CHAPTER 103

THE CORE-LOC: OPTIMIZED CONCRETE ARMOR

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ABSTRACT: This paper outlines the development and initial testing of a new optimized armor shape, called CORE-LOC, that balances and optimizes engineering performance features such as hydraulic stability, strength, and layer porosity. The new shape has significantly reduced design stresses over many existing shapes, yet has superior interlocking and therefore greater stability. The unit has internal maximum tensile stress levels of approximately half that of dolosse and, therefore, should not need reinforcement. For over 1000 flume tests, the core-loc has demonstrated two-dimensional no-damage stability numbers over 7 and Hudson stability coefficients over 250. In nearly all tests, the core-loc layer could not be damaged up to the wave height-period capacities of the flumes. A site-specific three-dimensional stability test of the proposed Noyo, California, offshore breakwater showed a stable no-damage stability number of 2.7 for H_s or a Hudson stability coefficient of 13 when the core-loc armor layer was exposed to repeated attack of a very severe design-level storm. The unit has been designed to be used alone or as a repair unit for dolosse. Core-loc-repaired dolos model slopes showed improved stability over the original dolos slopes. Finally, through reduced volumes, the core-loc layer is substantially more economical than all other commonly-used randomly-placed armor.

INTRODUCTION

The U.S. Army Corps of Engineers (USAE) maintains over 1500 rubble

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structures, 17 of which are protected by concrete armor units. Seven additional concrete armor layer projects are planned or are in the preliminary design phase. The Corps has primarily used dolos and tribar armor units but has also used tetrapods, quadripods, blocks, and tetrahedrons. Interest in concrete armoring has increased in the U.S. recently because stone quarries are becoming inaccessible due to increasing environmental constraints. Also, the existing armor shapes have not performed well, with significant breakage due to instability and structural fragility (Melby and Turk 1994a).

Recently, significant inroads into understanding slender armor unit structural response have been made. Terao et al. (1982), Burcharth (1981), and Melby and Turk (1994b, 1994c) developed and verified armor impact scaling criteria. Zwamborn and Phelp (1990) made measurements of prototype impact response. Timco and Mansard (1982) discussed scaled tensile strength modeling. Howell (1988), Melby and Howell (1989), Howell et al. (1990), and Kendall and Melby (1990, 1992), discussed the first measurements of internal strains in in-situ prototype dolosse as part of the Crescent City Prototype Dolos Study. These measurements led to the calibration for hydrodynamic loading of load cell instrumentation, similar to that developed by Scott et al. (1986), for laboratory measurement of dolos structural response (Markle 1990).

One of the primary conclusions from the Crescent City study was that the maximum wave loading-induced stresses were less than the static mean stress, for large dolosse. So static stresses dominate the structural design of stable non-rocking dolosse. This made accurate measurements of static strains very important; but the prototype data were insufficient to quantify static response because only 17 prototype dolosse were sampled and accurate quantification of the static response statistics requires a tremendous number of permutations of random boundary conditions, slope, and armor unit position on the slope.

Melby and Turk (1994b, 1994c, 1995) made large-scale measurements of 26-kg dolos static, wave loading, and impact strains to fill in the missing pieces in the dolos structural response quantification. Although these data are still being analyzed, they showed that the impact strains are very large and dolos movement should be avoided.

Recently, reasonable design methods for stable dolosse have been proposed based on the prototype and large scale measurements discussed above (Melby 1990, 1993, Melby and Turk 1992). Yet concrete armor breakage surveys of USAE breakwaters and jetties, combined with the existing structural data, have produced conclusive evidence that armor unit structural and hydraulic stability response can be improved significantly through small modifications in armor shape (Melby and Turk 1994a). This is therefore the focus of the research reported herein.

DEVELOPING NEW ARMOR SHAPES

The Corps has an ongoing research effort to develop optimized concrete armor shapes. The optimal armor engineering characteristics are summarized as

follows:

> *a.*   High hydraulic stability in a single-unit-thickness layer on any slope. Reserve stability for wave conditions exceeding the design event.

