Technical Report CHL-97-4
March 1997

US Army Corps of Engineers
Waterways Experiment Station

CORE-LOC Concrete Armor Units

by Jeffrey A. Melby, George F. Turk

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Waterways Experiment Station
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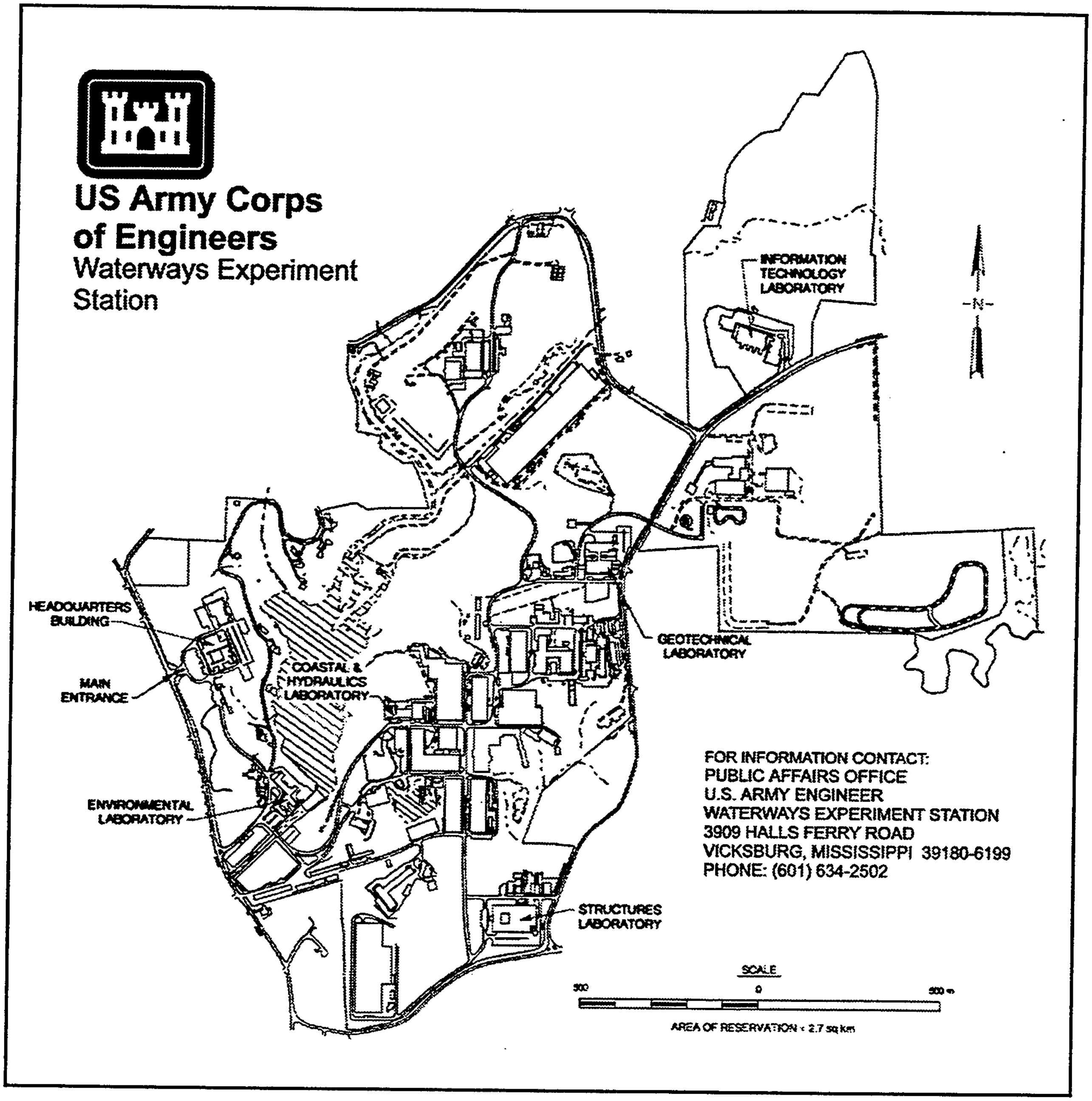

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Preface

Funding for CORE-LOC development, as discussed in this report, was provided by the Coastal Engineering Research Program (CERP), and the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program, which are both part of the Civil Works Research and Development Program, Headquarters, U.S. Army Corps of Engineers (HQUSACE). CORE-LOC was developed under CERP Work Unit 32536, "Concrete Armor Unit Design" and REMR Work Unit 32662, "Breakwater Concrete Armor Units for Repair" at the Coastal Engineering Research Center (CERC) of the U.S. Army Engineer (USAE) Waterways Experiment Station (WES). CERC and the WES Hydraulics Laboratory were merged in October 1996 to form the WES Coastal and Hydraulics Laboratory (CHL). Dr. James R. Houston is the Director of the CHL and Messrs. Richard A. Sager and Charles C. Calhoun, Jr., are Assistant Directors. Many of the two-dimensional stability tests reported herein were conducted under CERP Work Unit 32534, "Breakwater Stability: A New Design Approach."

Mr. David Mathis, HQUSACE, was the CERP Coordinator and Mr. William N. Rushing, HQUSACE, was the REMR Coordinator, both of the Directorate of Research and Development. Members of the REMR Overview Committee were Mr. James E. Crews, Chairman, and Dr. Tony C. Liu, HQUSACE. Messrs. John J. Lockhart, Jr., Barry Holliday, and Charles Chesnutt served as HQUSACE Technical Monitors. Ms. Carolyn Holmes, CHL, was the CERP Program Manager and Mr. William F. McCleese, WES Structures Laboratory, was the REMR Program Manager. Mr. D. D. Davidson, CHL, was the REMR Coastal Problem Area Leader. Mr. Jeffrey A. Melby, CHL, was the Principal Investigator of research Work Units 32536 and 32662. Mr. Robert Carver, CHL, was the Principal Investigator of research Work Unit 32534.

CORE-LOC was developed from July 1992 through September 1994 by Mr. Melby and Mr. George F. Turk, Research Hydraulic Engineers, CHL. Much of the two-dimensional stability testing was done by Mr. Carver and Ms. Brenda Wright, CHL, beginning in June of 1993 and continuing through the present. The studies were done under the general supervision of Dr. Houston and Mr. Calhoun, and under the direct supervision of Mr. C. Gene Chatham, Chief, Wave Dynamics Division, and Mr. D. D. Davidson, Chief, Wave Research Branch, CHL. Mr. Davidson and Dr. Steven A. Hughes, CHL, provided technical review of this report.

Authorization and funding for the Noyo Stability Study, also discussed herein, were provided by the USAE District, San Francisco (SPN). The CORE-LOC stability tests on the Noyo breakwater were carried out between August and September of 1994. Mr. Ernest R. Smith, CHL, was the Project Engineer on the Noyo Study. Periodic consultation was provided by SPN engineers.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

1 Introduction

Concrete armor units are commonly used to protect coastal rubble structures. The units are individually placed on the breakwater in a regular pattern or quasi-random matrix. Concrete armor units come in a variety of shapes and sizes, and some have several recommended placement configurations. Concrete armor units are used on structures when stone of a sufficient size to resist wave action is not available or is uneconomical.

In the past, the choice of armor unit shape and method of application have relied in large part on engineering judgement, partly because no optimal armor unit existed. All of the existing armor units had some distinct weakness in the form of low stability, high structural stresses, low on-slope porosity or roughness, and/or complex and sometimes impossible specified construction techniques. Some units have overly specific placement requirements and are nearly impossible to construct in low visibility or deep water. In addition, some armor shapes are simply inefficient, producing layers requiring excessive amounts of concrete. As a result of these weaknesses, concrete armor units have historically performed poorly, from both engineering and economic perspectives. Typical armor units, as shown in Figure 1, include the dolos, tribar, tetrapod, ACCROPODE® (hereafter referred to as accropode), and block. These units have a range of stability and structural capacity characteristics. Most existing armor units require rather shallow structure slopes to maintain hydraulic stability. None of the units shown are specifically designed to be used as repair units for existing dissimilar armor slopes. Some of these units can be stacked to minimize casting yard space while others cannot.

The Coastal Engineering Research Center at the U.S. Army Engineer (USAE) Waterways Experiment Station (WES) has an ongoing research effort to develop improved concrete armor unit shapes for both new coastal construction and repair of existing coastal concrete-armored rubble structures. This development requires incorporating all of the best engineering features from the various existing armor shapes into a single unit while eliminating the major weaknesses.

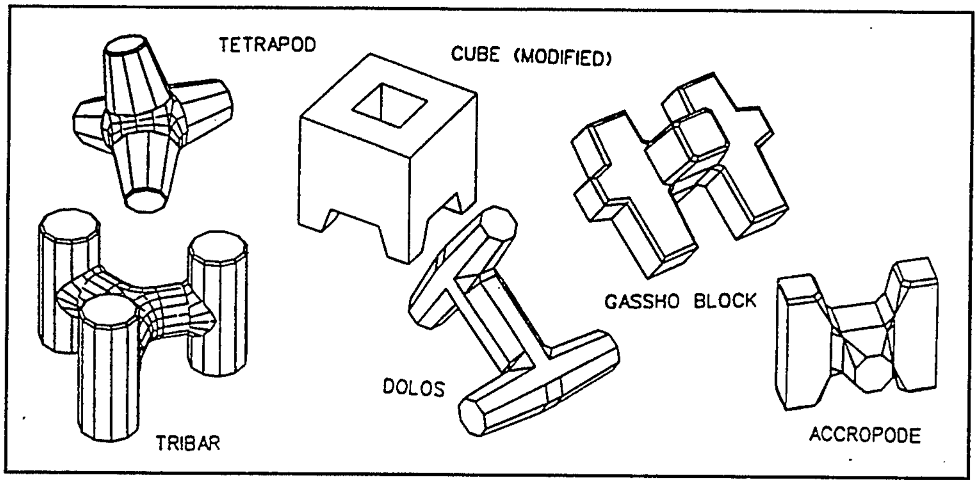

Figure 1. Various concrete armor unit shapes

Optimal armor engineering characteristics are summarized as follows:

a. High hydraulic stability when placed in a single-unit-thickness layer at any slope angle.

b. Reserve stability for wave conditions that exceed the design event.

c. No tendency for units to rock on slope.

d. Continued stability when broken or following renesting resulting from local instability.

e. Efficient combination of porosity and slope roughness to dissipate the maximum wave energy.

f. Maximum performance with a minimum concrete armor layer volume.

g. Hydraulically stable when placed as a repair with other shapes.

h. Low internal stresses, so no reinforcement required.

i. Easy to cast.

j. Easily constructed armor layer, even in low visibility water.

k. Uses minimal casting yard or barge space.

l. Utilizes conventional construction materials and techniques.

