State of California
The Resources Agency
DEPARTMENT OF WATER RESOURCES
Division of Design and Construction

DELTA LEVEE SLOPE PROTECTION ALTERNATIVES

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FOREWORD

Responding to pressures to address the problems of local levees in the Sacramento-San Joaquin Delta, the California Legislature passed, and the Governor signed, the Delta Flood Protection Act of 1988 (Senate Bill 34) in March 1988. This Act increased the financial assistance to Delta reclamation and levee districts maintaining local levees.

Levee slope protection is a key element in rehabilitating and maintaining the integrity of the Delta levees, and slope protection works will vary widely in character and cost. Recognizing the importance of both these factors, the Division of Design and Construction undertook the task of investigating various types of bank protection devices that can be used to prevent erosion by surface water.

This report summarizes the cost, engineering effectiveness, and potential for vegetal cover that the various slope protection installations can provide. A table comparing these findings is included in the report for easy reference.

John H. Lawder

John H. Lawder, Chief
Division of Design and Construction

State of California
GEORGE DEUKMEJIAN, Governor

The Resources Agency
GORDON K. VAN VLECK, Secretary for Resources

Department of Water Resources
DAVID N. KENNEDY, Director

JOHN P. CAFFREY
Chief Deputy Director

ROBERT G. POTTER
Deputy Director

LAWRENCE A. MULLNIX
Deputy Director

L. LUCINDA CHIPPONERI
Assistant Director for Legislation

SUSAN N. WEBER
Chief Counsel

DIVISION OF DESIGN AND CONSTRUCTION

John H. Lawder, Chief

Keith G. Barrett .... Chief, Design Office
William M. Verigin .... Chief, Civil Design Branch
Leslie F. Harder, Jr. .... Chief, Canals and Levees Section

This report was prepared under the supervision of

Ted Tsuruda .... Senior Engineer

by

Teresa Geimer .... Associate Engineer

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I. EXECUTIVE SUMMARY

This investigation was undertaken to compare costs, engineering effectiveness, and potential for revegetation of various erosion control alternatives for levees in the Sacramento–San Joaquin Delta. The methods studied included riprap, articulating blocks, grouted rocks, interlocking concrete blocks, vegetation management, geosynthetics, and gabions. This report describes the results of the investigation

The ideal means of protecting the waterside slopes of Delta levees from wave-induced erosion is a method, or a combination of methods, that:

- Dissipates wave energy without soil erosion.
- Deters increases in hydrostatic energy in underlying materials caused by wave action.
- Prevents animals from burrowing into the levee embankment.
- Is not undercut by scour.
- Presents an aesthetically pleasing appearance and maintains environmentally suitable conditions.
- Is easy to install.
- Accommodates significant soil settlement and/or erosion.
- Is easy to extend if levee height must be increased.
- Is economical.

In reality, no single slope protection alternative accomplishes all the aims listed above. Table 1 summarizes the slope protection alternatives considered in this study. Except for riprap and natural vegetation, none of these alternatives has ever been adequately tested in the Delta.

Vegetation alone has been regarded as a poor slope protection alternative, but riprap has been used extensively, and it is generally considered to have performed well. As Table 1 indicates, riprap satisfies most of the foregoing criteria. Riprap costs only about a third of other slope protection materials, but it does have drawbacks. Riprap does not offer complete protection against burrowing animals. Riprap tends to reduce regrowth of vegetation, although there are many areas upstream where substantial regrowth has occurred. The expanses of rock on riprapped levees are viewed by some as aesthetically displeasing. Some studies indicate that riprap may adversely impact fish.

Most other slope protection alternatives also affect aesthetics and habitat adversely, but some allow extensive revegetation with grasses and small shrubs. This feature could be important where the preservation of endangered grass-like plants, such as Mason's Lilaeopsis, is considered vital.

This report describes a variety of slope protection materials to facilitate the selection of a method or methods for various levee reaches. Because no single method satisfies all situations, different alternatives may prove optimal for different projects. For example, if economics and proven performance

Table 1. SUMMARY OF LEVEE SLOPE PROTECTION ALTERNATIVES

Slope Protection Alternative	System[1,4] Cost per Sq. Ft.	Description	Flexibility for Levee Settlements	Ease of Extension in Levee Raising	Relieves[5] Hydrostatic Pressure	Deters Burrowing Animals	Possibility of Revegetation	Performance History in the Delta	Ease of Installation	Durability	Special Advantages & Limitations
Riprap	1.75	Broadly graded rocks	Excellent	Excellent	Yes	Fair	Poor	Excellent	Excellent	Excellent	Proven performance & cost effectiveness
Grouted-rock Soil-cement		Cemented masses or layers	Poor	Poor	No	Excellent	Poor	Unknown	Poor	Excellent	Too rigid for Delta environment
Articulating block	5.25–5.75	Nylon fabric connecting & forming concrete blocks	Fair	Poor	Yes	Fair	Poor	Unknown	Fair	Good	
Armorflex[3]	5.00–5.50	Preformed concrete blocks joined by cables	Excellent	Fair	Yes	Fair	Good	Unknown	Good	Excellent	Some control of kind & quantity of revegetation on slope
Tri-Lock Armorloc[3] Monoslab	5.00 4.25–4.50 4.00	Interlocking preformed concrete blocks	Good	Poor	Yes	Fair	Good	Unknown	Fair	Excellent	Blocks depend on each other; if some break, the revetment fails
Vegetation (Co-Composting)[2]	1.50	Plants growing on slope	Excellent	Excellent	Yes	None	Excellent	Poor	Excellent	Poor	Must be used with other slope protection
Geosynthetic	0.30	Porous synthetic covering	Excellent	Excellent	Yes	Fair	Good	Poor	Fair	Poor	Must be used with other slope protection
Reno mattress	2.25–3.00	Rectangular wire boxes filled with rocks	Fair	Fair	Yes	Fair	Poor	Unknown	Good	Excellent	Wire cage damaged or corroded away would make revetment useless

