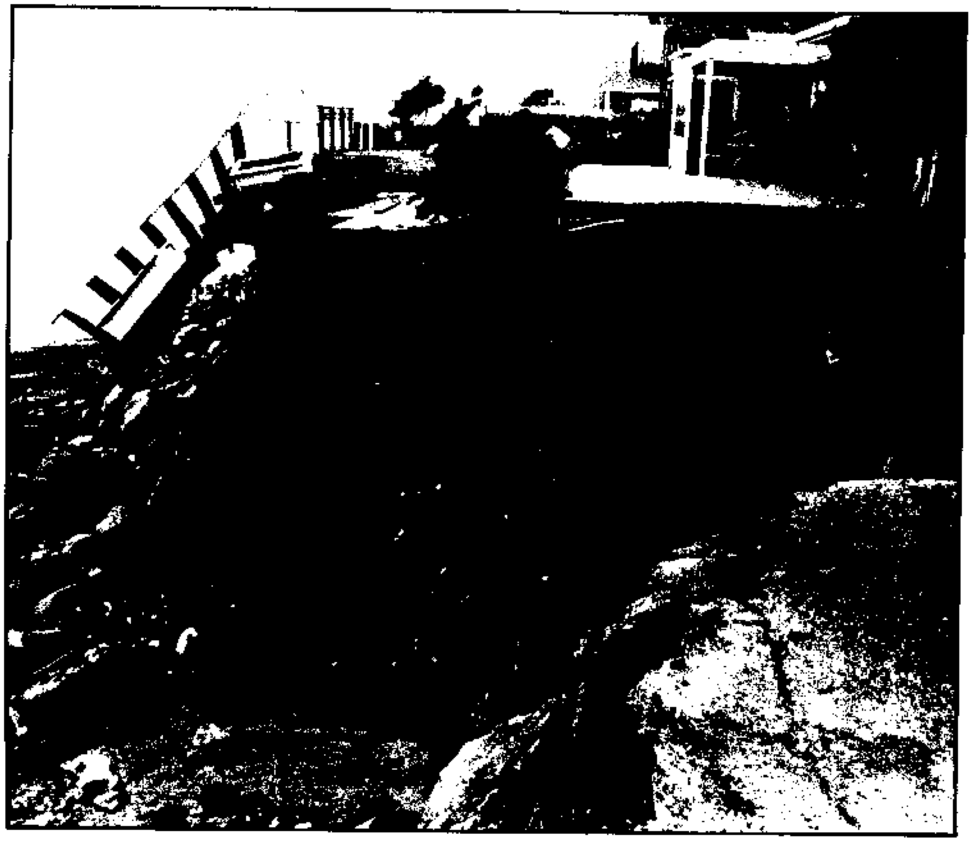


Figure 42
Rip rap has been outflanked leading to serious erosion of unprotected area as well as property itself (Site 14).

OUTFLANKING

Outflanking occurs when material to either side of a seawall erodes to a point where it threatens or damages the wall itself, or property behind it. Along a progressively eroding coast, all successful, isolated protection structures will be gradually outflanked, because the coastline on either side will erode more rapidly than that behind the wall. This is a relatively predictable process, and should be planned for in the design of any isolated wall in a rapidly eroding area. Most often, it is taken into account through the use of "wing walls" running landward from the ends of the main structure. However, because of high costs and practical difficulties (particularly along cliffed coasts), such future outflanking is usually ignored until it causes property damage (Figure 42). In this case, the costs of outflanking must be considered in the expected maintenance costs and overall lifetime of the structure (Griggs, 1986).

Often, outflanking of one wall leads to the construction of additional walls adjacent to the first. As the amount of continuously protected coastline increases, outflanking becomes a problem in the unprotected gaps. Nonetheless, both for isolated walls and for gaps in protected coastlines, one question remains: do sea walls increase the erosion of adjacent areas?

The answer to this question depends on many factors, such as how far seaward the wall extends, the type of coastal environment, and the type of wall involved. No systematic observations have apparently ever been made to support a generalized answer to this question for the California coast. For two concrete walls in dune environments, (Sites No. 1 and 3), no accelerated wave-caused erosion along the flanks of the walls has been documented. Rip rap at one site settled much more around gaps in the continuous revetment than elsewhere during 1983 storms. However, this settlement may have been due to outflanking, or to some other factor.

