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CORE-LOC™ Concrete Armor Units: Technical Guidelines

by George F. Turk, Jeffrey A. Melby

Prepared for Headquarters, U.S. Army Corps of Engineers

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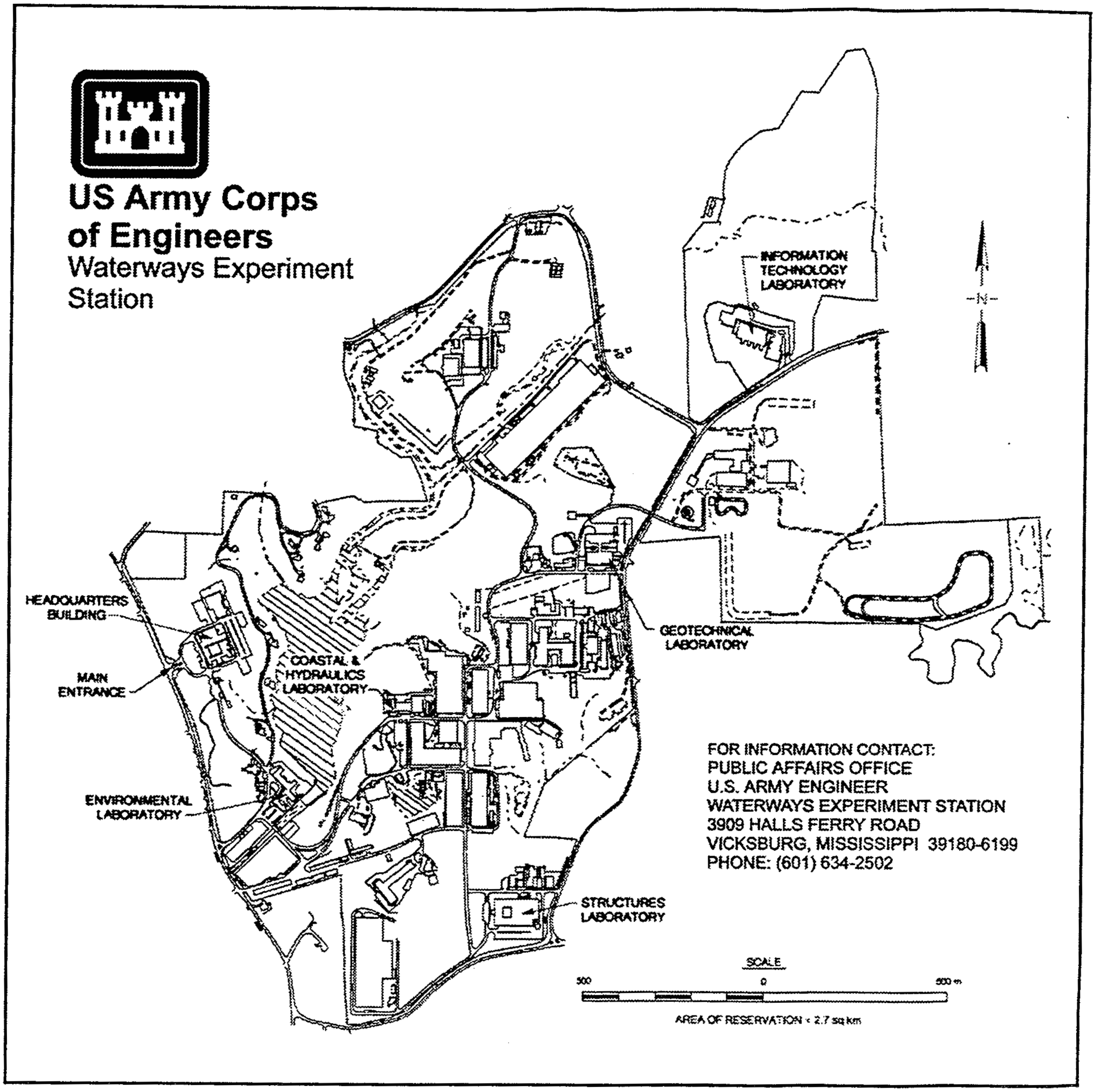

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Preface

Funding for CORE-LOC development, as discussed in this report, was provided by the Coastal Navigation and Storm Damage Reduction Research Program (Coastal Program), 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).

Mr. Harold Tohlen, HQUSACE, was the REMR Coordinator and the Coastal Program Coordinator was Mr. David Mathis, both of the Directorate of Research and Development, HQUSACE. Members of the REMR Overview Committee were Mr. Harold Tohlen and Dr. Tony C. Liu, both of HQUSACE. Messrs. John H. Lockhart, Jr., Barry Holliday, and Charles Chesnutt served as HQUSACE Coastal Program Monitors. Ms. Carolyn Holmes, Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Waterways Experiment Station (WES), was the Coastal 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.

The studies were completed under the general supervision of Dr. James R. Houston and Mr. Charles C. Calhoun, Jr., Director and Assistant Director, CHL, respectively, and under the direct supervision of Mr. C. Gene Chatham, Chief, Wave Dynamics Division, and Mr. D.D. Davidson, Chief, Wave Research Branch, CHL.

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

1 Core-loc Unit and Armor Layer Characteristics

The U.S. Army Engineer Waterways Experiment Station (WES), Coastal and Hydraulics Laboratory is involved in an ongoing research effort to further the understanding of concrete armoring for navigation and shore protection structures. This research stems from the need to design and build reliable structures in high-wave-energy environments. Because of the very difficult construction, in-service, and repair conditions associated with these environments, the basic developmental program has focused on randomly placed armor units. From this research, a new type of concrete armor unit called CORE-LOC™, hereafter referred to as core-loc, has been developed at WES and patented worldwide (Melby and Turk 1995).