Most existing armor units have been successfully applied, but all have weaknesses in one or more of these engineering performance characteristics. For instance, block shapes are often uneconomical because the armor layers require larger units and more concrete than layers of slender armor. Pattern-placed blocks such as Shed and Cob (Wilkenson and Allsop 1983), Haro (de Rouck et al. 1994), and Seabee (Brown 1983), have improved economies over solid blocks, but require idyllic construction conditions to assure the armor layer transitions will not be mobile. Pattern-placement of any shape, particularly without interlocking, will always be subject to unraveling if any single unit is removed from the layer (weakest link analogy). Also, hollow block shapes can be structurally fragile and generally require reinforcement. Slender interlocking units, such as the dolos, gassho, and tribar, have long legs and slender central sections producing very high stresses in the central region. Requiring reinforcement makes these units too expensive and breakage of unreinforced units has been a recurring problem (Melby and Turk 1995). The accropode shape produces a more economical armor layer than most units but could be improved by modifying the shape to increase layer porosity and stability.

A new series of coastal rubble structure concrete armor units called CORE-LOC™, hereafter referred to as core-loc, has been developed that attempts to incorporate all of the features shown in the above list. While several different core-loc shapes have been developed,, this report discusses preliminary hydraulic stability tests of only one shape. This is the middle aspect ratio and is expected to be the most widely used unit.

Core-loc units have been designed to be placed in a single-unit-thickness layer on steep or shallow slopes. Steep armor layer slopes typically are between 3V:4H and 1V:1.5H. The core-loc shape has been optimized to maximize hydraulic stability, unreinforced strength, and residual stability, but minimize casting yard space.

The primary intent of the shape optimization is to produce a very stable armor layer and yet have stresses low enough that regular strength unreinforced concrete can be used with little or no armor breakage occurring during the life of the structure. Many breakwater concrete armor layers built between 1950 and 1985 in the United States have lasted less than 10 years between rehabilitations, primarily due to armor breakage (Melby and Turk 1995). The core-loc strength has been maximized, through optimization of the unit shape, to minimize armor unit breakage. During the last few years of research on the structural response of dolos units it was found that very high flexural and torsional stresses occurred in the slender central cross sections on the dolos units (Melby and Howell 1989, Melby and Turk 1992). Field inspections and finite element analyses have shown a similar response in tribar units. Because of the contiguous shape of the dolos and close proximity of the highly stressed central regions and the slender outer regions, it is nearly equally likely to have very high stresses in the outer sections. The core-loc units were designed to eliminate the slender central sections by requiring that the dimensions of any centrally cut section be no less than two-thirds of the maximum dimension of the unit. This is accomplished by chamfering all intersecting internal angles. Chamfering also decreases the stresses in the outer portions of the unit. Although the chamfered core-loc has a slender appearance, it is actually quite robust with large central-section modulii, as will be shown in the following structural analyses. The multitude of symmetrically tapered appendages promotes wedging and assures good interlocking between units.

The core-loc unit was specifically designed to interlock well with dolosse so that it could be used as a repair unit. Dolosse are usually designed with a waist ratio of 0.32. This is the ratio of the maximum unit dimension, the fluke length, to the depth of the central shank. The most commonly used core-loc shape was designed such that the separation and taper of its flukes are approximately the same as that of a dolos with a waist ratio of 0.32.

2 Core-Loc Characteristics

Figure 2 shows schematicised dimensions of commonly used chamfered core-loc. Table 1 summarizes engineering characteristics of core-loc units and core-loc layers. The table includes the range of values measured for model core-locs with and without chamfers and typically recommended values for a prototype design using smaller core-loc. The table also includes similar values for the dolos unit for comparison. Engineering characteristics herein are defined as per Chapter 7 of the *Shore Protection Manual* (SPM 1984). The outer dimension, sometimes called the fluke length, of both units is denoted as *C*. Dolos calculations are done for the usual dolos application with waist ratio 0.32. The number of units per unit area can be determined using the equations

$$\frac{N_r}{A} = \phi V^{-2/3} \tag{1}$$

$$\phi = n k_\Delta \left(1 - \frac{P}{100} \right) \tag{2}$$

$$r = n k_\Delta \left(\frac{W}{\gamma_r} \right)^{1/3} \tag{3}$$

where

N_r = number of units in a given onslope area
A = onslope area
V = armor unit volume
ϕ = packing density coefficient
n = number of layers
P = porosity
k_Δ = layer coefficient
r = layer thickness
W = armor unit weight
γ_r = specific weight of the concrete

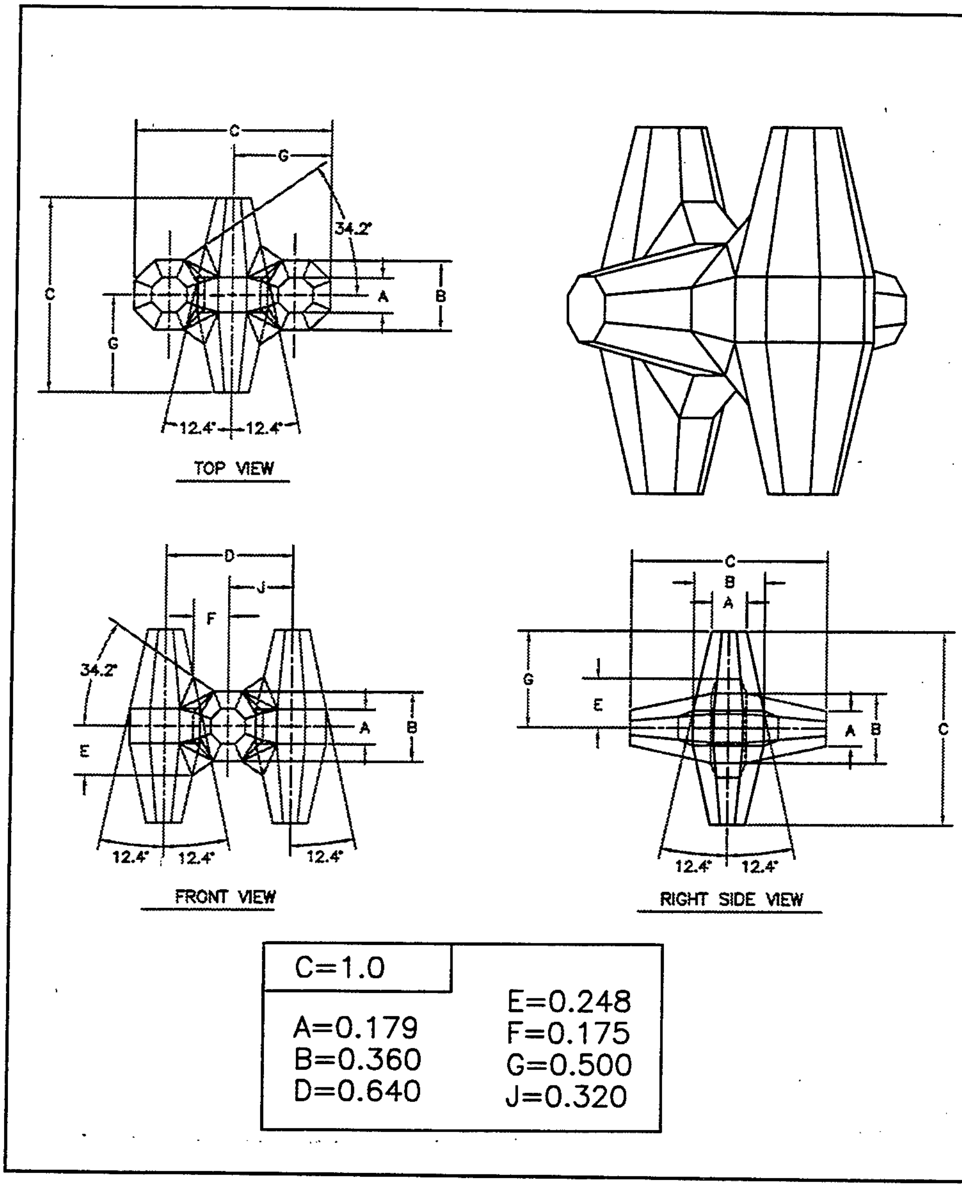

Figure 2. Core-loc schematic

The packing density coefficient for core-locs has not been defined with accuracy yet. Simple box tests yield a packing density coefficient from 0.54 to 0.67. The higher coefficients are achieved by carefully placking the units and may not be achievable in the prototype. The lower coefficients are loose and will likely exhibit unwanted downslope packing in the prototype. Actual packing on a structure will vary due to bends at the toe and crest. Therefore, a short structure will exhibit different packing density coefficients than a tall structure, even if the onslope unit-to-unit spacing is similar. Tests to-date show that, on completed three dimensional physical models, packing density coefficients generally vary from 0.58 to 0.64, and porosity from 0.54 to 0.67. Estimates of these values is difficult and will vary from three to five percent due to the subjectiveness in estimating the surface area perimeter. Moreover, the prototype units will not pack as tight as model units because the frictional force is believed to be relatively higher in the prototype and crane maneuverability less than that achieved by hand placement. This difficulty in handling large units will also lead to smaller prototype units packing tighter than larger units.