> *b.*   Hydraulically stable with no rocking, even when broken or following renesting resulting from local instability.

> *c.*   Efficient combination of porosity and slope roughness to dissipate the maximum amount of wave energy with the minimum armor volume over a critical range of wave periods.

> *d.*   Hydraulically stable when placed as a repair with other shapes.

> *e.*   Low internal stresses, so no reinforcement required.

> *f.*   Constructable casting yard forms and armor layers (need to be able to construct armor layer in low visibility water.)

> *g.*   Uses minimal casting yard or barge space.

> *h.*   Utilizes conventional construction materials and techniques.

A new series of concrete armor units, called the CORE-LOC, was recently developed at the USAE Waterways Experiment Station Coastal Engineering Research Center with the above features as prerequisite (Melby and Turk 1993, 1994d). The unit has a balance of the above engineering features such that the armor layer performance is maximized while the armor layer costs are minimized. The core-loc appears to have improved engineering performance due to a balance of the hydraulic stability, structural strength, wave energy dissipation, and constructability. The armor layer costs are reduced through less concrete and fewer and smaller units. The core-loc was designed to be placed in a single-unit-thick layer on steep or shallow slopes. The unit interlocks well on any slope and even interlocks well with dolosse, providing an efficient repair unit for those dolosse slopes in need of repair.

CORE-LOC ENGINEERING CHARACTERISTICS

The core-loc armor unit and its engineering characteristics are shown in Table 1 and Figure 1. Table 1 also gives a comparison with dolos. The design parameters, such as the packing density and volumes, are defined using the traditional Shore Protection Manual (SPM 1984) methodology.

Table 1. Engineering Characteristics of the Core-loc							
Unit	Volume	Number of Layers[1]	Poro-sity	Layer Coeffi-cient	Packing Dansity	Typical Slope	Number of Units[2]
	V	n	P as %	k_A	ϕ	cot α	N_r/C^2
Cora-loc	$0.2240C^3$	1	66	1.6	0.54	1.5	1.46
Dolos	$0.1561C^3$	2	56	0.94	0.83	2.0	2.86

Footnotas
1. The two dolos armor layers are always constructed as a single layer but n = 2 corresponds to k_A = 0.94 in equations 2 and 3.
2. Here the number of units is given per square armor unit dimension.

TOP VIEW

C = 1.0
A = 0.180
B = 0.360
D = 0.643
E = 0.256
F = 0.182
J = 1.013
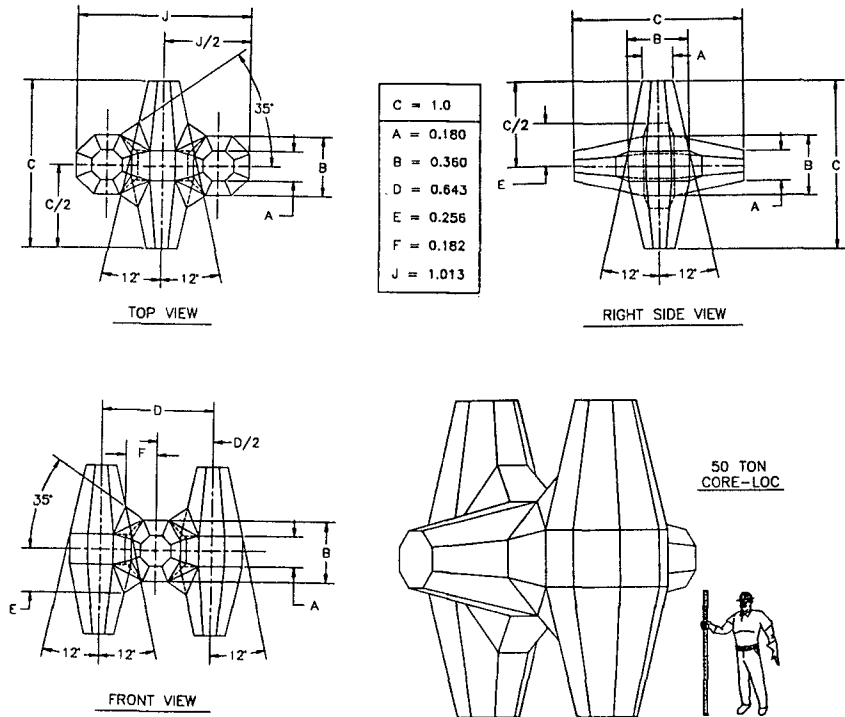
RIGHT SIDE VIEW