Core-loc Geometry

The core-loc (Figure 1) consists primarily of three tapered octagonal members. The two outer members are parallel along their longitudinal axes, while a third central member has a longitudinal axis normal to the outer members. All geometric dimensions can be normalized by the primary or characteristic length. In the case of the core-loc, this is referred to as the "*C*" dimension, which is the overall length of each of the three tapered octagonal members. Figure 2 shows the nondimensional relationship between *C* and other basic dimensions where the volume of an individual core-loc V_{CL} can be expressed in terms of *C* as

$$V_{CL} = 0.2236\, C^3 \qquad (1)$$

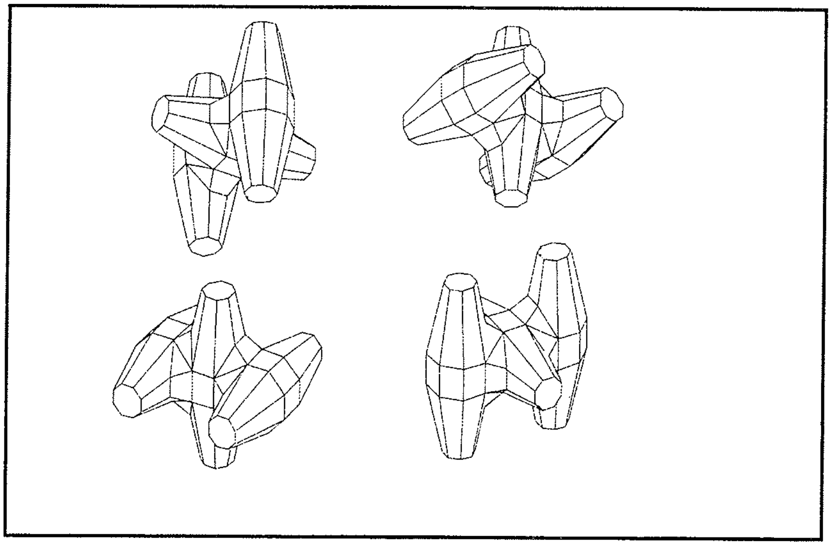

Figure 1. Four views of core-loc

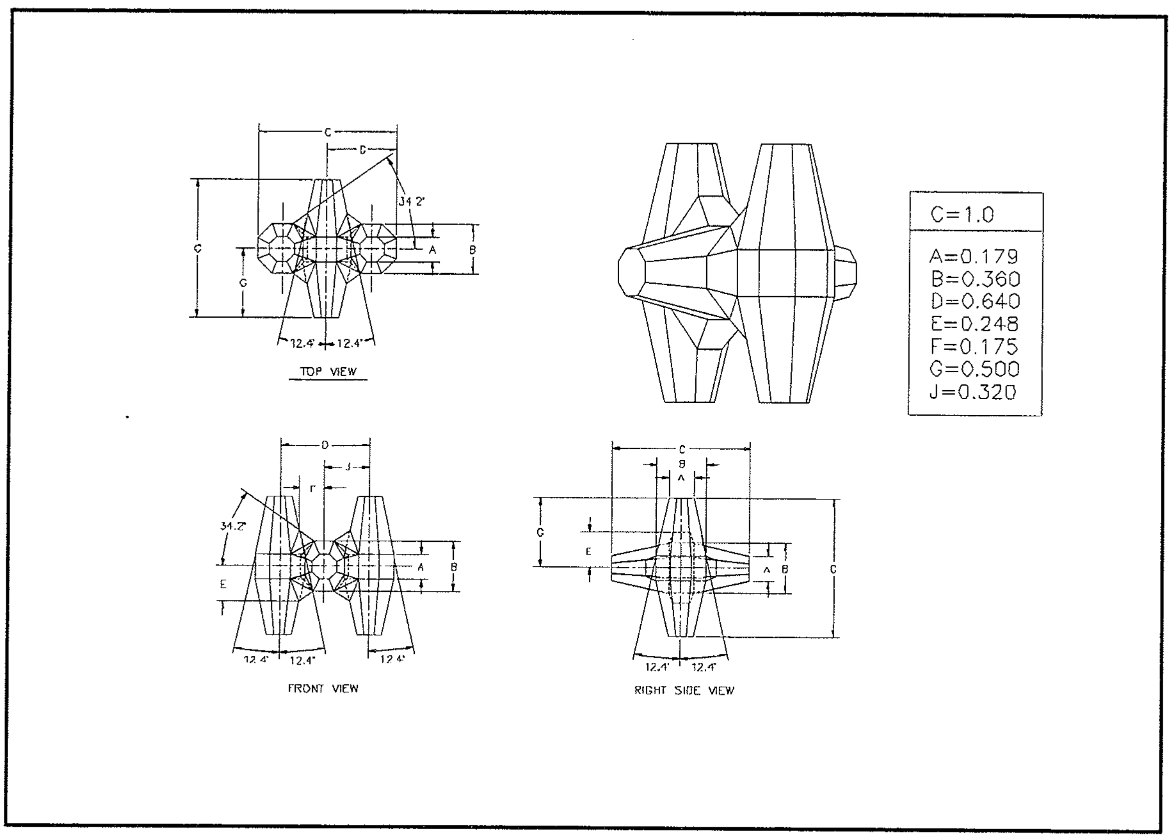

Figure 2. Nondimensional schematic of typical core-loc

Another important geometric parameter that can be based on the C dimension is the surface area of a unit. This is primarily used to determine the amount of steel plate required to fabricate forms. The surface area of a core-loc S_{CL} is given by

$$S_{CL} = 2.70\, C^2 \qquad (2)$$

Figure 3 shows the dimensions, expressed in terms of C, of the seven individual shapes of plate elements (labeled *a* thru *g*) required to construct a core-loc form. The surface area of the core-loc can also be expressed in terms of the individual plate elements as