Rip rap revetments placed within some rocky coves appear to have increased erosion problems along their flanks. This increased erosion may be due to a concentration of wave energy in indentations of the rocky coast, especially during storms and high tides. During high tides and low sand levels, wave splash is thrown further inland from these indented areas than from the more linear portions of the bluffs. This situation may be analogous to that created by indented portions of seawalls, or gaps between seawalls.

RECOMMENDATIONS

☐ CONCRETE RUBBLE

This material should only be used for temporary protection in relatively low wave environments. It should not be dumped along with dirt or other loose fill, and should be stacked at a low angle (3:1 or less), to reduce settling. Elongated or flattened pieces should be removed if practical, but the material will still be much less stable than rip rap, due to its tabular form, relatively low density, and low friction between units. It is recommended that rubble not be used for core material in rip rap walls, especially if concrete pieces are likely to be placed at the toe of the wall or exposed by minor failure of the armor stone. It also presents an particularly serious aesthetic problem.

Large concrete blocks are not likely to provide any significant protection on sandy beaches during storms, since they not only sink into the sand, but may disperse rapidly. Even very massive blocks (5 to 15 tons) are not recommended for simple placement on top of sand surfaces. They must be rigidly tied together, so that if they settle, they will still present a continuous barrier to the waves. Even so, they will be difficult to stack high enough to provide significant protection from overtopping, and are likely to be outflanked.

☐ RIP RAP

In placing rip rap over bedrock, the most important need is to determine the depth to bedrock offshore, as well as along shore. By identifying low areas in the rock, such as surge channels, and areas where rock platforms slant steeply seaward, the degree of seaward spreading of the revetment can be anticipated. Excavating a keyway in a bedrock surface should be helpful, unless the rock surface is narrow, slopes steeply seaward, or is likely to be eroded by wave action (either because it is weak and only exposed when severe storms remove sand, or because it is constantly exposed to wave action and abrasion).

For engineered rip rap on sand, at least 2 to 5 feet of vertical settlement must be planned for in design; for non-engineered rip rap placed on top of sand, as much as 10 to 15 feet of settlement is possible. In general, rip rap should never be dumped directly on top of the beach surface, but this is particularly true in late summer, when sand levels are usually highest. Because it's maintenance costs are so high, non-engineered rip rap may cost more than engineered rip rap in the long run. In sand, a deeply buried toe (-3 feet MLLW) of large rock (3 to 5 tons) and filter cloth may reduce downward movement of the rock, but may be less successful in preventing toe stones from rotating and/or moving (horizontally) seaward. Finally, the strategy of engineering a toe does not provide a guarantee of overall stability, because even minor rotation and settlement of toe stones may destabilize the upper portions of the structure.

For all rip rap walls, both vertical and horizontal settlement should be planned for, either by building the wall higher and deeper than necessary for a design storm, or by preparing for the rapid addition of new rock under storm conditions. The second strategy may allow significant damage to occur behind the wall if it settles rapidly and unexpectedly. Because virtually all rip rap walls will settle, they should not be used as foundations for any permanent, rigid structures. Finally, rip rap is much more stable at a 2:1 slope than at the standard 1.5:1, but varying the slope may be secondary in importance to controlling settlement of the stone. Where property boundaries are not a problem, rip rap stacked in mounded, self-supporting walls should require less long-term maintenance than revetments.

Some erosion and structural damage caused by splash overtopping of rip rap revetments against bluffs up to 30 feet above MLLW can be prevented by piling the rip rap up to the top of the bluffs (to protect terrace deposits). In 1983, lots on 30 foot cliffs along northern Monterey Bay which had rip rap piled to the top of the cliff experienced much less erosion of terrace deposits than did similar lots with rock only part way up the bluff. For bluffs less than 15 to 20 feet above sea level, even piling rip rap above the level of the bluffs may not eliminate erosion, flooding, or damage by overtopping.