FRONT VIEW

50 TON
CORE-LOC

Figure 1. Core-loc Dimensions and Engineering Characteristics

CORE-LOC STRUCTURAL RESPONSE

Finite element method (FEM) structural analyses have been done to compare the structural response of core-locs to dolos, accropode, and tribar for several loading modes. The model and analysis specifications are shown in Table 2 for the FEM analysis. The FEM grid is shown in Figure 2. An example loading, shown in Figure 2, imposed the worst case flexural condition with one outer member fixed rigidly along the outside surface and the load applied to the end of the opposing member. This condition generated the maximum flexural stresses at the internal intersection on the units. The load was equal to the armor weight, which was 9 tonnes. Another pure flexural loading, a pure torsion loading, and a combined torsion and flexural loading were also analyzed. For the other pure flexure load condition, the load of 9 tonnes was applied transversely at the center of the outer member while the opposing member was held rigid. For the torsion loading, four 4.5-tonne loads were applied to the four outer member tip ends to generate the maximum twisting force on the unit. The unit was pinned at the center for this case. For the combined loading case, two 9-tonne loads imposing torsion and flexure, were applied to one outer member end while the opposing member was held rigid along its entire length. FEM results are shown in Table 3.

Table 2. Finite Element Model Properties	
Model Properties	Fully three-dimensional linear elastic model with about 2000 nodes and 1500 elements, depending on the unit shape.
Armor end Material Properties	Armor Weight, W = 9 tonnes Modulus of Elasticity, E = $3.5*10^4$ MPe Poisson Ratio, v = 0.21 Specific Gravity, S = 2.33 relative to fresh water

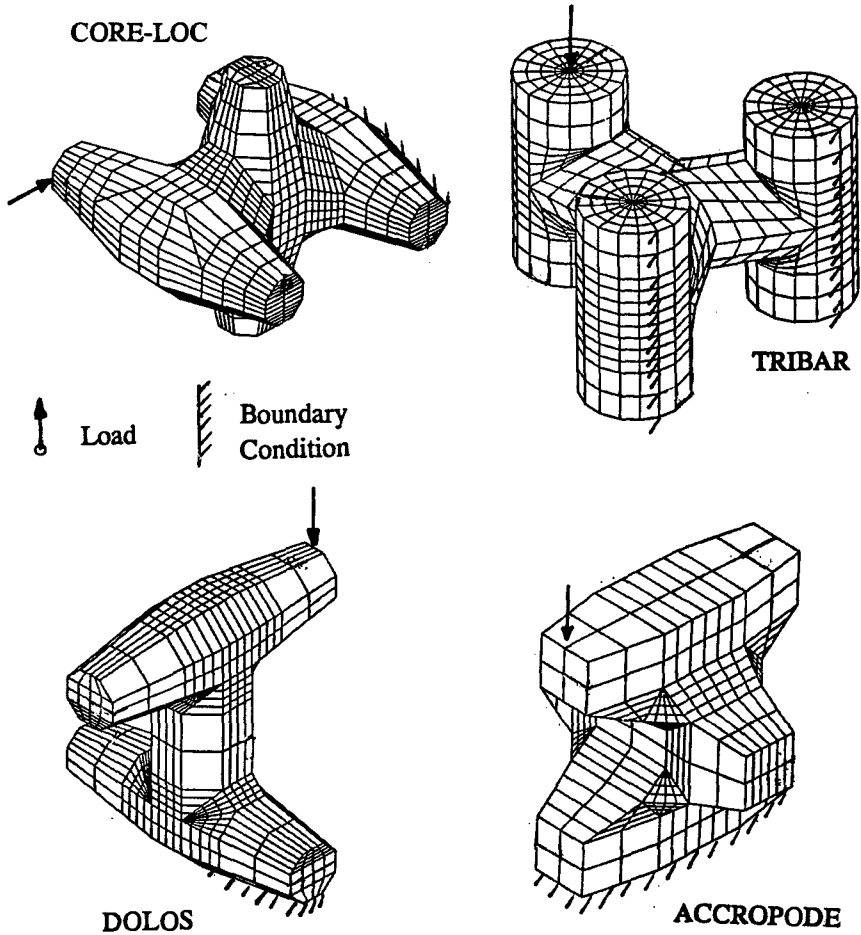| Table 3. FEM Static Stress Comparison				
Load Case	Stress, σ_z, MPa			
	Core-loc	Dolos	Accropode	Tribar
Torsion	1.12	2.08	1.52	2.98
Flexure - fluke tip load	1.12	2.41	1.52	3.36
Flexure - fluke center load	2.10	3.42	–	–
Combined flexure end torsion	1.91	3.83	–	–