$$S_{CL} = 6(a) + 12(b) + 24(c) + 8(d) + 8(e) + 16(f) + 16(g) \qquad (3)$$

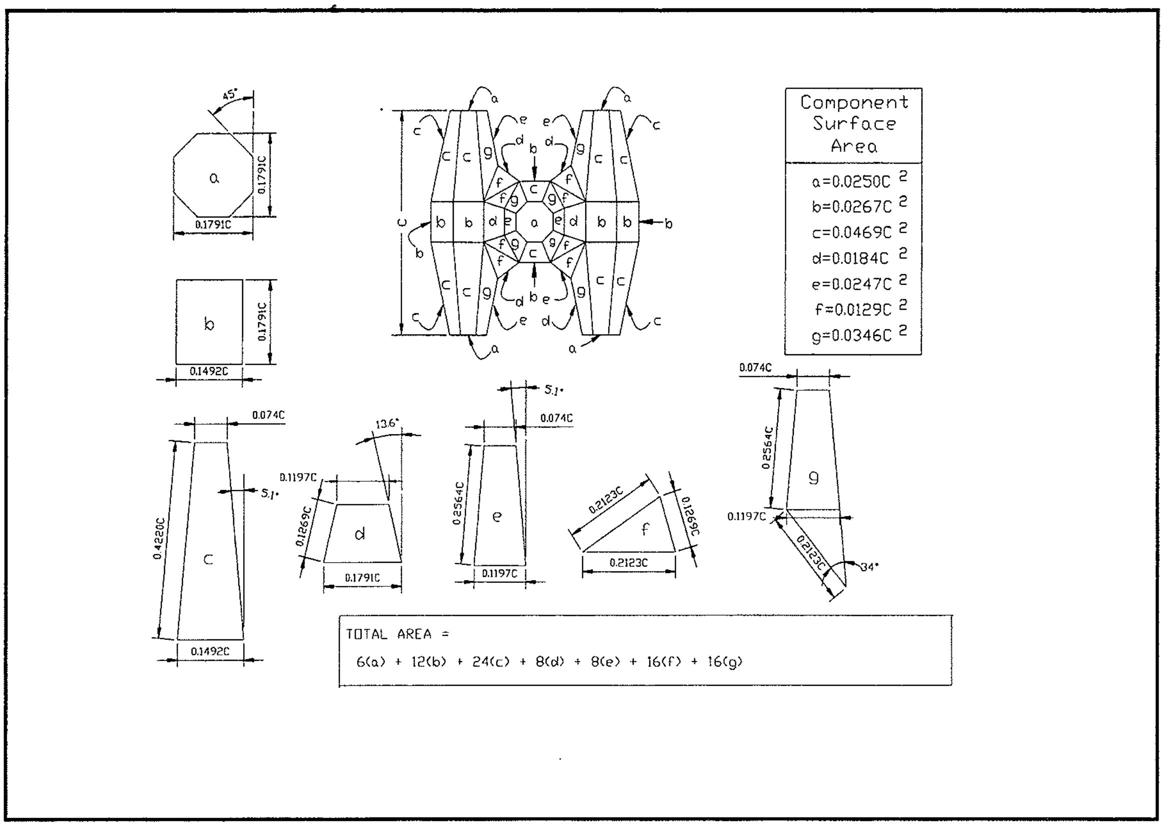

Figure 3. Nondimensional schematic of core-loc surface area

Stable Weight Estimation

The U.S. Army Corps of Engineers *Shore Protection Manual* (SPM 1984) recommends preliminary design estimations of concrete armor unit stable weight using the Hudson Formula

$$W_a = \frac{\gamma_a H^3}{K_D (S_a - 1)^3 \cot\theta} \quad \textbf{(4)}$$

where

K_D = Hudson stability coefficient

H = design wave height (i.e. $H_{1/3}$)

θ = angle of the structure slope measured from horizontal

W_a = weight of an individual armor unit

γ_a = specific weight of armor unit

S_a = specific gravity of armor unit relative to water (γ_a/γ_w)

γ_w = specific weight of water

For preliminary design of core-loc armor units under breaking wave conditions and a no-damage criteria (less than 2 percent displacement by count), the recommended Hudson stability coefficients are $\boldsymbol{K_D = 16}$ for trunk sections and $\boldsymbol{K_D = 13}$ for head sections. These coefficients are valid for structure slopes from 1V:1.33H to 1V:2H. Assuming proper placement technique and sufficient buttressing at all transitions, these stability coefficients should provide a conservative estimate for core-loc design. However, final designs should be validated with three-dimensional physical models replicating local bathymetry and actual design wave conditions and directions where possible.

Armor Layer Thickness

The cost of an armor layer depends primarily on the volume of concrete used to protect the slope. Unit construction costs include material, transportation, and placement costs. Yard costs include construction of form works; concrete placement, storage, and handling; and the cost of equipment necessary to handle the units. But concrete volume dominates the armor layer cost and therefore should be minimized by maximizing the porosity and minimizing the armor layer thickness. The porosity P for a core-loc armor layer is approximately 60 percent. While most randomly placed concrete armor units are placed in two layers, core-loc are placed in a single layer thickness. The thickness of a core-loc armor layer $r_{C\text{-}L}$ expressed as a function of the characteristic length C is

$$r_{C\text{-}L} \approx 0.92\,C \tag{5}$$

The layer thickness can also be expressed by Equation 7-121 of the SPM (1984) as

$$r = n\,k_{\Delta}\,(W_a/\gamma_a)^{1/3} \tag{6}$$

where

n = number of layers

k_{Δ} = layer coefficient (k_{Δ} = 1.51 for core-loc)

Armor Layer Packing Density

In order to provide adequate coverage on a breakwater slope with concrete armor and maintain integral unit-to-unit interlocking, a proper packing density should be achieved. Packing density is defined as the number of individual armor units required to cover a given area of slope as given by

$$\frac{N_a}{A} = n\,k_{\Delta}\,(1 - P/100)\,(\gamma_a/W_a)^{2/3} \tag{7}$$

or

$$\frac{N_a}{A} = \phi\,V^{-2/3} \tag{8}$$

where

N_a = number of armor units

A = unit area of breakwater slope to be armored

ϕ = packing density coefficient

V = volume of an individual concrete armor unit

P = armor layer porosity

For core-loc two-dimensional model studies, a wide range of physical model experimental wave and water level conditions, as well as several cross-sectional geometries, have shown stable structures built with packing density coefficients as low as $\phi = 0.54$ and as high as $\phi = 0.64$. Based on the results of these tests, a packing density coefficient of $\phi = 0.60$ is recommended. However, certain model-to-prototype scale effects exist and, for the newly developed core-loc, there are few data on prototype packing densities.

Sogreah Ingénierie has built over 85 structures using the ACCROPODE®, hereafter referred to as accropode, a concrete armor unit which is also placed in a single layer. Sogreah recommends a lower packing density for larger armor units (Sogreah 1996). This may be due in part to the difficulty of handling larger units, which limits the ability to pack them tightly. For example, for accropode model units, and prototype armor under 5 m^3, Sogreah recommends $\phi = 0.656$, for units with volumes of 6.3-12 m^3, Sogreah recommends $\phi = 0.615$, a decrease of 6.25 percent, and for volumes of 14-22 m^3, $\phi = 0.577$, a decrease of 12 percent from the model scale packing density.

Using Sogreah's recommendations for accropode, a rationale for comparison of prototype core-loc packing density coefficients to be used for economic evaluation can be developed. Table 1 lists accropode packing density coefficients recommended by Sogreah and possible core-loc packing density coefficients based on the accropode experience. Actual values may vary. In the interim, these core-loc packing density values are given for economic evaluation and preliminary design, and may prove to be higher in the prototype and therefore not recommended for final design until validated with considerable field experience. In all cases, the core-loc units should be packed as tightly as possible.

Table 1
Possible Core-Loc Prototype Packing Density Coefficients Based on Prototype Accropode Experience

Volume (m^3)	≤ 5 m^3	6.3-12 m^3	14-22 m^3
ACCROPODE® ϕ	0.656	0.615	0.577
CORE-LOC™ ϕ	0.60	0.56	0.54

2 Core-Loc as a Repair Unit for Dolos Armoring

Maintenance and repair of concrete-armored slopes poses an entirely different set of challenges from new armor layer construction. With broken dolos armor units found on many Corps concrete-armored structures and on structures worldwide, a need exists for high-integrity rehabilitation. In the past, dolos layers have been repaired using similar dolosse, with less than favorable results. Scale model testing has shown, with its unique geometric shape, core-loc has an affinity for interlocking with and stabilizing dolosse.