For a single thickness of armor, a higher packing density will usually produce a more reliable armor layer with respect to stability, particularly if the toe can move. Therefore it is reasonable to use the highest packing density coefficient that can be resonably achieved, within the funding and construction constraints of the project. Also, underestimation of the number of units required can cause serious contractual and logistical problems during the final period of armor layer construction. But an attempt to over-pack the layer can result in bridging of the units, which can lead to settlement problems. Packing density coefficient and porosity are given for a smaller unit in Table 1, but prototype experience by Sogreah (1997) indicates the packing density coefficient should be reduced as the unit size increases. Consult the Core-Loc Technical Guidelines (Turk and Melby 1997) for selection of design values for a particular case.

Table 1
Engineering Characteristics of Core-Loc

Unit	Nondimensional Volume V/C^3	Typical Number of Layers n	Nondimensional Layer Thickness r/C	Layer Coefficient k_Δ	Porosity P as %	Packing Density Coefficient ϕ	Typical Slope $\cot \alpha$
Unchamfered Model Core-Loc	0.2240	1	1.00	1.60	66	0.54	1.33-2.0
Chamfered Model Core-Loc	0.2234	1	0.85-1.10	1.39-1.77	54-67	0.58-0.64	1.33-2.0
Example: 5 t Prototype Core-Loc	0.2234	1	0.92	1.51	60	0.60	1.33-2.0
Dolos	0.1561	2	1.02	0.94	56	0.83	2.0

3 Core-Loc Structural Response

Finite element method (FEM) structural analyses were performed by Jaycor, Inc. of Vicksburg, MS, to compare the structural response of dolosse, tribar, and accropodes with core-locs for several static loading modes. For the FEM analysis, the armor weight was 9 tonnes (10 tons), modulus of elasticity was $3.5*10^4$ Mpa ($5.1*10^6$ psi), Poisson's ratio was 0.21, and specific gravity was 2.32 relative to fresh water. The FEM grids for the four units are shown in Figure 3. An example loading, shown in Figure 3, imposed the worst case torsional condition with four 4.5-tonne (5-ton) loads applied to the four fluke tip ends to generate the maximum twisting force on the unit. The unit was pinned at the center for this case. Another loading condition imposed a 9-tonne (10-ton) flexural load on one fluke tip with the opposing fluke fixed rigidly along the outside surface (Figure 4a). This condition generated the maximum flexural stresses at the internal intersection on the unit. Another pure flexural loading and a combined torsion and flexural loading also were analyzed (Figures 4b and 4c, respectively). For the other pure flexure load condition, the load of 9 tonnes (10 tons) was applied transversely at the center of the fluke while the opposing fluke was held rigid. For the combined loading case, two 9-tonne (10-ton) loads imposing torsion and flexure were applied to one fluke end while the opposing fluke was held rigid along its entire length.

Figure 5 shows tensile stress contour plots for the pure torsional loading condition for the four units. The plots show that even though the maximum tensile stress in the accropode is larger than that in the core-loc, the average stress over the highly stressed chamfer region is less. A closer inspection of Figure 5 shows that the stress varies by over a factor of two near the chamfer edge. The discontinuity at the chamfer leads to a much higher stress gradient than would be present if no chamfer existed. Therefore, for all four units, using fillets rather than chamfers would reduce the maximum tensile stresses significantly. For core-loc and accropode units, however, this generally is not required as the design stresses are far less than dolos and tribar, and the latter units have performed reasonably well on all Corps structures. The only projects that have proved less than satisfactory are dolos layers where the units were undersized with respect to stability. Note that on Figure 5 the highly stressed regions near the ends of the flukes are point stresses due to the loads and are not of interest.