CORE-LOC

Figure 2. Loading and Boundaries for Flexural Stress Comparison of Core-loc, Tribar, Accropode, and Dolos.

As illustrated in Table 3, for equivalent weight units, the core-loc maximum tensile stress for static loads ranges from 34% to 62% that of dolos. The maximum core-loc tensile stress is 74% for torsion and 74% for flexure that of accropode, and 38% for torsion and 33% for flexure that of tribar.

CORE-LOC HYDRAULIC STABILITY TEST RESULTS

Two-Dimensional Hydraulic Stability

The first *proof-of-concept* tests of core-loc hydraulic stability were two dimensional and showed the unit to be exceptionally stable, with no damage

measured for Hudson stability coefficients over 300 (stability numbers, N_s, over 7). The tests were done in a 0.6-m-wide flume with the structure 30 m from the wave generator. A wide range of monochromatic wave conditions were tested. The waves were generated by an electro-hydraulic powered, computer-controlled, bottom-hinged paddle. The approach slope was 1V:20H for 5 m seaward of the structure, 1V:16H for 2.4 m, flat for 6.7 m, and 1V:33.3H to the generator pit. Two three-electrical-capacitance-gage arrays were used to measure water surface elevations near the wave generator and at a position 3 m from the structure toe. The incident and reflected waves were resolved using the method of Goda and Suzuki (1976). The armor layer was composed of 220 g core-locs (Table 4) on a slope of 3V:4H with a stone underlayer mean weight of 41 g and a stone core mean weight of 2 g. The core had a very low permeability and was therefore more critical to armor stability. The maximum wave conditions are summarized in Table 5. The armor could not be damaged up to the limit of the wave generator for nearly all tests. The only instability, the first entry in the table, appeared to be due to low randomness in the armor placement. It was noted during all tests that only a few of the units on the slope were rocking, and then only slightly, even for the most severe wave conditions.

Table 4. Model Core-loc Specifications

C	B	J	A	Mass	Voluma	Specific Gravity
		cm		gram	cm^3	
7.2	2.7	8.0	1.5	220	93.2	2.35

Dimansions era dafinad in Figure 1. Initial model units not chamfered and had elightly differant gaomatry than shown in Figura 1.