1 Cost of material and installation only. Cost of slope preparation will vary with slope protection method and condition of slope.
2 Co-composting may be used to help establish vegetation on the slopes. However, the existing and surrounding peat soil is as good a growth medium.
3 Requires geosynthetic or graded filter beneath rocks.
4 Cost may vary with quantity. Area to be covered for pricing ranged from 50 feet x 20 feet to 5 miles x 20 feet.
5 Slope protection must be permeable enough to allow water collected behind the protection to equalize with the water in the channel.

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have the highest priorities in one location, riprap would then be the logical choice. On the other hand, if revegetation is of prime importance, a product such as Armorflex might be selected. For some levee projects, combinations of slope protection methods or the use of vegetated waterside berms may prove to be the best solution.

A note of caution is necessary regarding the use of slope protection methods not yet tested in the Delta. Because their performance is unproven, it would be desirable to test them before selecting the methods to be specified for critical large-scale projects. Additionally, due to the unique conditions of the Delta nonfederal levees, recommendations or conclusions of this report may not be germane for other areas requiring slope protection.

II. INTRODUCTION

Background to the Investigation

The Sacramento–San Joaquin Delta is a unique area where the Sacramento and San Joaquin rivers join and flow to San Francisco Bay and the Pacific Ocean. The Delta occupies more than 1,100 square miles, including more than 700 miles of scenic waterways. It includes about 70 leveed islands and tracts, many of them lying 15 to 20 feet below sea level. The network of levees, which together is about 1,100 miles long, protects 500,000 acres of prime agricultural land.

Most of the Delta islands are made up of weak foundation soils at or near ground surface. These soils are generally composed of organic clays, organic silts, peat, or a combination of them. Levees constructed over these soils are often unstable and prone to subsidence. The weak soils extend to depths of as much as 60 feet in places, with depths of 10 to 30 feet common.

Most Delta levees are designated as *local* or *federal*. Federal levees are levees along the Sacramento and San Joaquin rivers that have been adopted as federal flood control project levees. They are maintained to standards of the U.S. Army Corps of Engineers and generally provide adequate protection.

The levees in the central Delta are mostly local levees that have been constructed and maintained over a long period by private interests or local reclamation districts. Most of them were built of available nonselect materials, without engineering design or standard construction practices such as compaction.

Since 1980, 24 levee breaks have occurred, flooding numerous islands and tracts, mainly involving failure of local levees in the northern and central Delta. Twice as many floods have been caused by structural levee failure as by the overtopping of levees by high tides, winds, and floodflows. Structural failures are generally attributed to the unstable organic Delta soils that form many of the levee foundations and to instability or piping within the poorly constructed levees themselves.

Slope Protection Problems in the Delta

The waterside levee slopes in the Sacramento-San Joaquin Delta are subject to continuing attack by wind, waves, soil movement, and burrowing animals. Slope protection methods attempt to dissipate wave energy without allowing erosion of the slope protection or the soil beneath it. A major aspect of most approaches is preventing the development of strong hydrostatic pressures that might push out the slope protection material or the soil beneath it. In addition, almost all slope protection alternatives require a filtering medium that prevents the underlying soils from washing out.

A number of special problems are involved in providing slope protection for Delta levees.

- The many miles of levees, rivers, and sloughs make dewatering an impractical alternative. Consequently, some sections of slope protection must be installed and/or repaired under water.

- Tidal action can cause the water levels in some channels to vary as much as four feet daily.
- Existing levee slopes are often steep and irregular, which makes placement of slope protection materials difficult.
- Delta levees have relatively little freeboard. Waves may spill over the top of the slope protection during flooding, causing embankment erosion and degradation of the slope protection.
- Because many levees are continually settling, they require periodic additions of material to maintain freeboard. This new material increases settlement of the levee, which means that the slope protection material must accommodate this additional movement. The protective material must also be extended upward to protect the added levee material.
- Many Delta rivers and sloughs have water velocities strong enough to scour their channels. This in turn tends to undermine the levee slope protection.
- Many rodents and large mammals such as muskrats and beavers found in the Delta often weaken the levees by burrowing into them and creating tunnels and voids. Some of the animal dens are large enough to accommodate an adult person. In addition to increasing the likelihood of internal levee erosion, the dens may collapse, creating sinkholes and causing the the levee crown itself to collapse.
- Many reaches of Delta sloughs and rivers have levees overgrown with trees and other large vegetation. These plants sometimes aid in resisting wave-induced erosion, but they also conceal the weakness and instability that may have developed in a levee. Furthermore, high winds can topple these trees, whose root systems pull away and leave large gaps in the levee.