Filter cloth does not significantly reduce gullying due to wave splash and water running over the bluffs from streets and other impermeable surfaces. Where rip rap has settled, or is low to start with, erosion behind the revetment is particularly difficult to prevent. Careful attention to drainage paths, and the use of filter cloth, filter rock, or gunnite may help, but all will be damaged by direct wave attack. In low bluff areas, such as those in San Mateo County, replacement and repair during and after storms may be the only viable option, short of building walls so high or so wide that overtopping splash will not reach the erodible material behind the walls. Such walls would not only be prohibitively expensive, but would probably cover significant summer beach areas and/or block any view of the ocean from these areas.

CONCRETE SEAWALLS

Concrete walls founded on rock must be deeply embedded in the rock (5 to 10 feet) to provide a safety margin, if the bedrock is erodible or subject to frequent wave action. At every study site, engineered concrete structures proved more resistant to erosion than the bedrock around them, and thus were likely to be undermined or outflanked before significant degradation of the concrete occurred. Rip rap placed at the toe and flanks of such structures may help reduce these problems, but the rip rap itself often settles during storms, exposing the base of the wall.

Concrete walls on sand should incorporate deep (to -8 to -15 feet MLLW depending on the height of the wall), interlocking sheet pilings, to eliminate the possibility of sand being scoured out from underneath the toe of the wall. The interlocking segments should be carefully grouted with some material (flexible not brittle) to as great a depth as possible (in theory, walls should be grouted to the expected depth of beach scour and/or liquefaction) to prevent piping of sediment from behind the wall. In all cases, the walls should be at least 10 to 12 inches thick, and designed to retain their stability and structural integrity even after major loss of fill. They should also be inspected after every major storm, if possible, to identify any loss of fill before it becomes a major problem.

The potentially large volumes of seawater overtopping concrete walls must be drained carefully. The best approach is to do as O'Shaughnessy did in San Francisco: Prevent water from seeping in behind the wall by installing a thick, continuous reinforced concrete apron (not clay or asphalt) extending ten to twenty feet landward of the wall, grouted, and underlain by a layer of impervious clay. Also, oversized drainage holes should be incorporated at the seaward edge of this apron to allow rapid drainage during severe overtopping conditions.

WOODEN SEAWALLS

Wooden seawalls, even when new, are generally less able to resist direct wave forces on an open coast than concrete or rip rap walls. The repeated destruction of piling and timber walls indicates that they should not be used by themselves, especially where large logs and debris are likely to be washed ashore during storms. Also, they should not be expected to maintain their structural rigidity after more than about twenty years, if that long.

Because they are limited by the strength of their materials, wooden walls at most exposed sites cannot be made high enough to eliminate overtopping. Also they can seldom be constructed deep enough to resist undermining. Using a concrete apron to prevent overtopping water from seeping into fill behind a wooden wall will be successful only if the apron is very well sealed and drained. Alternately, a region 10 to 20 feet inland of the wall may be filled with large filter stone. However, large volumes of water will then be forced to drain out through, around, or beneath the wall, and accommodating this water may be difficult. Another option that can be used in some cases is to direct surface water inland into oversized storm drains, which will not be clogged by sand and debris.

Wooden walls, like other seawalls, should not rely on the fill behind them for stability, because this fill is often washed out by waves, exhuming buried deadman anchors. Wooden walls incorporating horizontal planks on both the landward and seaward sides of their pilings may resist wave forces better than those with only one layer of planks (Figure 43). However, if the supporting pilings themselves do not extend deeply enough, then failure can occur through scour (Figures 32 and 33). Timber lagging (four to six inches thick) placed in the slots of steel H beams which are driven into the sand, fared somewhat better than piling-supported structures, particularly where drainage has been incorporated into the structure. Incorporating a reinforced concrete cap into the wooden wall may also help prevent the removal of planking (Figure 36). Wakefield piling walls appear to resist undermining and loss of fill better that the designs generally used today, but they are even more limited in maximum height, due to earth pressures.

Figure 43
"Sacrificial" lagging was added to the front of this timber seawall in an effort to prevent damage to the wall from wave and debris impact.