When core-loc units are intermeshed with dolosse, the separation and taper of the outer flukes provide superior interlocking with dolosse when sized properly. Proper sizing is achieved when the characteristic length of a core-loc C_{CL} is approximately 0.92 the characteristic length of a dolos C_{DO}. When $C_{CL} = 0.92$ C_{DO}, the volume of an individual core-loc V_{CL} will be 1.11 times the volume of an individual dolos V_{DO}. However, because of the significantly lower packing density for core-loc compared to dolos, the total volume of concrete used for the core-loc repair of dolos layers is less than the volume of concrete used on the original dolos armoring. The core-loc repair is more economical even though the individual core-loc weighs more than the individual dolos.

3 Structural Considerations

Concrete used in the fabrication of armor units must be durable, abrasion-resistant, and strong enough to resist loads associated with the harsh ocean environment. It is generally recognized that the primary loads concrete armor units are subjected to are quasi-static, wave loads, and unit-to-unit impact. It is anticipated that, except in special circumstances (i.e. extremely large units), core-loc will be manufactured from unreinforced concrete. Thus the tensile strength of the concrete must have the capacity to withstand the aforementioned harsh loading conditions. Most of the concrete armor unit structural research by the Corps of Engineers has focused on dolosse. Comparative finite element analysis between dolosse and core-loc has revealed that maximum tensile stresses in core-loc generated by static loading are approximately half those of equivalent size dolosse. Due to the similar tapered octagonal sections shared by core-loc and dolosse, wave loads are estimated to be approximately equal. Unlike most types of concrete armor units which are placed in two layers, core-loc is placed in a single layer. During construction of two-layer systems, it is often difficult to prevent some units in the upper layer from rocking. These units often break due to unit-to-unit impact loads. Properly designed core-loc armor layers exhibit very little movement. Thus in most cases, there is little need for structural capacity to resist unit-to-unit impacts. While detailed structural requirements should be addressed on a case-by-case basis, as a general rule-of-thumb for most conditions and structures, core-loc units should meet the present Corps of Engineers minimum concrete strength standard. In the United States, concrete used for all but the largest concrete armor units should obtain a 28-day compressive strength of 35 Mpa (5,000 psi) or 3.5 Mpa (500 psi) tensile strength in order to possess reserve structural capacity.

4 Fabrication, Handling and Placement

Mixing, casting, and curing are all integral to the concrete armor fabrication process. A concrete mixture must be proportioned to produce concrete that is capable of withstanding harsh marine environments. Ideally, concrete should be impervious to seawater attack, be abrasion-resistant, and possess adequate strength. Quality assurance requires that concrete have a consistent homogeneity, free of defects and flaws. Concrete quality is a function of proportions and type of cement, aggregate, water, and admixtures. The following information on a recommended concrete mixture serves only as a starting point for mixture proportioning studies. Many factors affect the integrity of the final product. Variability in the chemical and physical interaction of the individual constituents requires rigorous testing of the final mixture proportions. Therefore, it is imperative that the mix design be "fine-tuned" and tested in a certified concrete testing laboratory. It is recommended that axial compression and splitting tensile tests be used for evaluating mixture proportions, and for quality control of the final product.

Concrete Quality

Guidance for specification of concrete materials for civil works structures is provided in Engineer Manual 1110-2-2000 (U.S. Army Corps of Engineers 1994). Guidelines for concrete used in casting and handling of core-loc units are as follows:

A. Concrete used for core-loc should possess the following qualities:

(1) 28-day compressive strength: 35 Mpa (5,000 psi) (minimum).

(2) 28-day splitting tensile strength: 3.5 Mpa (500 psi) (minimum).

(3) Slump: 50 mm (2 in.) to 100 mm (4 in.).

(4) Air entrainment: ≤ 5%.

B. A typical baseline specification for trial mixture proportions is as follows:

(1) Cement.

a. Type II or III.

b. Concentration: 218-230 kg/m^3 (365-385 lb/cy).

c. Water/cement ratio: 0.35-0.55.

(2) Aggregate.

a. Non-alkali-silica reactive.

b. Maximum size: 38 mm (1.5 in.) - 76 mm (3 in.)(dependent on armor unit size).

c. Gradation conforms to American Society for Testing and Materials (ASTM) C33-84.

d. Fineness modulus for fine aggregate: 2.4-3.0.

e. Adequate hardness to provide abrasion resistance.

(3) Water.

a. Potable, free from high concentration of sodium or potassium.

(4) Admixtures.

a. Minimum air entrainment.

b. Superplasticizers, increase workability and reduce water content.

c. If steel reinforcement is used, avoid chloride-based accelerating agents.

American Standards for Concrete, Cement, and Aggregates

The following ASTM standards should be followed in the selection and testing of concrete, cement, and aggregate to be used in the fabrication of core-loc:

(1) ASTM C33 - Concrete aggregates.

(2) ASTM C40 - Organic impurities in fine aggregate.

(3) ASTM C70 - Surface moisture in fine aggregates.

(4) ASTM C94 - Ready-mixed concrete.

(5) ASTM C109 - Compressive strength of hydraulic cement mortars (using 50-mm cubes).

(6) ASTM C114 - Chemical analysis of hydraulic cement.

(7) ASTM C131 - Resistance to degradation of small-size aggregate by abrasion and impact in Los Angeles machine.

(8) ASTM C136 - Sieve analysis of fine and coarse aggregate.

(9) ASTM C143 - Slump of portland cement concrete.

(10) ASTM C150 - portland cement.

(11) ASTM C151 - Autoclave expansion of portland cement.

(12) ASTM C186 - Heat of hydration of hydraulic cement.

(13) ASTM C191 - Time of setting of hydraulic cement by Vicat needle.

(14) ASTM C227 - Potential alkali reactivity of cement-aggregate combinations.

(15) ASTM C231 - Air content of freshly mixed concrete by the pressure method.

(16) ASTM C260 - Air-entraining admixture for concrete.

(17) ASTM C348 - Flexural strength of hydraulic cement mortars.

(18) ASTM C349 - Compressive strength of hydraulic cement mortars.

(19) ASTM C494 - Chemical admixtures for concrete.

(20) ASTM C496 - Splitting tensile strength of cylindrical concrete specimens.

(21) ASTM C535 - Resistance to degradation of large-size aggregate by abrasion and impact in Los Angeles machine.

(22) ASTM C566 - Total moisture content of aggregate by drying.

(23) ASTM C596 - Drying shrinkage of mortar containing portland cement.