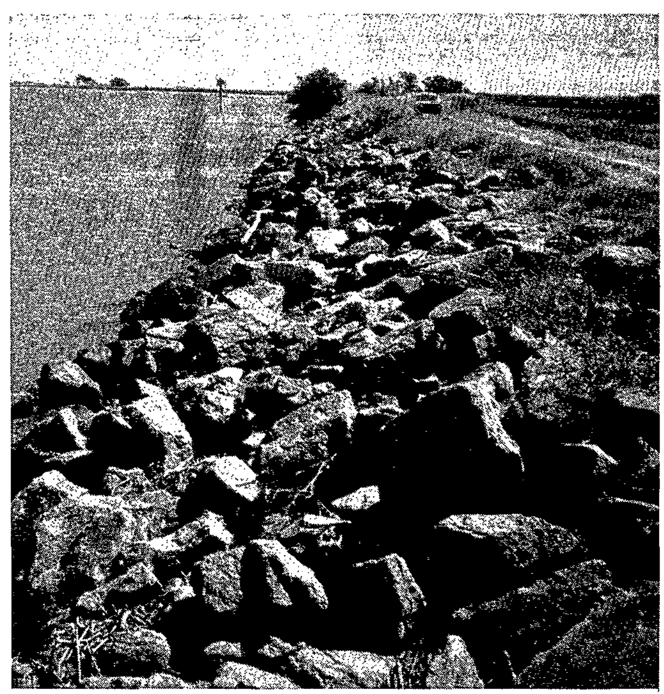
III. SLOPE PROTECTION ALTERNATIVES

Riprap

Riprap, which is loose broken rock, has been used widely in the Delta to protect levee slopes from erosion. Quarry rock is the principal type of riprap used, although other materials such as broken concrete and old cars have been substituted on occasion. Quarry rock effectively dissipates the force of the waves, preventing the underlying embankment from loosening and eroding. The stability of riprap is determined by the size, shape, weight, roughness, gradation, and thickness of the rocks that compose it. The particle sizes and thicknesses needed increase as the levee slope and potential wave height increase.

Riprap is usually placed on a bedding or backing material of smaller rocks intended to prevent the finer-grained levee material from migrating. Riprap of the proper composition should be made up of rocks large enough to resist wave action and should be broadly graded to prevent underlying material from washing away. A toe trench, a ditch excavated at the base of the slope protection, should be positioned below the scour depth of the channel and filled with rock to support the riprap. Riprap intended to protect a levee from wave action will also be effective in protecting against other types of erosive attacks, such as high stream velocities and precipitation runoff.

One reason riprap is successful is its flexibility. Differential settling is a common event for Delta levees. Since riprap does not form a rigid structure, sections of placed rock can settle along with the underlying levee embankment without disturbing its function or the adjacent embankment. Large voids in the riprap relieve excess hydrostatic pressures caused by waves washing against the slope.



Riprap protection.

The roughness of the rocks also reduces wave runup on the slope. Riprap is easy to place and repair, and it also can be easily removed and placed again if the height of an embankment must be increased.

Problems sometimes experienced with riprap installations are scour at the toe of the levee, migration of fine material from beneath the rock, and the surcharge weight of the rock and bedding. Scour and soil migration can usually be minimized with a properly designed and placed riprap and bedding scheme. However, the weight of the riprap and its bedding is significant, and it compounds the settling problems of Delta levees. In areas such as the Delta, where waterside berms are nonexistent, ground squirrel activity is most prevalent on the landside slope. Waterside burrowers such as beaver and muskrat are most likely to burrow in unrocked levee sections or at the edge of rock, rather than amongst it, since the spaces between the stones are generally too small to admit these larger rodents.

Where levees have large freeboards, riprap is often placed only as high on the slope as needed to fully protect it from flood waves. At these sites, the portion of the levee above the riprap develops significant vegetative growth, sometimes even large trees. However, many Delta levees have relatively little freeboard and are riprapped all the way to the levee crown. The result is that, even though riprap is a natural material, only limited vegetation will grow between the unshaded rocks. Consequently, the potential for fish and wildlife habitat development is not high. Moreover, many consider the uniform, bare rock facing aesthetically unpleasing. Even so, riprap has been an extremely effective means of slope protection in the Delta. Rock is readily available near the periphery of the Delta and the cost is relatively low. Labor cost in placing the riprap is also relatively low.