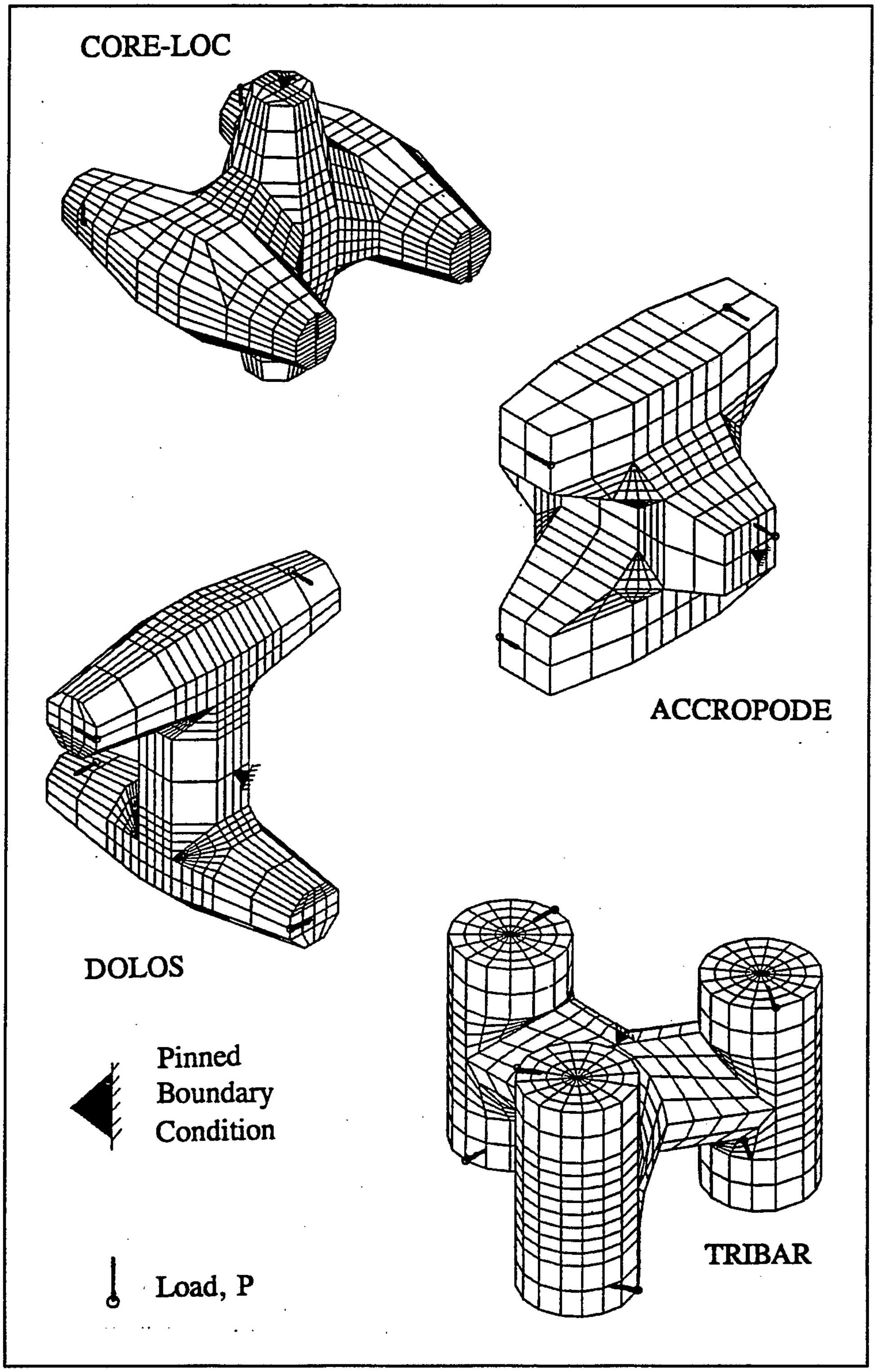

Figure 3. Loading and boundary conditions for torsional stress comparison

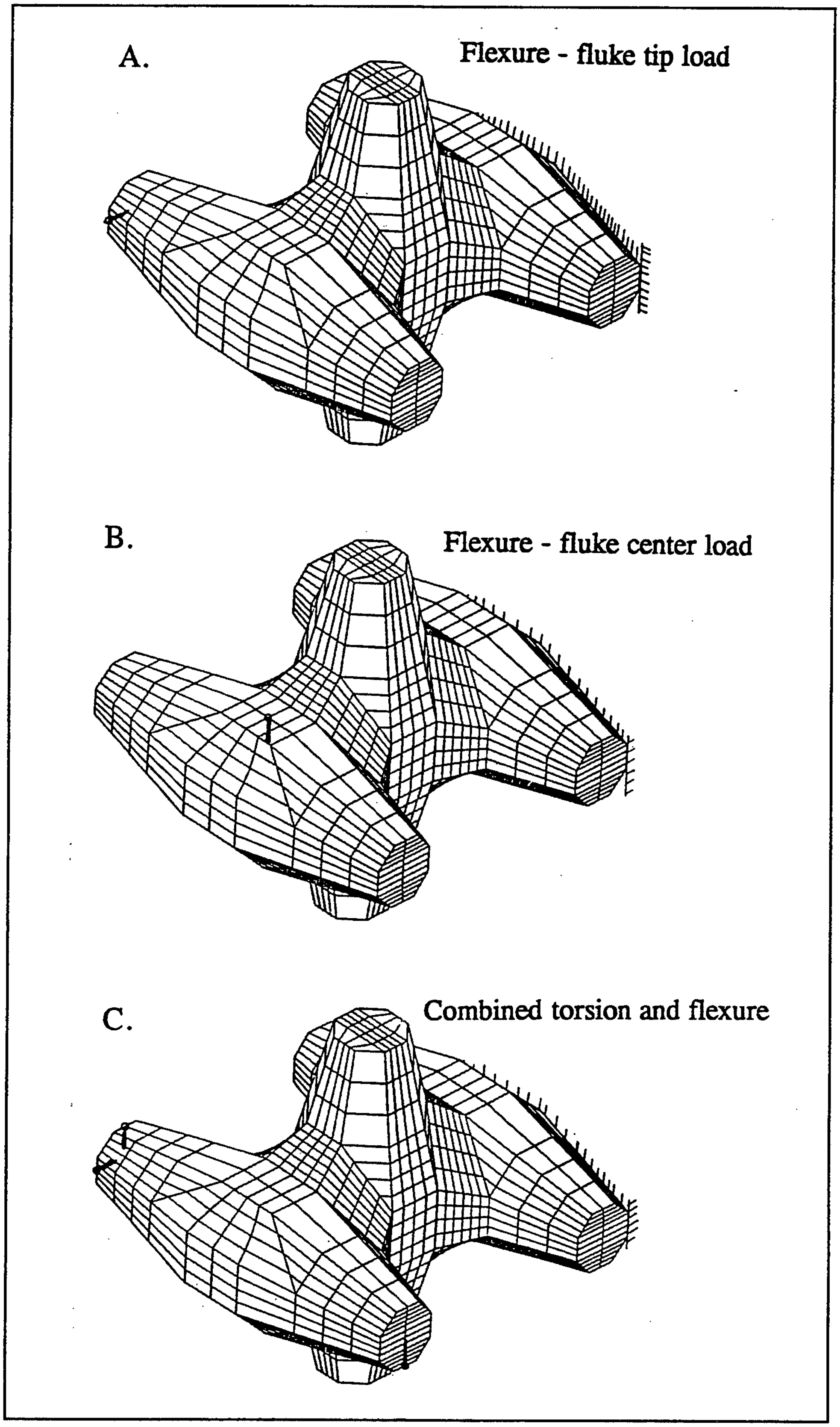

Figure 4. Loading and boundary conditions for other load cases

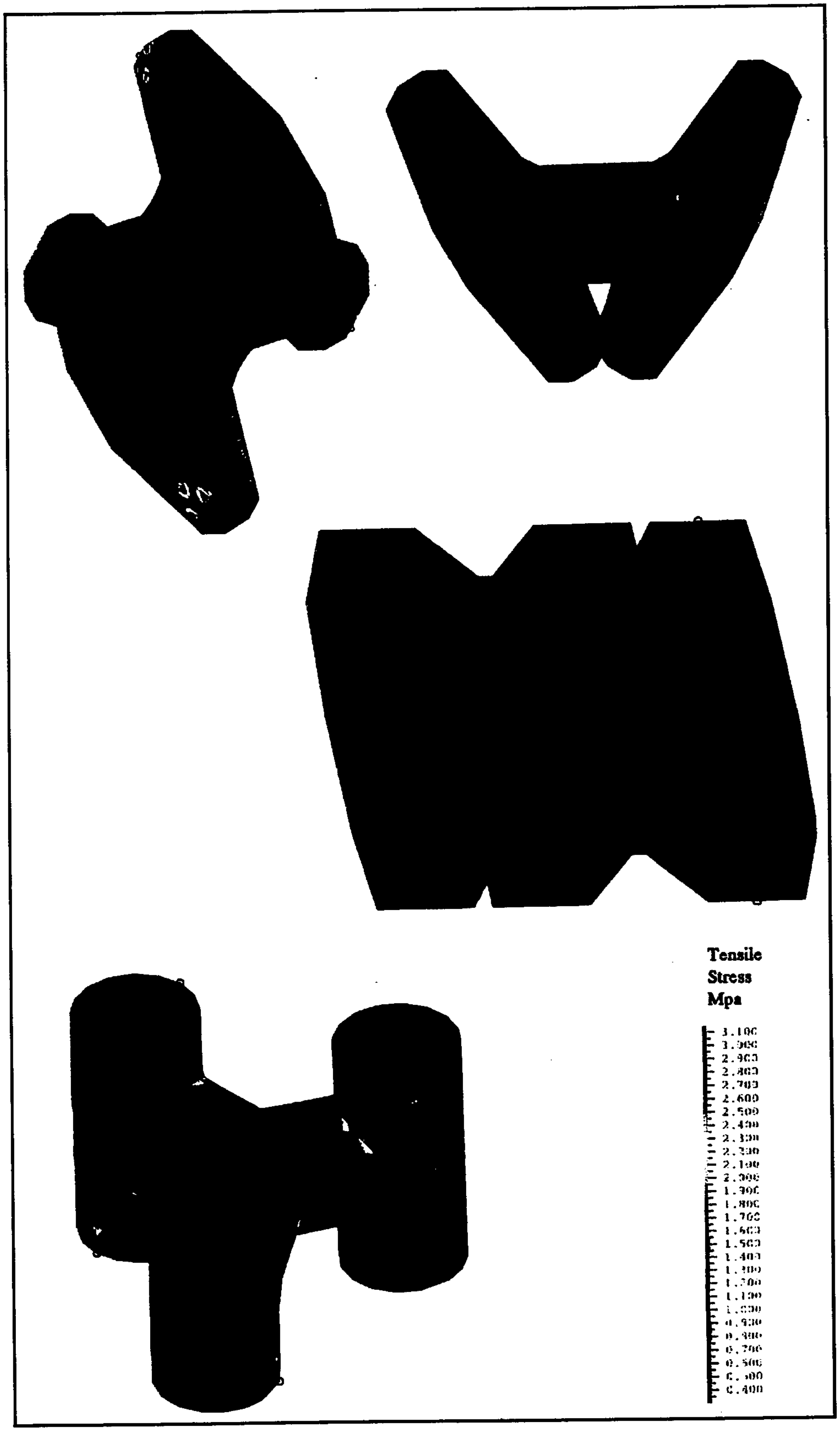

Figure 5. Tensile stress contours from FEM static torsional loading

Maximum tensile stresses from the FEM analyses are summarized in Table 2. All load cases were analyzed for the dolos and core-loc but only the pure torsion and pure flexure with tip load were analyzed for the accropode and tribar. The maximum tensile stresses for each unit for torsion and fluke-tip flexure are illustrated in Figure 6. As shown in Table 2 and in Figure 6, for equivalent weight units, the core-loc maximum tensile stress for static loads ranges from 46 percent to 62 percent that of dolos. The maximum core-loc tensile stress is 74 percent for torsion and 74 percent for flexure that of accropode, and 38 percent for torsion and 33 percent for flexure that of tribar.

Table 2
FEM Static Stress Comparison

	Stress, σ_t, Mpa (psi)			
Load Case	**Core-Loc**	**Dolos**	**Accropode**	**Tribar**
Torsion	1.12 (162)	2.08 (302)	1.52 (220)	2.98 (432)
Flexure - fluke tip load	1.12 (162)	2.41 (350)	1.52 (220)	3.36 (487)
Flexure - fluke center load	2.10 (305)	3.42 (496)	N/A	N/A
Combined flexure and torsion	1.91 (277)	3.83 (556)	N/A	N/A

For Crescent City 38-tonne dolosse, the design stress level corresponding to a 2 percent exceedance was approximately 4.8 Mpa (696 psi). This structure is performing reasonably well with 2 percent breakage since the 1986 rehabilitation. The core-loc design stress, estimated at 62 percent of this value, would be approximately 3.0 Mpa (435 psi). This stress is below the 28-day splitting tensile strength met on all Corps concrete armor projects. Further, recent concrete armor 28-day strengths have ranged from 4.5 (650) to 5.0 (720) MPa. Thus, core-loc maximum stresses should be well below design strengths, even for large unreinforced units.

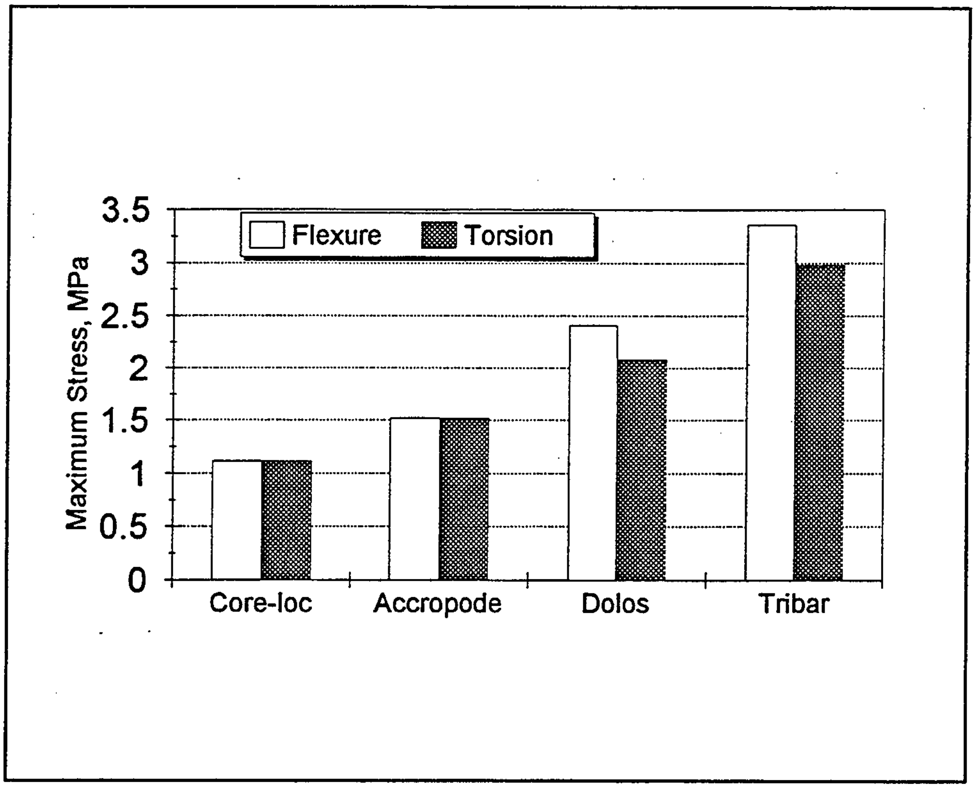

Figure 6. Comparison of maximum tensile stresses from FEM analysis

4 Core-Loc Hydraulic Stability

Initial Two-Dimensional Tests

Experimental setup

Preliminary hydraulic stability tests were conducted using core-loc to test the feasibility of the unit. These tests were kept very simple and were only intended to provide an initial estimate of the core-loc stability relative to other commonly used armor units. Test results were to be used to determine whether or not to proceed with development of engineering guidance for the core-loc.