(24) ASTM C805 - Rebound number of hardened concrete.

(25) ASTM D2419 - Sand equivalent value of soils and fine aggregate.

Casting Guidelines

For successful casting of core-loc, the following guidelines are recommended:

(1) Concrete is usually placed in formworks in lifts no more than 60 cm (24 in.).

(2) Each lift vibrated to remove voids.

(3) Armor units with cold joints should always be rejected.

(4) In general, forms should be stripped no sooner than 24 hr unless sufficient high early strengths are attained.

(5) Curing agent should be applied as soon as forms are stripped.

(6) Steam curing should be avoided unless the contractor can prove an acceptable level for the heat of hydration.

(7) Heat of hydration should never be allowed to exceed 75 ^{0}C.

(8) Quality control test cylinders should be made for each 150-m^3 (196-yd^3) placed, and cured at the same temperatures found within the concrete armor unit being cast.

Once the units are cast, the following items warrant consideration:

(1) Units must be handled carefully -- excessive impact stresses can be generated from even moderate drop heights (< 0.5 m (20 in.)).

(2) If a unit is dropped, it must be carefully inspected -- if cracked it should be rejected.

(3) Once on site, if a unit is found to be cracked it should not be placed on the armor layer.

(4) During shipping, units should be secured (shimmed if necessary to avoid rocking) to prevent unit-to-unit impacts during transport.

Handling and Stocking

The easiest way to handle core-loc units in the casting yard is to use a crane with either single or double slings. With minor modifications, forklifts and front-end loaders can be used to move smaller units (usually less than 15 tonnes). Lifting eyes or inserts can also be placed in the top of the outer flukes for a two-point pick or an additional eye can be placed at the tip of the central fluke for a three-point pick.

When storing core-loc units in a casting yard, the most efficient storage pattern is to place the units in a row, tipped over, resting at a 45-deg angle on the central fluke with minimal space between adjacent units (Figure 4). The required area A_Y needed for storing a single row of 10 core-loc units can be expressed in terms of the characteristic length C (which is also the width of the rectangular row) as

$$A_Y = 5.23\ C^2 \qquad (9)$$

If storage area is at a premium, rows of core-loc units can be stacked on top of each other in a "herringbone" fashion, which effectively doubles yard capacity (Figure 5). Adjacent rows can be placed side-by-side close together, and stacked or unstacked from the row ends. This eliminates the need for most access roads between rows.

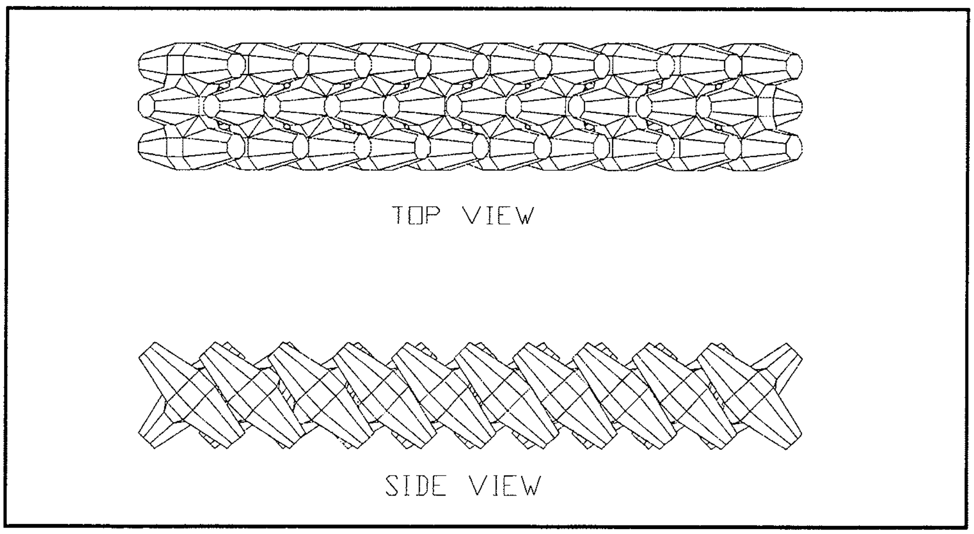

Figure 4. Efficient storage pattern for core-loc in casting yard

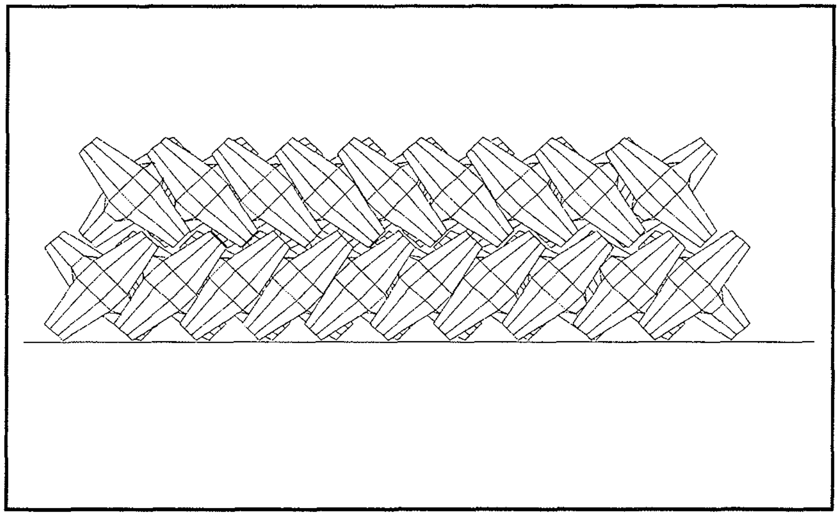

Figure 5. Core-loc stacked two courses in height

Core-loc Placement

Core-loc was designed to be placed in a single layer thickness in a random matrix. However, the most vulnerable portion of an armor layer is at the structure toe. Special consideration may be given to placement of the toe units and the second course of units. Although core-loc units can be placed randomly along the toe, based on experimental results, a pattern placement along the toe is more stable. Figure 6 shows a possible arrangement for placing the toe units. The individual core-loc units are set in a three-point stance in "cannon" fashion with the central fluke pointing seaward, up at a 45-deg angle like the cannon barrel. All toe units are placed side-by-side with minimal space between