Table 2. SOURCES OF RIPRAP

Company	Location of Material	Size (inches)	Cost, $ per ton: FOB Plant	Cost, $ per ton: Including Delivery	Cost, $ per ton: Including Placement	Barge Loading Facilities	Rock Type
Blue Mountain Minerals	Columbia	Any size	5.00			No	High calcium Limestone Dolomite
Claude C. Wood Co., Lodi	Yuba R. east of Marysville	4–15	7.00		18.00	No	Greenstone
Granite Construction	Coalinga	>6	6.00			No	Alluvial
Kaiser Sand and Gravel	Walnut Creek	4–12 6–15 3–9	8.90			No	Basalt
Langley Hill Quarry	Woodside	4–12 All other	10.00 9.00			No	Basalt
Lonestar	Clayton	4–12	9.70			No	Basalt
Sierra Rock Placerville	SW Shingle Springs	6–12	8.80			No	Greenstone Limestone
Syar Ind. Inc. (Dutra)	Vallejo and Napa	Any size	10.95	19.95		Yes, in Napa	Blue basalt

Grouted–Rock and Soil–Cement

Grouted–rock, a type of slope protection used to prevent erosion, is riprap cemented together with a grout mixture, normally made of portland cement. When grout fills the voids in riprap, no backing or bedding material is needed.

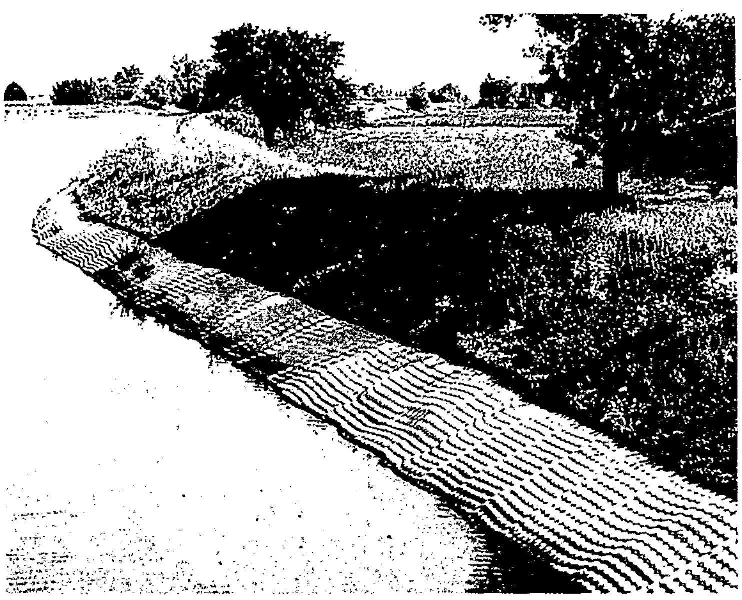
Soil–cement consists of a mixture of portland cement, water, and soil. When properly designed and compacted, it forms a hard, durable material similar to concrete.

If water washes out the underlying soil, either by overtopping the slope protection or intruding elsewhere behind it, both grouted–rock and soil–cement will lose support and collapse. Even if the underlying soil is not washed out, the build–up of hydrostatic pressure during tidal drawdown may cause the slope protection to fail.

Both grouted–rock and soil–cement are very difficult to construct under water or on uneven surfaces. Even more significant, neither grouted–rock nor soil–cement is flexible enough to conform to the unevenness caused by levee subsidence. Once an embankment settles, the slope protection has no support and it will fail, exposing the unprotected levee soils. Of all of the slope protection methods, rigid cemented masses such as grouted–rock or soil–cement probably provide the least potential for revegetation and a pleasing appearance. Moreover, these methods require significant construction control. Therefore, these and other inflexible cemented materials are judged to be infeasible as slope protection for local Delta levees.

Fabriform Articulating Block

Fabriform Articulating Block is made by casting concrete in place to form individual rectangular blocks within a network of nylon fabric cells. The fabric may be further strengthened with reinforcing cables laced through it before the concrete is pumped between the cells. The connecting fabric and cables maintain the relative block positions, allowing the blocks to move independently and the entire installation to change shape as the embankment settles. The fabric also allows the release of



Articulating block protection.

hydrostatic pressure from behind the slope protection. The fabric cells can be filled with concrete either above or below the water surface.

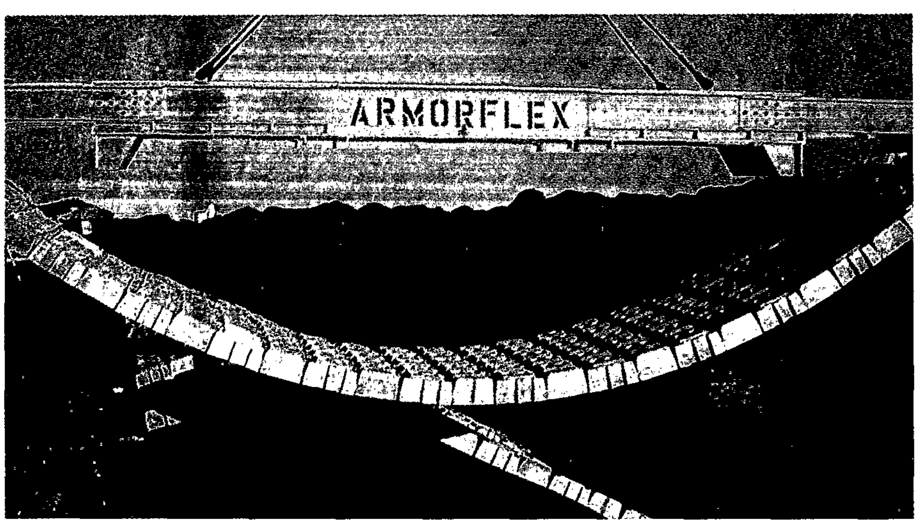
Fabriform Articulating Block has several drawbacks. The main objection is its expense. Added to the cost of preparing the slope is the cost of backing or bedding materials that are normally placed on the slope before this product can be installed. Furthermore, the fabric–encapsulated blocks are usually fastened to the slope by ground anchors at the crown of the slope, a practice that makes it difficult to extend the protection if the levee height is increased. Another disadvantage is the fabric's vulnerability to ultraviolet rays, which limits its service life to about 15 years. In addition, little or no vegetation is able to grow on the slope while the fabric is intact.