The model parameters were determined using Froude scaling (Stevens et al. 1942) (Table 3). The model units, schematicized in Figure 2, were cast using a polyester resin (Richter 1988). Specifications for the intially tested model core-loc are given in Table 4.

Table 3
Froude Scaling Model Parameters

Characteristic	Dimension	Model-Prototype Scale Relation
Length	L	N_L
Area	L^2	$N_A = N_L^2$
Volume	L^3	$N_V = N_L^3$
Time	T	$N_T = N_L^{1/2}$

Table 4
Model Core-Loc Specifications

C	B	J	A	Mass	Volume	Specific Gravity
cm (in.)				gram (lb)	cm^3 ($in.^3$)	
7.2 (2.83)	2.7 (1.06)	8.0 (3.15)	1.5 (0.59)	220 (0.49)	93.2 (5.69)	2.35

Dimensions are defined in Figure 2. Note that these initial model units were not chamfered and had slightly different dimensional relationships than those shown in Figure 2.

The structure layout schematic is shown in Figure 7 and a profile view photograph of the structure is shown in Figure 8. The core material was sized at the lower end of that recommended by the SPM to achieve a nearly impermeable structure, which increases the back pressures and is conservative for armor stability. Using the SPM recommendation for randomly placed armor, the underlayer mean weight was one-fifth of the armor weight with a gradation of ±30 percent by weight.

The tests were conducted in a 61 cm (24 in) wide, 45.7 m (150 ft) long, 1.4 m (4.5 ft) deep flume. Figure 9 shows the flume layout. Four electrical-capacitance wave gages were used to measure the water surface oscillations in the flume. A single wave gage was placed near the wave generator while three gages were placed in an array near the structure. Incident and reflected waves were resolved using the method of Goda and Suzuki (1976). Waves were generated by an electro-hydraulic powered, computer-controlled, bottom-hinged paddle.

Experimental results

Table 5 summarizes the initial stability tests accomplished for the core-loc unit. Only the maximum wave heights tested for each wave period-water level combination are shown in Table 5. The full list of tests is shown in Appendix A, Table A1. All tests utilized monochromatic waves.

The only test condition that showed any instability during the hydraulic stability tests is the first entry in Table 5; a wave 36 cm (14 in.) high with a period of 1.4 sec in a water depth of 46 cm (18 in.). For this case, the entire layer slumped downslope due to the long slope length and extraordinarily large waves.

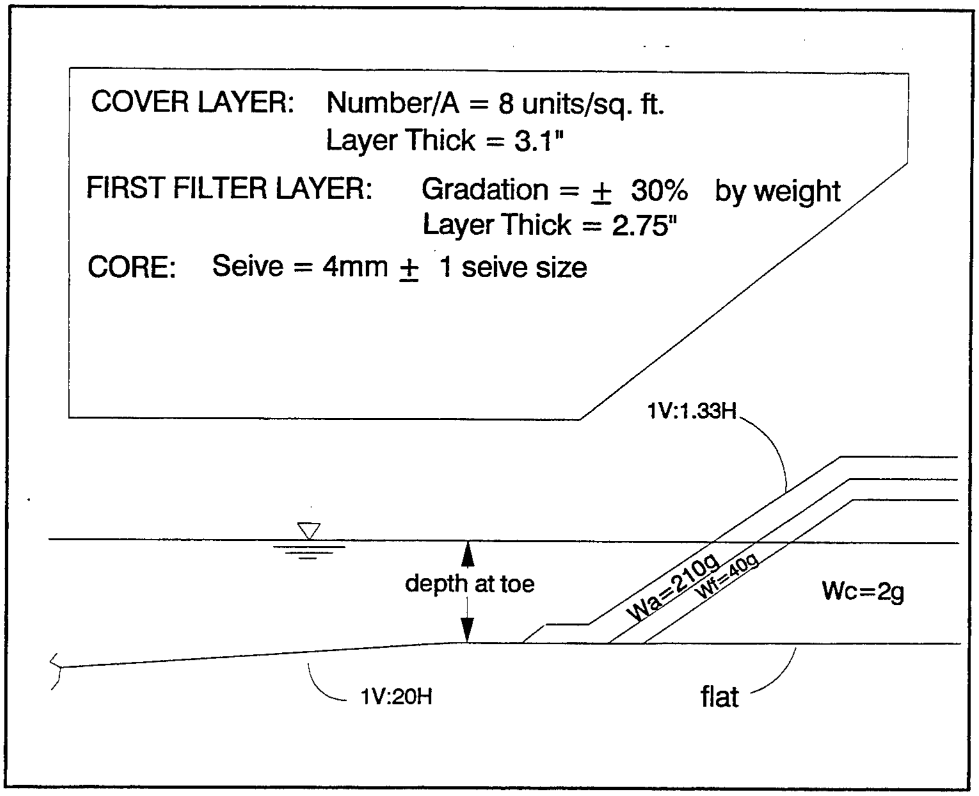

Figure 7. Structure layout

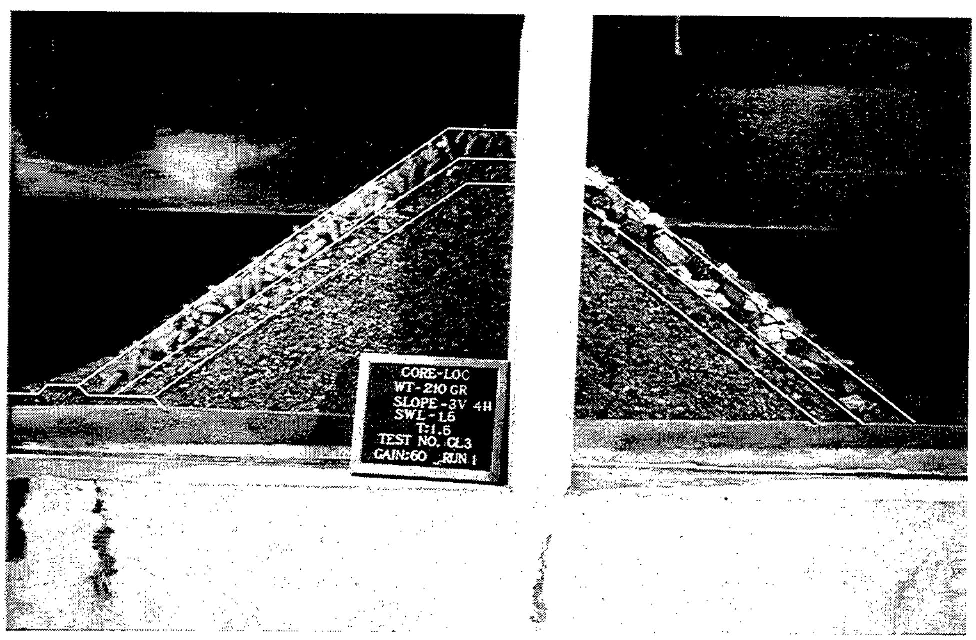

Figure 8. Profile view of structure as tested

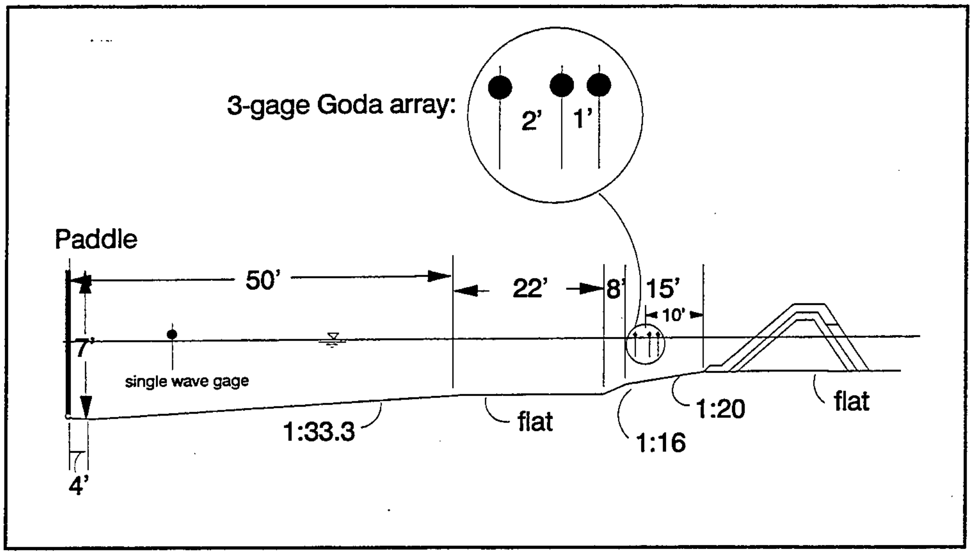

Figure 9. Flume layout

Table 5
Summary of Test Data for Maximum Wave Conditions

Gain	Depth at Toe cm (in.)	Wave Period at Gage (sec)	Incident Wave Height cm (in.)	Reflection Coeff	Movement	Stability Coeff K_D
64	46 (18.1)	1.38	36 (14.2)	0.23	rocking	159
68	46 (18.1)	1.78	32 (12.6)	0.51	none	111[1]
94	38 (15.0)	1.26	45 (17.7)	0.27	none	321[1]
94	38 (15.0)	1.58	36 (14.2)	0.38	none	163[1]
94	38 (15.0)	1.96	31 (12.2)	0.51	none	102[1]
90	38 (15.1)	2.09	18 (7.1)	0.61	none	21[1]

[1] Wave generation capacity limited, no instability.