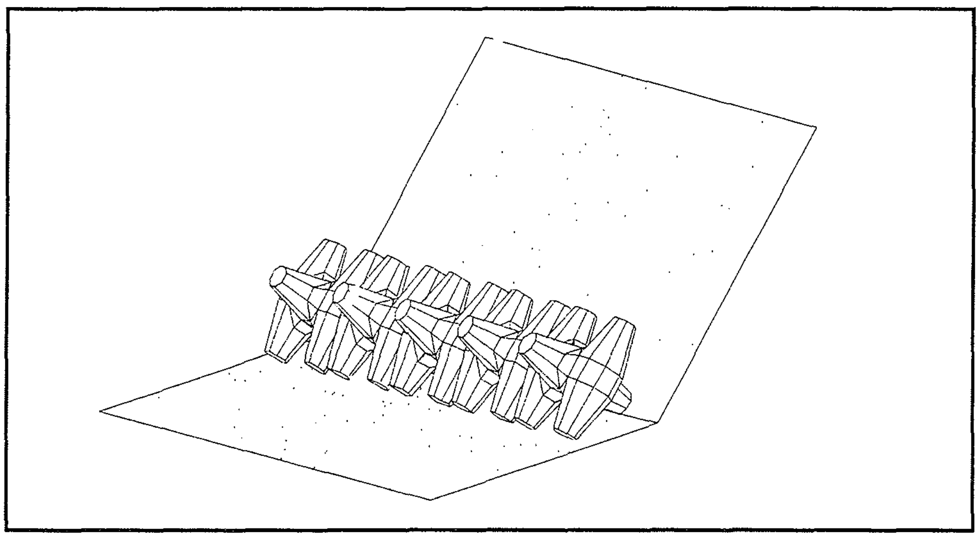

Figure 6. One possible method for placement of toe units: cannon fashion

adjacent units. The second course of units is laid atop of the toe units such that they straddle each toe unit (Figure 7). Once the second row has been placed, all subsequent armor units are placed in a random matrix. While these units are placed in a variety of random orientations, care must be taken to assure that all overlying units are interlocked with and constrain underlying units.

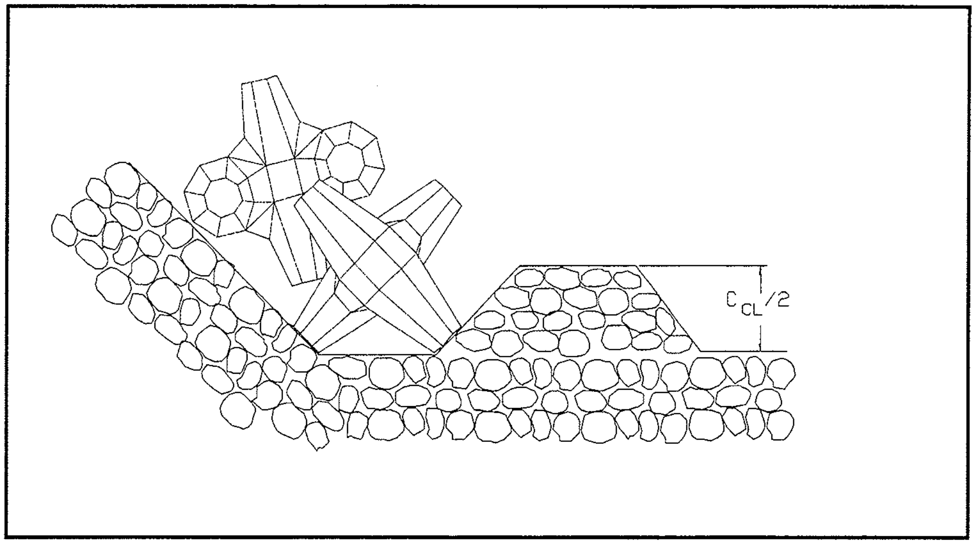

Figure 7. Possible method for toe and second course placement

The specified packing density must be strictly maintained during construction to assure proper interlocking, and therefore hydraulic stability, of the armor layer. During placement, packing density can be maintained by specifying a mean and allowable deviation for the centroidal distance (in three dimensions) between units. Although the orientation of the core-loc units is random, in general, each subsequent row of armor units is offset laterally from the previous lower row. To specify the placement grid, D_H is the distance between the centroids of two adjacent units on the same horizontal row and D_U is the distance between the centroids of units upslope in the plane of the structure slope (Figure 8). For core-loc sizes and packing density coefficients listed in Table 1, values of D_H and D_U are given in Table 2 in terms of characteristic length C.

In a random matrix of core-loc units, every effort should be made to achieve maximum interlocking. The maximum centroidal distance D_{max} should not exceed 110 percent of the values specified in Table 2. Greater spacing may jeopardize interlocking and the integrity of the armor layer.

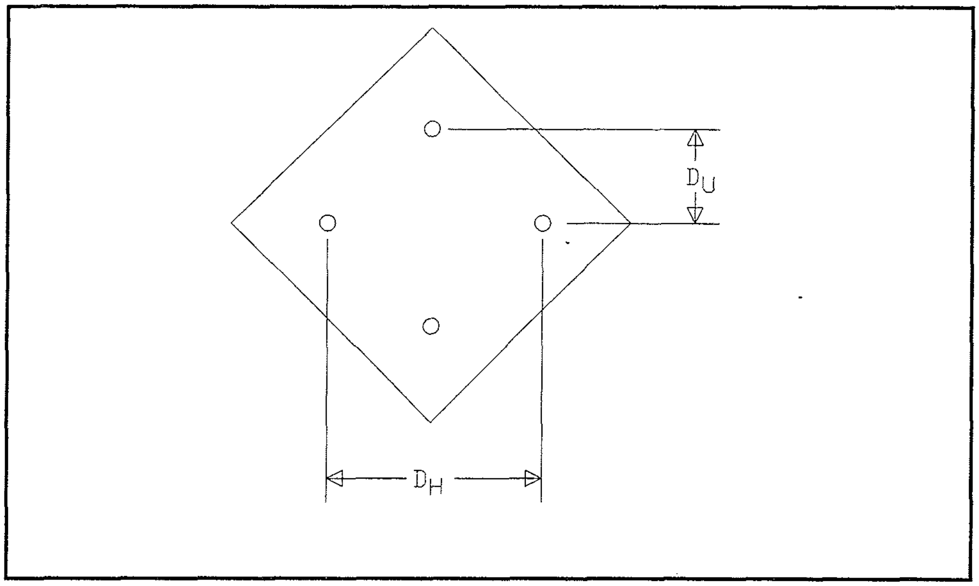

Figure 8. Schematic of core-loc placement grid

Table 2
Specifications for Placement Grid Coordinates

Volume (m^3)	$\leq 5\ m^3$	$6.3\text{-}12\ m^3$	$14\text{-}22\ m^3$
P. D. Coefficient, ϕ	0.60	0.56	0.54
D_H	$1.11C$	$1.15C$	$1.18C$
D_U	$0.55C$	$0.57C$	$0.59C$

During quality control inspections, the packing density should be checked by measuring out a control area (an area of 100-200 m^2 is typical) of the randomly placed armor units on the slope and counting the number of units within this area. This gives an estimate of the packing density *N/A*. Several overlapping control areas should be laid out and multiple counts made. Sometimes it is difficult to determine whether an individual core-loc is within the perimeter boundary of a control area. When counting units along the perimeter, if 50 percent or more of an individual core-loc is within the boundary, it should be included in the count.