The manufacturer reports about 5,000 lineal feet of Fabriform Articulating Block has been successfully employed on the banks of the River Arun in England, where it has withstood high tidal fluctuations and waves generated by boat traffic. The manufacturer also stated that this type of slope protection has been used along the Canadian side of the St. Lawrence waterway near the lower Great Lakes.

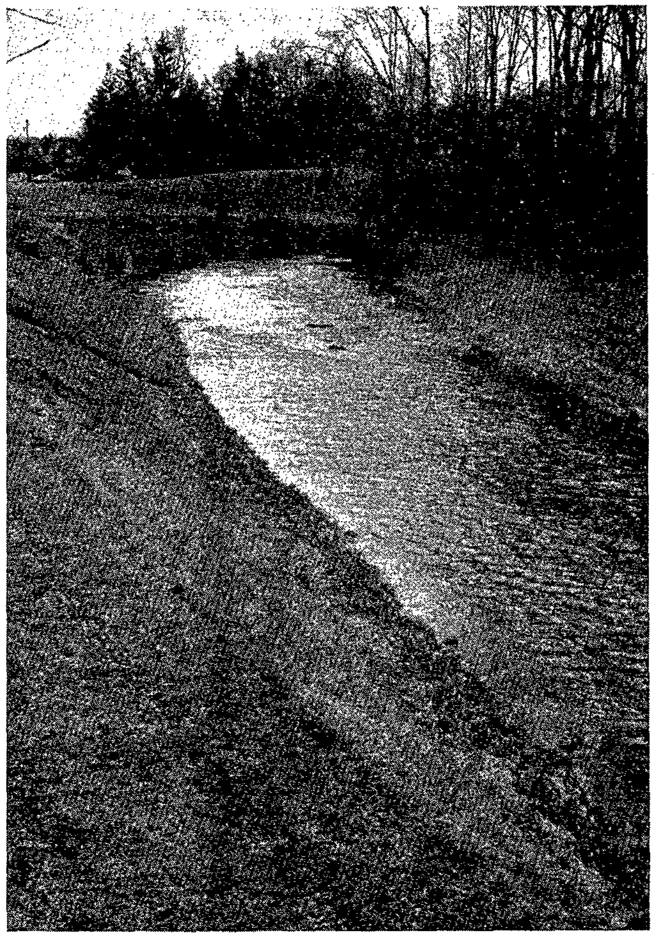
The cost of Fabriform Articulating Blocks ranges from about $2.75 to $3.00 per square foot for 4-inch-high blocks and from about $3.00 to $3.25 per square foot for 6-inch-high blocks. The labor cost for installing the articulating block is about $2.50 per square foot, depending on the location.

Armorflex

Armorflex is a type of slope protection in which cellular concrete blocks, either open or closed, are cabled together without fabric encapsulation. The Armorflex blocks are held on the levee slope by anchors placed at the top of the levee and by friction between the slope and the blocks. Because the blocks are flat, they provide large surfaces for frictional resistance. The cables, which consist of a polyester core encased in nylon rope, can absorb significant tensile stresses. The blocks can be assembled at the factory or on site. Sections of precabled concrete blocks can be placed by using special spreader bars available from Armorflex, a procedure that may lower costs at large projects by reducing hand labor.



Armorflex mat being placed.



Trees have been planted where Armorflex blocks were omitted.

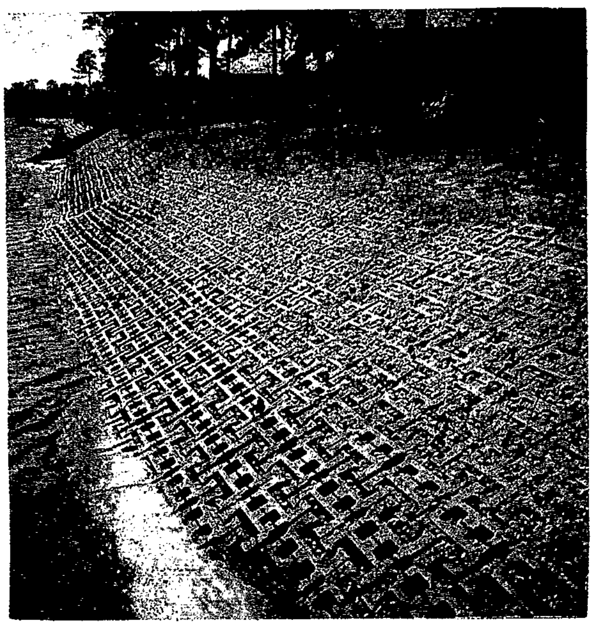
Armorflex offers several advantages. It is environmentally beneficial because grasses and small shrubs can start growing on the slope protection immediately. The opening in the blocks and the spaces between them prevent excess hydrostatic pressure from developing behind the slope protection. Also, the blocks are of equal size and weight, factors that distribute an even load on the levee slope. They weigh from about 68 to 78 pounds per square foot, compared to about 200 pounds per square foot for equivalent riprap protection. Another advantage of Armorflex is its flexibility. If an embankment settles unevenly, Armorflex is able to conform to the distorted shape.