The Hudson stability equation is as follows:

$$W = \frac{\gamma_r H^3}{K_D (S_r - 1)^3 \cot\alpha} \tag{4}$$

where

W = stable armor weight

γ_r = armor specific weight

H = wave height

S_r = armor specific weight relative to the specific weight of water in which it is placed, i.e. $S_r = \gamma_r/\gamma_w$, where γ_w is the specific weight of water

α = structure slope

K_D = Hudson stability coefficient

This equation can be used to compare core-loc stability with other randomly placed armor units. However, it is likely that this equation will not adequately describe the response of core-loc units. For instance, stability may increase with structure slope rather than decrease. Table 5 lists K_D for the maximum wave conditions. It can be seen that the stable K_D are significantly greater than any documented stability tests of other randomly placed concrete armor shapes.

Other Two-Dimensional Stability Tests

A comprehensive series of two-dimensional hydraulic stability tests of the core-loc has also been carried out (Carver and Wright 1994). These tests were done in a 0.9-m-wide (3-ft-wide) section of a 3.4-m-wide (11-ft-wide) flume which was 75 m (245 ft) long. The remainder of the flume width was left clear for waves to be dissipated on a rock wave absorber on the rear wall of the flume. Monochromatic and irregular waves were generated by an electro-hydraulic powered, computer-controlled, horizontal-displacement paddle. For the irregular waves, the spectra were of the Texel, Marsen, and Arsloe (TMA) type. Incident and reflected waves were resolved from water surface measurements made with two sets of three electrical capacitance wave gages using the methods of Goda and Suzuki (1976). The structure slopes tested included 3V:4H and 1V:1.5H. The approach slope was at 1V:100H for 6 m (20 ft) seaward of the structure, 1V:75H for 34 m (112 ft), and flat for 15.2 m (50 ft) to the generator pit. The deep and shallow wave gage arrays were positioned near the wave generator and 3.4 m (11 ft) from the structure toe, respectively. For the irregular wave tests, approximately 1,000 waves were generated per test. The water depths at the structure toe were 36 cm (14.2 in.) and 61 cm (24 in.). The incident wave height H_{mo} at the shallow water gage array ranged from 4.6 cm (1.8 in.) to 39 cm (15.4 in.) and the peak wave period T_p from 1.5 to 4.7 sec. The armor layer was composed of 219-g (0.48-lb) core-locs with a stone underlayer mean mass of 45 g (0.10 lb) and a stone core mean mass of 1 g (2.0E-3 lb). As in the previous tests, this core had a very low permeability and was also more critical to armor stability. The structure was 0.9 m (2.95 ft) tall and 2.7 m (8.86 ft) wide at the base. For these tests, several parameters of relative measure were calculated including the relative depth d/L_o, the wave steepness H_{mo}/L_o, and the surf similarity parameter or Irribarren number

$$\xi = \frac{\tan \alpha}{\sqrt{H_{mo}/L_o}} \tag{5}$$

where

α	=	structure front slope angle
H_{mo}	=	incident wave height at the shallow gage array
L_o	=	$2\pi/gT_p^2$ = deep water wave length computed from the peak period at the shallow gage array
T_p	=	peak period
d	=	structure toe depth
g	=	acceleration of gravity

The range of ξ tested was 2.13 to 15.9, the range of relative depths was 0.012 to 0.175, and the range of wave steepnesses was 0.001 to 0.098.

These early tests showed that the core-loc armor layer was two-dimensionally stable for wave heights far exceeding those causing damage to most other armor shapes. No-damage Hudson coefficients were consistently over 150. En-masse sliding of the armor layer was observed for the largest waves due to the long slope length and the high rundown velocities. As long as the prototype toe is reasonably stable, this would not be of concern because a conservatively designed armor layer would never be subjected to these extreme wave conditions. A conservative design would never specify armor weights using very high stability coefficients, such that the non-interlocked armor stability was significantly different from the interlocked stability, because of the risk of catastrophic failure. Therefore, based on 2-D testing reported herein, a conservative K_D of 16 is recommended for core-loc used on a breakwater trunk. It is clear from these tests there should be considerable reserve stability beyond the design wave or when repeatedly subjected to the design wave.

Researchers made note of the fact that the units showed almost no movement on the slope, including in-place rocking. It seems likely that the units would therefore have a very low probability of experiencing impact stresses. Also, reflection coefficients from the core-loc slope ranged from the same to no more than 5 percent less than those of dolosse, indicating that existing dolos reflection and runup design information could be used for preliminary estimation of reflection and runup on core-loc slopes.

Noyo, CA, Site-Specific Stability Tests

Smith et al. (1994) carried out three-dimensional stability tests of a core-loc armor layer for a site-specific test of the offshore Noyo, California, Harbor breakwater. This site is subjected to depth-limited 7- to 9-m (23- to 30-ft) waves repeatedly each winter and the breakwater is subjected to very high flow velocities due to wave focussing from several surface-piercing pinnacles just off the seaward toe. Noyo therefore provided a very severe test of core-loc stability.

Three-dimensional stability tests of the Noyo breakwater were carried out at a geometrically undistorted scale of 1:50 with molded bathymetry using irregular waves. The model offshore breakwater was scaled from prototype dimensions of 122 m (400 ft) length between two round head centers and initial crown widths of 29 m (95 ft) on the large head, 20 m (66 ft) on the small head, and 7 m (23 ft) between the heads. The initial armoring was 20-tonne (22-ton) accropodes on the small, more landward head and 33-tonne (37-ton) accropodes on the larger, more seaward head. The slope of the breakwater was 1V:1.5H and prototype specific gravity was 2.34. The initial storm series consisted of 17 tests of 15 min each with a succession of 13-, 17-, and 20-sec peak period waves of increasing significant wave heights from 3.4 to 8.4 m (11 ft to 28 ft) (Storm I). The maximum wave height was depth-limited and the shallow-water spectra were fully saturated.

The accropode toe repeatedly failed due to erosion of the toe apron at higher wave heights in the design storm series. Upon further testing of higher waves, the main armor would fail. Various toe apron configurations were tried but none provided toe stability for the entire storm series. The armor was stable with no damage if the toe was firmly scotched with a metal strip around the entire structure. The structure was stable when additionally subjected to the 10 highest wave height tests in the Storm I series (Storm IA).

Since the original breakwater layout prescribed would not meet the required economic benefit-to-cost ratio, the breakwater footprint was reduced to a minimum with a 9-m (29-ft) crown width on the large head and a 6-m (20-ft) crown width over the remainder of the breakwater. A toe apron configuration was found that was stable for at least two successive storm events with this new configuration. In addition to the accropode sizes tested previously, core-locs at weights of 28 and 16 tonnes (31 and 18 tons) were also tested. These units had approximately 15 percent less volume per unit than the accropode previously tested and the core-loc armor layer had approximately 19 percent less total volume than the accropode layer.

Although the accropodes were placed by hand according to the technique prescribed by Sogreah, Inc. representatives, several placement techniques were tested for the core-locs. These included selective hand placement, non-selective hand placement, and slinging the units with a small string or cable. The selective hand placement technique proved to be more stable because the unit orientations were optimized. But it is doubtful that quality control measures could ever be employed to match this placement in the field. Dynamic placement, where the units were dropped from a small height in order to promote wedging, was tried. This method is probably more effective with higher friction prototype concrete units. With the plastic model units no advantage to using this method could be observed. The two techniques used for the majority of the tests were non-selective hand placement and sling placement. For these methods, if a unit was mistakenly dropped or if it rolled during release, it was left in place. By placing each unit with a small string in a slinging fashion, to simulate crane placement, a more realistic representation of prototype placement was realized. No discernable difference in the performance of the armor layer was noted for these two methods.

Both accropodes and core-locs were stable for two successive Storm IA wave series. Both required rehabilitation after being subjected to an additional three Storm IB series, each consisting of the highest three waves in Storm I. In other words, neither armor was stable when subjected to the five successive storms. It appeared that the primary damage was instigated by toe instability, although lesser unraveling did occur in areas of wave focussing. The Hudson stability coefficient corresponding to the larger core-loc was 28 for the highest $H_{1/10}$ in the series and 13 for the highest H_s. The corresponding accropode stability coefficients were 23 and 11, respectively. During the tests it was noted that the core-loc toe scoured less than the accropode toe. This was due to the much higher wave energy dissipation and therefore reduced runup and overtopping velocities on the core-loc layer.

Accropode armor weight was increased to 48 tonnes (53 tons) for the large head. This armor layer lost several units but was considered stable for a succession of five Storm IB series. The stability coefficients for this larger accropode were 16 for $H_{1/10}$ and 8 for H_s.

The design waves tested above were considered to be quite conservative, so a somewhat more realistic wave condition also was tested. The final storm series consisted of a five-Storm-IB sequence, except that the 20-sec, 8.4-m (28-ft) test was omitted from the middle three series. The 28- and 16-tonne (31- and 18-ton) core-locs were stable for this sequence of storms, with four units or 0.4 percent displaced.

In summary, both core-locs and accropodes were stable for high stability coefficients when subjected to the repeated attack of very high energy design storm events. However, the final stable core-loc structure had 19 percent less concrete than the stable accropode armor layer. The core-loc structure also met the required economic benefit-to-cost ratio and therefore was accepted as the final design.

As a final comment, no evidence of massive failure of the "single layer" core-loc units was evident in these tests. After the toe apron eroded and the toe armor became mobile, the armor layer would begin to loosen gradually. Even after significant instability of the units, the slope destabilization rate was gradual. Rapid failure of other single layer armor has been noted on other studies but only at wave heights greatly exceeding the non-interlocked stability threshold (van der Meer 1988). The Noyo tests confirmed that, for high stability units, such as the core-loc, the failure rate is a function of armor interlocking rather than the layer thickness and significant damage occurs only at high stability coefficients.

5 Core-Loc Repair of Dolos Layers

A short series of two-dimensional stability tests was conducted to determine the comparative stability between dolos, core-loc, and a dolos slope repaired with core-locs. The tests were performed in shallow water with a 1.5-m-wide (5-ft-wide) fronting reef in a 0.6-m-wide (2-ft-wide) flume. The structure was 17 cm (6.7 in.) high with a front slope of 1V:1.5H. Monochromatic waves were generated, producing a maximum incident wave height of 22 cm (8.7 in.) and period of 3.75 sec in a depth of 17 cm (6.7 in.) at the structure. A very high wave height-to-depth ratio occurred at the structure because the fronting reef was narrow relative to the wavelength; therefore, wave height was not stabilizing before it hit the structure. Approximately 180 waves were generated per run. The number of wave cases and complexity of this experiment were kept to a minimum for this proof-of-concept test.