5 Recommended Standard Core-loc Sizes

To provide efficient utilization of formwork, a need exists to standardize core-loc sizes. By doing this, an inventory of standard form sizes can be made available for projects around the world, thus reducing the need of building custom forms for each individual project. With standard sizing, forms can be reused. A single form, properly constructed and maintained, can be expected to last 10-15 years. The initial fabricators of core-loc forms benefit from the ability to sell or lease used forms. Future project owners benefit by purchasing or leasing used forms instead of fabricating new ones.

Tables 3 through 8 suggest standardized core-loc sizes with their associated geometric relationships, hydraulic stability capacity, and structural requirements. Standard sizes of core-loc range from 0.7-31.0 m^3. Table 3 shows the geometric relationship between the characteristic length *C* and the other basic dimensions of the standard core-loc sizes expressed in meters. A reference schematic accompanies the table. Table 4 provides surface area relationships for the standard sizes of core-loc units. This table is helpful in estimating the amount of steel sheeting required to construct formworks. Tables 5-7 show the hydraulically stable weight for core-loc units for a range of specific gravity between 2.18-2.66 for structure slopes of 1V:1.33H, 1V:1.5H, and 1V:2H, respectively. Table 8 provides information on packing density, layer thickness, and storage area requirement for the standard sizes of core-loc.

Table 3
Geometric Relationships of Standard Core-loc Sizes

Volume (m^3)	Basic Dimensions of Standard Core-loc Sizes (in meters) (from Figure 2)							
	C	A	B	D	E	F	G	J
0.7	1.46	0.26	0.53	0.94	0.36	0.26	0.73	0.47
1.4	1.85	0.33	0.67	1.19	0.46	0.32	0.93	0.59
2.4	2.20	0.39	0.79	1.41	0.55	0.38	1.10	0.70
3.9	2.59	0.46	0.93	1.66	0.64	0.45	1.29	0.83
6.2	3.02	0.54	1.09	1.93	0.75	0.53	1.51	0.97
8.5	3.36	0.60	1.21	2.15	0.83	0.59	1.68	1.08
11.0	3.67	0.66	1.32	2.35	0.91	0.64	1.83	1.17
15.4	4.10	0.73	1.47	2.62	1.02	0.72	2.05	1.31
20.8	4.53	0.81	1.63	2.90	1.12	0.79	2.26	1.45
31.0	5.17	0.93	1.86	3.31	1.28	0.91	2.59	1.66

Table 4
Surface Area Relationships of Standard Core-loc Sizes

Vol-ume (V in m^3)	Basic Area Dimensions of Standard Core-loc Sizes (m^2)								Total Area
	C	a	b	c	d	e	f	g	S_CL
0.7	1.46	0.05	0.06	0.10	0.04	0.05	0.03	0.07	5.78
1.4	1.85	0.09	0.09	0.16	0.06	0.08	0.04	0.12	9.29
2.4	2.20	0.12	0.13	0.23	0.09	0.12	0.06	0.17	13.06
3.9	2.59	0.17	0.18	0.31	0.12	0.17	0.09	0.23	18.08
6.2	3.02	0.23	0.24	0.43	0.17	0.23	0.12	0.32	24.61
8.5	3.36	0.28	0.30	0.53	0.21	0.28	0.15	0.39	30.55
11.0	3.66	0.34	0.36	0.63	0.25	0.33	0.17	0.46	36.25
15.4	4.10	0.42	0.45	0.79	0.31	0.41	0.22	0.58	45.32
20.8	4.53	0.51	0.55	0.96	0.38	0.51	0.26	0.71	55.36
31.0	5.17	0.67	0.71	1.26	0.49	0.66	0.35	0.93	72.31

Table 5
Hydraulically Stable Weight for Core-loc on 1V:1.33H Slope

Volume (V in m^3)	Typical Range of Specific Gravity (S_r)			Range of Hydraulically Stable Weight (W in tonnes)			Effective Wave Height Protection Trunk with K_D = 16 (H_s in m)		
	min	mean	max	min	mean	max	min	mean	max
0.7	2.18	2.42	2.66	1.5	1.7	1.9	2.7	3.3	3.9
1.4	2.18	2.42	2.66	3.1	3.4	3.8	3.5	4.2	4.9
2.4	2.18	2.42	2.66	5.2	5.8	6.3	4.1	5.0	5.8
3.9	2.18	2.42	2.66	8.4	9.4	10.3	4.8	5.9	6.9
6.2	2.18	2.42	2.66	13.4	14.9	16.4	5.6	6.8	8.0
8.5	2.18	2.42	2.66	18.5	20.6	22.7	6.3	7.6	8.9
11.0	2.18	2.42	2.66	24.0	26.6	29.3	6.8	8.3	9.7
15.4	2.18	2.42	2.66	33.5	37.2	40.9	7.7	9.3	10.9
20.8	2.18	2.42	2.66	45.2	50.2	55.3	8.5	10.2	12.0
31.0	2.18	2.42	2.66	67.5	75.0	82.5	9.7	11.7	13.7

Volume (V in m^3)	Typical Range of Specific Gravity (S_r)			Range of Hydraulically Stable Weight (W in tonnes)			Effective Wave Height Protection Head with K_D = 13 (H_s in m)		
	min	mean	max	min	mean	max	min	mean	max
0.7	2.18	2.42	2.66	1.5	1.7	1.9	2.6	3.1	3.6
1.4	2.18	2.42	2.66	3.1	3.4	3.8	3.2	3.9	4.6
2.4	2.18	2.42	2.66	5.2	5.8	6.3	3.8	4.6	5.4
3.9	2.18	2.42	2.66	8.4	9.4	10.3	4.5	5.5	6.4
6.2	2.18	2.42	2.66	13.4	14.9	16.4	5.3	6.4	7.5
8.5	2.18	2.42	2.66	18.5	20.6	22.7	5.9	7.1	8.3
11.0	2.18	2.42	2.66	24.0	26.6	29.3	6.4	7.7	9.1
15.4	2.18	2.42	2.66	33.5	37.2	40.9	7.1	8.6	10.1
20.8	2.18	2.42	2.66	45.2	50.2	55.3	7.9	9.6	11.2
31.0	2.18	2.42	2.66	67.5	75.0	82.5	9.0	10.9	12.8