The main disadvantage of the Armorflex system is the cost of the extensive labor involved in assembling the blocks, which must be individually strung onto the cable by hand. The slope on which Armorflex is to be placed must be prepared to a smooth surface, and a geotextile must be placed beneath the blocks. Special equipment, such as spreader bars, are required to place the Armorflex under water. The top of the Armorflex mat must be anchored and the toe of the levee must be protected from scour, either by extending the lengths of Armorflex or placing extra rock. There also remains the possibility that the top anchor can be eroded by wave action, thereby endangering the stability of the installation.

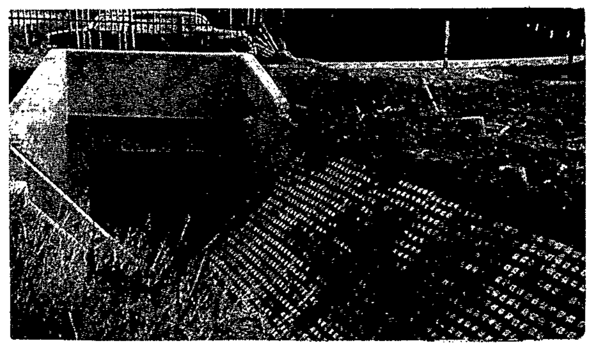
Armorflex costs about $3.50 per square foot, plus about $0.20 per square foot for shipping from the manufacturing plant in Stockton, California, to Delta locations. If the slope has already been prepared, a four–member crew and one crane operator can typically install 10,000 to 15,000 square feet of mats a day.

Interlocking Concrete Blocks

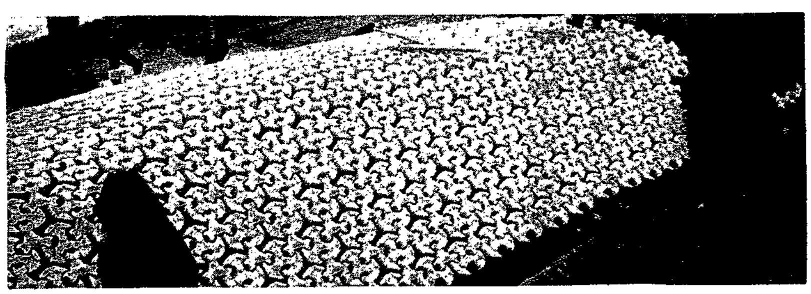
Tri–Lock, Armorloc, and Monoslab are examples of slope protection consisting of interlocking concrete blocks of various shapes whose stability relies on the way they fit together. No cables or fabric encapsulation are used to connect them. The blocks are placed by hand at the site or several can be fitted together over a geosynthetic fabric and placed on the slope in sections. As with Armorflex, placing a geosynthetic fabric beneath the blocks is recommended to prevent migration of levee material. The primary physical difference between Armorflex and interlocking concrete blocks is that Armorflex blocks are connected by cables, while the interlocking blocks fit together geometrically without cables. Armorloc and Monoslab blocks have uniform rectangular shapes, while Tri–Lock has two styles of triangular blocks. None of the three types are reinforced.



Armorloc protection.



Monoslab protection.



Tri-Lock protection.

The various types of interlocking concrete blocks have many of the same characteristics as does Armorflex: flexibility, room for growth of grasses and small shrubs, relief of hydrostatic pressure buildup, and even distribution of weight. Individual blocks are free to move in relation to one another and, because they have uniform height and weight, the embankment beneath them will tend to settle more uniformly. The interlocking blocks present a neat and uniform appearance that may be aesthetically pleasing to some but displeasing to others who prefer the sight of natural materials.

Unlike Armorflex, however, the interlocking blocks themselves form the interconnections among them. Lacking reinforcement, the blocks are easily broken during installation on site or whenever they are placed in tension. Maintaining the interlocking feature among the units is essential. Once one block has moved free of its grouping, others soon become dislodged and the installation may fail completely. By comparison, the nylon cables that connect Armorflex blocks can withstand considerable tension.

Another disadvantage is that both interlocking blocks and Armorflex present smooth face slopes that allow higher wave runup than occurs with riprap. Also, when blocks of either system are placed below the water surface, divers are needed to connect the blocks under water. This is a labor-intensive operation that increases costs. Another drawback is the expense of replacing or removing the slope protection when a levee needs to be repaired or increased in height.