Table 5. Summary of Initial Stability Test Results for Maximum Wave Conditions

Dapth at Toe (cm)	Wava Period at Gage (aec)	Incidant Wava Haight (cm)	Reflec-tion Coeff	Movament	Stability Numbar N_s	Stability Coeff K_D
46	1.38	36	0.23	1% Displ	6.0	159
46	1.78	32	0.51	nona	5.3	111*
46	1.26	45	0.27	none	7.5	321*
38	1.58	36	0.38	nona	6.0	163*
38	1.96	31	0.51	nona	5.1	102*
38	2.09	18	0.61	nona	3.0	21*

* Wava ganaration capacity limited, no instability

Carver and Wright (1994) carried out a much more comprehensive series of two-dimensional hydraulic stability tests of the core-loc and also could not damage the armor layer for significant wave heights corresponding to stability numbers over 7 (Hudson stability coefficients over 250). These tests were done in a 1-m-wide section of an 3.3-m-wide flume 75 m 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. A second section of 1 m width was filled with an identical dolos structure for comparative tests partially through this test series. 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 TMA type. Incident and reflected waves were resolved from water surface measurements made with two sets of three electrical capacitance wave gages, again using the methods of Goda and Suzuki. The test parameters are summarized in Table 6. The approach slope was at 1V:100H for 6.5 m seaward of the structure, 1V:75H for 34 m, and flat for 15.2 m to the generator pit. The wave gage arrays were positioned near the wave generator and 3.3 m from the structure toe.

Table 6. Flume Stability Test Parameters	
Structure Height	0.9 m
Structure Base Width	2.7 m for 1V:1.33H and 3.0 m for 1V:1.5H
Structure Slopes	1V:1.33H and 1V:1.5H
Mean Armor Mass	219 g
Mean Underleyer Mass	45 g
Mean Core Mass	1 g
Number of Waves per Test	~1000
Water Depths at Structure Toe	36 and 61 cm
Incident Wave Heights, H_{mo}	4.6 to 39 cm (61 cm depth)
Peak Period, T_p	1.5 to 4.7 sec
Surf Sim. Param, ξ_p	2.13 to 15.9
Relative Depth, d/L_o	0.012 to 0.175
Wave Steepness, H_{mo}/L_o	0.001 to 0.098

For these tests, several parameters of relative measure were calculated including the surf similarity parameter or Irribarren number, $\xi = tan\ \alpha\ / (H_{mo}/L_o)^{1/2}$, the relative depth, d/L_o, and the wave steepness, H_{mo}/L_o. Here α is the structure front slope angle, H_{mo} is the incident wave height at the shallow gage array, $L_o = 2\pi/gT_p^2$ is the deep water wave length computed from the peak period at the shallow gage array, and d is the structure toe depth. The ranges of these

parameters are also summarized in Table 6.

 The 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, in the dolos and core-loc side-by-side tests, the reflection coefficients from the core-loc slope were almost indistinguishable from 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.

 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. It was noted that 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 these tests show that the core-loc armor, when designed conservatively for two dimensional situations, such as on a revetment, will have considerable reserve stability beyond the design wave or when repeatedly subjected to the design wave.

Three-Dimensional Stability

 Although generic three-dimensional stability tests have not been done, several site-specific studies have been completed. Smith et al. (1994) carried out three dimensional stability tests of a core-loc armor layer for a site-specific test of the proposed Noyo, California Harbor offshore breakwater. This site is subjected to depth limited 7 to 9 m breaking waves repeatedly each winter, and therefore provided a very good test of core-loc stability. Also, the breakwater is subjected to very high flow velocities that are due to wave focussing from several surface-piercing pinnacles just off the seaward toe.

 Three-dimensional stability tests of the Noyo breakwater were carried out at a geometrically undistorted scale of 1:50 with molded bathymetry. The model offshore breakwater was scaled from prototype dimensions of 122 m length between two round head centers and initial crown widths of 9 m on the large head, 6.1 m on the small head, and 7 m in between. The slope of the breakwater was 1V:1.5H. The initial storm series consisted of 17 tests of 15 minutes model, 106 minutes prototype, each with a succession of 13, 17, and 20 second peak period waves of increasing significant wave heights from 3.4 to 8.4 m (Storm I). The maximum wave height was depth limited. The primary armor tested consisted of approximately 500 28-tonne core-locs on the large head and 500 17-tonne core-locs on the small head.