The first series of tests utilized 82 core-locs placed at a packing density of 0.54. The armor unit mass was 104 g (0.23 lb). For these tests, only a single unit was displaced more than one characteristic armor length, even though the incident waves were very severe. The no-damage Hudson stability coefficient for this monochromatic wave case was approximately 72.

The second series of tests utilized 97 dolosse placed at a packing density of 0.83. The armor unit mass was 125 g (0.27 lb). For these tests, 15 units were displaced and most of the dolosse were mobile during the tests. The Hudson stability coefficient for this case was approximately 61, but represented excessive damage (15 percent displacement).

For the third series of tests, the damaged dolos slope was repaired with 15 core-locs. The repair units were 145 g (0.32 lb) and were placed rather haphazardly along the toe and in two pockets on the slope. The remaining dolosse were not touched. This is not a recommended repair procedure but represents a worst-case emergency spot repair. For this test series, three core-locs were displaced off the slope and three additional dolosse were displaced. It was noted that, where placed in groups, the core-locs had interlocked and stabilized the original damaged regions on the slope. The displaced units were lone repair units placed near the cap and were never interlocked. For an actual repair, the existing armor near the repair region would be removed from the slope so the core-locs could be interlocked with these units as they were placed. It is expected that this more careful repair procedure would have resulted in a much more stable armor layer.

Although very brief, these tests showed that the core-loc-repaired areas were qualitatively more stable than the original dolos slope, and the higher structural strength of the core-loc further justify its use as a repair unit for dolos slopes. More extensive tests are being done to systematically quantify the stability of a core-loc-repaired dolos slope and to determine the most effective repair methods.

6 Armor Volume Comparison

The cost of an armor layer, for a given structure, depends primarily on the volume of concrete on the slope, number of units, unit material cost, and the unit construction costs. The unit construction costs include casting yard, transport, and placement costs. Yard costs include construction of forms; unit pouring, storage, and handling; and the cost of equipment necessary to handle the units. Per unit yard costs will increase with unit size but decrease with the number of units, due to economies of scale. Per unit transport costs are due to costs associated with trucking the units and, sometimes, barging the units to the site, and are a function of the unit size. Unit placement costs include rental of crane and are primarily a function of the time required to place each unit. Obviously, larger units will cost more to place than smaller units. For a given construction technique and armor type, the construction costs are primarily a function of the size and number of armor units.

The cost optimization can be fine-tuned by adjusting the armor unit size. The total volume of armor material onslope is proportional to $V^{1/3}$ while the number of units is proportional to $V^{-2/3}$. Using these relationships, the total cost of an armor layer can be minimized for a given small range of armor sizes, where the construction equipment required and the handling time per unit do not vary substantially. The question of whether to go with more smaller units or less larger units is complex depending on the type of equipment available, number of units, handling time per unit, material cost, and the construction process. These construction cost items are site specific and not within the scope of this report.

But the total armor material volume dominates the armor layer cost and therefore should be minimized by maximizing the porosity and minimizing the armor layer thickness. Of course, if the crest height is to be maintained, then as the armor layer thickness is reduced the core height must be increased. On the other hand, if we assume that the core height and underlayer thickness are fixed, then the armor layer runup performance becomes very important. In the following analysis, we assume that the core and underlayer heights are constant so that we can focus on the armor volume comparison. This is reasonable for comparing other armor to a core-loc layer because the core-loc layer has excellent wave energy dissipation characteristics, similar to that of a dolos layer. But for design, the effects of variation in crest height between armor layers must be considered.

The text that follows gives the gross cost minimization for various armor units based on total armor layer volume for a given slope area. This information should be helpful in comparing the various types of armor shapes. Values for Hudson stability coefficients (K_D's) and packing densities in Table 6 are per the 1984 SPM for dolosse, tetrapods, tribars, and stone; for accropodes, recommended values from Sogreah informational reports are used; and Core-loc K_D's are conservatively taken from both 2-D and 3-D physical model studies as discussed previously in this report. K_D's listed in Table 6 are for breaking waves that occur on the appropriate structure slopes. Please note the comments for each armor type.

For the onslope concrete volume comparison, several "correction ratios" are calculated in order to find the ratio between the total volume of concrete for a given type of armor unit to that of the core-loc. For this comparison core-loc placed on a 1V:1.5H slope will be used to "normalize" the ratios to be developed. To develop a relationship for total volume required, the Hudson equation is expressed in terms of volume instead of weight. This gives the volume of a stable armor unit. The volume of concrete in the armor layer can then be expressed in terms of unit volume by multiplying the number of units N by the individual unit volume V_{unit}. Also, by inserting the proper slope correction ratio $S_{unit}/S_{C\text{-}L}$ all volumes can be related to the 1V:1.5H core-loc layer by

$$\frac{V_{unit_T}}{V_{C\text{-}L_T}} = \frac{S_{unit}}{S_{C\text{-}L}} \frac{\phi_{unit}}{\phi_{C\text{-}L}} \left(\frac{K_{D_{unit}} \cot \alpha_{unit}}{K_{D_{C\text{-}L}} \cot \alpha_{C\text{-}L}} \right)^{-1/3} \left(\frac{S_{a_{unit}} - 1}{S_{a_{C\text{-}L}} - 1} \right)^{-1} \tag{6}$$

For the concrete armor units listed in Table 6, the individual parameter correction factors in Equation 6 are provided in Table 7. Using Equation 6 and the correction factors of Table 7, a rational comparative approximation of the total volume of concrete needed to construct a particular armor section as compared to a section constructed of core-locs built on a 1V:1.5H slope can be made. These calculations are summarized in Table 8 and graphically illustrated in Figure 10.

Table 6
Armor Unit Stability Coefficients (K_D[a])

Armor Unit	Structure Slope cotα	Packing Density φ	Breaking Waves	
			K_{DH}, Head	K_{DT}, Trunk
Core-Loc	1.5	0.580[i]	13[c]	16[d]
Core-Loc	2	0.580[i]	13[c,e]	16[d,e]
Tribar-*u*[b]	2	0.599	7[e]	12[e]
Tribar-*u*[b]	5	0.599	7.5[e]	12
Tribar	1.5	0.938	8.3[e]	9[e]
Tribar	2	0.938	7.8[e]	9[e]
Tribar	3	0.938	6	9[e]
Dolos	1.5[e,f]	0.827	7[e,f]	16[e,f]
Dolos	2	0.827	8[e]	15.8
Dolos	3	0.827	7[e]	16[e]
Accropode	1.5	0.650	10[g]	10[g]
Accropode	2	0.650	10[g]	10[g]
Tetrapod	1.5	1.040	5[e]	7
Tetrapod	2	1.040	4.5[e]	7
Tetrapod	3	1.040	3.5[e]	7[e]
Stone[h]	2	1.260	1.6[e]	2
Stone[h]	3	1.260	1.3	2[e]

COMMENTS:
a) Values are based on no-damage criteria (<5% displacement) and minor overtopping (SPM 1984).
b) *U* designates uniform, laid-up placement. All other units are random placement.
c) These values were exceeded in the site-specific Noyo, CA, model study.
d) Conservatively based on over 500 2-D tests where K_D ranged from 200 to 400 (<1% displacement, no rocking).
e) Unsupported by model tests and are only provided for preliminary design purposes (SPM 1984).
f) Stability of dolosse on slopes steeper that 1V:2H should be substantiated by site-specific model tests (SPM 1984).
g) These values are from Sogreah informational brochure but no delineation is provided for various slope angles.
h) Rough angular stone
i) Packing density coefficient adjusted to meet mid-range armor size.

Table 7
Volume Correction Factors

Armor Unit	Structure Slope $\cot\alpha_{unit}$	Slope Length S_{unit}/S_{C-L}	Stab. Coeff. Breaking Wave: Head $K_{DHunit}/K_{DH\,C-L}$	Stab. Coeff. Breaking Wave: Trunk $K_{DTunit}/K_{DT\,C-L}$	Packing Density ϕ_{unit}/ϕ_{C-L}	Slope Steepness $\cot\alpha_{unit}/\cot\alpha_{C-L}$	Specific Gravity $(S_{a\,unit}-1)/(S_{a\,C-L}-1)$
Core-Loc	1.5	1.00	1.00	1.00	1.00	1.00	1.00
Core-Loc	2	1.24	1.00	1.00	1.00	1.33	1.00
Tribar	2	1.24	0.54	0.75	1.03	1.33	1.00
Tribar	5	2.83	0.58	0.75	1.03	3.33	1.00
Tribar	1.5	1.00	0.64	0.56	1.62	1.00	1.00
Tribar	2	1.24	0.60	0.56	1.62	1.33	1.00
Tribar	3	1.75	0.46	0.56	1.62	2.00	1.00
Dolos	1.5	1.00	0.54	1.00	1.43	1.00	1.00
Dolos	2	1.24	0.62	0.99	1.43	1.33	1.00
Dolos	3	1.75	0.54	1.00	1.43	2.00	1.00
Accropode	1.5	1.00	0.77	0.63	1.12	1.00	1.00
Accropode	2	1.24	0.77	0.63	1.12	1.33	1.00
Tetrapod	1.5	1.00	0.38	0.44	1.79	1.00	1.00
Tetrapod	2	1.24	0.35	0.44	1.79	1.33	1.00
Tetrapod	3	1.75	0.27	0.44	1.79	2.00	1.00
Stone	2	1.24	0.12	0.13	2.17	1.33	1.25
Stone	3	1.75	0.10	0.13	2.17	2.00	1.25