Table 6
Hydraulically Stable Weight for Core-loc on 1V:1.5H Slope

Volume (V in m^3)	Typical Range of Specific Gravity (S_r)			Range of Hydraulically Stable Weight (W in tonnes)			Effective Wave Height Protection Trunk with $K_D = 16$ (H_s in m)		
	min	mean	max	min	mean	max	min	mean	max
0.7	2.18	2.42	2.66	1.5	1.7	1.9	2.8	3.4	4.0
1.4	2.18	2.42	2.66	3.1	3.4	3.8	3.6	4.4	5.1
2.4	2.18	2.42	2.66	5.2	5.8	6.3	4.3	5.2	6.1
3.9	2.18	2.42	2.66	8.4	9.4	10.3	5.0	6.1	7.1
6.2	2.18	2.42	2.66	13.4	14.9	16.4	5.9	7.1	8.3
8.5	2.18	2.42	2.66	18.5	20.6	22.7	6.5	7.9	9.3
11.0	2.18	2.42	2.66	24.0	26.6	29.3	7.1	8.6	10.1
15.4	2.18	2.42	2.66	33.5	37.2	40.9	8.0	9.6	11.3
20.8	2.18	2.42	2.66	45.2	50.2	55.3	8.8	10.7	12.5
31.0	2.18	2.42	2.66	67.5	75.0	82.5	10.1	12.2	14.3
Volume (V in m^3)	Typical Range of Specific Gravity (S_r)			Range of Hydraulically Stable Weight (W in tonnes)			Effective Wave Height Protection Head with $K_D = 13$ (H_s in m)		
	min	mean	max	min	mean	max	min	mean	max
0.7	2.18	2.42	2.66	1.5	1.7	1.9	2.7	3.2	3.8
1.4	2.18	2.42	2.66	3.1	3.4	3.8	3.4	4.1	4.8
2.4	2.18	2.42	2.66	5.2	5.8	6.3	4.0	4.8	5.7
3.9	2.18	2.42	2.66	8.4	9.4	10.3	4.7	5.7	6.7
6.2	2.18	2.42	2.66	13.4	14.9	16.4	5.5	6.6	7.8
8.5	2.18	2.42	2.66	18.5	20.6	22.7	6.1	7.4	8.7
11.0	2.18	2.42	2.66	24.0	26.6	29.3	6.7	8.0	9.4
15.4	2.18	2.42	2.66	33.5	37.2	40.9	7.4	9.0	10.6
20.8	2.18	2.42	2.66	45.2	50.2	55.3	8.2	9.9	11.7
31.0	2.18	2.42	2.66	67.5	75.0	82.5	9.4	11.4	13.3

Table 7
Hydraulically Stable Weight for Core-loc on 1V:2H Slope

Volume (V in m^3)	Typical Range of Specific Gravity (S_r)			Range of Hydraulically Stable Weight (W in tonnes)			Effective Wave Height Protection for Trunk with K_D = 16 (H_s in m)		
	min	mean	max	min	mean	max	min	mean	max
0.7	2.18	2.42	2.66	1.5	1.7	1.9	3.1	3.8	4.4
1.4	2.18	2.42	2.66	3.1	3.4	3.8	4.0	4.8	5.6
2.4	2.18	2.42	2.66	5.2	5.8	6.3	4.7	5.7	6.7
3.9	2.18	2.42	2.66	8.4	9.4	10.3	5.5	6.7	7.9
6.2	2.18	2.42	2.66	13.4	14.9	16.4	6.5	7.8	9.2
8.5	2.18	2.42	2.66	18.5	20.6	22.7	7.2	8.7	10.2
11.0	2.18	2.42	2.66	24.0	26.6	29.3	7.8	9.5	11.1
15.4	2.18	2.42	2.66	33.5	37.2	40.9	8.8	10.6	12.4
20.8	2.18	2.42	2.66	45.2	50.2	55.3	9.7	11.7	13.8
31.0	2.18	2.42	2.66	67.5	75.0	82.5	11.1	13.4	15.7
Volume (V in m^3)	Typical Range of Specific Gravity (S_r)			Range of Hydraulically Stable Weight (W in tonnes)			Effective Wave Height Protection for Head with K_D = 13 (H_s in m)		
	min	mean	max	min	mean	max	min	mean	max
0.7	2.18	2.42	2.66	1.5	1.7	1.9	2.9	3.5	4.2
1.4	2.18	2.42	2.66	3.1	3.4	3.8	3.7	4.5	5.3
2.4	2.18	2.42	2.66	5.2	5.8	6.3	4.4	5.3	6.2
3.9	2.18	2.42	2.66	8.4	9.4	10.3	5.2	6.3	7.3
6.2	2.18	2.42	2.66	13.4	14.9	16.4	6.0	7.3	8.6
8.5	2.18	2.42	2.66	18.5	20.6	22.7	6.7	8.1	9.5
11.0	2.18	2.42	2.66	24.0	26.6	29.3	7.3	8.9	10.4
15.4	2.18	2.42	2.66	33.5	37.2	40.9	8.2	9.9	11.6
20.8	2.18	2.42	2.66	45.2	50.2	55.3	9.0	10.9	12.8
31.0	2.18	2.42	2.66	67.5	75.0	82.5	10.3	12.5	14.7

Table 8
Volume and Area Requirements of Standard Core-loc Sizes

Standard Volume	Volume of Concrete per m² of slope facing (m^3/m^2)			Layer Thickness	Area required to store row of 10 C-L
(m^3)	ϕ = 0.54	ϕ = 0.56	ϕ = 0.60	(m)	(m^2)
0.7			0.53	1.3	7.6
1.4			0.68	1.7	9.7
2.4			0.80	2.0	11.5
3.9			0.94	2.4	13.5
6.2		1.03		2.8	15.8
8.5		1.14		3.1	17.6
11.0		1.24		3.4	19.1
15.4	1.34			3.8	21.4
20.8	1.48			4.2	23.6
31.0	1.69			4.8	27.0

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13. ABSTRACT *(Maximum 200 words)*

This report provides technical guidelines for a new type of concrete armor unit called CORE-LOC™ (hereafter referred to as core-loc), which was developed and patented worldwide by the U.S. Army Engineer Waterways Experiment Station. Information is provided on core-loc geometry, stable weight estimation, armor layer thickness, and armor layer packing density. The use of core-loc as a repair unit for dolos armoring is discussed. Fabrication guidelines are provided, including a discussion of American standards for concrete, cement, and aggregates. Recommended standard core-loc sizes are discussed and tables are provided that suggest standardized core-loc sizes with their associated geometric relationships, hydraulic stability capacity, and structural requirements.

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