Undermining of the lowest boards on wooden walls can best be reduced by placing rip rap in front of the wall to a level at least even with the top of the wall. This measure will also reduce damage caused by floating debris, if the rip rap does not settle too much. Four to six inch thick lagging should provide greater resistance to debris battering than do two or three inch thick planks.

■ AVOIDING DAMAGE TO BUILDINGS AND PAVED AREAS

Buildings: Assuming that for economic and aesthetic reasons, seawalls will continue to be built to allow some splash overtopping, some precautions can be taken to minimize damage caused by this overtopping. Wherever possible, decks, buildings, and all other permanent structures should be set back as far as possible from the crests of seawalls, preferably twenty feet or more (depending, of course, on such factors as the seawall height, wave exposure, and local geology). To protect such structures, a concrete splash wall three to five feet high should be erected behind the main seawall, especially where the top of the main wall is less than 15 to 20 feet above Mean Lower Low Water. Alternately, all or part of the seaward wall of a building may be reinforced and designed as a splash wall. However, this will usually leave weak points at doors and windows, and provides little margin for error if large waves, rocks, or debris may be expected to hit.

Concrete slab foundations on short pilings or poured directly over sand or other loose deposits are most susceptible to serious damage by scour or erosion behind seawalls. Even a small amount of scour or liquefaction under the seaward edge of these foundations can cause them to crack, settle or tilt seaward, destroying an entire house. This took place at a number of locations along the California Coast in 1983 (Figure 44). Buildings on deep (well below any maximum scour depth), carefully poured concrete pilings, and those with high floor levels, generally fare better than buildings with low floors and/or wooden pilings. A strong bond between the piling and the floorings is also

Figure 44
Complete destruction of house on far left occurred when slab foundation was undermined and tilted seaward. Only minimal rip rap protected house.

important to resist vertical wave forces. In general, the further inland on a beach a building is, the less wave damage it will incur, if the factors mentioned above are all equal. However, flooding and damage caused by debris are still possible far inland on a wide, flat beach particularly near stream and lagoon mouths (Figure 45).

Bluff-top houses are seldom damaged directly by wave forces, but are often threatened indirectly by flooding and/or erosion, depending on the height of the bluff (Figure 46). As indicated elsewhere, a well-maintained seawall (along with periodic bluff fill in some severe cases) may significantly reduce long-term erosion, particularly at the toe of a bluff. Small but strong splash walls can reduce flooding damage in areas with low, easily overtopped bluffs, but should be located as far inland as possible to make them less vulnerable to undermining if cliff retreat occurs. Along high bluffs, unprotected terrace deposits often continue to fail despite the presence of seawalls below, but careful control of surface drainage and (if possible) subsurface drainage can reduce these types of failures. Placing buildings as far inland from the bluffs as possible is always a good idea.

Paved Areas: Asphalt has a relatively low density, and in thin slabs, a very high surface area to mass ratio. For this reason, it is easily moved (and removed) by wave action (Figure 47). Because of its flexibility and softness, waves can erode rapidly through cracks in asphalt pavement, exposing the fill beneath. Once fill is exposed to wave attack, asphalt tends to be lifted up in large slabs, and "floated" inland or broken up and destroyed. Concrete pavement is also easily undermined, but if anchored to deep pilings, may resist mild wave attack and overwashing.

Rip rap, because of its tendency to settle and its high permeability, generally provides poor protection for fill beneath asphalt or concrete paved surfaces. Where coarse rock is incorporated into roadbed and slope fill, and where the roadbed is relatively high, rip rap may be more successful. However, runoff must be directed away from the seawall, or gullying will erode behind the rip rap. Concrete walls with concrete splash aprons behind them probably provide the most satisfactory protection for paved areas, but surface runoff and subsurface piping may still present persistent problems.

Figure 45
Storm waves overtopped a low concrete seawall in Capitola during the winter of 1983 and washed debris into the streets (Site !9).

Figure 46
Erosion at base of bluff led to bluff collapse and loss of house support.

CONCLUSIONS

Figure 47
Stripping of asphalt from parking lot by waves which overtopped or broke through timber seawall (Site 22).