Table 8
Armor Volume Comparison for Breaking Waves

Armor Unit	Structure Slope $\cot\alpha_{unit}$	Head Volume Ratio $V_{H\,unit}/V_{T\,C\text{-}L}$	Trunk Volume Ratio $V_{T\,unit}/V_{T\,C\text{-}L}$
Core-Loc	1.5	1.00	1.00
Core-Loc	2	1.13	1.13
Tribar-u	2	1.40	1.28
Tribar-u	5	2.35	2.15
Tribar	1.5	1.88	1.96
Tribar	2	2.16	2.21
Tribar	3	2.91	2.73
Dolos	1.5	1.75	1.43
Dolos	2	1.89	1.61
Dolos	3	2.44	1.99
Accropode	1.5	1.22	1.31
Accropode	2	1.38	1.48
Tetrapod	1.5	2.47	2.36
Tetrapod	2	2.88	2.66
Tetrapod	3	3.87	3.29
Stone	2	3.95	3.93
Stone	3	5.23	4.86

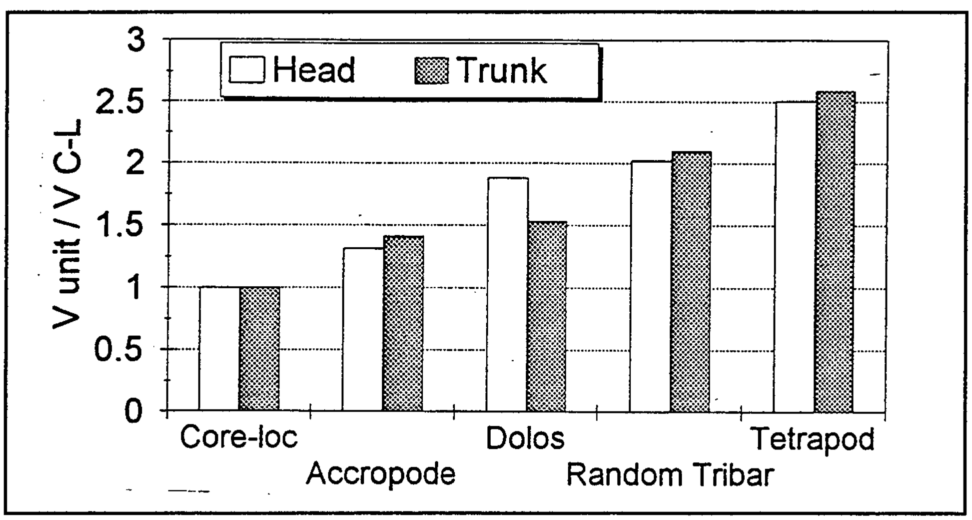

Figure 10. Required armor layer volumes relative to core-loc for breaking waves on 1V:1.5H sloped structure heads

7 Conclusions

A new series of coastal rubble structure concrete armor units called core-loc has been developed. The characteristics of the core-loc units can be summarized as follows:

a. The core-loc units have been designed to be placed randomly in a single-unit-thickness layer on steep or shallow slopes.

b. The core-loc shapes have been optimized to maximize hydraulic stability, porosity, wave energy dissipation, unreinforced strength, and reserve stability, but minimize onslope volume and casting yard space.

c. Core-Loc is designed to interlock well with dolosse so that it can be used as a repair unit.

d. Finite element studies of core-loc showed maximum flexural tensile stresses to be 46 percent, 74 percent, and 33 percent those of dolos, accropode, and tribar, respectively. Torsional stresses were 54 percent, 74 percent and 38 percent those of dolos, accropode, and tribar, respectively.

e. Initial two-dimensional hydraulic stability tests of the core-loc shape indicate that the unit is one of the most stable randomly placed armor units ever tested, withstanding breaking wave heights 5 to 7 times the maximum dimension of the unit on slopes of 3V:4H and 1V:5H. The -no-rocking no-damage Hudson stability coefficients for these tests varied widely depending on the period and wave generation capabilities of the flumes, but were consistently over 150.

f. Initial site-specific three-dimensional stability tests of the Noyo, CA, breakwater showed that, under repeated attack of severe breaking-wave storm events, the core-loc was stable for a Hudson stability coefficient of 13, based on H_s and less than 1 percent displacement. The units were placed using a technique that simulated placement by a crane in the prototype.

g. Initial hydraulic stability tests of dolos armor layers repaired with core-loc showed core-loc to be an effective repair unit of dolos slopes from a hydraulic stability point of view, without the inherent structural weakness of dolosse.

h. Preliminary no-rocking, no-damage design stability coefficients for core-locs are conservatively suggested to be 16 for trunk sections and 13 for head sections, based on H_s. No differentiation of stability coefficient has been made for breaking or nonbreaking waves or other parameters in the Hudson equation.

i. Finally, it is shown that core-loc layers require significantly less concrete than layers composed of other, randmly placed armor units.

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Appendix A
Initial Core-Loc Hydraulic Stability Results

A complete listing of the wave generation and wave height data acquired is provided in Table A1. Wave height data were acquired from the three-gage Goda array positioned in shallow water. Wave heights were verified by visual inspection of a ruler gage mounted on the flume wall. In the table, wave heights and depths are in feet and wave periods are in seconds.

Table A1
Initial Stability Test Data

No. of Runs	Gain	Depth at Toe h	Wave Period at Board T_b	Wave Period at Gage To2	Incident Wave Height H_i	Reflection Coeffi-cient R	Hudson Stability Coeff K_D
		ft (m=ft* 0.3048)	sec	sec	ft (m=ft* 0.3048)		
1	40	1.50	1.5	1.42	0.72	0.29	
1	42			1.43	0.75	0.31	
1	44			1.44	0.79	0.31	
1	46			1.44	0.82	0.32	
1	48			1.40	0.85	0.33	
1	50			1.38	0.89	0.33	
1	52			1.38	0.92	0.32	
1	56			1.41	0.98	0.30	
1	58			1.39	0.98	0.38	
1	60			1.40	0.99	0.38	
1	62			1.36	1.12	0.24	139
2	64			1.38	1.17	0.23	159
2	66			1.36	1.21	0.23	175

Table A1
Initial Stability Test Data

5	40	1.50	2.0	1.91	0.61	0.49	
4	42			1.92	0.64	0.50	
3	44			1.91	0.67	0.50	
3	46			1.88	0.70	0.51	
3	48			1.87	0.73	0.52	
3	50			1.87	0.76	0.52	
3	52			1.85	0.79	0.52	
3	54			1.85	0.82	0.53	
3	56			1.83	0.85	0.53	
3	58			1.82	0.87	0.54	
3	60			1.79	0.90	0.54	
3	62			1.80	0.94	0.52	
3	64			1.77	0.97	0.52	
3	66			1.80	1.01	0.50	102
2	68			1.78	1.04	0.51	111
1	46	1.25	1.5	1.43	0.78	0.32	
1	48			1.45	0.80	0.34	
1	50			1.44	0.84	0.34	
1	52			1.40	0.87	0.36	
1	54			1.37	0.91	0.37	
1	56			1.37	0.94	0.37	
1	58			1.42	0.96	0.37	
1	60			1.39	0.96	0.37	
1	62			1.37	1.00	0.35	
1	64			1.35	1.03	0.32	
1	66			1.35	1.08	0.30	
1	70			1.36	1.18	0.28	
1	72			1.29	1.24	0.31	
1	74			1.30	1.23	0.34	
1	76			1.34	1.22	0.33	
1	78			1.34	1.28	0.30	
1	80			1.30	1.32	0.31	
1	82			1.28	1.33	0.32	
1	84			1.28	1.35	0.29	243
1	86			1.28	1.38	0.28	260
1	88			1.25	1.38	0.28	260
1	90			1.24	1.41	0.27	277
1	92			1.26	1.45	0.27	302
1	94			1.26	1.48	0.27	321
1	65	1.25	1.75	1.56	0.82	0.50	
1	68			1.55	0.87	0.50	
1	70			1.58	0.88	0.51	
1	74			1.67	0.94	0.50	
1	78			1.68	1.02	0.49	
1	82			1.61	1.08	0.49	
1	86			1.52	1.09	0.52	
1	90			1.49	1.12	0.50	139
1	94			1.58	1.18	0.38	163
1	80	1.25	2.0	1.90	0.89	0.55	
1	88			1.96	1.00	0.52	
1	94			1.96	1.01	0.51	102

Table A1
Initial Stability Test Data

1	40	1.25	2.5	2.48	0.26	0.65	
1	45			2.45	0.29	0.64	
1	50			2.42	0.33	0.64	
1	55			2.38	0.37	0.64	
1	60			2.34	0.39	0.64	
1	65			2.30	0.42	0.64	
1	70			2.25	0.45	0.64	
1	75			2.21	0.49	0.63	
1	80			2.17	0.52	0.63	
1	85			2.13	0.57	0.61	
1	90			2.09	0.60	0.61	

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13. ABSTRACT *(Maximum 200 words)*

A new series of coastal rubble structure concrete armor units called CORE-LOC has been developed at the Coastal Engineering Research Center, U.S. Army Engineer Waterways Experiment Station. CORE-LOC units have been designed for random placement in a single layer on steep or shallow slopes. CORE-LOC shapes have been optimized to maximize hydraulic stability, unreinforced strength, and reserve stability, but minimize onslope volume and casting yard space. CORE-LOC is designed to interlock well with dolosse so that it can be used as a repair unit. While several different CORE-LOC shapes have been developed, this report discusses preliminary hydraulic stability tests of the middle aspect ratio.

Finite element studies of CORE-LOC showed maximum flexural tensile stresses to be 47 percent, 74 percent, and 33 percent those of dolosse, accropode, and tribar, respectively. Torsional stresses were 54 percent, 74 percent, and 38 percent those of dolosse, accropode, and tribar, respectively.

Initial two-dimensional hydraulic stability tests of the CORE-LOC shape indicate that the unit is one of the most stable randomly placed armor units ever tested, withstanding breaking wave heights 5 to 7 times the maximum dimension of the unit on slopes of 3V:4H and 1V:1.5H.

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