The material cost of the Tri-Lock is about $3.00 per square foot. Armorloc costs from about $2.25 to $2.50 per square foot, and Monoslab is about $2.00 per square foot. The labor cost of placing interlocking concrete blocks on dry land is about $2.00 per square foot.

Vegetation Management

Vegetation on levee slopes is important for environmental and aesthetic reasons. Vegetation also helps protect levees from erosion caused by precipitation and wavewash. The roots of plants help to hold the soil in place, and the leaves and stems help dissipate wave energy.

Vegetation alone, however, has not proven to be an effective slope protection in many reaches in the Delta. Because vegetation does not usually extend below the mean water level, the levees are exposed to wave energy during low tides. In places of average to steep slopes, large waves commonly erode the soil and dislodge vegetation. Further, vegetation shelters burrowing animals and conceals the detrimental effects of animal dens and tunnels.

Vegetation that is allowed to grow uncontrolled and become dense is particularly hazardous. It can shield the true condition of a levee, preventing levee inspectors from spotting potential problems and correcting them in time. Also, during times of high water, flood fighting workers must have bare levee slopes on which to place plastic sheets, sand bags, and other flood fight materials, if they are to prevent leaks or seepage areas from developing into levee breaches.

Trees on levees are a major concern during times of high water and storms. When a large tree is toppled by strong winds, it pulls its entire root system with it, leaving a great hole that reduces the levee's size and strength and allows water to enter the embankment. In an extreme case, a fallen tree near the crown of a levee could remove enough material to cause a levee breach.

Controlled or managed vegetation on slopes, used in conjunction with riprap or interconnected concrete blocks, provides a combination of benefits. For example, the openings between cabled or interlocked concrete blocks could be filled with soil or other growth mediums to allow revegetation. Many of the cabled or interlocking systems could be constructed to allow openings for trees or large brush, provided they are not located on steep slopes or near the levee crown. Alternatively, a small waterside berm could be built to support growth of trees and other vegetation. The slopes above and below the berm could be protected economically and effectively with riprap, leaving the top of the berm to provide the aesthetics and wildlife habitat.

One growth medium, known as Co–composting (Reference 1) is a "microbiological, aerobic, dynamic fermentation process utilizing (a) household trash at approximately 80 percent, and (b) either sewage sludge, horse manure, non–toxic dairy waste, or fish leavings at approximately 20 percent of the total waste stream." The high organic content and permeability of Co–composting presumably provides a growth medium. However, these properties are similar to the peaty soils available in great abundance in the Delta. Consequently, it would be an unneeded expense to import Co–composting for vegetation management when peaty soils are already available locally. Furthermore, there may be some environmental concern regarding the effects of recycled trash, sewage, and other organic waste on Delta water quality.

Information on the use of vegetation to protect levee slopes is presented in *Interim Guide for Vegetation on Flood Control Levees* (Reference 2).

Geosynthetics

The use of geosynthetics is a relatively new technology for erosion control. Geosynthetics are divided into four categories: geotextiles, geogrids, geomembranes, and geocomposites. (The four groups are compared in Table 3.)

Geotextiles, which form the largest group, are thin sheets of woven or nonwoven synthetic fibers. The product is generally nonbiodegradable, flexible, and permeable. Geotextiles may be used as separators, reinforcers, filters, drains, or moisture barriers. Geogrids, a small but rapidly growing group, are generally plastics formed into very open grids. They are most often used to separate and reinforce soils. Geomembranes are thin, impervious sheets of rubber or plastic that are often used as liners or moisture barriers. Geocomposites are any geosynthetic used with another geosynthetic and/or another material such as deformed plastic sheets, steel cables, or steel anchors. They are mostly used as separators, reinforcers, filters, drains, and moisture barriers.

For geosynthetics to be used on the Delta levees, they would probably need to be combined with another method of slope protection. Geotextiles used without a protective covering have proven difficult to anchor and displayed degradation caused by ultraviolet rays. For example, a three-section test slope near Valcros Dam in France was protected in three ways: with riprap only, with riprap and a geosynthetic fabric, and with a geosynthetic fabric only. The section with the geosynthetic fabric alone was the only portion of slope that exhibited signs of erosion (Reference 5).

In theory, some geotextiles or geogrids could be used to reinforce and help stabilize vegetative growth on the levees, but in fact the vegetative cover would fail to protect the fabric against significant wave action. With any loss of soil or cover, the geosynthetic may be degraded by ultraviolet rays and from the forces of waves. Also, rodents have been known to damage these materials by chewing on them.