Of the three major types of protection, concrete walls generally have been most successful in reducing erosion and property damage, and have been most durable, over the long term. However, concrete walls supported on discrete pilings have required moderate to high maintenance, in the form of rip rap toe protection, to survive. Rip rap walls fared less well than concrete walls, but better than wooden walls. However, their maintenance costs have often been much higher than anticipated, particularly in sandy environments. Wooden walls have proven to be least successful in preventing erosion and damage, and most are easily damaged during severe storms. Wooden walls fronted entirely by rip rap have been more successful, as long as the rip rap does not settle.

On the whole, few protective structures in the study area have stood the long-term tests of time, surviving unassisted and preventing damage and erosion, for more than twenty years or longer than their design life. Many structures have become structurally unsound, required considerable maintenance or repair, and/or failed to adequately reduce property damage for more than one severe storm period. Thus, the effective lifetime of a structure often depends on how many mild winters pass before the next severe storm. However, most of the structures have reduced erosion rates, at least over the short term.

Following the severe coastal storms of 1978 to 1983, a large number of protective structures were designed and emplaced, and many more are being planned and considered. We have presented our observations along the central California coast with a view that these will be of assistance to those who must make decisions about protective works in the future. There are a number of options for those with threatened property—some structural, some non-structural. Before any protective structure is to be built, it's initial costs and maintenance costs and its probable lifespan must be carefully considered, as well as its technical merits and limitations.

TABLE 1

An Overview of the Case-Study Sites

	SITE NAME	PROTECTION TYPE	LENGTH (ft.)	SHORE TYPE	PLANNING PROCESSES
1	O'Shaughnessy Seawall	C	4500	Dunes	s
2	The Great Highway	R D W G	13000	Dunes	s
3	Daly City Dump	R D	2700	High Bluff	s
4	Pacific Skies Estates	R D G	650	Low Bluff	s
5	Beach Blvd (Pacifica)	R D G	2400	Low Bluff	s
6	Rockaway Beach	R C W	1000	Low Bluff	s
7	Moss Beach	R D C G	800	Low Bluff	i
8	El Granada	R	1000	Low Bluff	s
9	Miramar (Mirada Rd)	R D C	1000	Low Bluff	s
10	Waddell Bluffs	R	3500	High Bluff	s
11	West Cliff Dr. (S.C.)	R D C W	14000	Low Bluff	s
12	S.C. Boardwalk area	C W	3000	River-mouth	s
13	Twin Lakes Beach	R D C W G	500	Low Bluff	i
14	Corcoran Lagoon	R D C	1800	Low Bluff	i,g
15	Moran Lake	R D C W	800	Low Bluff	i,g
16	Pleasure Pt. Drive	R C G	500	Low Bluff	i,g
17	Opal Cliffs Drive	R D C G	4500	High Bluff	i,g
18	Capitola Bluffs	R	1000	High Bluff	s
19	Capitola Beach	R D C	800	River-mouth	s
20	Potbelly Beach	R W	900	Stable Bluff	i,g
21	Las Olas Drive	R W	2400	Stable Bluff	i,g
22	Seacliff State Beach	R C W	5000	Stable Bluff	s
23	Rio Del Mar Beach	C	500	River-mouth	s
24	Beach Drive (north)	R D	700	Stable Bluff	g
25	Beach Drive (middle)	R C W	2500	Stable Bluff	s
26	Beach Drive (south)	R C W	2000	Stable Bluff	i,g
27	Via Gaviota	R C	500	Stable Bluff	i,g
28	Pajaro Dunes	R D W	6000	Dunes	i,g
29	Moss Landing Laboratory	R C	300?	Dunes	s
30	Stillwell Hall (Ft Ord)	R C	500?	High Dunes	s
31	Holiday Inn (Sand City)	C	500?	Dunes	s
32	Carmel Beach	R	2500	Low Bluffs	s

Protection Types:

R—Rip Rap
D—Concrete Debris
C—Concrete Seawall
W—Wooden Seawall
G—Gunnite.

Planning Processes:

i—Separate protection by many individuals at one site.
g—Group protection effort by many individuals at one site.
s—site owned or controlled primarily by one individual or agency that plans virtually all protection measures in the area.

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