 The core-locs were stable for two successive Storm IA wave series (the 10 highest energy series from storm I) and began to unravel after being subjected to an additional three Storm IB series, each consisting of the 3 highest energy series in Storm I. It appeared that the primary damage was instigated by toe instability, particularly in areas of wave focussing, due to erosion of the toe apron. The stability number corresponding to the larger core-loc was 2.7 for the highest H_s

(Hudson stability coefficient of 13).

The design waves tested above were considered to be quite conservative, so a somewhat more realistic wave condition was also tested. The final storm series consisted of a five-Storm-IB sequence, except that the 20 sec, 8.4 m test was omitted from the middle three series. The apron was mostly stable for this sequence of storms, and only 4 core-loc units, or 0.4%, were displaced. In summary, the core-locs were stable for very high stability coefficients when repeatedly subjected to this very high energy design storm event. The core-loc structure was the only alternative to meet the required economic benefit-to-cost ratio and was accepted as the final design.

Dolos Repair Tests Using Core-loc

A short series of two-dimensional stability tests was conducted to determine the comparative stability between dolos and a dolos slope repaired with core-locs. The tests were done in shallow water with a 1.5-m-wide fronting *reef* in the same 0.6-m-wide flume described above. The structure was 17 cm high with a front slope of 1V:1.5H. Monochromatic waves were generated producing a maximum incident wave height of 22 cm and period of 3.75 sec in a depth of 17 cm 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, the 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.

For the dolos stability tests, 97 dolosse were placed at a packing density of 0.83. The armor mass was 125 g. 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.

For the repair tests, the damaged dolos slope was repaired with 15 core-locs. The repair units were 145 g 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, 3 core-locs were displaced off the slope and 3 additional dolosse were displaced. It was noted that the core-locs had interlocked and stabilized the original damaged regions on the slope. The displaced units were near the cap and were never interlocked. The additional core-loc weight contributed some to the increased stability of the dolos slope; but the effect was small because the incident wave heights were far greater than those corresponding to the non-interlocked stability threshold. The primary stabilization was from interlocking. For an actual repair, the same weight units would likely be used and the existing armor near the repair region would be removed from the slope so the core-locs could be interlocked with the dolos 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.

CONCLUSION

A new armor unit, called the core-loc, was discussed which solves the primary problems of existing randomly-placed units. The core-loc appears to have a unique balance such that the primary engineering performance criteria are maximized while the amount of concrete and number of units are minimized. These primary performance criteria are structural integrity, hydraulic stability, armor porosity, and constructability. A finite element study showed the core-loc maximum tensile stress for combined loading to be approximately 62% that of an equivalent-sized dolos. The study showed the core-loc maximum flexural and torsional tensile stresses to be slightly lower than those in an equivalently sized accropode.   Several stability studies are discussed which show two-dimensional flume stability numbers over 7 (Hudson stability coefficients over 300) for long slopes. A three-dimensional site-specific study of the proposed Noyo, California, breakwater   showed no-damage stability numbers of 2.7 (Hudson stability coefficients of 13 for H_s) for repeated exposure to severe design storms. A simple hydraulic stability test showed that core-locs would be effective at repairing dolos slopes.

Finally, for general design based on H_s, Hudson stability coefficients of 13 for the head and 16 for the trunk are preliminarily and conservatively recommended for core-locs. Using the stability coefficient of 13, for breaking waves on a head, and the recommended packing density of 0.54, the core-loc armor layer requires 47% less total volume than a dolos armor layer, 57% less than tetrapod, 51% less than tribar, and 24% less than accropode.

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