According to the manufacturers' recommendations, geosynthetics are potentially useful under armor units, such as cabled or interlocking concrete blocks, to keep fine-grain soil from washing out of the

Table 3. GEOSYNTHETIC TYPES

	Geotextiles	Geogrids	Geomembranes	Geocomposites
Application	Filtration, reinforcement, and drainage	Reinforcement	Liner, moisture barrier and separation	Filtration, reinforcement drainage, liner, moisture barrier and separation
Approximate puncture resistance (in pounds)	135	Not available	150	Not available
Possible use for Delta levees	Under armor protection as a filter and drain. Under levee road for reinforcement.	Levee construction for better stability of slope under levee road for reinforcement.	No apparent use for Delta levees	Can combine synthetic types for any reinforcement, separation, filtration, or drainage.
Can be used alone as slope protection	No	No	No	No
Cost per square foot	~0.30	~0.75	~0.50	Varies on the combination of geosynthetics.

embankment. They may in fact be the most practical method of preventing fines from migrating in problem areas. Geosynthetics also prevent hydrostatic pressure from building up behind the slope protection, and they can replace a filter bedding of graded sand under riprap, although the fabric is susceptible to damage when the riprap is unloaded directly on it.

In selecting a geotextile to place beneath concrete blocks, one often must rely on the advice of the armor block manufacturer and/or the geosynthetic manufacturer because little product history is available on the use of geosynthetics for slope protection. Consequently, disparity exists regarding the relative superiority of woven or nonwoven geotextiles for such installations.

Woven geotextiles are generally as strong as nonwoven geotextiles, and they are more elastic and more consistent in thickness. Nonwoven geotextiles, which are formed by fusing the fibers together with heat, tend to be brittle and may crack and break under the loading of slope protection, even with a bedding layer beneath. Nonwoven geotextiles with a thick, wooly felt consistency may not be as uniformly thick as woven geotextiles and therefore can be substantially weaker.

Care must be taken to choose a geotextile with openings large enough to allow the release of hydrostatic pressure, even after vegetation has grown over the material, but small enough to prevent migration of the underlying fine-grain material. Geotextiles are often selected according to their strength and their burst and tear resistances. Basing one's selection of products and designs on those used successfully on similar projects is the best approach.

Geotextiles range in cost from about $0.09 to $0.13 per square foot. The labor involved in placing the fabric costs about $0.16 per square foot.

Gabion Mattresses and Reno Mattresses

Two other methods of levee slope protection are the Gabion mattress and the Reno mattress. A Gabion mattress is a rectangular wire box filled with broken rock. Galvanized or PVC–coated wire is often used to provide some corrosion resistance. The mattress is filled and wired shut and then several mattresses are stacked on top of one another to form a stepped slope. This method is generally excellent for steep levee slopes.

A Reno mattress is a wire cage built in large sections, rather than as individual boxes. It is also filled with broken rock and several are laid end to end up the incline. Friction between the mattresses and the embankment holds them in place. No footings are necessary; however, protection at the levee toe is needed to prevent scour. Because the Delta levees typically slope about two feet horizontally to one foot vertically on the water side, the Reno mattress lends itself to consideration as an appropriate slope protection material.

Reno mattresses have the advantage of flexibility. They can respond to changes in configuration of the embankment as subsidence and differential settlement occur, and they do not lose strength or effectiveness with small earth movements. The mattresses are also permeable, a characteristic that prevents hydrostatic pressure from exerting force behind the mattress and lifting it. Reno mattresses can also accommodate rock in smaller fragments and smaller quantities than is commonly needed for riprap. As a further benefit, grasses and small shrubs may eventually establish themselves on the mattress.

Reno mattresses are not without drawbacks. One is that the wires forming them are subject to corrosion, and continuous wave action and abrasion can wear away their protective PVC coating, causing them to break. The unconfined rock released may be too small or too thin to protect the slope. Another disadvantage is the particular care required to fill the Reno mattresses without damaging the wire cages. Furthermore, Reno mattresses generally require a granular bedding or a geotextile to prevent the embankment fines from migrating through the rocks. Floating equipment is needed to place them under water. The mattresses are constructed on a flat extension of a barge and then lowered in place in the water. Extra underwater work is required to reinforce the toe to prevent scour

Reno mattress protection.

and slippage of the mattresses. Vandalism can threaten the effectiveness of an installation if the wire forming the mattresses is cut or broken. Rusted and broken wire baskets also pose a safety hazard.

The manufacturer of Reno mattresses reports its successful use in Italy to line the banks of the Velino River between Lake Piediluco and Marmore Falls, and on the banks of the Volano Canal near the town of Ostellato. The cost of a Reno mattress is about $3 per square foot installed.

Other Slope Protection Methods

Palisades, jetties, retards, or other similar methods of erosion retardants are not practicable in the Delta. These types of levee protection involve protrusions into the waterway at specific angles and/or locations that would interfere with boat traffic in many of the narrow channels. Also, because the flow of water changes direction with the tides, the effectiveness of these structures has not been proven. Furthermore, they are ineffective in resisting wave action, the main cause of levee erosion nor are they capable of obstructing rodents and other burrowing animals.

SOURCES OF PRODUCT INFORMATION

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Armortec Inc.
Belton Industries, Inc.
Celtits, Inc.
Construction Techniques, Inc.
Contech Construction Products, Inc.
Dean L. Bradfield, Inc.
Diversiform
Geoproducts Company, Erosion Control and Drainage
Maccafersi Gabion West Coast, Inc.
Presto Products, Inc.
Raymond International Builders, Inc.
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